Quench Development in Superconducting Cable Having Insulated Strands With High Resistive Matrix (Part 2, Analysis)

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Abstract - The evolution of quenches in multi-strand cables with high resistive matrix is analyzed. During the quench process, the growing normal resistance in certain strands will cause commutation of their current to other strands with less resistance (or still superconductive). This redistribution of current can lead to a quench of the whole cable. Furthermore, above a certain level of the initial current, an extremely fast quench process occurs with an apparent propagation velocity in the order of several kilometers per second. A model is presented that describes the above phenomena and special attention is given to the fast quench.

I. INTRODUCTION

In the previous paper [1] some experimental results were obtained for the quench process in multi-strand cables with insulated strands. Here, these results are analyzed by means of a numerical simulation using a model of magnetically coupled RL-circuits with time-dependent resistances.

When applying multifilamentary wires in switches or in AC power devices, an important requirement for the conductor is that its matrix should have a high resistivity, for example CuNi. Usually, several insulated wires are cabled either by twisting or by braiding in order to obtain the desired current-carrying capacity without causing excessive AC loss. Such a cable concept with poor electrical contact between the strands and a high resistivity matrix has major consequences for the quench behaviour and stability of the cable. First, above a certain current level (well below I_c) a normal spot in one of the strands will cause a quench of the whole cable [1,2]. Therefore, the cable is sensitive to local thermal disturbances and small defects in the strands. Secondly, the quench process is quite different from that of monolithic conductors, because in the cable a rapid commutation of current between the various strands occurs. This transfer of current takes place via the ends of the cable where the electrical contact with the leads is made. Therefore, the quench evolution is mainly determined by the magnetic coupling between the various strands in the cable and it cannot be regarded as the usual single normal zone propagating at a certain speed v_p.

In the experiment, the quench process was investigated by locally heating one of the strands using a heater energy just sufficient to create a normal spot, and measuring the current decay in the various strands. Depending on the initial current in the cable $I_{tot}(0)$, three regimes can be distinguished:

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1) Redistribution. The heated strand quenches and its full current is rapidly transferred to the neighbour strands without causing new normal zones. The total cable current I_{tot} remains practically constant.
2) Slow quench. The heated strand transfers its current to the neighbours, but now these neighbours also become resistive because their currents exceed some critical level which depends on the large dB/dt and the temperature rise caused by thermal conduction between the strands. Then, all strands successively obtain normal zones which propagate at the common velocities in the order of 10 to 100 m/s.
3) Fast quench. This type of quench is a purely electromagnetic phenomenon which happens so fast that thermal conduction between adjacent strands cannot play a relevant role. The whole cable becomes normal in a very short time and I_{tot} decays accordingly.

The fast quench process is particularly interesting because it leads to very high apparent propagation velocities of several km/s. It was observed before in multi-strand cables [3,4,5], but so far there was no satisfactory theoretical description or explanation of the phenomenon, except in [5]. We found that the fast quench is quite similar to the quench process of a magnet that is protected by subdivision in sections that are separately shunted. In such magnets a specific type of quench development was observed, the so-called "electromagnetic avalanche" [6]. In a cable, however, the inductances are small and the magnetic coupling between the strands is very good, so current transfer to adjacent strands can be extremely fast.

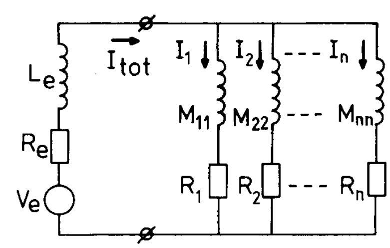

Fig. 1. Equivalent circuit of the n-strand cable.

II. THE MODEL

The different strands in the cable are modeled as magnetically coupled RL-circuits as shown in Fig. 1. The current leads and the power supply are taken into account as an external inductance L_e and resistance R_e in series with V_e. Kirchhoffs' laws give the following system of equations

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$$\begin{cases} M_{11}\dot{I}_1+M_{12}\dot{I}_2+\cdots+M_{1n}\dot{I}_n+R_1I_1=V \\ M_{21}\dot{I}_1+M_{22}\dot{I}_2+\cdots+M_{2n}\dot{I}_n+R_2I_2=V \\ \vdots \\ M_{n1}\dot{I}_1+M_{n2}\dot{I}_2+\cdots+M_{nn}\dot{I}_n+R_nI_n=V \\ V_e-R_eI_{tot}-L_e\dot{I}_{tot}=V \end{cases} \tag{1}$$

The term $V_e-R_eI_{tot}$ can be neglected, and after eliminating V and substituting $I_{tot}=\sum I_i$, the following system is obtained

$$\begin{cases} \sum_{j=1}^{n} D_{1j}\dot{I}_j=-R_1I_1 \\ \sum_{j=1}^{n} D_{2j}\dot{I}_j=-R_2I_2 \\ \vdots \\ \sum_{j=1}^{n} D_{nj}\dot{I}_j=-R_nI_n \end{cases} \quad \text{with} \quad D_{ij}=M_{ij}+L_e, \tag{2}$$

where the R_j are functions of time that can be found by calculating the resistance growth of a normal zone that propagates one-dimensionally in the strand, i.e.

$$\frac{dR(t)}{dt}=\frac{2}{A}\left(v_p\,\bar{\rho}(T_c)+\int_0^{x_n(t)}\frac{d\bar{\rho}}{dT}\frac{\partial T}{\partial t}\,dx\right), \tag{3}$$

with A the cross-section of the wire, $\bar{\rho}$ the averaged resistivity of the composite and $x_n(t)$ the position of the normal front. A factor 2 is included because the normal zone expands in two directions. The first term corresponds to the actual propagation of the normal region, and the second term to the ohmic heating of the composite in the normal zone. The dependence of the propagation velocity v_p on the current, wire parameters and cooling conditions has been calculated by several authors [7,8].

In the case of conductors having a CuNi matrix the equations simplify considerably because $\bar{\rho}$ is nearly independent of T so the second term in (3) vanishes. Furthermore, the minimum propagation current is almost zero and v_p is a linear function of I, therefore

$$\frac{dR}{dt}=2\,\frac{\bar{\rho}}{A}\,v_p(I) \quad \text{with} \quad v_p(I)=c\,I\,. \tag{4}$$

It was found experimentally [8,9] that (4) is a fairly good approximation for conductors having CuNi matrices, although it disagrees with the existing theory [7,8].

A. Analytical solution

The quench evolution in the cable can be calculated analytically as long as the number of normal zones is one. Such a case is equivalent to a single LR-circuit where dR/dt is a function of the instantaneous circuit current. The self inductance of the resistive strand is significantly lowered due to the good coupling with the others. For example, suppose that strand 1 is resistive then its effective inductance L_{eff} is

$$L_{eff}=D_{11}-\sum_{j=2}^{n}D_{1j}a_{j1} \ll M_{11}\,, \tag{5}$$

where a_{j1} represents $-\dot{I}_j/\dot{I}_1$, the current amplification factor from strand 1 to j, given by $-(D^{-1})_{j1}/(D^{-1})_{11}$. Using (4) for the resistance rate, the equations for the current decay in strand 1 become

$$\begin{cases} \dot{I}=-RI/L_{eff} \\ \dot{R}=2\bar{\rho}cI/A \end{cases} \quad \text{or} \quad I\,\frac{d^2I}{dt^2}-\left(\frac{dI}{dt}\right)^2+bI^3=0 \tag{6}$$

with $b=2\bar{\rho}c/(AL_{eff})$. For $\dot{I}(0)=0$, the solution of (6) is

$$I_1(t)=I(0)\cosh^{-2}\left(t\sqrt{bI(0)/2}\right)\,. \tag{7}$$

The currents in the other (non-resistive) strands are given by

$$I_j(t)=I_j(0)+a_{j1}\big(I_1(t)-I_1(0)\big)\,. \tag{8}$$

B. Numerical approach

The numerical approach is more general because it is applicable when several strands are resistive and $\dot{R}_j$ may be any function of the current and time. In a computer program the system of equations (2) is solved using the implicit "backward Euler" scheme. Note that explicit schemes don't function properly because (2) is a stiff system involving several characteristic times of quite different order. The time for current transfer between the strands, for example, is related to L_{eff}, whereas the decay of the total current is connected with L_e+L_c which is much larger.

A key point in the computer program is the modeling of the appearance of new normal zones during the quench process. Two questions arise:

1) What criterion should be used to determine whether a strand develops a (new) normal zone? The critical level I_q at which a strand becomes resistive depends on many factors and it can be significantly lower than the DC critical current I_c. Firstly, I_q is reduced by the large current rates of the order 10^6-10^7 A/s, which cause heating and affect the stability of the conductor [10]. Secondly, there may be a temperature rise caused by the dissipation in adjacent strands.
2) What is the initial resistance and resistance rate of the new normal zone? We will see later that the resistance rate $\dot{R}$ in a newly resistive strand can be much higher than given by (4), as if surpassing the critical level creates a multiplicity of normal spots.

III. RESULTS & DISCUSSION

A. Redistribution in a two-strand cable

As explained, the time dependence of the currents during redistribution can be calculated analytically. The data needed for the model were determined by direct measurement; the length of cable is 4 m, $A=1.96\ 10^{-7}\ m^2$, $\bar{\rho}=1.35\ 10^{-7}\ \Omega m$, $M_{11}=M_{22}=880\ \mu H$ and $L_{eff}=6.6\ \mu H$. The normal zone velocity of the strand was obtained from measurements in [9] and equals cI, with c=0.12 m/s/A.

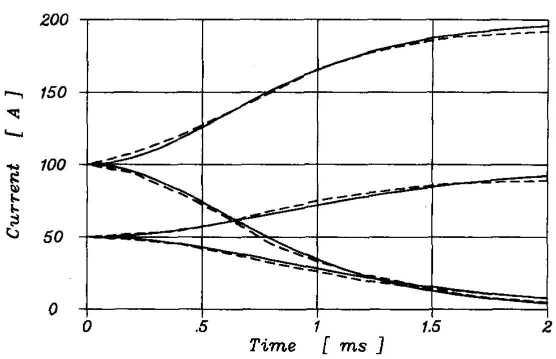

Fig. 2. Calculated (———) and measured (– – –) redistribution of current in a 2-strand cable.

In Fig. 2 one can see a good agreement between the calculated and measured redistribution process. This demonstrates that the various parameters included in the model are sufficiently accurate. The resistance is given by

$$R(t) = 2\, L_{eff}\sqrt{bI(0)/2}\, \tanh(t\sqrt{bI(0)/2}), \qquad (9)$$

so the final length of normal zone is $2\sqrt{cI(0)L_{eff}A/\rho}$. For an initial current of 100 A it corresponds to a normal length of only 20 mm. The maximum resistive voltage during the redistribution occurs after 0.6 ms and is equal to 0.6 V.

B. Slow and fast quench in a two-strand cable

The experiment [1] shows that if the initial current is increased above 100 A per strand, redistribution is not possible anymore. The second strand also quenches and the total current drops. Calculation of this quench process requires an assumption about I_q, and to start with we have used the simplest possibility: that I_q is constant for the various types of quench processes. A reasonable agreement with the experiment is obtained if I_q=180 A, i.e. about 40 % of I_c. A criterion based on the theory of Mints [10] was also used, but actually it had little influence on the results.

Concerning the resistance of the new normal regions that appear when exceeding I_q, three propositions were tested in the model (see also Fig. 3):

a) One normal spot that starts with R=0 and then propagates at v_p=cI. This can explain a "slow quench" where, soon after surpassing I_q, both strands carry nearly equal currents and have comparable normal zones that expand at the ordinary velocity. However, is not possible to simulate the fast quench phenomenon.

b) A step-resistance ΔR which appears when exceeding I_q and expands afterwards. This approach was also used in [5], but it does not agree with our experiments. A process similar to the fast quench can be simulated by using large values of ΔR and let them increase after each successive step of the quench process. But it is impossible to obtain satisfactory agreement between our calculations and the measurements, even when fitting the values of ΔR.

c) Several new normal zones starting simultaneously with R=0. The resistance rate is then proportional to mcI, where m represents the total number of normal zones in the quenched strand. In fact the assumption of multiple normal regions in a strand is equivalent to increasing the propagation velocity by a factor of m. So, in the model the propagation velocity in strand i is taken as $v_p=m_i c I_i$, where the number of normal zones m_i is adapted whenever I_i exceeds I_q. The values of m_i during the successive stages of the quench process are not known a priori, but by fitting them it is possible to obtain excellent agreement between the calculation and the experiment.

By comparing the calculations and experiments it was possible to understand that the fast quench is caused by an increase of the resistance rate $\dot{R}$ of the strands every time they exceed I_q. The physical explanation for this increase of $\dot{R}$ can be that a number of normal spots occur almost simultaneously when the transport current reaches I_q (i.e. assumption c). These new normal spots can be associated with weaker parts of the conductor due to inhomogeneities or places where the temperature or magnetic field is slightly higher. Essential for the fast quench (or multi-quench) is that a wire exceeds I_q more than once. During the first part of the quench the total current in the cable is almost constant, but the current is commutated several times from strand 1 to 2 and from 2 back to 1 again. The oscillations can be understood by considering that the largest current tends to flow in the strand with least resistance, but when the current in this strand approaches I_q, its resistance will grow very quickly and the current is expelled again. This process is illustrated in Fig. 4, which was calculated for a starting level of 170 A per strand. From 720 μs to 750 μs the resistive length of cable grows from about 1 m to 4 m (the full length). In our opinion, this apparent speed of 100 km/s should not be attributed to a normal region that travels at an extremely high velocity, but rather to a large number of normal zones that appear almost simultaneously and propagate at usual velocities.

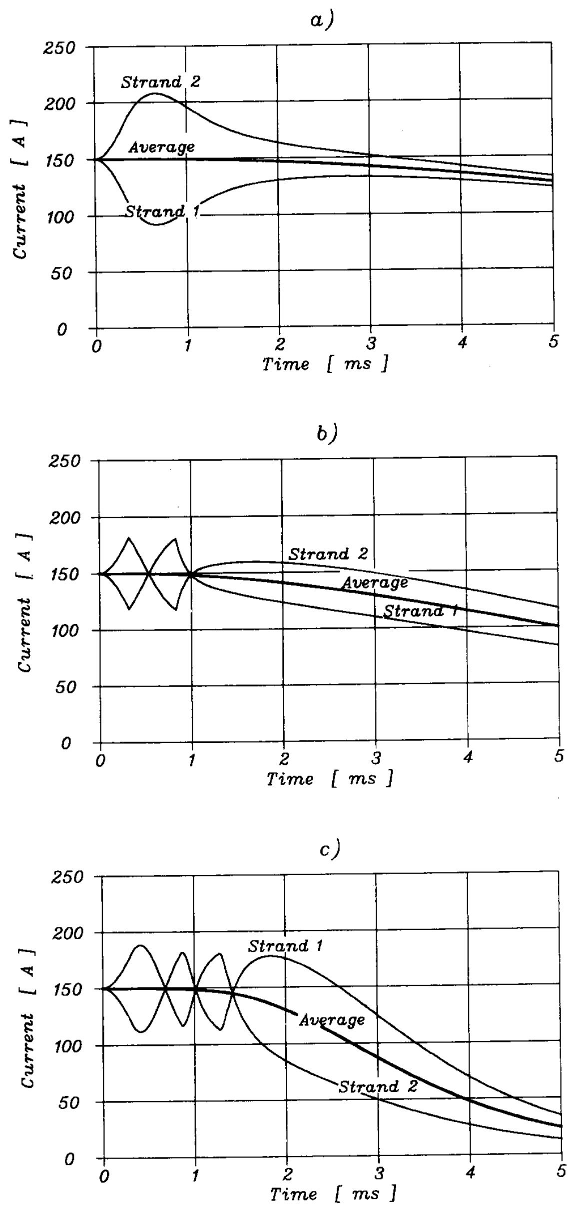

Fig. 3. Examples of different assumtions in the model:
a) one normal spot starting with R=0,
b) appearance of step-resistances ΔR,
c) several spots, i.e. propagation at v_p=mcI.

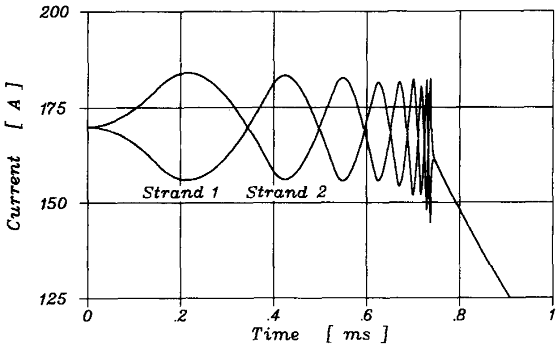

Fig. 4. Calculated fast quench for I(0)=170 A/strand.

In Fig. 5 the decay of the current in the cable has been plotted for different values of the initial level. The transition from slow quench (where both strands quench once) to fast quench occurs at 135 A/strand. It can be seen clearly that the time scale of the process decreases rapidly as the initial current level exceeds 135 A/strand. Above 160 A/strand, the full length of cable becomes normal within 1 ms and then the current decays exponentially with a time constant L_c/R_c, where L_c and R_c are the self inductance and resistance of the whole cable.

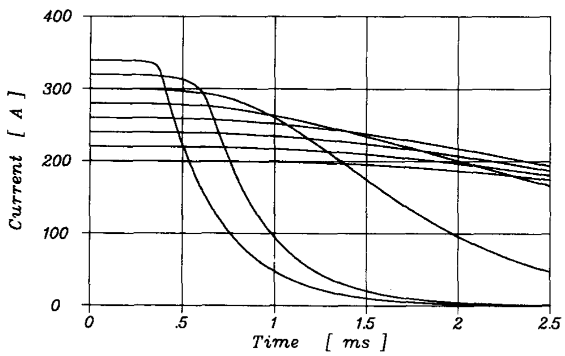

Fig. 5. Decay of the total current of a 2-strand cable for different starting currents.

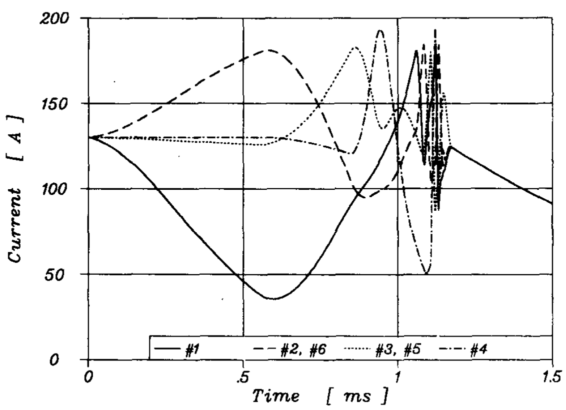

Fig. 6. Simulated quench process for a 6-strand cable.

C. Results for a six-strand cable

The simulation shows that full redistribution of current in a cable of six strands (twisted around a central dummy) is possible up to 120 A/strand. When strand #1 quenches, the current is mainly transferred to the direct neighbours #2 and #6. The excess current in #3, #4 and #5 is less than 5 %. The fast quench in the six-strand cable occurs at currents above 125 A per strand. A simulation is given in Fig. 6 and it appears to be in good qualitative agreement with [1] and [5]. The figure shows that the current is first transferred to the direct neighbours of the heated strand, #2 and #6. Next, strand #2 and #6 exceed I_q and transfer the current to their neighbours, i.e. #3, #5 and #1 again. Then, several successive quenches occur in a period of 100 μs and the full length of cable becomes normal. Due to the symmetry, the currents in the pairs #2/#6 and #3/#5 are identical. Of course, such a perfect symmetry is not present in the experimental case. For example, the initial current distribution in the cable which is determined by the joint resistances of the strands can be inhomogeneous. For the six-strand system, the region where slow quenches occur has almost disappeared. Furthermore, the quench process is even faster than for the two-strand case because the effective inductance of each strand is less due to the coupling with 5 others.

IV. CONCLUSIONS

A model is presented that describes the quench process in multi-strand cables and which is in good quantitative agreement with experimental results. The model gives a better understanding of the so-called "fast quench" and it can be used to predict under which conditions these fast quenches will occur. The fast quench is a result of rapid current commutation between the different strands of the cable, and it could be a useful phenomenon for protection purposes or for the realization of superconducting switches with very short opening times and large dR/dt.

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