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P2_9 Superconducting vs. Overhead Lines

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Abstract

High temperature (below liquid nitrogen boiling temps.) superconductors have potential applications in power transmission lines as they can carry currents with effectively no resistance. This report gives a first order estimate of losses in presently used overhead cables at around 15% of power output. To better this efficiency a superconductor would need to be clad in an insulator with an outer diameter of greater than 1.93 times that of its inner diameter, provided a liquid nitrogen refrigeration pump could work at 10% efficiency.

Introduction

Overhead power cables are used to provide electrical energy over large distances. The benefit of such a system is that they are cheap, as the insulation of the wires is provided by the air, and easy to maintain, as opposed to buried wires. However resistive losses in these lines can be high, estimated at approximately 7% of total transmission in the US [1]. With developments in high temperature superconductors this paper explores the feasibility of creating a more efficient transmission system using effectively lossless superconductors held at low temperatures by a powered cooling system.

UK Power Losses

Exact power losses through mains electricity transmission depend on many parameters e.g. wire material, voltages and currents used. In order to get an approximation for how much power is lost in the UK some typical values have been estimated. National Grid provide broad estimates of the current, I, going through an overhead line of ~700 A and that there is a total line length, l, of 7000 km in England and Wales [2]. The exact material used for wires depends again on many factors but primarily aluminium conductor steel reinforced (ACSR) wires are used to carry the load and mechanical strain respectively [3]. Diameters for such wires are between 5 and 40 mm [3]. In order to accurately calculate the resistance of a line full knowledge of the AC circuits used would be needed. The resistive and reactive components would be taken into account and a phase angle calculated. However at low mains frequencies a wire would have sufficiently small reactance such that the DC resistance is a good approximation to the AC resistance [4]. Based on manufacturer specifications the resistance, R_l, is approximately 1.97 Ω km^{-1} [4]. Using these values a first order estimate for the power loss, P, in the UK was calculated as,

$$P = I^2 R = I^2 R_l l, \tag{1}$$

resulting in a value of ~6750 MW. This is a simplified estimate from adding losses along the total length of the lines. Given that UK demand, on average, is in the region of 45000 MW [5] this represents a 15% loss. Given this is comparable to the US losses there is some confidence in the validity of the approximations used.

Superconducting Wire

An indirect form of power loss on a superconducting line would arise as the effectively zero resistance superconducting line would need to be kept below a certain temperature, requiring power. In order to be more efficient a line must be constructed that requires less power to cool the superconductor than would otherwise be lost in an overhead line due to its non-zero resistance. The superconducting line, as shown in Figure 1, has an inner section containing the superconductor and liquid nitrogen, LN_2, coolant surrounded by an insulating layer, which reduces the heat flow into the coolant.

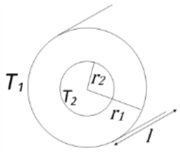

Figure 1: Schematic of the superconducting wire, of length, l, with an insulating layer with an inner radius r_2, at a temperature T_2, and an outer radius r_1, at an ambient temperature T_1.

In one dimension the thermal heat conduction in the x direction is given by [6],

$$\frac{dQ}{dt} = kA\frac{dT}{dx}. \quad (2)$$

For the pipe geometry shown in Figure 1 the thermal heat flow is in the radial direction. Therefore the thermal conduction equation becomes,

$$\frac{dQ}{dt} = k2\pi rl\frac{dT}{dr}, \quad (3)$$

where k is the thermal conductivity of the insulator. A is the area through which the heat current flows which, using the geometry of Figure 1, is $2\pi rl$. dT is the temperature difference over a length dx or dr. dQ/dt is the thermal current. The thermal current represents the heat flow into the coolant and therefore the energy we need to extract from the system via cooling to keep the interior at constant T_2. The thickness of the insulating layer required is calculated for the case where the power needed to cool the system, dQ/dt, is equal to the losses for the overhead line calculated previously, P. Therefore for any greater thickness the superconductor is more efficient.

Integrating equation 3 with respect to T and r between r_1 at T_1 and r_2 at T_2 gives,

$$\frac{r_1}{r_2} = \exp\left\{k2\pi l(T_1 - T_2)\left(\frac{dQ}{dt}\right)^{-1}\right\}. \quad (4)$$

Foam glass provides affordable and desirably low thermal conductivities. It is assumed the insulating layer is made of such a material with an estimated k of 45 mW m^{-1} K^{-1} [7]. Assuming an average outside temperature of ~300 K and that the inside temperature must be kept at just below the LN_2 boiling point, ~75 K, then the radius, r_1, of the outer insulating boundary only needs to be 1.07 times that of the inner radius, r_2. This assumes 100% efficient cooling of the system.

In practise any refrigeration pump has some efficiency. Nitrogen is only liquid between 63 K and 77 K. If there is a cold reservoir, T_C, of just above the freezing point, 65 K, and the extracted nitrogen is at, T_H, 75 K, as previously stated, then the most efficient heat pump between these two temperatures possible is a Carnot cycle which gives an efficiency of 87% [6]. If a true system was only 10% efficient this would leave a possible useful power of 675 MW. Taking this as the desired thermal current then equation (4) gives that r_2 would need to be 1.93 times the size of r_1.

Conclusion

Whilst there are benefits in operating a superconducting line to better the efficiency of present overhead lines, a superconducting wire would require an insulating layer, with the k value used, with a radius at least 1.93 times its inner radius. This assumes a refrigerating cycle for liquid nitrogen was able to work at 10% efficiency. This could require substantial amounts of multilayer material and further work could explore in more depth the thermodynamic and fluid mechanical considerations of such a line.

References

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