MAGNETIZATION AND DESIGN OF MULTISTRAND SUPERCONDUCTING CONDUCTORS*

CONF-740957--25

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ABSTRACT

Magnetization of cabled and braided samples which are long compared to their transposition lengths has been measured in a uniform magnetizing field directed at right angles to their widths. A separated double pancake with nonuniform windings was constructed to produce a suitably uniform radial field in which long coiled samples could be placed. Magnetization losses have also been measured in the ISA I magnet at BNL. Results are compared with theories which are due to Wilson¹ and, basically, Morgan.² Also, design optimization procedures have been defined for the use of multistrand conductors in magnet windings.

I. INTRODUCTION

Medium and large sized superconducting magnets are preferably operated between 10^3 and 10^4 A in order to simplify the problems of interturn and charging voltages. To overcome the problems of stability and magnetization, composite wires with large numbers of filaments, and overall diameters not usually greater than 1.0 mm, are cabled³ or braided together to make high current conductors. The strands in a multistrand conductor should be separately insulated from each other to stop inter-strand coupling. However, the resulting conductor is usually less stable in a magnet winding than a conductor having no strand insulation and possibly impregnated with metal. In the latter case, the conductor is better cooled and may have a greater specific heat, but interconnections between strands can result in large rate dependent magnetization and energy loss.

MULTISTRAND CONDUCTORS

In view of the stability problem, conductors with uninsulated strands, and preferably metal impregnated, should be used wherever possible. Indeed, a worthwhile compromise between these two requirements is to coat

Manuscript received September 30, 1974.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

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the strands with a high resistance metal such as Cupro-Nickel.⁴ One of the objects of this paper is to establish the limits at which metal impregnation becomes impractical.

Conductor magnetization, or more properly magnetization hysteresis, results in ac loss and in magnetic field perturbation. To some extent these are separate problems in that, a high ac loss may be tolerated in a magnet pulsed with a low duty cycle provided that the winding configuration effectively cancels the field perturbation effects. It is clear therefore that the magnetization tolerance limit depends on the particular magnet and must be estimated individually.

As a basis for these estimations, we have measured the magnetization produced by a uniform field applied at right angles to the wide face of multistrand cables and braids. Samples which were long compared to their transposition lengths were used in order to eliminate end effects. Both the results and theory give the rate dependent magnetization relative to the superconductor magnetization, and for this purpose a 'doubling $\tilde{B}$ ' is defined as the rate of change of external field which results in a rate dependent magnetization equal to the superconductor magnetization. In practice this is entirely relevant since the size of the superconducting filaments should already have been chosen such that the superconductor magnetization is not a problem.

Nomenclature

- $\tilde{B}_D$ = doubling $\tilde{B}$ as in the introduction,
- λ = filament filling factor (~ 0.5),
- D_0 = strand diameter,
- $2C$ = conductor width,
- $4L$ = conductor transposition pitch,
- J_c = superconductor current density,
- d = superconductor filament diameter,
- r = contact resistance of unit area between strands,
- $\rho(s)$ = interstrand matrix resistivity,
- $t(s)$ = strand insulation thickness,
- R_R = strand crossover contact resistance,
- n = number of strands in the conductor,
- N = number of filaments in a strand, and
- α = aspect ratio.

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II. MAGNETIZATION THEORIES

In his report, Wilson¹ uses a model which is probably more applicable to compacted cables than to braids, whereas Morgan's² model closely resembles a braid. In view of the background at the authors' respective laboratories, this is hardly surprising.

In the Wilson model the multistrand conductor is considered as a solid strip throughout which filaments spiral uniformly. He argues that there are two distinct patterns of eddy currents when the external field is perpendicular to the wide face, and that the dominant pattern involves interconnection between crossing strands rather than parallel ones. This means that dominant eddy currents flow along the strands and then parallel to the field across the thickness of the conductor. The currents are zero at the center of the conductor, increase to a maximum at the edges, and flow in opposite directions on opposite sides of the center. Results are obtained by continuous integration and may therefore become less accurate as the compaction is reduced.

In the Morgan model, the currents flow in closed loops formed by connections between crossing strands so that the current flowing in a particular strand at a particular position is the sum of the adjacent loop currents. Since it is irrelevant which side of a strand

a crossing strand contacts, his results can be applied to cables also. However, they may become less accurate as compaction is increased, so that the two approaches are complimentary. Morgan, in fact, arrives at an expression for the current in a strand at a given distance from the center of the wide face. In Ref. 5, an expression for magnetization has been derived from Morgan's expression by continuous integration, and is therefore strictly a hybrid result. This leads to a value of B_D which is $2/K$ times less than that derived from the Wilson model, which gives:

$$\dot{B}_D = \frac{5}{4} \times \frac{D_0}{C^2 L^2} \times J_c d \times r \quad (1)$$

where $r = c(s) \times 2t(s)$ for cables, and $\alpha \approx C/D_0$ so that:

$$\dot{B}_D(\text{cable}) = \frac{5}{2} \times \frac{t(s)}{D_0} \times \frac{1}{(\alpha L)^2} \times c(s) \times J_c d \quad (2)$$

For braids $r = R_R 8LC/(n-1)$.

As suggested by Morgan, the value of R_R may be measured directly. However, a reasonable approximation might be: $R_R = c(s) \times 2t(s)/(D_0/2)^2$, in which case, for a braid: $r = 64 c(s) t(s) LC/D_0^2 n(n-1)$. So that:

$$\dot{B}_D(\text{braid}) = 80\lambda \times \frac{t(s)}{D_0} \times \frac{1}{CLn(n-1)} \times c(s) J_c d \quad (3)$$

Thus, in a highly compacted cable: $B_D(\text{cable}) \propto 1/(\alpha L)^2$, and in a braid: $B_D(\text{braid}) \propto 1/CLn^2$. However, if $L \ll C$, and $n \approx 4\alpha$, then $B_D(\text{braid}) \propto 1/(\alpha L)^2$, as for the cable.

III. MAGNETIZATION MEASUREMENT

We adopt the usual method of measuring magnetization by placing the sample in one of a pair of search coils which are situated in a magnetic field and connected in series such that there is no signal from them in the absence of a sample. Thus, with the sample in place, the integrated output voltage from the coils is proportional to the sample magnetization.⁶

To avoid end effects, it is necessary to use a sample whose actual length is many times its twist or transposition pitch. Thus, we place a coiled sample in a uniform radial field produced by a separated pair of pancake coils (Fig. 2) which are energized in opposition. The current density within the windings is adjusted by inclusion of blank turns so that the field

Fig. 2. Separated double pancake magnet.

variation over an extended region about the mean winding radius is less than 2%. The computations were made by A.D. McInturff using the RHEL program GFUN. Constant field contours are shown in Fig. 3 ($\Delta H = 0.05$ T).

FIG. 3

The coil geometry and measured field are shown in Fig. 4.

The missing turns were included in the magnet computation, but were missed off because of winding difficulties. As a result, the field at larger radii droops. This double pancake configuration is very suitable and economical for all types of sample measurement, especially with large samples. Smaller versions can, of course, be constructed for wire samples. Not least of the advantages is the small inductance. The magnetization measurements were made using circular saddle shaped search coils so constructed that the samples may be wound directly on them. See Fig. 5.

Fig. 5. Circular saddle search coils.

Details of the samples measured are contained in Tables I and II.

TABLE I
Samples

Sample 1. Cable/8.23 mm x 1.85 mm x 3.86 m/88% compact/organic insulated/(RHEL, ACS conductor).
Sample 2. Braid/19.05 mm x 0.55 mm x 11.1 m/58% compact/thin AgSn strand coat with 275° C for 5 h/InTi impregnation (BNL, ISA I conductor).
Sample 3. Braid/15.9 mm x 0.69 mm x 10.2 m/59% compact/thin AgSn strand coat with 275° C for 10 h (BNL, 2I conductor).
Sample 4. Cable/sample No. 1 with insulation stripped and replaced with staybright and Pb impregnation.
Sample 5. Braid/18.3 mm x 0.66 mm x 3.65 m/56% compact/CuNi strand jacket, $R_{SI} = 0.129$.
Sample 6. Braid/sample No. 5 InPb impregnated/(ISA IV conductor, before rolling to 18.3 mm x 0.55 mm).

TABLE II
Sample Parameters

Sample No.	n	4L (mm)	D _O (mm)	d (μm)	N
1.	15	110	1.07	5.7	8917
2.	186	330	0.2	7.0	367
3.	93	267	0.28	9.7	361
4.	-----	as sample No. 1	-----	-----	-----
5.	93	355	0.305	9.8	379
6.	-----	as sample No. 5	-----	-----	-----

IV. RESULTS OF MAGNETIZATION HYSTERESIS MEASUREMENTS

Figures 6a and 6b show the graphs of magnetization hysteresis against $\dot{B}$ from which the values of $\dot{B}_D$ in Table III were obtained. Scales in the graphs are individually adjusted for each sample. ΔM scales are uncalibrated since we are interested only in ratios with ΔM_0 . Calibrations for $\dot{B}$ scales are indicated.

TABLE III

Sample No.	$\dot{B}_D$ T/s	$\rho(s)$ $\frac{\Omega}{\text{cm}}$	Remarks
1.	1.8		Composite $\dot{B}_D$
2.	4.0×10^{-6}	2×10^{-9}	ρ Cu Sn ?
3.	1.1×10^{-3}	9×10^{-8}	Intermetallic ⁹ ?
4.	1.8×10^{-3}	2×10^{-8}	ρ Staybright & Pb
5.	8.1×10^{-2}	1×10^{-5}	Poor contact
6.	2.3×10^{-5}	3×10^{-9}	ρ CuNi = 10^{-7}

Notes on Table III. $\dot{B}_D$ has been measured at 1.0 Tesla, $\rho(s)$ is therefore calculated from this assuming $J_c = 4.0 \text{ kA/mm}^2$ for all samples.

V. ISA I MAGNETIZATION

Loss, or magnetization, measurements were obtained from the ISA I dipole by integrating the loss component of the voltage at the magnet terminals. The inductive component of voltage is derived from the flux linked in the absence of screening currents. If this is cancelled using a signal externally derived from the magnet current then the remaining signal is due to screening currents. Thus we are using the magnet winding as its own search coil, bucking it against an external field coil. The method is further described in Ref. 7. The result is plotted in Fig. 7 and indicates $\dot{B}_D$ is probably less than $50 \mu\text{T/s}$. The absence of points at the lower end of the curve is due to very great difficulty in setting up the external circuit to keep the integrator⁸ drift small enough over the 5000 sec cycle time. This proved to be quite possible with the much simpler circuit in the sample magnetization experiments. The lowest point on the magnet curve has been appropriately adjusted and plotted on the sample curve in Fig. 6a.

NOTICE

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VI. CONCLUSIONS

Composition of the interstrand materials is somewhat unknown, except for sample No. 6. Taking this as a basis the braid is at least an order of magnitude more rate dependent than expected. This means that the effective crossover contact area is $\gg (D_0/2)^2$. By comparison $\rho(s)$ for 2 and 3 are not greater than tabulated. The one cable result gives roughly the correct value for $\rho(s)$.

VII. CONDUCTOR DESIGN

For a detailed discussion of this subject, see Ref. 5 in which it is shown that n or α are the major factors in determining conductor performance. Therefore, if we start with the assumption that the strand ratios and number of filaments are fixed, but that the strand diameter is a design variable, then the following optimization procedure may be adopted. Firstly, decide on a convenient n or α . Then calculate the actual conductor size required for the magnet. The sizes of the strands and filaments and the conductor current and magnetization are then calculated. We now change the value of n and recalculate. Only three or four such sets of calculations are necessary to produce plots of the various parameters against n in sufficient detail to make a clear decision on the required design optimum taking full account of all the parameters.

A computer program⁵ has been written to make the above calculations starting effectively from Ampere turns/m (azimuthal current density). The various conductor and compaction ratios are also input variables together with number of layers and superconductor critical current density. Using this program it has been shown that if a resistive jacket on the strands is used to reduce magnetization then there is a maximum effective thickness for the jacket as shown, for example, in Fig. 8. R is Cu:superconductor, RS_1 is strand insulation:total strand areas. For any magnet the $1/(magnetization)$ curves are similar. Optimization using the program essentially follows the above outlined procedure.

The analysis in Ref. 5 assumes $L/C = 2.6$ as a practical minimum. This can be achieved in cables, but for braids it is around 7.0, this, together with the unexpectedly large rate dependence of braids very much favors cables by comparison. Conclusions reached in Ref. 5 must therefore be considerably modified.

ACKNOWLEDGMENTS

I am particularly indebted to Tom Mullany for much help in the double pancake design. Also to Steve Kiss for his work in producing the search coils. A special vote of thanks goes to Cal Lasky, Manny Thomas, Ray Atkins, Frank Abbatiello, and particularly Ken Robins for their various contributions. I am grateful to Bill Sampson and Harald Hahn for their enthusiastic support. Also to Gerry Morgan, Al McInturff, and Per Dahl, for help and stimulation.

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