..... 2006

Applied Superconductivity



Integrated Electro-Thermal Model for Quench Simulation in YBCO Tapes.

Philippe Masson Marco Breschi Cesar Luongo







FAMU/FSU College of Engineering Center for Advanced Power Systems University of Bologna





Outline

- Tape configurations and physical properties
- Problem statement
- Quench process in YBCO 2G conductors
- Existing models in the literature and their limitations
- Effect of current diffusion on quench dynamic
- From tape to device quench modelling
- Key parameters
- Proposed improved model
- Preliminary qualitative results and future work



American Superconductor - Tape Configurations



• Physical properties strongly dependant on temperature

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE



Other Configurations

- Major manufacturers are American Superconductor, Sumitomo, EHTS, THEVA
- All have different configurations in terms of:
 - Layer thickness
 - Stabilization layer
 - Current density
- Maximum length achieved is 322 m by Sumitomo



typical configuration 1



Typical configuration 2



EHTS Tapes Available

EHTS	YBCO Coat	ted Tapes	mail	4-
		YHT-HC standard tape for high current densities	YHT-HC tape with optimized quench behavior	YHT-HC tape with high 2D-homogeneity
architecture	Substrate	stainless steel, thickness 100 µm or 50 µm		
	HTS film	YBCO, thickness 0.5 3 µm		
	protection layer	silver or gold, thickness 0.2 µm		
	Cu shunt layer	20µm thick	-	on request
electrical properties	engineering current density	300 1000 A/mm²		
@// K, UT	critical currents	135 A in 4 mm wide tape 350 A in 10 mm wide tape 1000 A in 40 mm wide tape		ape ape ape
mechanical properties	axial tensile strength	650 MPa		
(critical values	critical bending radius	9 mm		1 1 1 1 2 3
@ 300 K)	critical torsion	30 ang. deg. per cm-length (4m wide tape @ 40N axial force		h-length (4mm Naxial force)
typical dimensions	thickness	0.105 mm or 0.05 mm		nm
	width	1111	4, 10 or 40 mm	SHE
	unit lengths	4	0 m @ 4mm wide t	tape







The Problem

- Why is quench a problem in 2G wires?
 - Normal zone propagation velocity too slow 1-10 mm/s
 - Hot spot T could be very high and destructive
 - Non uniformity of material properties
 - Not yet well understood
- Stabilization and quench protection are VERY important
 - Quench development appears to be a 3D phenomenon from experiment (because it is so slow that turn to turn diffusion matters)
 - Need 3D simulation tool to analyze quench and develop protection schemes



Problem: quench propagation in 2G tapes



Buffer is highly resistive: how much current goes into Ni layer?



Existing Models

- Chyu Oberly first study (1990)
- Iwasa 1D steady state
- Fu 1D lumped circuit no magnetic coupling
- Ishiyama 1D current sharing
- Iwasa copper stabilized
- Vysotsky scaling theory

Existing Models (2)

- Stadel electrical field distribution due to hot spot
- No electrical breakdown to be expected



Figure 1. Cut-Out of simulated allocation of the electrical field in the model. The dimension of the electrical field is given in V/m.



Existing Models (3) : 1-D PDE

$$C_{avg}(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right) + Q_j - Q_c$$

$$Q_j = \begin{cases} 0 & I < I_c \\ \left(\frac{\rho}{A}\right)_m \frac{I}{A_t}I_m(T) & T < T_c, I > I_c \end{cases}$$

$$\left(\frac{\rho}{A}\right)_m \frac{I^2}{A_t} & T > T_c \end{cases}$$

One dimensional model Temperature uniform across the tape Nickel and silver in parallel Simple formula for the joule loss

 OR. C. Duckworth et al., "Quench dynamics in silver coated YBCO tapes", Proc. ICMC, Vol. 48, 2002



- Solder only considered for the transverse resistance
- Silver and copper not in parallel
- Inductive effects negligible

Section (i-1) -Section (i+1)-Section i YBCO $I_{s}(i+1)$ $I_{s}(i-1)$ $I_{s}(i)$ RA.(i+1) RA.(1-1) RAS(i) $I_{Ag}(i)$ Silver layer Rs.(i+2) $R_{so}(i+1)$ Rso(i Solder Is.(1) In(i+1) Iso(i+2) Rca (i-1) R_{Cu}(1 $R_{\alpha}(i+1)$ I_{Ca}(i) Copper lave In(i-1)

 Y. Fu, O. Tsukamoto, M. Furuse, "Copper stabilization of YBCO coated conductor for quench protection", IEEE Trans. Appl. Supercond., 2003

- Uniform temperature along the tape
- Power law for the superconductor
- Based on equilibrium theory
- Analytical solution relative to the tape heating



A. L. Rakhmanov, V. S. Vysotsky, Y.A. Ilyin, T. Kiss, M. Takeo, "Universal scaling law for quench development in HTSC tapes", Cryogenics 40, 2000

- Lumped electrical parameters model coupled with a discrete (electrical equivalent) thermal model
- Tape uniform along the length
- Tape divided into N_L layers and N_s sectors along the length
- Each layer sector has different thermal and electromagnetic properties
- Electrical coupling through electrical contact resistances and mutual induction coefficients
- Thermal coupling through thermal contact resistances
- Joule losses and temperature dependent properties link the two models



N-layer tape: lumped parameters electrical circuit model Inductive



Models Comparison with Experiments



lwasa et Al.



Ishiyama, et Al.

- Temperature simulations are accurate
- Large discrepancies for voltage



Conclusion on Models

- Presented models have been validated on dedicated experiments
- Current models cannot predict quench or recovery
- Tape is considered equipotential which is not the case in reality
- Models are limited to single tape



• Need to do better.





Typical Tape Configuration

	Tape length	(cm)	14
Cu	Tape width	(cm)	1
	d_cu	(µm)	50
A a	d_ag	(µm)	3
Ag	d_YBCO	(µm)	1
Buffer layers	d_Ni	(µm)	75
Ni allov	Ic (77 K)	(A)	146
	n (77 K)		21

	Material	Cp (J/m ³ .K)	K (W/K)	ρ (kg/m ³)	μ/μ₀	σ (Ω.m)
30 K	Copper	65	1.5 e+6	8960	1	7.8 e-9
	Silver	80	0.7 e+6	10490	1	7.55 e-9
-	Ni	30	0.4 e+6	8880	1240	2.5 e-8

	Material	Cp (J/m ³ .K)	K (W/K)	ρ (kg/m ³)	μ/μ ₀	σ (Ω.m)
77 K	Copper	230	0.6 e+6	8960	1	8.6 e-9
	Silver	170	0.45 e+6	10490	1	8.31 e-9
	Ni	150	0.2 e+6	8880	1240	2.8 e-8



Diffusivity and Time Constants

If homogeneous material considered for each layer
 – Thermal:



CENTRE NATIONAL DE LA RECHERCHE

• How do they compare?

• Diffusion time constants

	Material	Thermal diffusivity	Electromagnetic diffusivity	Thermal time constant	Electromagnetic time constant
	Copper	2.58	6.21 e-3	9.71 E-10	4.03 E-7
30 K	Silver	0.834	6.01 e-3	1.08 E-11	1.5 E-9
	Nickel	1.5	1.6 E-5	3.75 E-9	3.51 E-4

77	Κ

Material	Thermal diffusivity	Electromagnetic diffusivity	Thermal time constant	Electromagnetic time constant
Copper	0.291	6.84 E-3	8.59 E-9	3.65 E-7
Silver	0.252	6.61 E-3	3.57 E-11	1.36 E-9
Nickel	0.15	1.8 E-5	3.75 E-8	3.13 E-4

Time constants almost independent from temperature

Normal zone propagates at a few mm/s



Diffusion occurs in Ni layer and has to be taken into account



NZP Velocity



• Normal zone velocity in the same order of magnitude as current diffusion in Nickel layer !



Effect of Current diffusion (3)

• If model is 2D and tape considered infinite, how does current go into the Ni layer?



Current diffused in Ni layer much slower than in copper

- Current diffusion in Nickel has to be taken into account
- At beginning of quench, current can not develop in Ni and dissipates more losses than expected



Proposed Model for FEA Simulations

- FEA simulation
 - YBCO layer considered as a boundary condition
 - YBCO layer considered to have infinite resistance when T increases
 - Current diffusion in Ag and Cu neglected
 - Current diffusion in Nickel taken into account



Preliminary Qualitative Results

- Experiments show that current transfers on longer lengths into substrate
- This can only be explained by diffusion



- Typical sampling time in experiment around 1 ms
 Snapshot at t=1ms shows that current
- redistribution has already happened
- What happens before?
- What is driving the quench?



Edge Effects in Quench Development

• Layers may be in contact on the side



Current is forced in to Cu and Ni layers Current cannot diffuse fast into Ni More heat generated in copper while current goes "slowly" in buffer

Problem is not 2d but 3d (even for single tape)



From Tape to Device

- Quench in a coil will be different than in an isolated tape sample:
 - Magnetic coupling between winding layers
 - Heat transfer from one layer to another
- Quench simulation in coils is required to develop protection systems





Quench propagates in 3D by heat transfer and magnetic coupling between layers



Key Parameters

- Thermal and electrical characteristics of each of the materials forming layers
- Electrical contact resistance between layers
- Thermal contact resistance between layers
- Thermal and electrical diffusivity vs. temperature





• This implies to develop model with the help of experimental data



Promising Techniques to Speed Up Quench Propagation



- Implement contacts to force current to go into substrate
- Current density is increased at contacts thus generating more heating

Switching and quench propagation in coated conductors for fault current limiters, W. Prusseita, H. Kindera, J. Handkea, M. Noeb, A. Kudymowb, W. Goldackerb, Presented at ISS 2005, Tsukuba, Japan, 24.-26.10.2005



Conclusion and Future Work

- LTS protection techniques do not work. Need 3D model to develop transition protection
- Current diffusion in the substrate may have an important role in quench dynamics
- Contacts on side between layers have to be taken into account and require a 3D model
- Model development needs to be closely linked to experimental testing
- Tape model cannot be applied to quench propagation in devices. 3D approach is required to simulate interaction between layers

