

HTS Tapes Cooled by Liquid Nitrogen at Overloading Conditions

Sergey S. Fetisov, Vitaly S. Vysotsky, *Member IEEE*, and Victor E. Sytnikov

Abstract—For HTS electro - technical devices the overload currents due to faults in grids are the operational reality. Overloads are the working modes for fault current limiters as well. In this work we model the overload conditions in different HTS 1-G and 2-G tapes experimentally by use of the rectangular current pulses with different amplitudes and durations. Voltages and temperatures along tested samples have been measured. These experiments permitted us to follow the change of heat developments during overloads due to the difference of cooling regimes in the liquid nitrogen. Measuring of characteristic times of a heat development in different regimes provides the data about possible surviving times of HTS devices and bearable current overloads. We also studied the influence on heat developments of different shunting or reinforcing methods of HTS tapes. The data obtained can be used to analyze overload conditions at HTS power cables and HTS resistive FCL.

Index Terms— Heating development, High-temperature superconductors, Overload conditions

I. INTRODUCTION

THE most prospective applications of HTS are power electro-technical devices: power cables, transformers, generators, etc. All these devices must have one general feature – they must withstand fault currents dozen times more than their operating currents (if do not consider special current limiting devices). The fault currents may forcibly go to superconductors leading to overheating and possible destroying of a device. It is important to take into account especially for HTS power cables design. For FCL overloads is just one of the operational modes.

We studied before the overload conditions both theoretically [1]-[2] and experimentally [3]. It was shown by numerical experiments for overloaded tapes with cooling [1]-[2] that two possible heat development 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 and instability development time is rather small in

comparison with the uniform heating.

In the experimental study of voltage current characteristics (VCC) in HTS tapes at current overloads [3] the peculiarities at VCC were found. It was shown that that peculiarities are due to the change of cooling conditions at liquid nitrogen from the convection cooling to the nucleate boiling (NB). For all processes the characteristic times like nucleate boiling activation time and nucleation boiling development time were determined. It was shown also that depending on current and cooling conditions the switch from stable to unstable mode can happen with very little change of the transport current.

Thus, considering results of studies [1]-[3] the most important parameters determining stability limits during overloads of HTS are: the thermal quench (thermal runaway) current that separates stable and unstable modes I_q [4] and the time t_q before the fast current rise starts. If the fast current rise possible at the unstable mode, the next parameter could be the time $t_{max}(T_{max})$ – how quickly the temperature T_{max} could be reached at the overload. In other words – how much time we have before our device will be burn out?

Important question is also – how reinforcing or insulating materials affect the stability limits?

To determine the stability limit and parameters mentioned above it is possible to model the overload conditions by rectangular current pulse with rising step by step amplitude to watch the change of the heat development during the overload. Recording temperature and voltage on the sample versus time permits to follow heat development changes when current is rising.

In this paper we present the initial study of few HTS samples both 1-G and 2-G with different lamination and insulation. Characteristics times and I_q data are presented and discussed.

II. EXPERIMENT

Several 1-G and one 2-G HTS samples were tested listed in the Table 1. 1-G EAS samples were tested being either virgin or covered with insulation by KAPTON™ tape or laminated with copper tape. Both insulation and copper tapes had exactly same width as HTS tape. Two SEI samples were one not laminated and the second laminated one. One 2-G AMSC sample was laminated by copper

For testing, the samples were mounted on the sample holder shown in Figure 1. In these experiments five thermocouples (TC) were attached to each sample with distance 1 cm between them. We used standard copper-constantan calibrated thermocouples. One pair of the potential taps was attached

Manuscript received 19 August 2008.

All authors are with Russian Scientific R&D Cable Institute (VNIICP), 5 shosse Entuziastov 111024 Moscow, Russia.

Corresponding author: V. S. Vysotsky, phone: +7-495-542-22-70 (e-mail: vysotsky@ieee.org)

Presenting author: S.S. Fetisov (e-mail: sergey.fetisov@gmail.com)

with the distance 6 cm between them. Thus all TC were inside the potential taps measured. During tests the rectangular current pulse was put to the sample with the certain current magnitude and duration. The current, voltage and TC signals were recorded by multichannel Yokogawa™ SL-1400 analyzing recorder.

TABLE 1. LIST OF SAMPLES TESTED

##	MAKER	CROSS – SECTION, REINFORCING, INSULATION	I_C , SELF FIELD, 77 K
EAS-1	EAS-EHTS (former VAC) Germany	4.0mm x 0.22 mm, Not reinforced	92 A
EAS-2	1-G, Bi-2223	EAS-1+KAPTON™ tape – 0.05 mm	92 A
EAS-3		EAS-1+Cu tape 0.5 mm	92 A
SEI-1	Sumitomo Electric Industry, Japan	4.00 mm x 0.25 mm, high current, not reinforced	186 A
SEI-2		4.5mm x 0.53 mm, Brass laminated	175 A
AMSC-2G	American Superconductor, USA	Avg. 4.4 mm x 0.2 mm	79 A
	2-G, YBCO (344C™)	2-G, Cu – laminated	

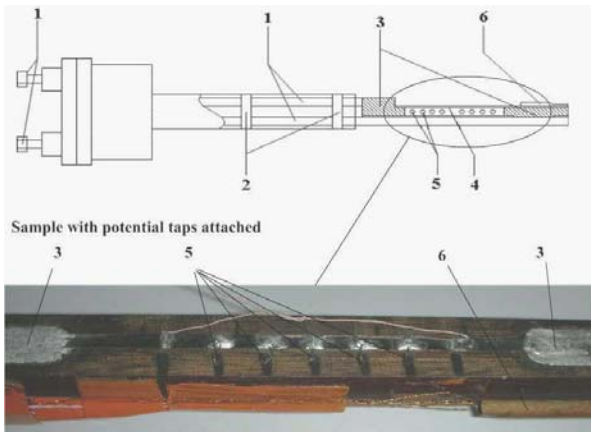


Fig.1. The view of the sample holder (above) and the sample mounted on the holder. 1 – gas cooled current leads, 2- Teflon spacers, 3- soldering joints, 4 – mount place, 5- holes to put thermocouples from below, 6 – copper tube for reference ends of all thermocouples.

If the magnitude of the current pulse was more than the critical current of the sample one can watch the noticeable voltage and the temperature rise. If the increase of the temperature at certain current level becomes too large the duration of the pulse was reduced not to burn out the sample. The successive rise of the current magnitudes continued until very fast and dangerous temperature rise was observed. Several typical examples of voltage and temperature recordings are shown in Figures 2-4.

In Fig.2 the typical voltage recordings are shown for wide currents range from 241A to 500 A for SEI-2 sample. At low currents one can see the typical picture of changing cooling conditions from convection cooling to the NB cooling. Heat removal coefficient at NB cooling starts to rise very quickly and cooling drastically improves [5]. This leads to reducing the sample resistance and, correspondingly, voltage. At higher

currents nucleate boiling becomes not enough and fast current rise starts after 491 A current.

In Fig.3 the voltage and temperature recordings are shown for AMSC – 2G samples for rather high overloads for this sample. At 250 A one thermocouple (located in the middle of the sample) demonstrates very fast temperatures rise that means switching to the unstable region.

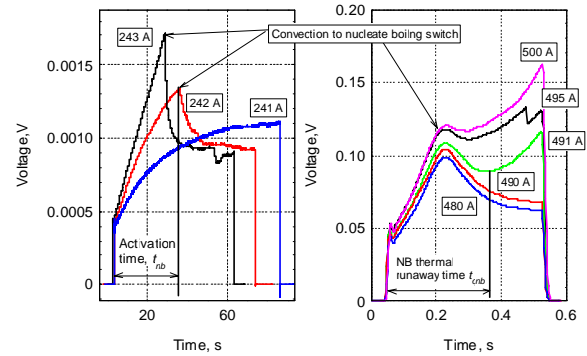


Fig.2 Typical voltage recordings for the sample SEI-2 at different currents.

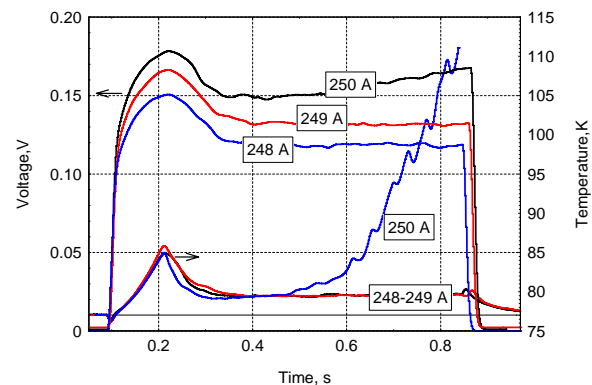


Fig.3 Typical voltage (left Y-axis) and hottest temperature (right Y-axis) recordings for the sample AMSC-2G at different currents.

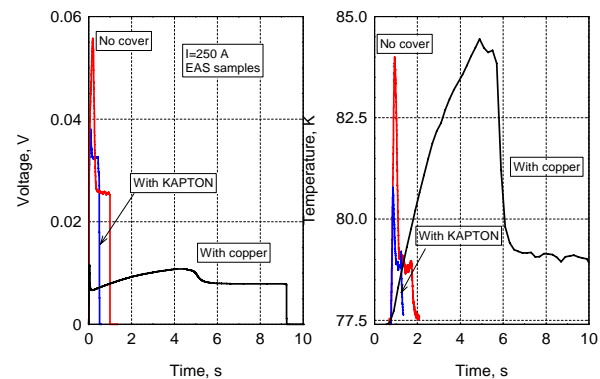


Fig.4 Typical voltage (left graph) and hottest temperature (right graph) recordings for the EAS samples at 250 A with different cover.

In Fig.4 the voltage and hottest temperature data are shown for EAS sample with different covers. One can see noticeable change of the heat development depending on type of cover.

The data similar to shown in figures 2-4 were measured in wide currents range and they served as the data base for further analysis.

III. DISCUSSION

The determinations of the typical parameters of the heat development at overloads are shown in Fig.2. The determination of the nucleate boiling activation time t_{nb} [3] is marked at the Fig.2 left. The change from the stable mode at convection cooling to the unstable one happens when current exceed 241 A in this sample. Thus, this current we can define as the convection cooling thermal runaway current I_{qcc} . With the following rise of the current shown in Fig.2 right, the change from the stable to the unstable mode happens at current 491 A. This current we can defined as the nucleate boiling thermal runaway current I_{qnb} . The time of very fast voltage (and temperature) rise starting we define as the NB thermal runaway time t_{qnb} . Its determination is shown in Fig.2 right also.

The parameters defined above describe the change of the heat development nature with the rise of the overload currents. These parameters are listed in the Table II for all samples tested in this work.

TABLE II. LIST OF HEAT DEVELOPMENT PARAMETERS OF THE SAMPLES TESTED

##	I_{qcc} , A	I_{qcc}/I_c	W_{qcc} , kW/m ²	I_{qnb} , A	I_{qnb}/I_c	W_{qcc} , kW/m ²
EAS-1	138	1.5	1.99	273	2.97	37.4
EAS-2	129	1.4	0.91	253	2.75	36.6
EAS-3	159	1.73	1.59	>870	>9.5	
SEI-1	253	1.37	2.28	340	1.84	20.4
SEI-2	241	1.36	1.38	491	2.77	75.7
AMSC- 2G	93	1.18	4.86	250	3.16	13.3

In Fig.2 one can follow to the typical heat development for HTS with overloading current. At low currents the convection cooling is enough to keep the sample at the stable mode. With current rise the convection cooling is not enough to keep voltage-temperature stable, their fast rising starts. At certain heat release, the NB activates, cooling increases and samples drops to the stable mode again at lower voltages and temperatures. The stable modes at NB may continue to rather high overload currents. But further current rise again leads to switch from the stable to unstable mode.

It is necessary to accentuate the typical peculiarities in the heat development observed, first described in [4], [6]. First, for the certain cooling level two possible modes do exist: stable and unstable one. Second, the change from the stable to the unstable modes happens with very little change of a transport current (240 to 241 A and 490 to 491 A shown in Fig.2 and 249 to 250 A shown in Fig.3). Less than 0.25% of the parameter change lead to the change of the nature of the process from stability to instability and catastrophic temperature – voltage rise [1]-[2], [4], [6]. This is typical for so called “blow-up” regimes for non-linear systems [7].

The threshold of the switching from one process to another one may be characterized also by the heat release at corresponding currents. The heat releases W_{qcc} and W_{qnb} for

currents I_{qcc} and I_{qnb} correspondingly are shown in the Table II also.

For most, but AMSC, samples characteristics values of W_{qcc} shown in the Table II are ~ 1-2 kW/m². It us just corresponds to typical heat releases when switch happens from convection cooling to the nucleate boiling for liquid nitrogen [5], [8].

The characteristic pick nucleate boiling magnitude for liquid nitrogen is ~100-150 kW/m² [9]. The magnitudes of W_{qnb} shown in the Table II for all samples are well below this value. That means that our samples were cooled within nucleate boiling mode at the current ranges measured.

The threshold currents I_{qcc} for all samples are ~1.3 - 1.7 I_c . It means that at overloads with current amplitudes below 1.3-1.7 I_c the convection cooling should be taken into account with its rather low heat removal coefficient. At currents above these values the nucleate boiling will be activated after time t_{nb} with the increase of cooling. The durations of the convection cooling regime on relative currents are shown in Fig.5 as dependence $t_{nb}(I/I_c)$ for different samples. This dependence show how long a sample remains at convection cooling mode when due to worse cooling the temperature may rise far enough.

Most samples tested switch to the NB mode rather quickly except EAS-3 sample covered by copper tape. In this sample voltage remains relatively low while temperature may rise as high as in non-stabilized sample as it is seen in Fig.4. The slower switches to the NB mode of this sample happens because of the lower total voltage, and, therefore, lower heat release in an HTS tape shunted by copper. This suggestion is confirmed in Fig.6 were the dependencies of the nucleate boiling activation time t_{nb} on heat release are shown.

One can see in this figure that dependence of t_{nb} on heat release lays close to the dependencies for other samples for the sample EAS-3 covered by copper. Thus, as soon as the heat release reaches the certain level – the switch from convection cooling to NB happens independently of what cover is. It leads to some paradoxical fact that apparently thermally insulated by the KAPTON tape sample EAS-2 has less temperature increase than sample EAS-3 shunted by copper (Fig.4). This happens because the heat release in the sample EAS-2 rise faster and it switches to good cooling at NB mode also faster with less heating during the convection cooling mode.

Another and may be most important parameter is the time to the fast current rise t_q [4],[6] or in our case t_{qnb} . After this time the voltage-temperature rise becomes catastrophically quick and barely can be managed. Actually, this time is the limiting time of an HTS sample surviving at the certain current. In principle, it is possible to consider the nest surviving time $t_{max}(T_{max})$ as it was mentioned above, but for very well stabilized HTS samples only.

The dependencies of time t_{qnb} on relative transport current for our samples are shown in Fig.7. In this dependencies the influence of reinforcing on instability appearance time is seen quite clearly.

One can compare the SEI-1 not reinforced sample with SEI-2 – brass reinforced. The later has much longer time before instability develops and higher thermal runaway current I_{qnb} (Fig.7). Also, EAS-2 sample insulated by the KAPTON tape

has less surviving time and current I_{qnb} than non covered EAS-1. And for the sample EAS-3 covered by copper we could not determine instability region for nucleate boiling because of limited current from our power supply used. Thermal quench current at NB mode for this sample is more than $9.5I_c$ at least (see the Table II).

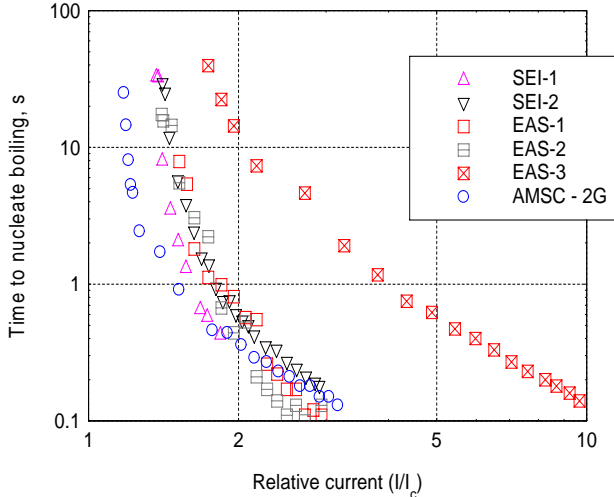


Fig.5 Nucleate boiling activation time vs. relative current for all samples.

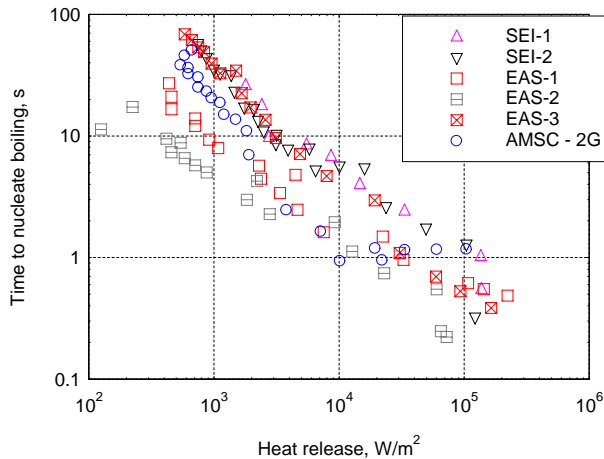


Fig.6 Nucleate boiling activation time vs. heat release for all samples.

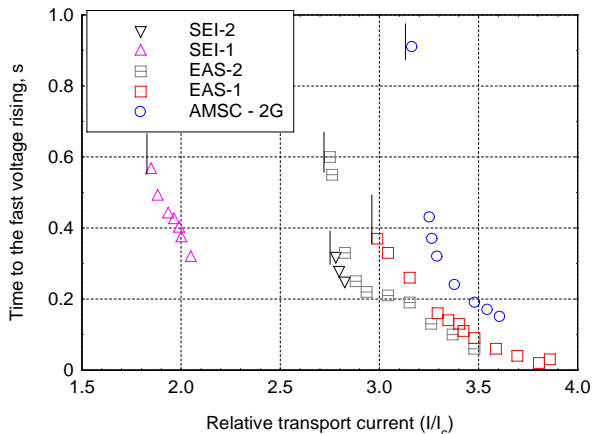


Fig.7 Time to the fast voltage rising start vs. relative transport current for all samples. Vertical lines show the border of the stable region.

IV. CONCLUSION

The overload during faults conditions were modeled for several 1-G and 2-G HTS tapes and parameters of the heat development at overloads were measured. It was shown that two cooling modes are present at liquid nitrogen cooling. The switch from the convection cooling mode to the much better nucleate boiling cooling happens if current and heat release exceeds certain level. For both cooling regimes two typical heat development modes are possible – the stable and the unstable one. The characteristic parameters of both cooling modes were determined for all samples like thermal runaway current I_q and time t_q to the fast heating rise.

It was found the influence of different covering or reinforcing on the heat development parameter. Covering by insulating tape reduces heating at convection cooling due to faster switch to the nucleate boiling. Covering by copper slow down the switch to the nucleate boiling at it may increase the initial heating. On the other hand it drastically increases the stability limit at nucleate boiling.

The measured parameters of the heat development processes at overloads can be used for HTS power cables and FCL design. Their also can be used for the numerical modeling of the heat development processes in HTS devices.

ACKNOWLEDGMENT

Authors thanks the American Superconductor and Sumitomo Electric Industry companies for presenting most advanced HTS tapes for tests.

REFERENCES

- [1] V. S. Vysotsky, V. E. Sytnikov, et al, *IEEE Trans on Appl Supercon.* June 2005, Vol. 15, Num. 2, pp. 1655-1658
- [2] V.S.Vysotsky, et al, *J. Phys.: Conf. Ser.*, vol.43 877-880, 2006 (Proceedings EUCAS – 2005)
- [3] V.S. Vysotsky, et al. , *J. Phys.: Conf. Ser.*, 2008, vol.97, 012015 (Proceedings EUCAS – 2008)
- [4] A.L. Rakhmanov, V.S.Vysotsky, Yu.A.Ilyin, et al, *Cryogenics*, 2000, v.40, N1, pp.19-27
- [5] B.I. Verkin, Yu.A.Kirichenko, K.V.Rusanov, *Heat exchange at cryogen liquids boiling*, Kiev, Naukova Dumka, 1987 (in Russian)
- [6] V.S. Vysotsky, V.E. Sytnikov, A.L. Rakhmanov, Yu.A. Ilyin, *Fusion Engineering and Design*, 2006, vol. 81, pp.2417–2424
- [7] A. A. Samarskii, V. A. Galaktionov, S. P. Kurdyumov *Blow up in quasi-linear parabolic equations*, Berlin-N.Y., Walter de Gruyter, 1995
- [8] S.S. Kutateladze *The basic theory of the heat exchange*, Novosibirsk, Nauka, 1970 (in Russian)
- [9] Iwasa Y *Case study of superconducting magnets* 1994 Plenum Press, New-York