Closely coupled, short-circuited shunt coils are proposed for quench protection of superconducting Maglev magnets which use high resistance, matrix composite conductors. It is shown that, by suitable design, the shunts can reduce induced ac losses and that the changing currents during magnet energization or vehicle lift off and landing can be tolerated.

Shunt protection for superconducting Maglev Magnets

D.L. Atherton

The conceptual design of the Canadian high speed magnetically levitated vehicle is shown in Fig. 1. The system has been described previously.[1] Suspension is provided by the interaction between five levitation magnets on each side of the vehicle and the motion-induced eddy currents in aluminium strips on the guideway surface. The conceptual design of the superconducting levitation magnets is shown in Fig. 2 and parameters are given in Table 1. Isochoric magnet operation is proposed in order to obtain a lightweight reliable cryogenic system. The dewars are partly filled with liquid helium at approximately atmospheric pressure then sealed and operated for a full working day without further attention. Temperature and pressure can rise up to about 10°K and up to 20 atmospheres (2.03×10^2 kNm^{-2}). The high pressure helium is vented and collected and liquid helium replenished during overnight servicing. In order to compromise between temperature and pressure rises, dewars are filled to between about 50% and 80% liquid helium.[2] The elevated temperature operation necessitates the use of a high critical temperature superconductor such as Nb_3Sn (Ng_3Ge may eventually be superior). Our present design is based on the use of multifilamentary Nb_3Sn composite conductor. Such conductors are typically manufactured using the bronze diffusion process. In order to protect coils during quenches, high purity, low resistance copper may be added to the composite if it is separated from the other components by a diffusion barrier.

An alternative method of protecting the coil during quenches is to use a separate, but closely coupled low resistance short circuited shunt. This proposal is described and examined for our Maglev levitation magnets. We show that by incorporating a small amount of suitable superconductor, the shunt may also be used to minimize the ac losses induced in the levitation magnets by suspension gap fluctuations. The effects of changing currents during magnet energization and curing vehicle take-off and landing are significant complications which must also be considered.

Quench protection

The magnets are operated in persistent mode in order to avoid input lead losses. Demountable leads are used to energize the coil, and high efficiency transformer rectifier flux pump power supplies using inductive current transfer,[3] make up the small energy losses due to resistive joints in the coil and ac losses. If a quench occurs all the energy must be converted into heat and dissipated in the dewar. A small over-pressure release vent prevents serious over-pressure. There is no safety problem on this scale[4] since the rate of heating and expansion of the helium is limited by surface heat transfer coefficients.

The coil mass is 24 kg and the stored energy 60 kJ. If this stored energy were dissipated uniformly over the coil during a quench, the resulting temperature rise would be relatively slight (approx 60 K) however, the relative high resistance of the bronze matrix of the Nb_3Sn composite conductor means that a normal spot only propagates slowly, and there is therefore a strong tendency for hot spot formation leading to possible burnout or damage to the conductor, insulation or joints.

We therefore propose that the bottom 24 turn double pancake shown in Fig. 2 be shorted and that it be constructured of a composite conductor with a high copper to superconductor ratio of about 20:1. The majority of the copper should be of high conductivity. The critical current for this conductor would be relatively low (say 40 A). The shunt coil is very closely magnetically coupled to the main coil. A quench and current decay in the main coil therefore generates a very large current in the shunt coil in an effort

Table 1. Levitation magnet parameters

Coil shape:	Racetrack
Coil size:	1.06 m long x 0.30 m wide
Conductor:	Multifilamentary Nb_3Sn for composite
Cross section:	See Fig. 2
Total number of turns:	420
Ampere turns:	308 kAt
Conductor mass:	24 kg
Stored energy:	60 kJ
Length/turn:	2.46 m
Primary suspension natural frequency:	9.5 Hz
Coil inductance:	0.20 H

The author is at the Department of Physics, Queen's University, Kingston, Ontario, K7L 3N6, Canada. Research supported by Natural Sciences and Engineering Research Council, Transport Canada Research and Development Centre, through Canadian Institute of Guided Ground Transport, and Queen's University.
Paper received 2 April 1979.

0011-2275/79/090537-05 $02.00

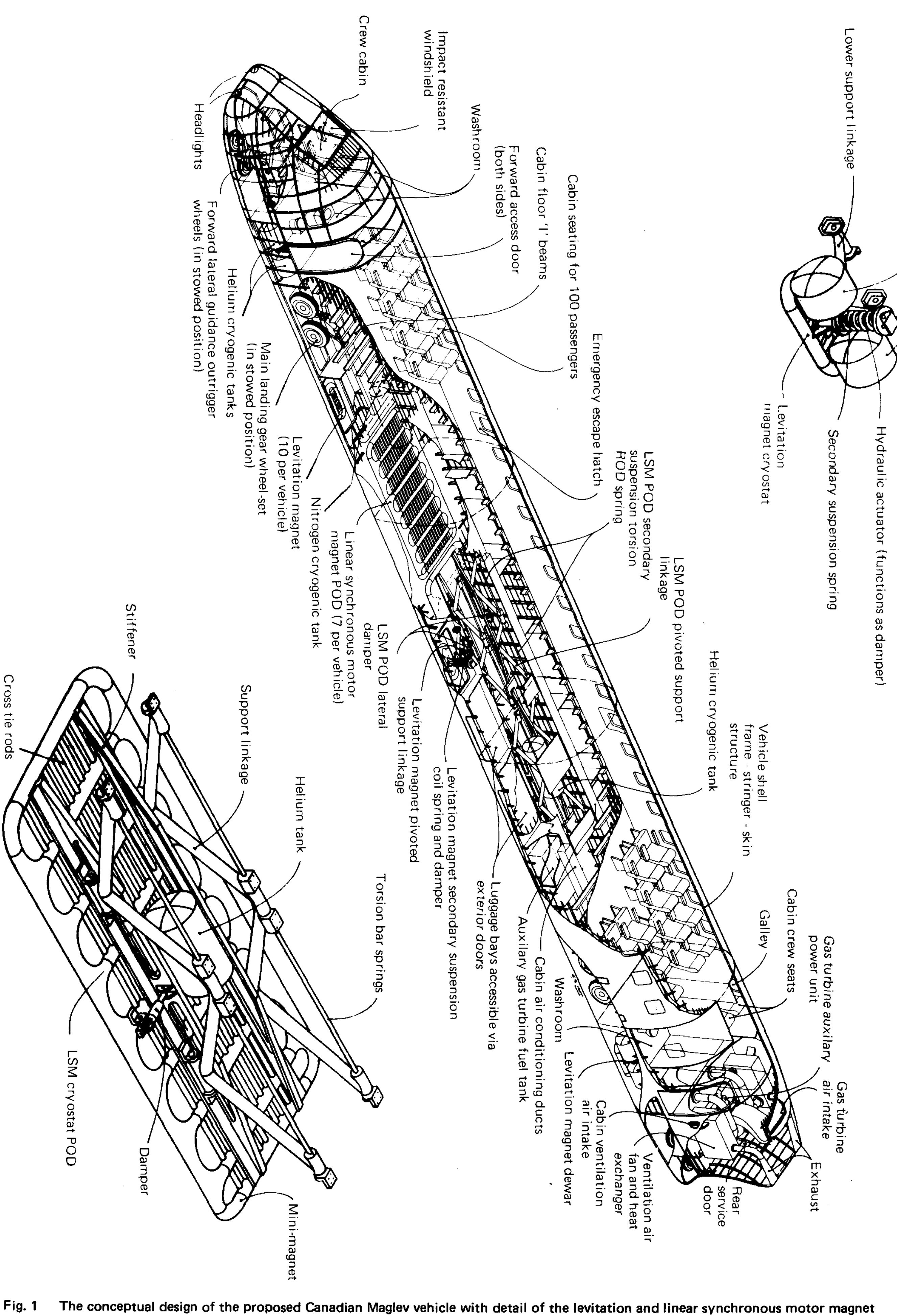

Fig. 1 The conceptual design of the proposed Canadian Maglev vehicle with detail of the levitation and linear synchronous motor magnet assemblies (courtesy: Division of Mechanical Engineering, National Research Council Laboratories)

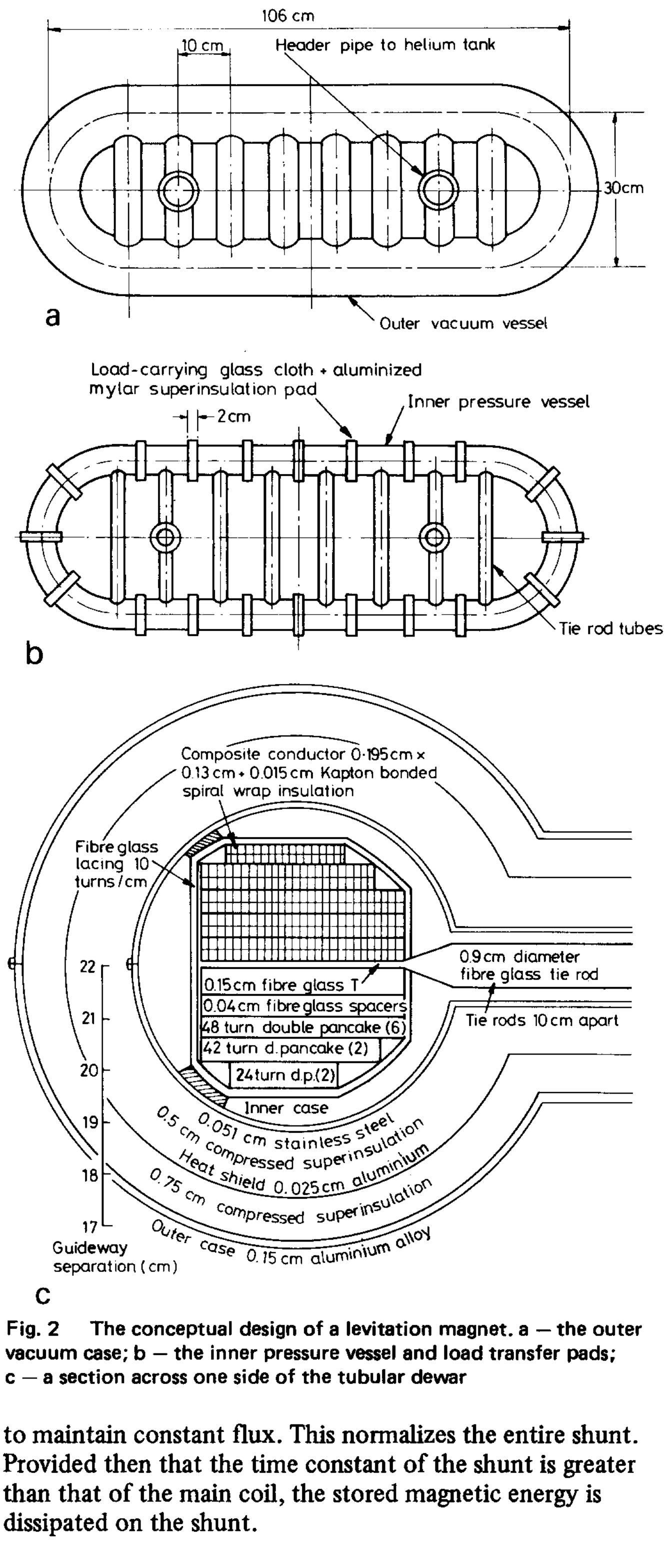

Fig. 2 The conceptual design of a levitation magnet. a — the outer vacuum case; b — the inner pressure vessel and load transfer pads; c — a section across one side of the tubular dewar

to maintain constant flux. This normalizes the entire shunt. Provided then that the time constant of the shunt is greater than that of the main coil, the stored magnetic energy is dissipated on the shunt.

The inductance of this size of racetrack coil is calculated as:

$$L = 1.2 \times 10^{-6} n^2 \mathrm{H} \qquad (1)$$

where n is the number of turns.

The resistance, using the indicated wire size, is:

$$R = 4.04 \times 10^4 \rho n^2 \ \Omega \qquad (2)$$

where ρ is the effective resistivity of the composite.

The time constant is therefore

$$L/R = 2.9 \times 10^{-11} \sigma \ \mathrm{s} \qquad (3)$$

where σ is the effective electrical conductivity of the composite.

The time constant is independent of the number of turns and, for the shunt, will be of the order of 0.1 s. The time constant of the main coil varies more rapidly because, in addition to temperature variation, the length normalized varies, but if it were to absorb much of the stored magnetic energy, the time constant of the quench would be less than the shunt time constant because of the higher resistance of the bronze matrix of the main coils' composite conductor. The majority of the energy is therefore absorbed by the shunt and because it is all normalized, it is uniformly distributed giving a maximum dissipation of 0.044 J kg^{-1} so that the temperature rise is about 210°K; the shunt remains below room temperature therefore.

ac losses

Dynamic fluctuations in suspension gap alter the levitation magnet inductance because of its fluctuating distance to the levitation strips. Since the magnets are operated in the persistant mode, magnetic flux linkage is constant and there are therefore fluctuating currents induced in the levitation magnets. Any induced currents are shared between the main and shunt coils, inversely as their inductances, or approximately as the inverse square of their turns, therefore currents induced in the shunt coil are much larger than those induced in the main coil.

Hayes[5] has estimated the rms amplitude of magnet motion as 8.1 mm relative to standard construction elevated guideway whose power spectral density surface roughness, A, is 1.5×10^{-6} m rad. An actively damped secondary suspension is used. We have deduced the amplitude of the induced ac ripple from experimental measurements of the fractional change in inductance by impedance modelling[6] as 0.3% in an unshunted levitation coil. In order to generate the same ampere turns and hence flux in the shunt, the ac induced shunt current is nearly 40 A. If the shunt were made simply of high resistance ratio copper, the power dissipated due to the induced ac would be about 10 W. This is intolerable. We therefore use a composite conductor for the shunt, 10% of the cross section of which comprises a composite superconducting bundle. The compostie superconducting bundle contains fine superconducting filaments in a relatively compact bronze matrix with an approximate 2:1 bronze superconductor ratio. This bundle is inserted into the main high conductivity copper of the conductor, but separated from it by a diffusion barrier. The superconductor is adequate to carry the ac induced currents as supercurrents. The conductor geometry is chosen for manufacturing convenience, in order to preclude the conductor from being strongly diamagnetic and for ac loss considerations.

We now use Ries[7] approach to estimate the ac losses using either untwisted or highly twisted superconducting filaments.

We consider first the case of an untwisted multifilamentary superconductor, admitting first that it is doubtful if it would be adequately stable for these high ac current densities.

Following Ries' analysis, we note that (7) gives an infinite time constant, τ, for the decay of internally induced field and currents because the twist pitch, l_p is infinite. Ries' equation (9) therefore gives zero eddy current loss using untwisted filaments.

The hysteretic loss is then evaluated using Ries' equation (10) and noting that the local field amplitude, $H \gg H_s$, the penetration field, since the conductor is being driven to a substantial fraction of the conductor critical current which is much greater than the critical current of a filament. This loss is also zero because of the infinite time constant.

The penetration loss is evaluated from Ries' equation (11) which, for untwisted filaments reduces to:

$$\text{Penetration loss, } W_\text{p} = \frac{\mu_0 V 32 H_0^3}{9\pi^2 \lambda j_\text{c} R} \text{ J cycle}^{-1} \qquad (4)$$

where V is the volume of the filament bundle; H_0 is the amplitude of the oscillating component of the external field; λ is the space filling factor of the superconductor; j_c is the critical current density (of the superconducting filaments); and R is the radius of the filament bundle.

This gives a calculated loss of about 2 mW at 4.2°K, increasing at higher temperatures because of the reduction in critical current density from the assumed value of $5 \times 10^9 \text{ A m}^{-2}$. The primary suspension natural frequency has been used in obtaining the power since, for lower spatial frequencies of guideway irregularities, the magnets will tend to follow the guideway and there will therefore be no gap fluctuations, whilst at higher frequencies the amplitudes of the guideway irregularities are greatly diminished so that the primary natural frequency is dominant.

We therefore conclude that by comparison with the estimated total levitation magnet heat leak of about 1.4 W, the ac losses in a coil with shunt protection using untwisted filaments would be very slight. However, we suspect that for the relatively large alternating currents induced in the shunts, an untwisted multifilamentary conductor would be unstable and therefore should not be used.

We now consider the case of a highly twisted multifilamentary composite. Because the superconducting section is a composite insert into a relatively small conductor, a short twist pitch is feasible. For a twist pitch of the order of 10 mm and noting that the bronze matrix of the superconducting section has a relative high resistivity ($2 \times 10^{-8}\,\Omega$m) the $\omega\tau$ product is about 1.7 ms and is therefore small.

The eddy current loss calculated from Ries' equation (9) is therefore about 30 μW, which is small.

The hysteretic losses are evaluated from Ries' equation (10) again using $H \gg H_\text{s}$ which, for small $\omega\tau$ product, reduces to:

$$\text{hysteretic loss} = \mu_0 V d \lambda j_\text{c} H_0 \text{ J cycle}^{-1} \qquad (5)$$

where d is the filament diameter which we will assume to be 10^{-6} m. This loss is calculated as 7 mW at 4.2°K, decreasing with increasing temperature. This is the dominant loss; it can be reduced by using finer filaments. The penetration loss using twisted filaments is negligible.

We conclude that the ac losses in the shunt coil, using a carefully designed conductor, are small, even using a twisted filamentary conductor for stability. The losses are, in fact, substantially less than would be generated in the main coil without a shunt because the superconductor in the shunt is designed to carry only the induced ac current without the large dc current which flows in the main coil.

Energization

The short circuited shunt coil is designed to provide quench protection and to minimize ac losses by absorbing a large part of any induced current changes. This is, of course, a problem during coil energization but, as we show, it can be overcome.

Denoting the main coil as 1 and the shunt coil as 2, the stored energy, u, is

$$u = \tfrac{1}{2} L_1 I_1^2 + M I_1 I_2 + \tfrac{1}{2} L_2 I_2^2 \qquad (6)$$

If I_1 is increased during energization I_2 will be greatly increased (but in the opposite sense) until it quenches ($I_2 \rightarrow 0$). During the quench, the total flux linkage ($L_1 I_1 + L_2 I_2$) will remain constant since the magnet will be energized from a relatively low voltage supply. The current I_1 in the main coil durectly after a quench of the shunt will be:

$$I_1' = \frac{L_1 I_1 + L_2 I_2}{L_1} \qquad (7)$$

The stored energy u will then be

$$u' = \tfrac{1}{2} L_1 I_1'^2 = \tfrac{1}{2} L_1 I_1^2 + L_2 I_1 I_2 + \tfrac{1}{2} \frac{L_2^2}{L_1} I_2^2 \qquad (8)$$

The energy dissipated in the quench Δu will then be

$$\Delta u = u - u' = I_1 I_2 (M - L_2) + \tfrac{1}{2} L_2 I_2^2 \left(1 \frac{L_2}{L_1}\right) \qquad (9)$$

Noting that the coils are very closely coupled so that $M \approx \sqrt{L_1 L_2}$ and that $L_2 \ll L_1$.

$$\Delta u \simeq I_1 I_2 \sqrt{L_1 L_2} \qquad (10)$$

During magnet energization I_1 varies linearly from zero to the final magnet current I.

Therefore

$$\text{mean } I_1 = \tfrac{1}{2} I$$

For each shunt coil quench at I_{2_c} quench, the change in main coil current ΔI_1 is

$$\Delta I_1 = \frac{L_2 I_{2_\text{c}}}{L_1} \qquad (11)$$

Therefore the total number of quenches, n, during energization is

$$n = \frac{L_1 I}{L_2 I_{2_\text{c}}} \qquad (12)$$

Therefore the total energy loss is

$$n \Delta u = \tfrac{1}{2} L_1 I_1^2 \sqrt{\frac{L_1}{L_2}} = \tfrac{1}{2} \frac{n_1}{n_2} L_1 I^2 = \frac{n_1}{n_2} U_\text{f} \qquad (13)$$

where n_1/n_2 is the turns ratio and U_f the final stored energy.

The total energy lost during energization is calculated as 9.9×10^5 J (= 275 Wh) which is clearly far too high to be tolerable.

The energy lost during a single shunt quench at full current in the main coil is 380 J (~0.1 Wh) which is not unduly large. We therefore consider the possibility of holding the shunt normal by the dissipation of induced current in it due to increasing main coil current.

We assume a surface heat loss rate of $100\,\mathrm{mW\,cm^{-2}}$ through an effective surface area of $600\,\mathrm{cm^2}$ (the bottom and edges only of the shunt). The required power dissipation is then 60 W.

The energisation time Δt is then determined since

$$\text{Dissipation loss} = \int \frac{v^2}{R}\,\mathrm{d}t = \frac{\Delta\phi^2}{R\Delta t} = \frac{L_1^2 I^2}{R\Delta t}$$

$$= \text{Power} \times \Delta t \qquad (14)$$

Since the resistance of the shunt is approximately $5\,\mathrm{m}\Omega$ this gives a required energization time of 284 s at a voltage of 0.55 V and a total energization loss of 17 kJ (= 4.7 Wh) or the equivalent of about 3 1/2 hours of normal operating loss. This appears reasonable. The thermal insulation required to limit the surface heat loss from the shunt is of the order of 2 mm thickness of epoxy fibreglass. Extra insulation must be on the top surface of the shunt in order to prevent the main coil being normalized.

Our simple assumptions and linear theory can be extended and optimized experimentally principally by varying the assumed thermal loss and insulation; but they suffice to show that it is indeed feasible to maintain the shunt normal by induced dissipation to give tolerable losses during magnet energization.

Vehicle lift off and landing. Since the magnets are operated in persistent mode, the changes of levitation coil inductance due to changing distance to the levitation strip during low speed acceleration and deceleration (lift-off and landing) cause a change in the coil current. We have shown[6] that the initial (zero speed) coil current should be about 2.8% below the final desired current. The changes occur rapidly in about 2 1/2 seconds.

As during magnet energization the increased current is initially largely in the shunt coil which soon quenches dissipating 380 J. At the assumed heat transfer rates this is sufficient to hold the shunt resistive during the rest of the lift-off or landing period whilst the current changes in the main coil. There is further induced shunt dissipation of the order of 10 W. The total energy loss of 400 J is therefore equivalent to about 5 min of normal operating loss and should be tolerable, although further optimization may be desirable. Further optimization is possible because the shunt coil quench dissipation may be reduced by deliberately quenching it immediately prior to lift-off by means of a small local heater.

Conclusions

We have shown that for typical Maglev magnets quench protection can be provided for conductors using Nb_3Sn in a bronze matrix, by using a closely coupled short circuited shunt instead of adding high conductivity material to the conductor. The induced ac currents are much greater in the shunt than in the main coil, but by inserting a small section of multifilamentary superconductor into the shunt the ac losses are minimized. If untwisted superconducting filaments are used stability is questionable, but ac losses are negligible. If twisted superconducting filaments are used there is a small hysteretic loss which may be minimized by careful design and using fine filaments. The calculated ac losses are substantially less than those calculated for a simple coil without a shunt.

The large currents induced in the shunt during magnet energization or vehicle lift-off and landing are a potential difficulty which is minimized by thermally insulating the shunt so that once normalized it can remain normal during large current changes without large losses, provided the main coil remains superconducting. In our analysis we have assumed that there is negligible ac current shielding by the dewar cases etc and that all the dissipation therefore occurs in the magnet.

We conclude that shunt protection is possible and that there is scope for optimization, particularly in the thermal design.

This work was stimulated by discussions with A.R. Eastham, W.F. Hayes and P.J. McLaren.

References

1. **Atherton, D.L., Belanger, P.R., Burke, P.E., Dawson, G.E., Eastham, A.R., Hayes, W.F., Ooi, B.T., Silvester, P., Slemon, G.R.** The Canadian high speed magnetically levitated vehicle system *Can Elec Eng J* 3 2 (1978) 3-26
2. **Atherton, D.L., Eastham, A.R.** Superconducting magnetic levitation and linear synchronous motor development – the Canadian program, Advances in Cryogenic Engineering, K.D. Timmerhaus ed. Plenum **21** (1976) 1-8
3. **Bernard, S.P., Atherton, D.L.** High-efficiency flux pump power supply using inductive current transfer *Rev Sci Instrum* **28** 10 (1977) 1250-1252
4. **Canty, J.M., Atherton, D.L.** Overpressure protection for quenched superconducting magnets *Bull Inst Int du Froid* **51** 3 (1971) 491-497
5. **Hayes, W.F.** unpublished communication
6. Canadian Maglev Group Superconducting magnetic levitation and linear synchronous motor propulsion for high speed guided ground transportation, A.R. Eastham ed. CI GGT Report 75-5 (March 1975) unpublished
7. **Ries, G.** ac-losses in multifilamentary superconductors at technical frequencies *IEEE Trans on Magnetics* **MAG-13** 1 (Jan 1977) p 524-526