Heating Development Analysis in Long HTS Objects – Updated Results

V.S.Vysotsky, V.V.Repnikov, E.A.Lobanov, G.H. Karapetyan and V.E.Sytnikov

All-Russian Scientific R&D Cable Institute, 5, Shosse Entuziastov, 111024, Moscow Russia

Corresponding author: VSV, e-mail: vysotsky@ieee.org

Abstract. During fault in a grid large overload current, up to 30-times fold, forcibly will go to an HTS superconducting cable installed in a grid causing its quench and heating. The upgraded model has been used to analyse the heating development in long HTS objects during overloads. The model better presents real properties of materials used. New calculations coincide well with experiments and permit to determine the cooling coefficients. The stability limit (thermal runaway current) was determined for different cooling and index n. The overload currents, at which the superconductor will be heated up to 100 K during 250 ms can be determined also. The model may be used for practical evaluations of operational parameters.

1. Introduction
The power electro-technical devices (power cables, transformers, etc.) made with HTS should have one general feature – they must withstand fault currents dozens times more than their operating currents (if do not consider special current limiting devices). For AC applications, fault over-currents 10 to 30 times the operating current and lasting up to 250 ms are expected, depending on the load and circuit breakers in the installation. A concern is whether the fault current will over-heat the HTS conductor and degrade the superconducting properties or burn-out the HTS tape altogether.

This situation differs from the usual quench of superconducting devices, were the transport current is below or about the critical current during quench. In superconducting power devices, the overload current forcibly becomes much more than operating/critical current of a device. In this case the usual approaches to analyze quench and heating are not valid. There is no the normal zone and its propagation in the usual sense used for superconducting devices. Different approach should be used to analyze the heating and temperature during overload conditions. The study to analyze heating development at overload, especially in long HTS objects like power cables, is underway in the Cable Institute in Moscow [1]-[3]. With numerical experiments we showed that in long HTS objects the blow-up regimes with strong heat localization take place [1]-[3]. In adiabatic conditions always happens fast temperature rise (“thermal runaway”). In conditions with cooling two possible modes are possible: stable and unstable, like it was found for the quasi – uniform heating by the analytical model [4]. There is the sharp border between stable and unstable regimes in relation to the current density change. At the unstable regime the heat localization takes place in case of the disturbance presented and instability development time is rather small in comparison with the uniform heating [3].

In works [1]-[3], rather simplified approximations for material parameters and heat release have been used. The simple models permitted us to show the general behavior of long non-linear HTS
objects under overloads. In the present work we modified the description of material parameters used in the model for better approximation. We also compared the calculated results with the some experiments performed to find out the cooling coefficients.

2. The updated model.
Like in our previous works [1-3] we considered one-dimensional case (that is proper for HTS cables) described by the standard equation:

\[
C(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \kappa(T) \frac{\partial T}{\partial x} \right] + q(T) - W(T),
\]

where \(C(T)\) is the specific heat, \(x\) is the coordinate along the cable, \(k(T)\) – is the heat conductivity, \(q(T) = jE, E\) is the electric field and \(j = I/A\), where \(A\) – is the cross-section of the superconductor.

We wrote the voltage – current characteristic of HTS in the usual form [4]:

\[
\eta \frac{\partial j}{\partial t} = \eta \left[ j / j_c(T) \right] ^n,
\]

where \(j\) is a transport current in a superconductor and \(j_c(T)\) is a critical current density that usually corresponds to \(E_0=1\mu\text{V/cm}\). In general, the value of \(n\) depends on \(j / j_c(T)\) and is smaller for larger \(j / j_c(T)\). To model these changes we made calculations for different \(n\) to find out its influence on the results. We suppose that \(j_c(T) = j_{c0}(1-T/T_c)\), where \(T_c\) is the critical temperature and \(j_{c0}\) is the initial critical current that we found by the linear extrapolation of \(j_c(T)\) dependence to zero temperature. For modeling purposes we took \(T_c \approx 100\text{ K}\).

The cooling we presented as the linear function:

\[
AT = hP(T - T_0)/A.
\]

Here \(h\) - is heat removal coefficient per unit area, \(P\) – is cooling perimeter and \(T_0\) is the ambient temperature (\(T_0=77.4\text{K}\) in our calculations). The cooling coefficient was also used as the variation and it was compared with the experimentally determined cooling coefficients. For the dependencies of \(C(T)\) and \(\kappa(T)\) we used the approximations of the data for pure silver [5] as: \(C(T) = aT + b\) and \(\kappa(T) = \text{const}\). These are quite fair approximations in the ranges of 70-100 K where our calculations have been done.

The equation (1) has been solved numerically for different parameters. We considered the model HTS sample tapes with cross-section 4 mm x 0.25 mm and two critical currents at self-field: 40 A and 100 A. Different transport current densities, different cooling conditions and different initial disturbances including uniform heating (without disturbance) to compare numerical data with the analytical model from [4] were analyzed.

3. The results

3.1. Quench current.
The results of the numerical experiments with the upgraded model confirmed the conclusions done in [3] and coincide in general with conclusions done in [4], [6]. Namely: two regimes do present in case of cooling with the sharp border between stable and unstable regimes in relation to the transport current change. It is illustrated in Figure 1 where time dependent traces of the temperature are shown for the experimental and measured temperatures for currents 94 A (stable regime) and 95 A (unstable regime). The measurements were done with the HTS tape with the self-field critical current \(\sim 40\text{ A}\) cooled by the liquid nitrogen. The experimental details will be published elsewhere. One can see the good coincidence of calculated and measured traces. It confirms the fairness of the amended model and the data used. We adjusted cooling parameters to fit the stable curve at 94 A and used them to calculate all other curves. The calculated curves for 105 A and 160 A are shown also. One can see very fast reduction of instability development time with current.

In Figure 2 the relative thermal runaway currents are shown in dependence on cooling for two types of HTS tapes mentioned. In Figure 2 solid lines are calculations by the analytical model [4], [6] (zero disturbance) and dashed lines are calculations by the present, upgraded model and by the previous model [3] with the temperature disturbances in the center of the sample (\(\Delta T \approx 0.5\text{-}4\text{ K}\)). One can see the practical coincidence of calculations with different methods. Symbols shown in Figure 2
are the experimental data. At low current, experiments coincide with calculations for $n$ close to 10 and at higher currents better coincidence is for $n$ close to 5. Obviously, it is connected to the fact that at higher currents the effective value of $n$ reduces. It was shown in [6] that the thermal runaway current $I_q \sim h^{1/n+1}$ [6]. That means rather very weak dependence on cooling at high index $n$.

![Figure 1. Time depended traces of the temperature for the sample with critical current ~ 40 A at the self field in LN$_2$. Dashed lines – experiments, solid lines – calculations with the updated model. Switch from the stable to the unstable mode happens with very little change of the current. Instability development time quickly reduces with the transport current.](image)

![Figure 2. Relative thermal runaway currents (transport current divided by the critical current) versus the heat removal coefficient. Solid lines – analytical calculations by theory [4], [6]. The upgraded model calculations (short dashed lines), the experimental data (symbols) and data from calculations by the model [3] (long dashed lines) are shown also.](image)

3.2. Instability development time
We call the instability development time $\tau$, the time when temperature reaches 100 K, as beyond this temperature the instability develops very quickly (see Figure 1 and [3]). Calculated time $\tau$ is shown in Figure 3 vs. relative transport currents for different $n$, critical currents and two cooling coefficients. No sounding dependence on the amplitude of disturbance has been observed. From the data in Figure 3 it is possible to evaluate the permitted overload current level, i.e. current at which 100 K temperature will be reached during 250 ms. Depending on index $n$ value it varies from 2 to ~5 of critical current density magnitudes. Cooling coefficient $h \sim 2500$ W/m$^2$K is about the maximum value for “low” cooling shown in Figure 2 and $h \sim 15000$ W/m$^2$K is the peak nucleate boiling magnitude for the liquid nitrogen [5]. Thus, in Figure 3 the data for the most favorable cooling conditions are shown.
4. Discussion

The upgraded model better describes the behavior of the long HTS objects at the overload conditions than previous models. The calculated and experimental temperature traces shown in Figure 1 for the stable and unstable regimes demonstrate good coincidence. From the comparison of experimental and theoretical data it is possible to determine the real cooling coefficients – most ambiguous parameters for calculations. That permits to make practical evaluations for two most important parameters of the heating at overload regimes: the stability limit or threshold thermal runaway current $I_q$ and instability development time $W$.

Threshold current may be calculated with good accuracy by different methods. It weakly depends on cooling as it was predicted by the analytical model [4], [6], but strongly depends on index $n$ if index is less than 5 [7]. At lower $n$ the HTS device may be called more stable, because the threshold runaway current becomes larger; at higher $n$ the stability limit is close to the critical current like in low-Tc superconductors. Instability development time quickly decays with current.

The stability limit for the HTS tape directly cooled by the liquid nitrogen is about $2-2.5I_c$ for index $n=10-15$ and $3-5I_c$ for $n=5$. To increase sufficiently the relative threshold current is barely possible as it weakly depends on most parameters, particularly on cooling. Thus, the only way to provide better overload limit is to increase the instability development time. It could be done by increasing the heat capacity of the HTS tape with adding of stabilizing material (say, copper). Other, let not very economical, way is the reduction of the operating current for high current density tapes. Say, for 100 A tape the overload limit is $\sim 5I_c$ (Figure 2), thus if the operating current will be $\frac{1}{2}I_c$, the tape should survive ten-fold overload during 250 ms. At $\frac{1}{4}I_c$ – twenty-fold overload looks possible.

5. Conclusions

The upgraded model of heating of long HTS objects with amended description of material parameters coincides well with the experimental data. Numerical experiments have been done for direct liquid nitrogen cooling. Stability limits and operation limits for overloading currents can be determined from the model.

References

[1] Rakhmanov A L, Vysotsky V S and Zmitrenko N V, 2003 *IEEE Trans. Appl Supercon.* 13 1942
[2] Vysotsky V S, Zmitrenko N V and Rakhmanov A L 2004 *IOP Conference series* 181 580
[3] Vysotsky V S, Sytnikov V S, Rakhmanov A L et al 2005 *IEEE Trans. Appl Supercon.* 15 1655
[4] Vysotsky V S, Ilyin YuA, Rakhmanov A L, 2002 *Advances in Cryogenic Engineering* 47 481
[5] Iwasa Y, *Case Studies in Superconducting Magnets*, 1994, Plenum Press, New-York
[6] Rakhmanov A L, Vysotsky V S, Ilyin Yu A 2000 *Cryogenics* 40 19
[7] Vysotsky V S, Rakhmanov A L, lyin Yu A 2004 *Physica C* 401 57

Figure 3. Dependencies the instability time on the relative transport current (transport current divided by the critical current).