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Towards the design of power switches utilizing HTS material

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Abstract. Conventional superconducting switches for power applications, which operate at liquid helium temperature, generally utilize Nb-Ti superconductor in a cupro-nickel matrix. For superconducting circuits based on High Temperature Superconductors (HTS) that work at higher temperatures, the associated superconducting switches must also be based on HTS. This paper addresses the issues concerning the requirements and the appropriate design of HTS switches, including approaches to fast triggering.

1. Introduction

Conventional superconducting switches for power applications which operate at liquid helium temperatures generally utilize Nb-Ti superconductor in a cupro-nickel matrix [1]. For superconducting circuits based upon High Temperature Superconductors (HTS) that work at higher temperatures the associated superconducting switches must also be based on HTS. So far most HTS based switches are either of the fault current limiter type [2], which are generally switched by over current [3]; or they are of the slower acting persistent current type such as those used in NMR magnets [4]. There are very few fast acting high power switches that could be used for energy extraction from superconducting magnets. However, there have been prior attempts to make LTS switches of this type, for example a thermally triggered switch for the Very Large Hadron Collider [5]. This paper addresses the issues concerning the requirements and appropriate design of HTS switches, including approaches to fast triggering, culminating in the manufacture and test of a thermally activated 60 A switch, which is operated at 77 K and undergoes transition in a few milliseconds.

HTS switches can be triggered by exceeding, either individually or as a combination, the critical values of current, temperature, or magnetic field; or indeed by mechanical means. Mechanical switches can be made to carry super currents [6] but are limited by the complexity of moving parts at cryogenic temperatures, as well as by arcing and breakdown of the contacts [7]. Thermally activated switches can require considerable heater power to raise the HTS above the critical temperature (Tc) in the required time. Switching via the quench propagation velocity alone is too slow as it is in the order of 1-3 cm/s for an adiabatic switch. Magnetically triggered switches require the excitation of a coil, which in itself may be slow, or the movement of the field relative to the crystallographic axis. Overcurrent switches, where the critical current (Ic) is exceeded, are limited by the electrical circuit

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that the switch is integrated within and also by any latching requirements. For this work, the switch transition is caused by a heater pulse as this can give switching times <10 ms virtually irrespective of the electrical circuit it is contained within, yet is also a less complex method to implement.

2. Material properties

In order to design a superconducting device, both the thermophysical and electromechanical properties of the material must be known. The thermophysical properties are the temperature dependant specific heat, thermal conductivity, normal state resistivity, and critical current; the electromechanical properties i.e. the degradation of critical current with strain must be well known in particular due to the brittleness of HTS material. Materials with potential for switch applications were tested at the University of Southampton (UoS) and also at CERN. The HTS materials that were tested are: YBCO tape stabilised with copper (YBCO-Cu) [9], and with stainless steel (YBCO-SS) [9] both provided by AMSC, MgB_2 with nickel, copper, and iron (MgB_2-Ni/Cu/Fe) [10] provided by Columbus, and BSCCO in a silver-gold alloy matrix (BSCCO-Ag/Au) provided by EHTS [11] and AMSC [9]. The specific heat, thermal conductivity, and resistivity (linearly extrapolated beneath Tc) of YBCO-Cu, YBCO-SS, and MgB_2-Ni/Cu/Fe were measured at the UoS with data recorded at a minimum of 30 points from 4.2 – 300 K; resolution was increased around regions of change of material properties.

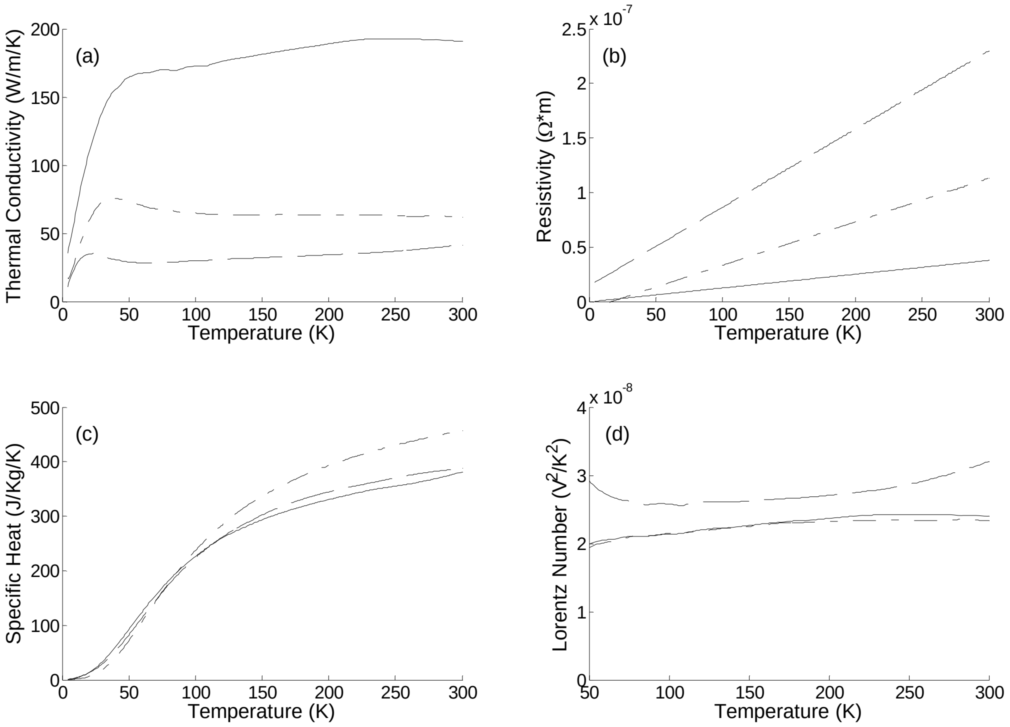

Figure 1: (a), (b), & (c) show measured thermophysical properties; (d) shows calculated Lorentz numbers. Solid lines represent YBCO-Cu, dashed lines YBCO-SS, and dash-dot lines MgB_2-Ni/Cu/Fe.

The measured values differ from those that can be computed from the material composition and the thermophysical properties of the constituents. This is due to the unknown purity of the materials used in the tapes, reaction layers at the material interfaces, and the possibility of voids in the MgB_2 and BSCCO due to incomplete compaction during manufacture. The measured thermal conductivity of MgB_2-Ni/Cu/Fe was found to be ~ 20 % lower than that measured on similar tapes [10]. The critical temperature of both YBCO-Cu and YBCO-SS was measured to be 89 K, for the MgB_2 it was measured to be 39 K. In the range 50-300 K the tested materials follow the Wiedmann-Franz law, with the Lorentz number being $2.29 \times 10^{-8} \pm 0.28$ V^2/K^2 for YBCO-Cu, $2.74 \times 10^{-8} \pm 0.46$ V^2/K^2 for the YBCO-SS, and $2.25 \times 10^{-8} \pm 0.31$ V^2/K^2 for MgB$_2$-Ni/Cu/Fe. YBCO-Cu and YBCO-SS show similar specific heat characteristics due the large volume fraction of the nickel alloy substrate, the small variation is due to the difference in the material and volume fraction of the laminations.

The degradation of Ic with strain applied at 77 K, was measured at CERN and the UoS. The strain which causes a 5 % degradation in the Ic being as follows: YBCO-Cu (0.4 % in axial compression, 0.7 % in bending), YBCO-SS (0.4 % in axial compression, 0.5 % in bending), and BSCCO in Ag matrix with stainless steel reinforcement (0.4 % in axial tension, 0.1 % in axial compression, and 0.5 % in bending) these measurements are in good agreement with data from NIST [12] and manufacturers' data. The measured and published data were used for the modelling of the switch.

3. Model

The suitability of different HTS materials for use in power switches has been evaluated. For initial comparison of adiabatic switches, where quench propagates along the material's length, the minimum quench energy (MQE), minimum propagation length (MPL), and the quench propagation velocity (QPV) have been computed. For the case of simultaneous global quench, where the transition occurs along the whole length of the switch at once, the required energy has been computed. Table 1 presents these quench parameters for HTS materials carrying 0.9 Ic at 77 K.

Table 1: Quench parameters for HTS tapes operating adiabatically at 77 K.

Material	MPL (mm)	MQE (mJ)	QPV (mm/s)	Energy to raise from 77 K to Tc (J/m)	Ic @ 77 K (A)	Tc @ 0 A (K)
YBCO-SS	1.13	13.8	23	12.2	60	89
YBCO-Cu	8.38	143	18	17.1	70	89
BSCCO-Ag/Au	6.66	225	14	33.7	85	110

To fully describe the transition of a thermally activated switch the heat equation in its second order, non-linear partial differential equation (PDE) form, with temperature dependant material properties, has been solved numerically on MatLab via second order spatial discretization [13] to an ordinary differential equation which is then solved using numerical differentiation formulas, the coordinates were constrained to one spatial direction and time.

The PDE model allows switches comprising of HTS tape, insulation, and heating elements to be simulated. This model includes current sharing between the superconductor and its stabilization, which is calculated as a function of the normal state resistance of the superconducting tape and its critical current temperature dependence. Both the transport current and heater current are time variant to mimic their associated electrical circuits and temperature dependant cooling is also included. However, the main limitation of the model is the use of the axial instead of transverse thermal conductivity for the simultaneous axial quench simulation. The PDE model was verified by comparison with QPVs which were measured in a dedicated set-up at CERN. The modelled QPVs, the experimental results, and the quench induced burnout, compared well to each other and similar experiments carried out on YBCO-Cu at national high magnetic field laboratory, Florida [15].

The analyses showed that, when thermally triggered, the only way to achieve switching in a few milliseconds is by simultaneous axial quench. In order to compare the effect of different HTS materials for use as switches YBCO-Cu, YBCO-SS, and BSCCO-Ag/Au were modeled with a constant transport current of 60 A, adiabatic cooling, a heater generating 100 J in 1 ms, and 12 μm thick polyimide insulation between layers. In addition to this the effects of different thicknesses of insulation and heater were investigated, as were different cooling and heater parameters. The PDE model output temperature profiles, resistances, and switching times.

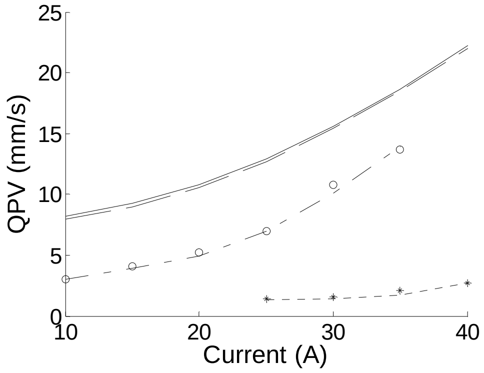

Figure 2: Calculated and measured QPVs for YBCO-SS with different transport currents and cooling. The solid line represents the PDE model with no cooling and a 3.6 W heater, dashed line 3.2 W; dash dot line with low cooling and lower heater power, dotted line with high cooling and higher heater power. Circles represent measured data for YBCO-SS with low cooling and a 3.2 W heater; stars represent measured data for YBCO-SS with high cooling and a 3.6 W heater.

Different switches based on the three HTS materials show similar temperature profiles due to the dominance of the heater over this timescale (0-5 ms). The rapid temperature rise of the heater during its pulse leads to an initially high (~100 K) thermal gradient through the insulation. Due to the thinness of the polyimide tape, the thermal energy is rapidly transferred into the rest of the switch, with only a ~10 K thermal gradient through the switches after 5 ms. The higher resistance of the YBCO-SS does not cause a faster transition due to increased ohmic heating as the generated energy is dominated by the heater. However, the resistance of the tape after transition initiation is much higher for the YBCO-SS making it more suitable for use as a switch. The model has shown that under adiabatic conditions, the transport current must decay within 1 s to prevent damage to the tape with the fastest temperature rise (YBCO-SS) due to limitations in the tapes' manufacture (section 4).

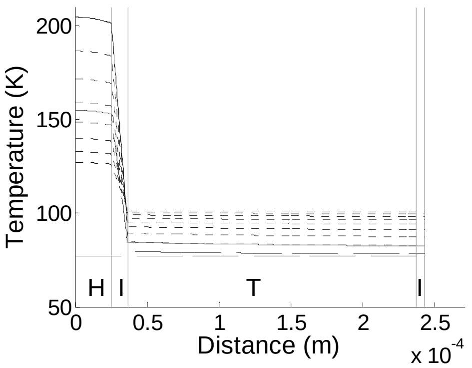

Figure 3: Temperature at 0.5 ms intervals through the switch. Dashed lines represent temperature whilst the heater is on, dotted lines when it is off. The solid line is at the instant the heater turns off. The vertical lines bound regions of the switch with H representing the heater, I insulation, and T YBCO-Cu tape.

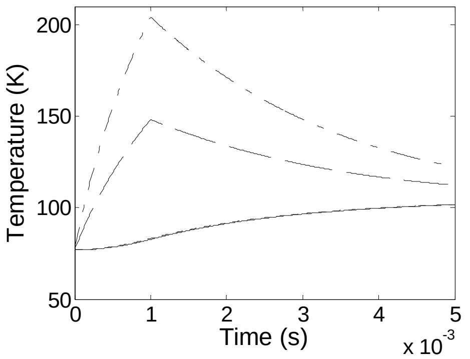

Figure 4: Temperature profiles at the mid point of the: heater (dash-dot line), the insulation between heater and HTS (dashed line), the YBCO-Cu (dotted line) and the insulation between HTS layers (solid line).

The YBCO-SS based switch has both the fastest rate of resistance increase and the highest normal state resistance, making it a strong candidate for power switch applications. Under these operating conditions the time to initiation of transition is predominately governed by the switches' stability margin, of which YBCO-SS has the lowest. BSCCO-Ag/Au has both a higher normal state resistance and stability margin than YBCO-Cu making it more suited to switch applications.

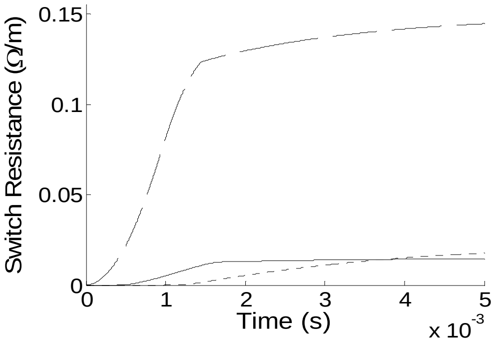

Figure 5: Comparison of modelled switch resistances as a function of time. The solid line represents a switch made of YBCO-Cu, dashed line a switch of YBCO-SS, dotted line a switch of BSCCO-Ag/Au.

4. Design and manufacture

The switch was a multilayer spiral coil containing non-inductive bifilarly wound HTS tape, a coiled resistance heater, and polyimide insulation. The HTS section comprised of two lengths of tape, of total length 2 m and which were soldered over 50 mm at one end. The heater was a stainless steel strip. Epoxy coated polyimide (12 μm thick) was used between each layer to provide insulation and mechanical support. The strands were wound around a 100 mm diameter stainless steel cylinder which acted as a mandrel, mechanical support, and, during operation, a cold finger. The voltage taps, heater current leads, and transport current leads were attached by means of terminals formed of 0.2 mm thick copper sheets, which were soldered to the relevant switch element; the instrumentation, or current, wires were then soldered to these terminals. The YBCO tapes' layers were soldered at 170 °C by the manufacturer and so to ensure the tape did not delaminate during manufacture of the switch, subsequent soldering was performed at 160 °C with 99.99% pure indium. Joint resistances were measured at 77 K in self field to be 213 nΩ/cm^2 for YBCO-SS, and 54.2 nΩ/cm^2 for YBCO-Cu. The heater coil had an extra turn to ensure that the outermost layer of superconductor receives enough heat to compensate for cooling to the surrounds. The epoxy was cured at 140 °C for 2 hours with pressure being applied to the winding by means of a continuously pumped vacuum; this also helped to prevent voids formed by out gassing.

Figure 6: Schematic of a switch (not to scale) showing the non-inductive bifilar HTS winding co-wound with a resistive heater and insulation. The current and voltage terminals, support, and outer insulation/heater section have been omitted for clarity. White regions represent insulation, black the heater, and light and dark grey the HTS which were soldered together over the crossed region.

Heating of the switch was predominately caused by means of a thyristor triggered capacitor discharge circuit with the heater energy being controlled by the capacitor charge voltage. The heater resistance varied as a function of temperature (measured to be 351 mΩ/m at 77 K, and 752 mΩ/m at 300 K), which was dependant upon on both heater current and ohmic heating of the superconductor in the current sharing/quenched states. The inductance of the coil was calculated to be ~ 4.2 nH. In order to allow greater control and increased energy generation, a heater circuit utilising an insulated gate bipolar transistor controlled capacitor discharge and a cupro-nickel strip will be used in the future.

5. Test and results

Switches utilizing YBCO-Cu and YBCO-SS were manufactured and tested at CERN. Due to the high n-value of the YBCO tapes, particularly the YBCO-SS, an Ic criterion of 0.1 μV/cm in self-field was used. The Ic did not degrade during switch manufacture and was measured on the YBCO-Cu and YBCO-SS to respectively be: 48 A and 77 A (90 cm length), and 46 A and 45 A (110 cm length). An insulation test was performed at room temperature, before cold testing, between the HTS and the heater; the resistance was of the order of MΩ-GΩ. The switches were tested in pool boiling liquid nitrogen with transport currents from 10 A to Ic, and initial heater voltages from 0.1-1 kV. The Ic was retested after each switching cycle with no degradation being found. With a transport current of 40 A, and initial heater voltage 1 kV, the YBCO-Cu switched < 8 ms and the YBCO-SS < 4 ms.

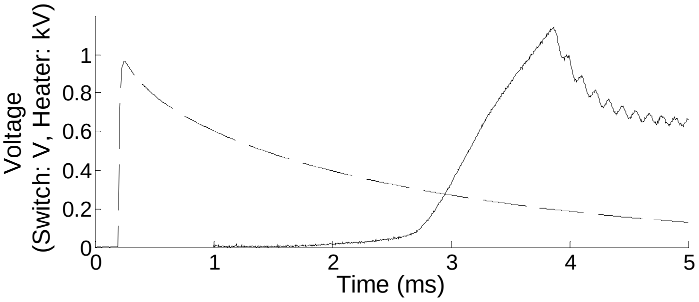

Figure 7: Voltage across a switch utilizing YBCO-SS (solid line) and across the heater (dashed line). The induced voltages in the laminations and substrate of the YBCO-SS by the heater pulse have been removed. After 4 ms the switch current source decreased to protect the HTS.

6. Conclusions

It has been shown that HTS material can be used for power switches that undergo transition in < 10 ms when thermally activated. The thermophysical and electromechanical properties of HTS materials suitable for power switches have been determined both experimentally and from the available literature. The heat equation in its second order, non-linear PDE form, with temperature dependant material properties has been solved numerically and verified in a dedicated experiment. The model was used to evaluate thermally activated switches formed of various HTS material. Prototype switches utilizing YBCO-Cu and YBCO-SS have been manufactured and tested. At 77 K the YBCO-Cu switch has an Ic of 46 A, YBCO-SS 45 A, and with a transport current of 40 A switching times were < 8 ms for YBCO-Cu and < 4 ms for YBCO-SS.

The potential of utilizing HTS material in power switches is strong enough to warrant continued research and development. Future work will include the design, manufacture, and test of switches utilizing other HTS materials, including MgB_2 in both wire and bulk form. The modelling will be extended to cover more complex multi spatial dimension designs which can be excited by both thermal and magnetic means. The operating conditions of such switches will be expanded to include operation at different temperatures, higher transport currents, and switching times < 2 ms.

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