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A COMPUTER PROGRAM TO CALCULATE COMPOSITE CONDUCTOR LOSSES IN PULSED POLOIDAL COIL SYSTEMS*

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A COMPUTER PROGRAM TO CALCULATE COMPOSITE CONDUCTOR LOSSES IN PULSED POLOIDAL COIL SYSTEMS*

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ABSTRACT

In the design of the cryogenic system and superconducting magnets for a poloidal field system in a tokamak fusion reactor, it is important to have an accurate estimate of the heat produced in the superconducting magnets as a result of the rapidly changing magnetic fields. Until recently, this estimate was obtained by assuming that the field and the time rate of change of the field were constant throughout the coil windings. A more accurate method of estimation involves integrating the losses over the coil windings, thus taking into account the spatial variation of the magnetic field. A computer code, PLASS (Pulsed Losses in Axisymmetric Superconducting Solenoids), has been written to perform this integration.

PLASS has been used to analyze the present design for the poloidal coil system of the ORNL Experimental Power Reactor (EPR). This design requires that superconductor hysteresis losses, superconductor coupling losses, stabilizing material eddy current losses, and structural material eddy current losses be taken into consideration in the calculation of conductor losses. A tabulation of individual losses vs variations in superconductor characteristics and coil current changes is presented to demonstrate the parameters which significantly affect the design. Results indicate that the total energy released into the cryogenic system is less than one-half of that predicted by the previously oversimplified calculation.

I. INTRODUCTION

In the design of the cryogenic system and superconducting magnets for a poloidal field system in a tokamak, it is important to have an accurate estimate of the heat produced in the superconducting magnets as a result of the rapidly changing magnetic fields. Until recently, this estimate was obtained by assuming that the field was constant throughout the coil windings. A more accurate method of estimation involves integrating the losses over the coil windings, taking into account the spatial variation of the magnetic field. A computer code, PLASS (Pulsed Losses in Axisymmetric Superconducting Solenoids), has been written to perform this integration.

II. LOSS MECHANISMS

The principal power loss mechanisms inherent in the design of the ORNL Experimental Power Reactor (EPR)[1] poloidal coil system are superconductor hysteresis losses, superconductor coupling losses, stabilizing material eddy current losses, and structural material eddy current losses. The conductor specifications for this design are listed in Table I. Figure 1 shows a schematic diagram of the conductor, which is composed of mixed-matrix Cu:CuNi: NbTi wires in a stainless steel conduit. The cable is cooled by forcing supercritical helium through the conduit and the interstices of the cable.[1,2]

The losses for this design are approximated using the following assumptions:

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(a) For superconductors with small diameters, the hysteresis loss, W_H, per unit volume of superconductor for a cyclical magnetic field variation from B_{min} to B_{max} and back to B_{min} can be expressed as[3,4]

$$\frac{W_H}{V} = \frac{\alpha_c}{2}\, d\, \ln\left(\frac{B_o + B_{max}}{B_o + B_{min}}\right) (\text{in J/m}^3) , \qquad (1)$$

where V is volume, d is the superconductor filament diameter, and α_c and B_o are constants defined in the critical state equation

$$J_c(B) = \frac{\alpha_c}{B_o + B} \ (\text{in A/m}^2) , \qquad (2)$$

where J_c is the critical current density for a magnetic field equal to B.

(b) The coupling losses are due to currents flowing through the matrix which have been induced by a perpendicular magnetic field. For a composite wire with radius r_o, the coupling energy loss, W_c, per unit volume is[5]

$$\frac{W_c}{V} = \frac{S}{V}\int_{t_i}^{t_{i+1}} \frac{\dot{B}^2}{2\rho_m} r_o^3 \left(\frac{\dot{t}}{2} + \frac{1}{4}\right) dt \ (\text{in J/m}^3) , \qquad (3)$$

where S is the wire surface area, $\dot{B}$ is the derivative with respect to time of the perpendicular magnetic field, t is time, ρ_m is the matrix resistivity, x_o is the normalized twist pitch $(2\pi r_o/\ell_p)$, and ℓ_p is the twist pitch length.

(c) The model for the structural material eddy current loss is a cylindrical (as used in the ORNL Reference Design) conductor subjected to a time-varying magnetic field perpendicular to its axis. If the flux-penetration depth is assumed to be much longer than the cylinder size, the structural material eddy current loss, W_E, per unit volume can be conservatively estimated by

$$\frac{W_E}{V} = \int_{t_i}^{t_{i+1}} \frac{\dot{B}^2 R^2}{\rho_{ss}} dt \ (\text{in J/m}^3), \qquad (4)$$

where R is the radius of the cylinder and ρ_{ss} is the resistivity of the structural material.

III. NUMERICAL PROCEDURE

PLASS uses finite element techniques to numerically perform a two-dimensional Gaussian axisymmetric integration on a body-of-revolution to obtain the individual values of the loss terms for a given time. (We have recently learned that a numerical procedure for calculating pulse losses was developed by Lefrancois.[6] His computer program does not use the same numerical method nor, due to the requirements of our magnet design, is it as general as the techniques discussed in this paper.) If the current in a magnet is assumed to be a linear function of time over a finite time increment, then the derivative of the current with respect to time and hence the derivative of the magnetic field with respect to time are constant in that time increment. Therefore, the differential times may be replaced with the difference between t_{i+1} and t_i. Further, we assume that the resistivities are not functions of magnetic field. These relationships are used to perform a piece-wise linear integration in time to obtain the total energy loss for a particular poloidal field magnet system and pulse-time history.

The spatial variation of the magnetic field, which is taken into account directly during the Gaussian integration, is complicated by the fact that poloidal field magnet systems may have up to three distinct magnet sets (ohmic heating (OH), vertical field, and trim), each of which may have a different current vs time characteristic. The computer program linearly superimposes the magnetic field at a point due to each magnet set where each set may contain several poloidal magnets.

A limitation of this computer program is that significant modification would be required in order to apply it to non-coaxial and non-circular coils, because of its body-of-revolution integration algorithm. However, due to its modularity, other loss formulations can easily be implemented.

IV. CALCULATION OF THE ENERGY LOSS IN THE SUPERCONDUCTING POLOIDAL COIL SYSTEM OF THE ORNL EPR DESIGN

PLASS has been used to estimate the superconductor losses for the ohmic heating (OH) coil system for the latest ORNL EPR reference design.[2] The coil outlines of the OH system described in Ref. 2 are shown in Fig. 2. The area enclosed by the outline of each coil is proportional to the number of ampere-turns in that coil.

All of the magnets in the OH system are operated in the bipolar mode, i.e., the current in the coils is reversed during the duty cycle. The current waveform used in this study starts with full current in one direction and linearly changes to full current in the opposite direction in two sec. The current is increased slightly over the next 100 sec and is then returned to its initial state in 2 sec. The losses in the 100-sec period are negligibly small and are not calculated.

The total superconductor loss for this example is 1.36×10^5 J. Of this loss, 66% is in the central solenoid with the remainder in the outboard coils. In this design the helium present in the coil cannot be changed in one duty cycle and must absorb the total energy input. However, the refrigerator power is averaged over the longer period of time rather than over both of the 2-sec periods when the current is reversed. Over 100 sec, the average power is 1.36 kW.

The output of PLASS has been contoured to illustrate the distribution of energy input to the central solenoid due to superconductor losses. The contours of constant energy input (J/m^3) due to hysteresis losses are presented in Fig. 3. These losses are for the central solenoid only; the outboard coils are turned off. Near the midplane, the hysteresis losses are large at the inside radius of the windings and fall off rapidly towards the outside radius. Near the end of the solenoid the losses are large but do not decrease rapidly near the outside radius. As an example, consider two coil segments each 1/8 of the total solenoid length, one at the end and one at the midplane of the solenoid. The hysteresis losses in these segments are compared in Table II. The hysteresis losses in the end segment are slightly larger than the losses in the middle segment even though the peak magnetic field is in the middle segment. Both losses are about the same because of the zero in the magnetic field in the middle segment. Figures 4 and 5 are contour plots of constant energy input for the coupling loss in the conductor and the eddy current losses in the stainless steel conduit, respectively. The comparison of these losses in the middle and end segments is also given in Table II.

A contour plot of the hysteresis losses in the central solenoid due to the other poloidal coils is illustrated in Fig. 6. The hysteresis losses in the middle and end segments are about 15% of the hysteresis losses due to the self-field of the central solenoid (see Table II). The total losses in the end segment are about 13% greater than the losses in the middle segment when all of the coils are considered. Therefore, the distribution of the superconductor losses is nearly uniform throughout the central solenoid.

V. CONCLUSIONS

A computer code, PLASS, has been written to estimate the superconductor losses in sets of axisymmetric superconducting solenoids, taking into account the spatial variation of the magnetic field in the coil windings and the time schedule for current changes up to three coil sets. PLASS has been used to estimate the heating due to superconductor losses in the EPR OH system and has shown that the losses in the central solenoid are nearly equally distributed to its windings.

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NOMENCLATURE

W	= Energy
V	= Volume (m3)
B	= Magnetic field
$\dot{B}$	= dB/dt (T/sec)
α_c	= Constant defined in the critical-state equation (A T/m^2)
B_o	= Constant defined in the critical-state equation (T)
$J_c(B)$	= Field dependent critical-current density
P	= Power (W)
S	= Surface area (m^2)
r_o	= Wire radius (m)
ρ_m	= Matrix electrical resistivity (-m)
x_o	= $2\pi r_o/\ell_p$ = normalized twist length
ℓ_p	= Twist pitch length (m)
ρ_{ss}	= Structural electrical resistivity (--
t	= Time (sec)

TABLE I

Poloidal Field Magnet Conductor Parameters from Ref. 3

Symbol	Value	Units	Description
			NbTi
J_c	7×10^8 @ 4.2K, 7 T	A/m^2	Critical current density
J	3.54×10^8	A/m^2	Operating current density
			Matrix
ρ_{Cu}	4×10^{-10} @ 7 T	Ω-m	Cu resistivity
ρ_{CuNi}	5×10^{-8} @ 7 T	Ω-m	CuNi resistivity
			Structure
ρ_{ss}	5×10^{-7} @ 7 T	Ω-m	Stainless steel resistivity
			Wire
I	18.36	A	Current
d_w	3.74×10^{-4}	m	Diameter
—	0.2 : 0.7 : 0.1	—	Composition NbTi : Cu : CuNi
d_f	4	μm	Filament diameter
n_f	4106	—	Number of filaments
—	3.15×10^{-3}	m	Twist pitch
			Strand
d_s	3.9×10^{-3}	m	Diameter
n_w	37	—	Number of wires
			Other
n_s	37	—	Number of strands
—	3.48×10^{-2}	m	Bundle outside diameter
—	1:1	—	Metal/helium area
—	5×10^{-4}	m	SS tube wall thickness
—	3.5×10^{-2}	m	SS tube wall diameter

TABLE II

Comparison of the Superconductor Losses in Two Segments of the Central Solenoid; Each 1/8 of the Total Coil Length is Located at the End of the Solenoid and the Other Near the Midplane

	Hysteresis		Coupling		Eddy Current (SS)	
	Middle Segment (J)	End Segment (J)	Middle Segment (J)	End Segment (J)	Middle Segment (J)	End Segment (J)
Central Solenoid Only	1400	1600	109	98	731	676
Outboard Magnets Only	210	230	2.2	9.6	23	66
Combined	1610	1830	112.3	107.6	775	748

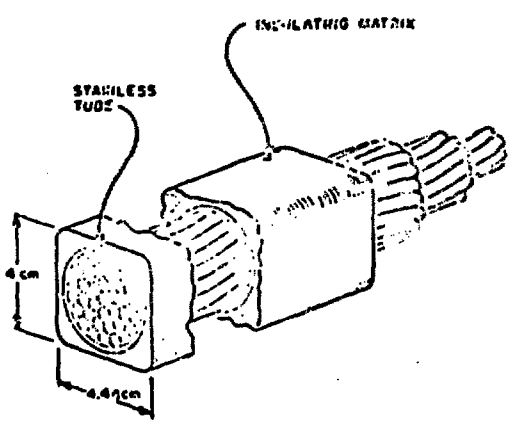

Fig. 1. Round bundle with 37 strands enclosed in rectangular conduit showing transposition of strands.

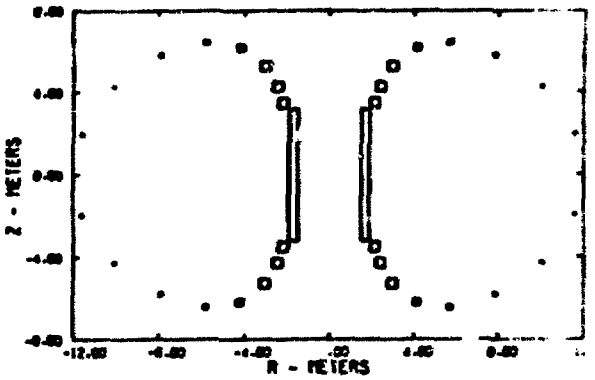

Fig. 2. Poloidal Coil Geometry.

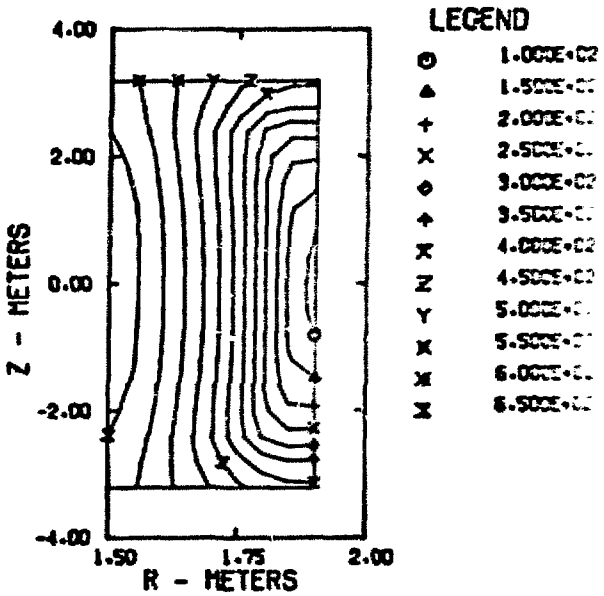

Fig. 3. Contours of constant hysteresis loss in J versus position in the central solenoid of the OMSL reference design. The losses are due to self-field.

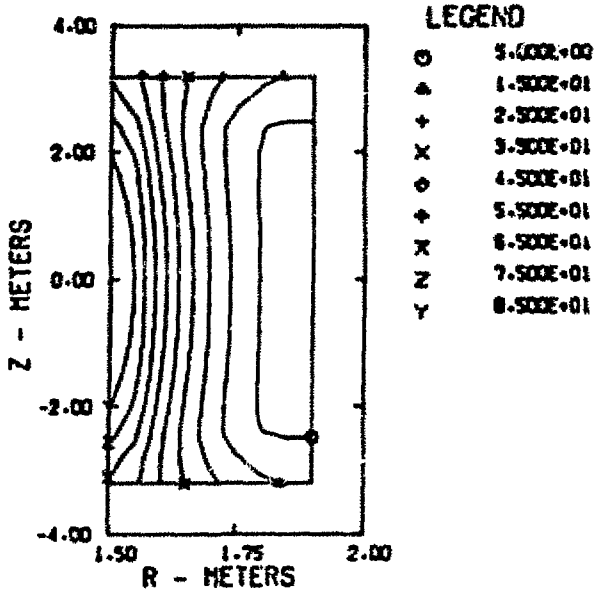

Fig. 4. Contours of constant coupling loss in J/M**3 versus position in the central solenoid of the ORNL EPR reference design. The losses are due to self-field.

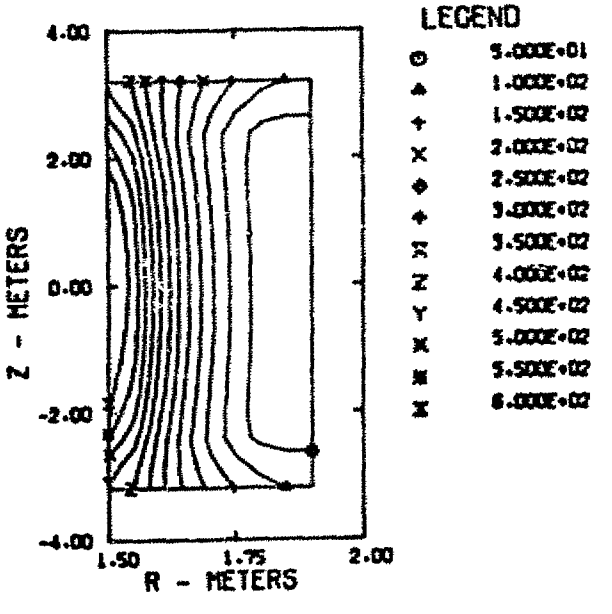

Fig. 5. Contours of constant eddy current loss in J/M**3 versus position in the central solenoid of the ORNL EPR reference design. The losses are due to self-field.

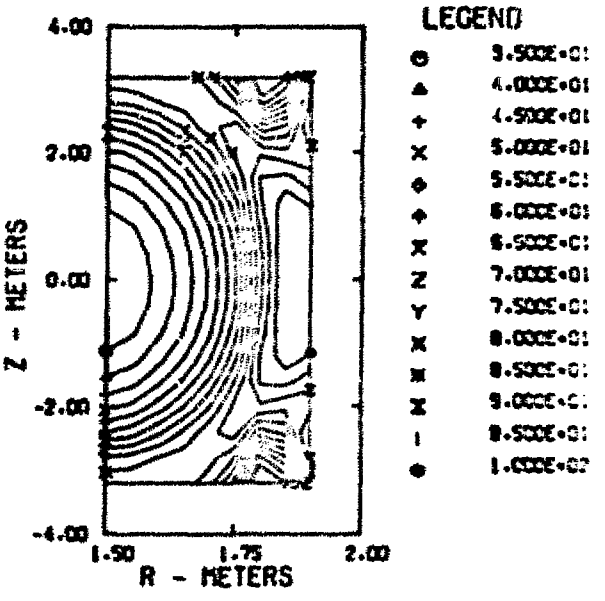

Fig. 6. Contours of constant hysteresis loss in J/M**3 versus position in the central solenoid of the ORNL EPR reference design. The losses are due to other solenoid magnets.