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WIRE ROPE SUPERCONDUCTING CABLE FOR DIURNAL LOAD LEVELING SMES

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ABSTRACT

This paper is concerned with the design of a wire rope cable for a superconducting magnetic energy storage (SMES) unit. The superconducting wires in the rope permit the passage of large currents in the relatively small conductors of the windings and hence cause large electromagnetic forces to act on the rope. The diameter of the rope, from a strength point of view, can be considerably reduced by supporting the rope at various points along its length.

INTRODUCTION AND SUMMARY

The high magnetic fields of large SMES devices produce very large outward forces on the superconducting wires. One such design to resist these forces would be to support the superconducting wires with a wire rope. The superconducting wires could be wrapped helically around the outside of a stainless steel wire rope.

Figure 1 shows a schematic drawing of a rope loaded with a force per unit length, p. The force, p, per unit length acts normal to the deformed centerline of the rope. The arc

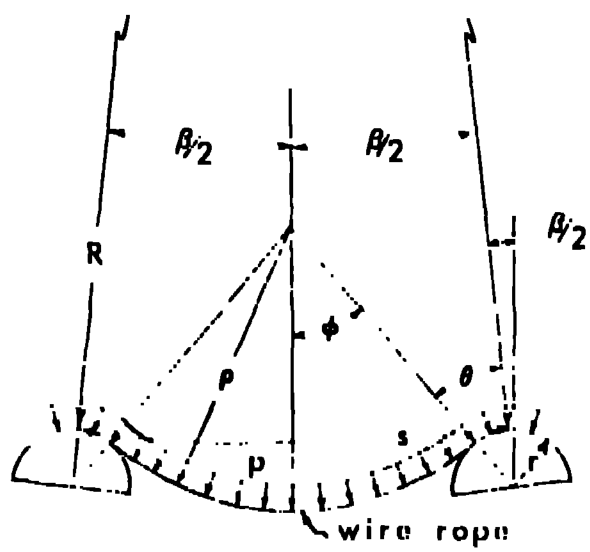

Fig. 1. Superconducting cable wire rope schematic with uniform force loading.

length spacing, s, of the support points is determined by the radius, R, to the support points and the number of supports, n. Hence

$$s = \frac{2\pi R}{n}, \text{ and} \tag{1}$$

$$\beta = \frac{s}{R} \tag{2}$$

An examination of Fig. 1 yields the following equations

$$\phi = \theta + \frac{\beta}{2}, \tag{3}$$

$$\rho\phi + r\theta = \frac{L^*}{2}, \text{ and} \tag{4}$$

$$(\rho + r) \sin \phi = (R + r) \sin \frac{\beta}{2}, \tag{5}$$

where L^* is the final stretched length of the rope between supports. The above relations were determined by neglecting the bending stiffness of the wire rope and thus allowing each section of the rope to deform into a segment of a circle.

Figure 2 shows the general loading system acting on a wire rope which is deformed into a circular segment of radius, ρ. F and M_t are the axial force and axial twisting moment, respectively, and M_B is the bending moment applied to the rope. The twisting moment, q, per unit length must be applied to keep the rope in equilibrium. In general, q is small and will be neglected in this analysis.

The component parts of a wire rope are shown in Fig. 3. The core of the rope will be, in our present design, another wire rope strand. Additional strands will be wrapped helically around the core to provide the required strength.

The axial force, F, in the rope is given by the equilibrium equation

$$\rho q = F \tag{6}$$

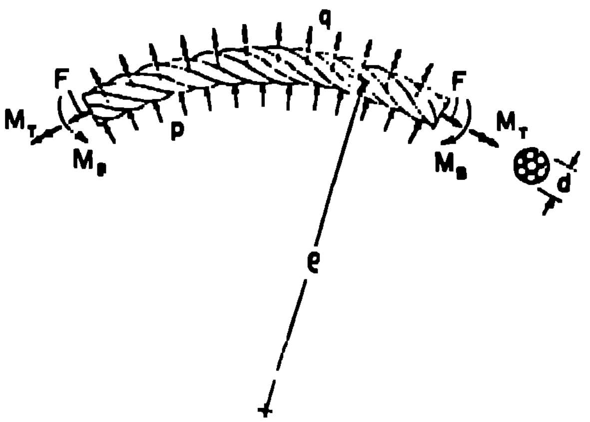

Fig. 2. Wire rope loading system.

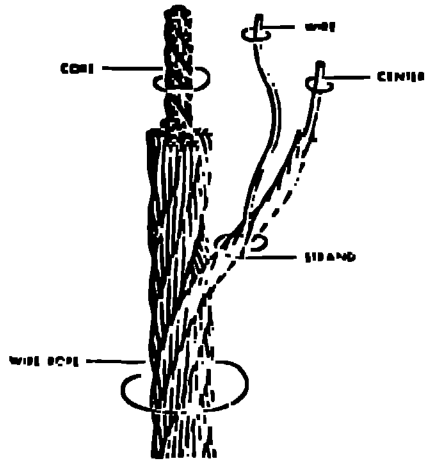

Fig. 3. Wire rope components.

The axial force is also given by the expression[1]

$$F = A\bar{E}\frac{(L^* - L_0)}{L_0} = A\bar{E}\varepsilon \ , \qquad (7)$$

where A is the metallic area of the rope, $\bar{E}$ is the modulus of elasticity of the rope, L_0 is the unstretched length of the rope between supports, and ε is the axial strain in the rope.

Recent investigations[2,3,4,5] have shown that the largest tensile stresses occur in the center wire if the residual stresses are neglected. The axial straight wire in the center of the rope will receive the largest axial stress and the largest stress due to bending. The stresses in the nearby wires are close to the stresses in the center wire, and, hence, the center wire stresses will be used as a basis for design. The maximum tensile stresses in the center wire are given by the expression

$$\sigma_{max} = E\frac{(L^* - L_0)}{L_0} + \frac{Er}{\bar{\rho}} \ , \qquad (8)$$

where E is the modulus of elasticity of the material in the rope, r is the center wire radius, and $\bar{\rho}$ is the radius of curvature of the center wire. For the curvatures under consideration the stresses due to bending will be rather large unless the wire radius, r, is very small.

Consider, for example, a wire rope consisting of a 7 x 19 wire rope core around which will be wrapped helically six strands consisting of 7 x 19 wire rope. This process can be continued until the required area is formed. The next layer would contain twelve strands, etc. Let, for example, the total number of wires in the rope be given by

$$133 + 6(133) + 12(133) + 18(133) = 4921$$

Assuming the same wire radius, the area is given by the expression,

$$A = 4921 \times \pi c^2 \ . \tag{9}$$

Values for the wire rope superconducting cable representative of a typical 1 to 10 GWh diurnal load leveling SMES coil[6] have been chosen to demonstrate the practical nature of a wire rope cable. The example presented is not an optimized design. Let R = 2598.43 in. and a = 78.74 in. The angle β is then equal to 1.735°. Let the load per unit length p equal 1341.67 lb/in., the value of r_0 equal 15 in., and ϕ = 50°. Equation 3 determines θ and Eq. 5 determines ρ. Hence θ = 45.132° and ρ = 34.245 in. Let the metallic area equal 1.15 in.^{2} and E = 13,000,000 psi. A very safe working stress limit of 100,000 psi was chosen for the wire in the rope. The yield stress for three-quarter hard 304 stainless steel is 170,000 psi at liquid helium temperature. The 0.00862 in. radius wire will more nearly be full hard with >50% cold reduction with a yield stress near 220,000 psi. Equations 6 and 7 yield a strain ϵ equal to 0.00307. Since the area is 1.15 in.^{2}, Eq. 9 yields c = 0.00862 in. The maximum tensile stress is then given by Eq. 8 and hence

$$\sigma_{max} = [illegible],000,000\ (0.00307) + \frac{30,000,000 \times 0.00862}{17.49}$$

$$= 9[illegible],100 + 14,785 = 1[illegible]6,800 \text{ psi} < 110,000 \text{ psi}$$

The final length of the rope between supports is given by Eq. 4; hence,

$$L^* = 2(34.245\ (0.8726) + 15) = 89.[illegible] \text{ in.};$$

and the original length of the rope between supports is

$$L_0 = 89.589 \text{ in.}$$

The diameter of the rope is 1.81 in., and the bearing stresses on the support is

$$\sigma_{bearing} = \frac{[illegible]}{1.0 \times 1.81} = 2,192.6 \text{ psi.}$$

CONCLUSION

A method of design has been developed which will determine the necessary dimensions of a wire rope used as a support structure for superconducting wires. The design takes advantage of the properties of a wire rope, that is, the ability to resist large tensile forces with relatively small bending stiffness. A superconducting cable based upon a wire rope for use in a diurnal load leveling SMES unit provides a simple means of fabrication at the SMES site. Inherent in a wire rope is that continuous lengths of cable can be made by very conventional means at low costs without concern for making joints in either the superconducting strands or the wires of the rope.

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