Analysis of quench propagation using coupled electrical-thermal FEM model

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Abstract. The 2D and 3D FEM (Finite Element Method) dynamical model of quench is the aim of the paper. It is based on a coupled electrical-thermal model. The small grain of non-superconducting impurity existing inside of superconducting wire initiates quench in the model. Nonlinear, temperature dependent electrical and thermal parameters are assumed. The quench propagation is modelled with the sequential coupled electric thermal analysis resulting in its 3D dynamics. The dynamics is expressed by spatial distribution of current, Joule heat and temperature. The modelling is carried out for low temperature NbTi wire and high temperature BiSCCO-2223 tape under sinusoidal current excitation and self magnetic field. Obtained computational results can be taken as a tool for optimisation for superconducting wire structure and improvement of quench protection systems in superconducting applications.

1. Introduction
The quench phenomenon in superconducting wires and devices is an extremely important problem. Very high energies delivered in the wire or device in a very short period of time are dangerous and destructive. Because experiments on quench phenomenon are expensive (single setup for single test), therefore computational analyses and simulations are excellent means for this research. What is more, computational analysis allows one to reconstruct even those variables that cannot be measured.

Much work was devoted to quench phenomenon (theory, calculations and measurements). The most important are papers focusing on modeling quench phenomenon using FEM (Finite Element Method). These papers are devoted to both, wires [1], [2] and devices [3], [4]. Authors of these papers use two different types of software, COMSOL [2] and ANSYS [1], [3], [4]. A majority of these papers are based on standard finite elements built-in solvers. Only authors of paper [1] decided to modify existing electrical-thermal element of ANSYS, that is based on given formulas. They did it in order to use resistivity vs. current density characteristic, and did not report on advantages of their approach. ANSYS software can be applied for electromagnetic analysis [5]. The current density and magnetic flux density are the results. The electromagnetic field can be easily coupled to the thermal field by Joule heat using multifield solver. Authors of this paper apply coupled electrical and thermal analysis to modeling quench phenomenon in 2D and 3D dynamic (transient) analysis. The analysis was carried out using ANSYS v. 12 software with its new feature – multifield analysis.
2. Motivation
The quench propagation using coupled electrical – thermal ANSYS FEM model is the aim of the paper. The model realizes multifield analysis. Many papers on quench propagation modeling focuses only on thermal phenomenon. In order to use the software efficiently the Authors used a fully coupled thermal – electromagnetic transient model. The analysis is presented by means of two different examples. The first one is an example of axial symmetry (wire with circular cross-section) while the symmetry of the second example is planar (tape – rectangular cross-section). The first case could be modeled as 3D or 2D. Calculations based on 2D model result in increased modeling accuracy and reduced time consumption in comparison with a 3D model. In the second example of planar symmetry could be calculated using only 3D. An important point in such an analysis is accuracy. It was estimated by results when the dimension of elements were reduced.

3. The coupled electrical – thermal model
The computational model of quench propagation is based on transient nonlinear multifield analysis. In this paper two fields were taken into consideration, electrical (current flow) field and thermal field. In each step of transient analysis, the Joule heat generation was calculated as a result of ohmic power losses, that was then applied in thermal analysis as a source of heating. The exciting source is a lumped current source connected to the FEM model of the wire. Both analyses are nonlinear because the material properties are the function of temperature [6]. Additionally, resistivity is dependent on critical current and is included in advanced programming procedures (APDL - ANSYS Parametric Design Language).

Calculations were carried out according to the flow chart given in Fig. 1. It starts with all the necessary data, ambient temperature $T_{\text{amb}}$, load current $I_{\text{load}}$ and initial resistivity $\rho(T_{\text{amb}})$. Then the current density distribution ($J=f(T, \rho)$) is calculated. If the current is over critical current ($J>J_c$) the resistivity is modified to normal state resistivity ($\rho=f(J_c)$ – Bean model). If NO then the next step is calculation of power losses ($P=f(J, \rho)$) that is applied as the load in thermal calculations. Each step is repeated until the final time ($t_{\text{max}}$) is reached. The final results are current and temperature distribution obtained in each step of the calculation.

![Figure 1. Flow chart of FEM calculations](image)

3.1. Description of input parameters
Modeling of quench propagation requires some characteristics of materials that are temperature and current dependent [6]. They are: electrical resistivity of superconductor ($\rho=V=|f(I)|$), thermal conductivity $\lambda=f(T)$, specific heat $c_p=f(T)$ and heat removal coefficient $h$. From $V=f(I)|T$ the critical current $J_c$ is derived. No dependence of the critical current density has been used.
3.2. Details of computational model

The computational model was created using APDL of ANSYS ver. 12. The model for transient multifield analysis is made of PLANE230 element for the electric (conducting) field and PLANE 55 for the thermal field in 2D model. The 3D model was created using SOLID 231 and SOLID 70, respectively. The model contains also CIRCU 124 element, which enables one to choose any waveform of the current or voltage which are loads for wire. Two example of such waveforms generated by CIRCU 125 are shown in Fig. 2 [9]. The CIRCU 124 is part of the circuit analyzer.

Figure 2. Example waveforms of current generated by CIRCU 124 element of ANSYS

The sequel of the section is devoted to two different models, 2D of NbTi and 3D of Bi-2223/Ag. The first model (2D of NbTi wire) is the model with axial and also planar symmetry. The filaments are modeled as “stranded wires”. The geometry of the model is shown in Fig. 3. The idea of using 2D for modeling 3D physical object is shown in Fig 3. The axial symmetry is based on axis 2 and planar symmetry is based on plane 3.

Figure 3. The idea of using 2D for modeling 3D physical object
1 – area of 2D model, 2 – axis of axial symmetry, 3 – plane of planar symmetry; violet – superconducting region, blue – Cu region, red - clamps

The second model was 3D model of Bi2223/Ag tape. It is shown in Fig. 4. In this case the tape was modeled with a monofilament with 4 mm x 1.6 mm cross-section area. The geometry of the tape was simplified to rectangular in cross-section. The tape contains an impurity of Ag in the middle. Material parameters of model are similar to parameters of 2D model (Bi instead NbTi, Ag instead Cu and LN2 instead LH2). The parameters of the current source are the same as in 2D model.
4. **2D modeling and simulations of the quench propagation in NbTi wire**

Modeling of NbTi wire was carried out using 2D transient ANSYS model with the geometry given in Fig. 3. The wire was excited by sinusoidal current (single pulse of half period of sinusoidal waveform was taken into consideration). Calculations were carried out for different amplitudes of current. Results, such as current density, voltage and temperature distribution were determined before and after the quench. Selected results are presented in subsection 4.2 and 4.3.

4.1. **Assumptions**

The analysis of NbTi wire were carried out under the following assumptions.

i) the analysis was carried out for NbTi wire OK3900 type with outer diameter 575 μm and length 2 mm; inner and outer diameter of NbTi matrix in the wire were 245 and 483 μm respectively [7],

ii) the wire was loaded by the single sinusoidal pulse 4 ms duration (frequency of current 125 Hz) and given amplitude,

iii) heat removal coefficient for wire to ambient fluid flow was assumed as temperature dependent and determined using experimental data,

iv) the mesh density was homogenous with the maximum element size 10 μm

v) time step for nonlinear analysis was 20 μs.

The details of geometry and symmetry of the model were described in subsection 3.2.

4.2. **Results of superconducting state**

Analysis of superconducting state was carried out with the current of single sinusoidal pulse of amplitude 273.55 A and 4 ms. The current is close to the critical one. Voltage and current waveforms are depicted in Fig. 5. The shape of voltage waveform is the same like temperature waveform (the latter one is not given in Fig. 5). The maximum value of voltage (and temperature) occurs slightly delayed in respect to the maximum of current. It is the result of thermal capacity of superconducting wire. Density and direction of the current in the wire for 2 ms shown in Fig. 6. Temperature distribution (in Kelvins) for the same instant of time 2 ms presented in Fig. 7. In Fig. 6 the current density is lower in the vicinity of clamp (right bottom) and it is caused by the clamp. The influence of the clamp on the temperature distribution is also observed in Fig. 7 which is visible in upper right corner.
4.3. Results of calculations after the quench

The quench for the axial symmetrical model was reached for amplitude of current 273.58 A. The current and voltage waveforms are shown in Fig 8. After the quench the current distribution changes and the current flows in the outer part of the copper region – Fig. 9. That is because resistivity of copper is lower than NbTi that is in normal state. Also low current density can be observed in the inner part of the copper region.

Figure 5. Voltage across NbTi wire for single current pulse (non-quenched state)

Figure 6. Current density distribution and its direction for maximum value of current (at time 2 ms)

Figure 7. Temperature distribution at 2 ms in superconducting state

Figure 8. Voltage across NbTi wire for current pulse (after the quench at 2.2 ms)

Figure 9. Current density distribution and its direction after the quench occurs (at time 2.4 ms)
The distribution of current density influences the temperature distribution. Because of the current flow in the outer part of the copper region the temperature of the inner part of the copper region is lower near the clamps. The temperature influences also voltage distribution. The voltage across the wire is shown in Fig. 10 in two cases, before the quench and after the quench.

5. **The quench in Bi-2223/Ag tape – 3D modeling and analysis**

Analysis of Bi-2223/Ag tape [7] is carried out in order to illustrate how quench appears in tape containing impurity. Non-superconducting grain impurity (1 x 0.8 mm) is in the middle of the tape. Because of a decreased cross-section of superconductor density of flowing current is higher in this region. The distribution of current density before the quench (at 1.5 ms) is shown in Fig. 11. The closer to critical current the faster the transient quench is. The hot-spots are located in the vicinity of the impurity – Fig. 13. The temperature after the quench (at 1.55 ms) is shown in Fig. 14. After the quench current flows in Ag matrix in normal state – Fig. 12.
6. Conclusions

The following conclusions come from the analysis:

i) The behavior of the quench phenomenon was modeled and analyzed

ii) The obtained FEM model allows one to use it in defining safe and reliable operation limits of superconducting wires, tapes and devices as well as reliable operation of quench protection systems.

iii) The model can be improved by considering the dependence of \( J_c \) on the magnetic field.

iv) It is possible to use the model for constructional optimization of the superconducting wire structure.

v) The obtained model can be applied for measurements, especially those variables that are not accessible what can be also utilized as a tool for inverse engineering.

vi) It is possible to simplify (2D instead of 3D) the FEM model in case the model exhibits axial or/and planar symmetry.

vii) It is necessary to note that presented models need experimental validation.

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