FILAMENTARY SUPERCONDUCTORS FOR PULSED MAGNETS

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Abstract

The present stage in the development of superconducting composites and cables intended for use in pulsed magnets and based on niobium-titanium is described. The principal formulae for calculating ac losses are quoted and some numerical examples are given.

I. Introduction

In contrast with their loss-less conduction of dc current, the high field Type II superconductors do exhibit losses under conditions of changing current or changing external magnetic field. The mechanism of this loss is well understood as being due to the penetration of magnetic field into the bulk superconductor when the latter is in a flux flow resistive state.[1] It follows that the rate of dissipation of heat can be obtained by multiplying the critical current density of the superconductor by the voltage gradient associated with the changing flux, and integrating this product over the volume of the superconducting material. One salient point arising from the analyses performed along these lines is the need for fine subdividion of the superconductor into numerous individual filaments if acceptable losses are to arise in practical pulsed superconducting devices. Numerical examples given later in this paper illustrate the magnitude of the losses and indicate that for coils with field rise times of the order of 1 sec it is necessary to subdivide the superconductor into filaments of the order of 5 μ diameter. Now a 5 μ diameter filament, adopting niobium-titanium superconductor by way of example, will carry a current of about 30 mA at 5T. A conductor rated at 3000 A for a pulsed magnet would thus have to be subdivided into about 10^5 such filaments. It is this type of reasoning that sets the real problem for the designer of the conductors to be used in pulsed superconducting devices. How can an assembly of, typically, 10^5 superconducting filaments be made into a practical conductor bearing in mind that any direct electrical contact between individual filaments will tend to make them behave cooperatively with higher overall dissipation under pulsed conditions? Furthermore coil protection precautions must not be overlooked for following a 'quench' transition of the superconductor to its normal conducting state the current which each individual filament is carrying must transfer safely to a low resistance shunt path. This is necessary since the resistivity of a superconductor on reversion to its normal state is high, and indeed too high in most practical cases to avoid coil burn-out unless precautions of the type described are taken. Unless an individual shunt path is provided for each superconducting filament and electrically insulated from all other filaments, a problem which has yet to be solved in practice, some electrical coupling between filaments must be accepted and with it increased losses under pulsed field conditions. The inevitable compromises involved in developing a satisfactory geometry of superconductor for pulsed field applications are described in the following sections with particular reference to the latest prototype filamentary conductors and cables under development.

II. Losses in filaments

The hysteresis loss in a cylindrical sample of superconductor of unit volume may be calculated from the formula:[2]

$$Q_f = \frac{4dJ_oB_o}{3\pi} \ln\,[(B + B_o)/B_o] \qquad (1)$$

where Q_f is the loss per cycle during a field pulse which rises to B and then falls again to zero. The diameter of the sample is d, J_o is the critical current density at zero field and B_o is the field in the well known Kim-Anderson formula $J_c = J_oB_o/(B + B_o)$. It will be noted that the dissipation is not dependent on the rate of field rise. To put this relationship into perspective, a practical example is quoted. Suppose unit volume of niobium-titanium, subdivided into 5 μ diameter filaments, is cycled from zero field to 5 T and returned to zero, then the loss per cycle is given by:

$$Q_f = 3.4 \times 10^4 \ \mathrm{Jm^{-3}} \qquad (2)$$

The value of B_o has been assumed to be 1 T and that of J_o 9×10^9 $\mathrm{Am^{-2}}$. Design considerations for pulsed magnets for superconducting synchrotrons, which have provided the main motivation for the development of pulsed superconductors, indicate that dissipation rates of this order, or perhaps a little more, are tolerable. Thus it is generally accepted that subdivision of the superconductor to the 5 to 10 μ level is necessary and a greater degree of subdivision is desirable if this can be achieved.

III. Matrix losses

The practical multifilament superconductors produced to date have all been manufactured by co-processing niobium-titanium in a metallic matrix, usually copper or copper/cupro-nickel.

Electrical problems then arise from the fact that the filaments are now connected together by the normally conducting material of the matrix and this causes them to be coupled together in a changing magnetic field. The hysteresis of the composite is greater than the hysteresis of the sum of the separate filaments, losses are increased, and stability against flux jumping is reduced. Twisting of the composite about its longitudinal axis is the first remedy to be adopted to minimise coupling.[2] As the number of filaments is increased and with it the overall wire diameter it becomes increasingly difficult to twist the composite tightly enough to decouple filaments sufficiently for pulsed operation at field rise times of the order of 1 sec.

It has been shown that the magnetisation of a twisted filament composite exposed to a changing external field may be written:[3]

$$M = M_o \left(1 + \frac{\dot{B}\ell^2}{\lambda J_c d}\frac{1}{\rho_e} + \ldots\ldots\right) \tag{3}$$

$$\text{where } M_o = \frac{2\mu_o \lambda J_c d}{3\pi} \tag{4}$$

is the magnetisation of the individual filaments, $\dot{B}$ the rate of change of field, 4ℓ the twist pitch, λ the filling factor (superconductor to total volume), J_c the critical current density and d the filament diameter. For a simple composite with only one metal in the matrix and a uniform arrangement of filaments, ρ_e is given by:

$$\rho_e = \frac{\pi\omega\rho_\omega}{3d} \tag{5}$$

where ω is the thickness of normal metal between each filament and ρ_ω is its resistivity.

The loss per cycle is given by integrating MdH over the complete cycle. Substituting for M_o from Equation (4) into Equation (3) and integrating over a cycle consisting of a linear field rise followed by a linear field fall gives:

$$Q = \frac{4\lambda}{3\pi} J_o d B_o \ln\left[(B + B_o)/B_o\right] + \frac{4}{3\pi}\frac{\dot{B}B\ell^2}{\rho_e} \tag{6}$$

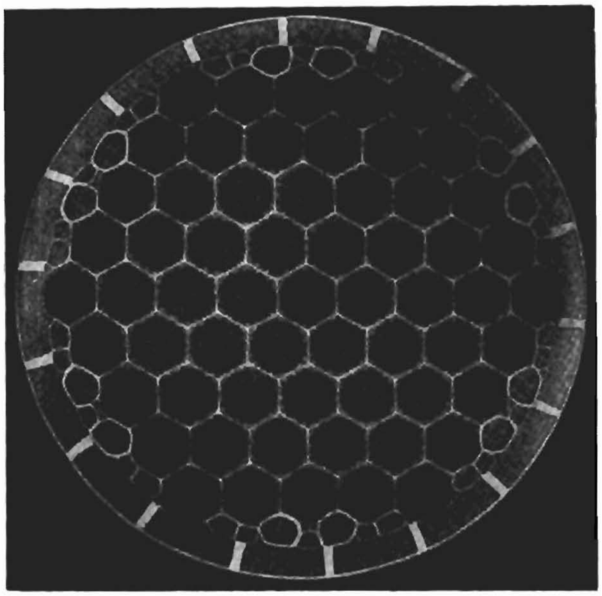
The first term is the simple filament loss term, Q_f, already given by Equation (1) but differing in this case by the factor λ since the loss is now expressed in terms of unit volume of composite rather than unit volume of superconductor. The second term defines the matrix losses Q_M.

As an example consider a composite in which 1000 5 μ filaments are embedded in a copper matrix, uniformly distributed to give an overall composite diameter of 0.25 mm with a matrix: superconductor ratio of about 1.5:1. In practice it proves impossible to twist such a composite wire with a twist pitch much tighter than about five times the wire diameter. (Even if this were possible the current carrying capacity of the helical filaments in the forward direction would become seriously reduced.) If a value of ℓ of 0.3 mm (4ℓ = 5 x wire diameter) is substituted into the second term in Equation (6) together with a value for ρ_e of 4×10^{-11} Ωm then the matrix loss associated with a single triangular shaped pulse in which the field varies at rate $\dot{B}$ from zero to 5 T and back is given by:

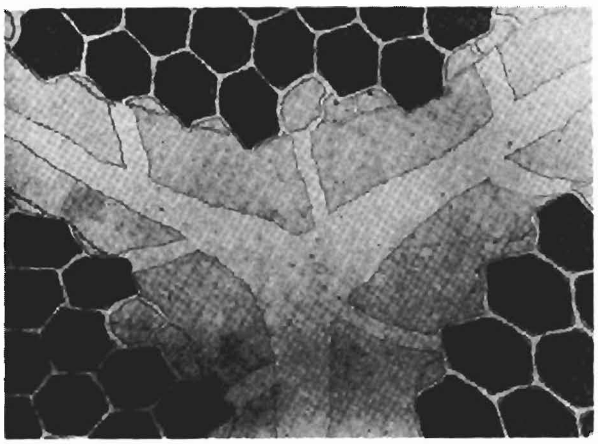
$$Q_M = 4.8 \times 10^3\, \dot{B}\ \text{Jm}^{-3} \tag{7}$$

A comparison of the matrix loss in the model composite conductor taken in this example with the losses in the superconducting filaments, can readily be performed by calculating the value of $\dot{B}$ at which these two losses become equal. Equating Q_M from Equation (7) with $\lambda\, Q_f$ where λ the filling factor for this conductor has the value 0.4 and Q_f is given by Equation (2) yields the value $\dot{B} = 2.8$ T sec^{-1} at which the total losses are double the filament loss. That the charging rate at which losses double is inversely proportional to the number of filaments in composites of the same type can readily be shown since the maximum permissible twist pitch is proportional to the diameter of the composite. Thus if a 10,000 filament conductor is considered, losses will double at $\dot{B} = 0.28$ T sec^{-1}. Since the tendency in high current pulsed magnets now appears to be towards even higher numbers of filaments per strand, composite conductor with resistive barriers of cupro-nickel between filaments are becoming increasingly accepted to minimise matrix losses at fast rates of field rise. Now the effective resistivity of cupro-nickel matrix is about 7×10^{-8} Ωm ie. some 2000 times that of pure copper matrix. Unfortunately fine filament composites with cupro-nickel matrices have been shown not to perform well in magnets and some copper must always be included in the matrix to improve thermal conductivity and provide magnetic damping if satisfactory operation is to be obtained. Furthermore the copper provides coil protection as a low resistance shunt path. Composites with both copper and cupro-nickel in the matrix, the so-called three component composites, are therefore frequently employed for pulsed magnet applications.

A three component composite with 14,701 individual 5 μ filaments is shown in Figure 1. Photographs of other less sophisticated three-component filamentary conductors are given elsewhere.[3] The composite illustrated in Figure 1 is the most advanced that has yet been produced and is available at present only in sample form. It is intended for use in multi-thousand ampere cables or tapes in applications where field rise times of order 1 sec are required.



(a)



(b)

Fig. 1a. A cross-section of a 14,701 filament niobium-titanium composite conductor.

b. An enlargement of a region of the cross-section.

1.06 mm dia; 5.3 μ filaments; ∿430A at 5T and 10^{-14} Ωm measuring sensitivity; effective resistivity (ρ_e) ∿ 8 x 10^{-8} Ωm.

Each filament is surrounded by copper and then cupro-nickel. Groups of 241 filaments are assembled into a "spider can" of cupro-nickel with cupro-nickel radial spokes separating copper regions. 61 groups of 241 filaments are then assembled into a similar "spider-can".

[Manufacturer:
Imperial Metal Industries (Kynoch) Ltd.]

IV. Self Field Losses

A transport current flowing in a circular composite wire produces self field lines in the form of concentric circles centred on the centre of the wire. There is always a self field flux enclosed between the outer filaments of the wire and those near the centre. This flux tends to couple the filaments together and thus increase the hysteresis loss. It is not possible to reduce the coupling by twisting and, to a first approximation the self field behaviour of a twisted filamentary composite is the same as that of a solid wire. The effect could be removed if it were possible to transpose fully the filaments so that outer and inner filaments change places along the length of the wire but this seems unlikely in any practical composite.

If the current in a wire is increased from zero to critical and then reduced to zero again, the self field loss is given by:[3]

$$Q_s = \tfrac{1}{4}\,\eta\,\mu_o \lambda^2 J_c^2 a^2 \tag{8}$$

where a is the wire radius and η is a numerical factor depending on the past history of the wire. The usual case of repetitive pulsing of current in the same direction gives:

$$\eta = 3/2 - 2\ln 2 = 0.114$$

Thus the 0.25mm diameter wire used in the previous example will have a self field loss:

$$Q_s = 200\ \mathrm{Jm^{-3}} \tag{9}$$

which is negligible in comparison with Equation 2. If the composite radius were to be increased by a factor of ∿8 however (i.e. 60,000 filaments) the self field and filament losses would be comparable.

Self field losses are thus not important in any of the composites presently in use. There are also theoretical grounds for believing that Equation 8 is pessimistic and that the losses will in practice be reduced by spiral field effects and the displacement of the electric centres within the filaments.[3] It therefore seems not unreasonable to contemplate much larger composites containing ∿10^5 filaments and work along these lines is planned at Rutherford Laboratory.

V. Cables

It has already been pointed out that the need for a high magnet operating current, combined with the requirement for fine filament diameters, means that a typical magnet conductor must contain ∿10^5 filaments.

With presently available composites this means that between 10 and 1000 wires must be connected in parallel as a cable. The wires must be twisted to minimize magnetisation currents flowing between wires - either directly across the cable or through the end terminations. Because self field effects are expected to become troublesome in conductors of this size, it is also desirable that the wires are fully transposed.

So far, magnets have been made from two basic types of cable: woven braids and compound twisted ropes. Both types are fully transposed and have been shown to carry pulsed currents with good current sharing between wires and low hysteresis losses. Their principal disadvantage is a rather low filling factor. In an attempt to improve this the cables have been compacted using rollers but it has proved difficult to attain filling factors of better than ∿ 60% without damaging or even breaking the composite wires. The reason for this problem appears to be the closely interwoven structure of a transposed cable which gives rise to many cross-over points and kinks in the wires.

A recent development at Rutherford Laboratory has been the flat tape shown in Figure 2. This cable consists essentially of a hollow tube of helically twisted wires which has been rolled flat. Because the paths of the individual wires are now much less tortuous than in the interwoven cables, it has been possible to compact these tapes to filling factors of >85% with a negligible reduction in current carrying capacity.[4] All cables of this type are approximately two wire diameters thick and the width depends on the total number of wires. A practical limit seems to be about 20 wires, giving a maximum aspect ratio of 5:1. It is therefore necessary to make these cables from rather large composites containing up to 10,000 filaments if currents of 5000A or so are required. The conductor shown in Figure 2 is a model of the cable planned for the AC5 magnet which will contain 15 strands of 1.05 mm diameter, 8917 filament composite (7μ filament diameter).

If the wires in the cable are in electrical contact, a changing magnetic field can induce rate dependent magnetisation currents to flow across the cable. The process is very similar to the induction of magnetisation currents within the matrix of an individual composite wire and the increase in total magnetisation is given by a formula similar to Equation 3. If the rate dependent magnetisation is well below saturation, the two effects may simply be added together.

$$M = M_o \left[1 + \frac{\dot{B}}{\lambda J_c d}\left(\frac{\ell^2}{\rho_e} + \frac{L^2}{\rho_{ec}}\right)\right] \qquad (10)$$

where $4L$ = cable twist pitch

ρ_{ec} = effective resistivity across the cable

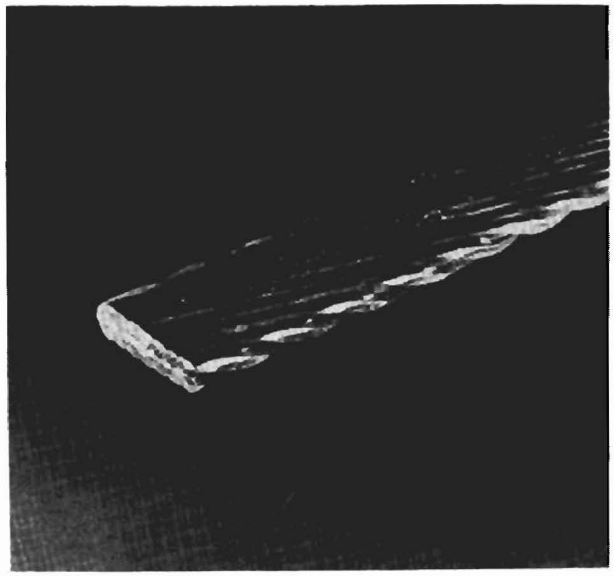


Fig. 2. A flat twisted cable: copper model of the conductor planned for the AC5 magnet. The superconducting version will be made from 15 strands of 1.05 mm dia. three component composite, each strand containing 8917 filaments 7μ in diameter.

For round or square cables the effective resistivity is given simply by the average resistivity across the cable multiplied by a geometrical factor of order unity. For flat tapes the magnetisation occurs with the applied field at right angles to the broad face of the tape. In this case we find:

$$\rho_{ec} = f\rho_a\alpha^{-2} \qquad (11)$$

where f is the geometry factor≃ 1, α is the aspect ratio of the tape and ρ_a is the average resistivity across the tape.[5]

It has been found that filling the cable with solder can reduce its susceptibility to wire movement effects - presumably by improving mechanical rigidity and increasing heat capacity. Unfortunately this also increases magnetisation loss by reducing the average resistivity across the cable. For example, a solder-filled flat tape will have an average resistivity of $\sim 10^{-8}$ Ωm. An aspect ratio of 3:1 will reduce ρ_{ec} to $\sim 10^{-9}$ Ωm so that, for a 10 cm twist pitch and 5μ filaments, the magnetisation (and hence the loss will double at a rate of change of field of only $\sim 5 \times 10^{-3}$ T sec^{-1}. A successful attempt at increasing ρ_{ec} by a factor of 10 or more has been reported.[6] It is also of course possible in principle to reduce the twist pitch. Nevertheless it seems reasonable to conclude that the losses in soldered braids will always be too high for the usual synchrotron rise times of a few seconds.

If each strand in the cable is organically insulated, eg. with PVA enamel, the effective resistivity is essentially infinite, the last term in Equation 10 is zero and there will be no additional losses due to the cable. Unfortunately, this approach results in the following practical problem. After rolling the flat tape it is desirable to heat treat in order to anneal the copper in the matrix (to increase conductivity and improve handling) and also to increase the current density in the superconductor. Typical heat treatments are 1 hour at 350°C - 400°C and this will burn most organic insulations. Work is in hand on heat resistant enamels.

The approach which has been adopted so far at Rutherford Laboratory lies between solder filling and total insulation. It has been found that the naturally occurring oxide layer on the copper produces a contact resistance between the wires which gives an average resistivity across the cable of $\sim 10^{-4}$ Ωm. For a 3:1 aspect ratio we have $\rho_{ec} \sim 10^{-5}$ Ωm so that the magnetisation loss will now double at 5 T sec^{-1} (5μ filaments, 10 cm twist pitch). A simple cable made from bare wires is therefore quite adequate for most purposes and if necessary the resistance of the oxide layer can be increased by electrolytic treatment. The layer is not destroyed by heating. The cables used for both the AC3 and AC4 pulsed magnets use oxide insulation.

VI. Conclusions

The present trend in the development of niobium-titanium composites for pulsed magnets is towards wires with larger numbers of 5 to 10μ filaments. Conductors with 14,000 filaments have already been produced in sample form and larger numbers of filaments are being attempted. Such composites allow multi-thousand ampere cables to be produced using as few as 5 to 10 such wires. Packing factors in the resultant simple cables and tapes of more than 80% are then possible. If conductors with $\sim 10^5$ filaments can be produced successfully, solid multi-thousand ampere conductors could perhaps then be used to advantage in pulsed magnet construction, but there still remain theoretical doubts about the 'self-field' stability of such large composites. Insufficient measurements have yet been performed on large composites to resolve this point.

VII. Acknowledgements

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VIII. References

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