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Quench Development in Superconducting Cable Having Insulated Strands With High Resistive Matrix (Part 1, Experiment).

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Abstract - The process of quench development in two- and six-strand cables was investigated in detail. Different types of quenches were found. The increase of the starting current level led to a change of nature of the quench, from current redistribution, to a quench in all strands, to multi-quench with acceleration of the process from step to step, and to fast quench. Strand currents never achieved the critical current value under DC circumstances. We could conclude that the reason of "fast quench" in AC-cables is a specific mechanism of electromagnetic development of quench.

I. INTRODUCTION

The understanding of quench propagation in superconducting (SC) AC and DC windings is a key requirement for the development of appropriate protection systems and also for designing devices such as fault current limiters and different types of superconducting commutators. In recent years the extremely fast normal zone propagation was observed in windings of AC-SC devices [1,2,3,4]. At first it was assumed that the reasons for such "fast quenches" were connected with the AC operation or with the high resistive matrix used in the multifilamentary wire to reduce AC losses.

In [5,6] the velocity of the normal zone propagation was measured under AC and DC conditions in coils wound with multifilament SC wires having high resistive matrix. It was shown for single wire coils that there is no difference between quench propagation in the AC and DC modes, and that it could be described by means of the usual theories (e.g. [7]).

So, the next assumption was that the fast quench is related to the specific construction of AC cables which generally have a high resistive matrix and insulated strands [4,5]. Up to now there was no direct experimental investigation to explain the fast quench phenomenon.

In [8] it was shown by means of computer simulations that the fast quench appears because of current sharing between the strands of the cable. If one strand is quenched, the currents in the adjacent strands increase up to a critical value and they also quench. Under certain conditions the process could develop very quickly which leads to a fast quench. This phenomenon is quite similar to the quench development in sectionned superconducting magnets [9]. In [10] such a quench process was referred to as "electromagnetic avalanche". The assumption that a fast quench appears because of redistribution of currents was in [4,5], and the quick current rising was proposed as the reason for the quench of adjacent strands [5]. The estimations showed that it also could lead to the fast quench [5].

In the presented work a direct measurement of current redistribution during the quench of two- and six-strand cables was carried out in order to study the quench development process in AC cables.

II. EXPERIMENTAL SET-UP

The overall view of the experimental arrangement is shown in Fig. 1. and it is similar the one used in [11]. The six strands were twisted around an insulated non-superconducting manganine wire. The insulated strands are NbTi multifilamentary wires having a diameter of 0.5 mm and CuNi matrix with a resistivity of $1.35\ 10^{-7}$ Ohm m. The thickness of the wire insulation is 0.1 mm. The wire has ~ 200 filaments, 25 μm in diameter. The total cable diameter is 1.53 mm (see Fig. 1) and its length is ~4 m. At one end, 0.1 m of cable is un-twisted and the strands are placed in grooves on the surface of a cylinder, ensuring that the mutual distances are equal. In order to retain the symmetry, the cable is returned through the center of

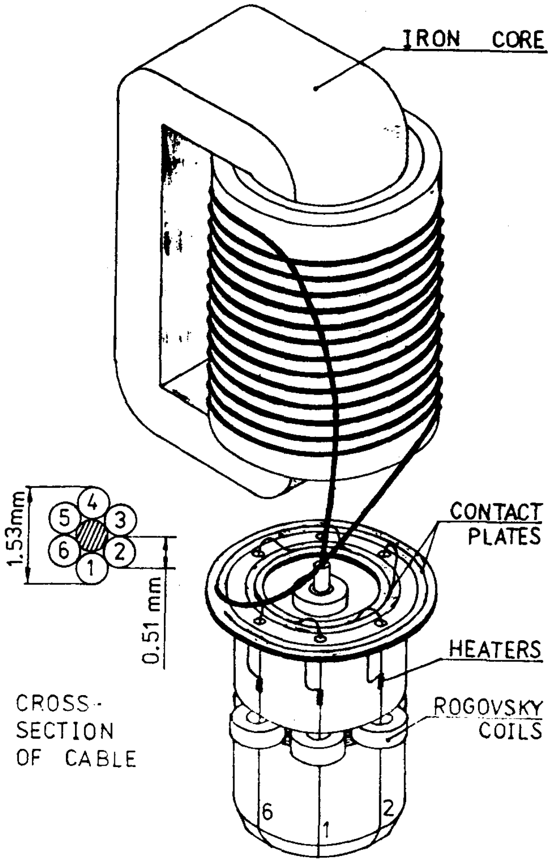

Fig. 1. Overall view of experimental set-up.

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the cylinder. The total current and currents in the strands were determined by Rogovsky pick-up coils. Both ends of the cable were connected with contact plates. It was possible to supply the cable either directly with DC or AC current or to supply it by means of the transformer method using a primary winding placed inside the main one. For better transformation an iron core was used. Each strand was supplied with potential taps and heaters for initiating quenches. It was possible to connect any number of strands in parallel.

The inductive coupling coefficient between strands was directly measured. For adjacent strands it was ~0.9972 and for opposite strands (1-4, etc.) it was 0.9963. So, the coefficients were very close to 1 which leads to a very fast process as we shall see later.

During measurements the coil was supplied with transport current (we will see later that it is not important whether DC or AC is used), the quench was initiated using a heater and the signals from Rogovsky coils and potential taps were recorded on digital oscilloscopes. After measuring the quench process, the data from the oscilloscopes were transmitted to a plotter and integrated to obtain the real currents in strands and cable.

The time resolution of the digital oscilloscopes was limited, so for very fast processes some peculiarities could be lost. Also the accuracy in determining the real currents does not exceed 10%. Nevertheless the obtained results are qualitatively good enough to understand the quench development in cables with insulated strands.

III. RESULTS

A. Two-strand cable.

At first we have studied the simplest two-strand system. The strands #1 and #4 (see Fig.1) were connected in parallel, while disconnecting the others. The quench was always initiated in strand #1.

It was found that depending on the initial current there are different types of quench development processes. At low currents, only the first strand quenched and all current was transferred to the second one (Fig.2). The total current remained constant.

When the current per strand was increased to ~110 A, the second strand quenched also and the total current decayed. So the whole cable was quenched (Fig.3a), but it is necessary to note that the quench of the second strand occurred at a current much less than the critical one. For our cable the critical DC current per strand in self field was approximately 500 A.

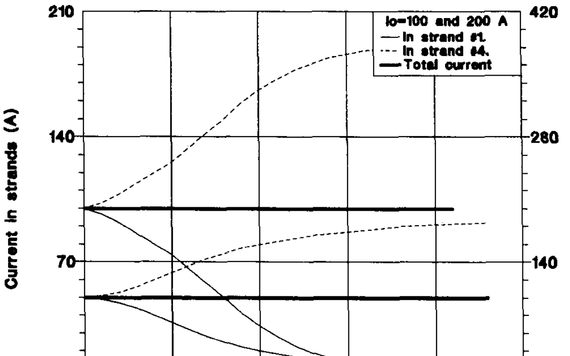

Fig.2. Redistribution of currents in the two-strand system at different starting current levels.

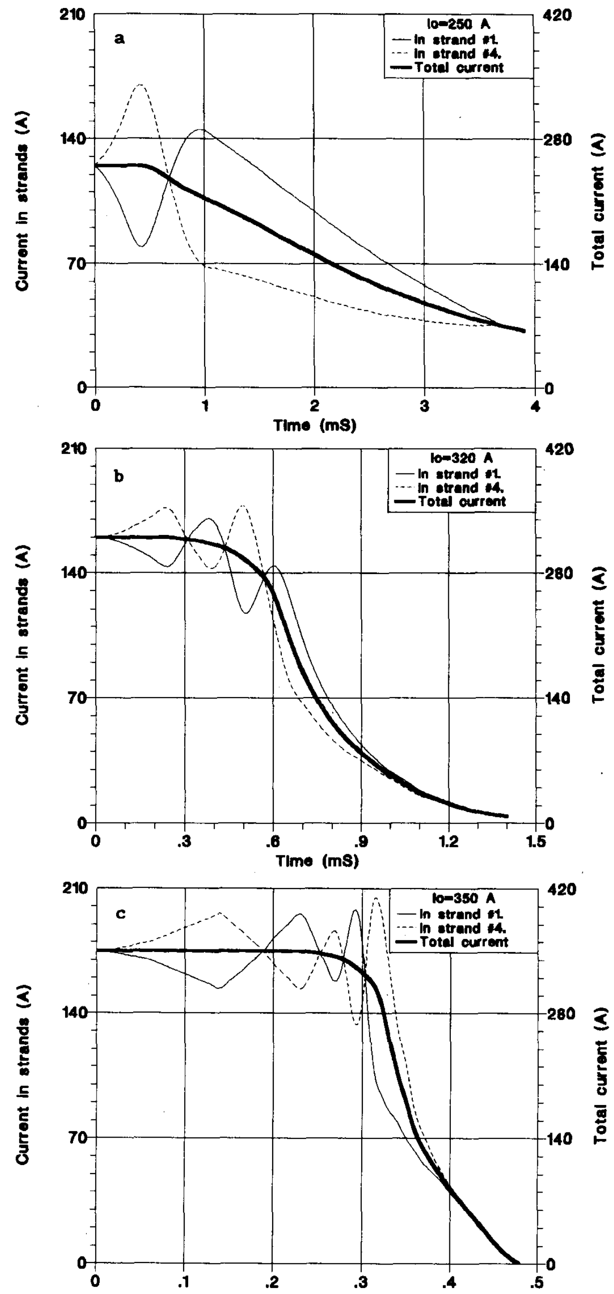

Fig.3. Quench development process in the two-strand system. a-slow quench process; b- multi-quench process; c- fast quench process.

At higher initial current levels, the quench in the second strand led to an increase of the current in the first one and to an additional quench in this strand with a faster velocity (Fig.3b). If the starting current is increased further, the quantity of quenches in each strand increases too with an acceleration of the quench from step to step (Fig.3c). Finally, this multi-quench process demonstrates a very fast total current decay and rise of the total resistance which was called a "fast quench" in previous works [3,4].

Some important notes about quench processes:

- strand currents **never exceed the DC critical value**. The maximum achieved currents in the strands are approximately the same during the quench and are less than one half of the critical current.
- the time of the process is less than a few ms. That is why it is unimportant whether the cable is supplied by AC or DC, because the time in which the total current decays due to quench process is much less than the period of 50 Hz AC.
- the acceleration of the quench increases very drastically when exceeding a certain current level. For example: when increasing the current by 8%, the time of the process decreases about 3 times (compare the time scales in Figs.3b and 3c).
- during a fast quench the total current decays in a step-like manner. The time in which the total current changes is much less than the overall process time. Such a characteristic could be useful for some superconducting commutators.

To illustrate the acceleration of the quench we have introduced two characteristic times: τ_1 and τ_2. The value of τ_1 was defined as the time between the start of quench in the first strand and the beginning of the total current decay. The second time is determined as: $\tau_2 = I_0/(dI/dt)_{max}$, where I_0 represents the initial current and $(dI/dt)_{max}$ the maximum rate of current changing. The last value can easily be determined with good accuracy from the maximum signal of the corresponding Rogovsky coil.

The dependence of τ_1 and τ_2 on the initial current per strand is shown in Fig.4. One can see that τ_1 changes exponentially with the initial current while τ_2 is constant in the region of slow quenches and then above a certain current it suddenly falls. So, there is a real boundary between slow and fast quenches, where the characteristic times change two orders of magnitude. Because repeated experiments do not reproduce exactly, the measured boundary is smooth, but it can be seen clearly.

So, in cables with insulated strands we have to deal with an extreme acceleration of the quench process.

B. *Six-strand system.*

In the six-strand cable there are also different types of quench development which are comparable to the two-strand system when taking into account the current per strand. At currents lower than ~110 A/strand only the redistribution of current was observed (Fig.5). It should be noted that in a six-strand system only the two nearest strands (#2 and #6) to the heated one (#1) show a significant increase of current. Attention to this phenomenon was first paid in [10]. It is connected with the properties of the inverse matrix of mutual inductances which is diagonally dominant and therefore only the nearest inductances have a strong reaction to a change of current in first one. Inductances placed far from the first are shielded.

This non-uniform redistribution of currents is typical for cables where the distance between strands remains the same along the twist pitch. A small difference between the inductive coupling coefficients leads to a big difference in current redistribution. When using special fully transposed types of cables, like a braid where all mutual inductances between the strands are the same, the current sharing will be more uniform and it could lead to an improved stability. A connection between the stability of AC cables and the observed quench process is very well possible [12].

At currents above 110 A/strand a very complicated multi-quench behavior was observed. Figure 6 shows an example of the quench development for an initial current of 840 A. Characteristic times for the six-strand cable are shown in Fig.4. It should be noted that for slow quenches the time τ_2 is less than in the two-strand system. Partially, this was caused by the diodes which were present to protect the primary winding against overvoltage in our experimental arrangement. The switching on of these diodes reduces the effective self inductance of the main coil and thus reduces the decay time. Some points obtained without the diodes are also shown in Fig.4; time τ_2 is slightly larger but still less than in the two-strand system.

With increasing current, the time τ_2 for the six-strand system approaches the value for two strands. So, it can be concluded that fast quenches in two and six-strand systems are nearly equal, but the slow quenches are different.

C. *Experiments with heaters.*

The natural question came up during the investigations: if normal spots are created simultaneously in all strands, in the fast quench region, will the redistribution process be suppressed or not? We have tested this idea in three different ways, 1) by energizing all heaters simultaneously, 2) by using an extra heater connected with all strands and 3) by using the central non-superconducting strand to initiate the quench. But in all cases we did not observe any change of the quench process, because always one of the strands was heated first and it led to the usual fast quench process. Note that the time of

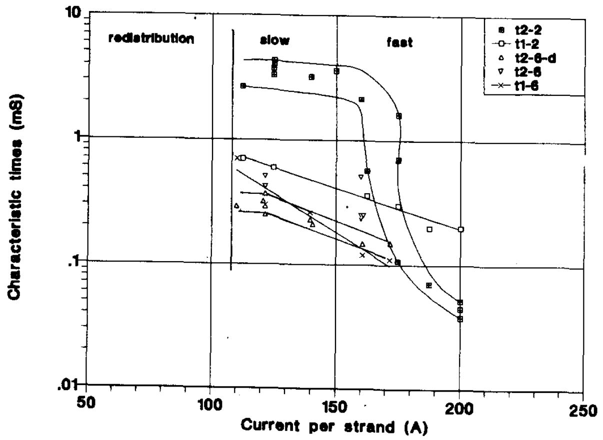

Fig.4. Charasteristic times τ_1 and τ_2 vs. initial current per strand.

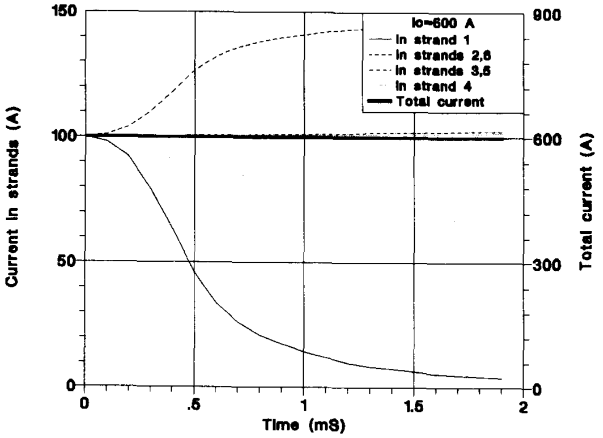

Fig.5. Redistribution of currents in the six-strand system.

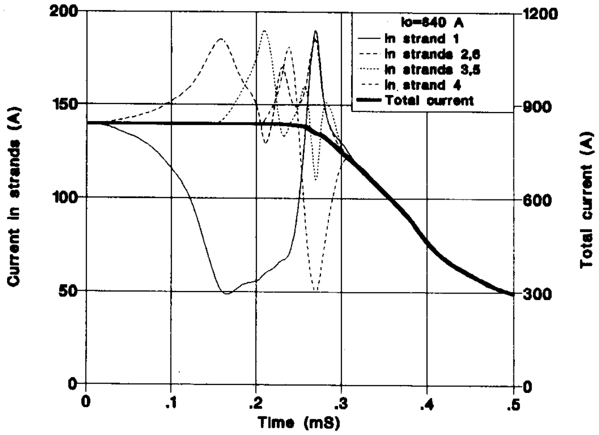

Fig. 6. Quench development process in the six-strand system.

the quench development is much less than the time required for heat transfer between heaters and strands.

This fact additionally proves that the fast quench is a pure electromagnetic process and that it is not connected with any heat conduction process. The phenomenon is very similar to the quench development of subdivided superconducting magnets with thermally insulated sections described in [9]. The main difference is that the inductive coupling coefficients are rather high in cables and therefore the characteristic times of the process become very short. As a result, the current rates during the quench are extremely high and it seems to us that is an intrinsic reason for the occurrence of fast quenches in AC cables at current levels far below the critical one. Possibly, this process is responsible for the instability of current capacity elements for AC applications [12].

IV. CONCLUSIONS.

1. The quench development process in cables with insulated strands was experimentally investigated in detail at different current levels.

2. Different types of quenches were found. The increase of the starting current level led to a change of nature of the quench, from current redistribution, to a quench in all strands, to multi-quench with acceleration of the process from step to step, and to fast quench. Finally, it resulted in a sudden step-like total current decay, which is very important for the practical use in superconducting commutators.

3. There is a clear boundary between regions of redistribution, slow and fast quenches in cables having insulated strands.

4. In all cases, the critical current level at which the strands develop a normal zone is much less than the DC critical current. The fast quench development can only have an electromagnetic origin because thermal processes are too slow.

So we can conclude that the fast quench in AC cables is caused by a rapid redistribution of currents between the strands which leads to a multi-quench process with acceleration of the normal zone propagation after each quench of a strand. The reason for the fast redistribution is the high inductive coupling coefficient between strands. This process could be responsible for the instability of AC cables having insulated strands or strands with high resistive matrix. A computer simulation model for this process will be presented in the next paper.

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