HARD AND SOFT MAGNETIC COMPOSITES IN HIGH SPEED FLYWHEELS

P.E. Mason, K. Atallah, D. Howe

Department of Electronic & Electrical Engineering, The University of Sheffield
Mappin Street, Sheffield S1 3JD, UK

SUMMARY: Flywheel systems based on fibre composites can have power densities which are significantly better than for electrochemical batteries. Hence, they have considerable potential for use as peak power buffers in drive-trains for electric and hybrid vehicles. As the rotational speed is increased, however, bearing friction power loss and iron losses in the motor/generator become more significant. Thus, high-speed flywheels are conducive to the use of magnetic bearings and an air-cored machine topology. The design of a high-speed flywheel peak power buffer unit based on a carbon fibre composite rim, supported by a magnetic bearing system and incorporating an air-cored permanent magnet brushless motor/generator, is described. The potential for using rare-earth permanent magnet composite materials for the rotor of the brushless machine, and for using a soft magnetic composite for the rotors of the active magnetic bearings, is considered.

KEYWORDS: Flywheel, soft magnetic composite, magnetically loaded composite.

INTRODUCTION

Although kinetic energy storage flywheels are a well established concept, it is only relatively recently that their specific energy and power capabilities have improved to a level at which they might be technically and economically viable for applications such as large scale uninterruptable power supplies and peak power buffers in electric and hybrid vehicles [1].

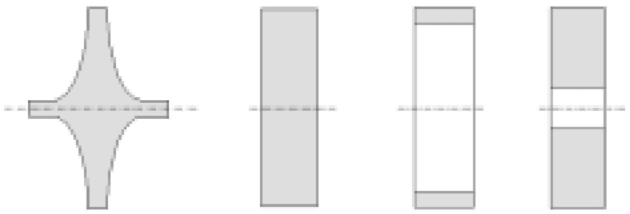
The kinetic energy storage capability of a flywheel is proportional to the product of its rotational inertia and the square of its rotational velocity. Thus, high speed flywheels offer a high energy storage per unit mass (specific energy). However, the maximum speed is limited by the tensile strength of the material from which the flywheel is constructed, whilst the relative energy storage capacity is dependent on its geometry. The theoretical maximum specific energy for a flywheel constructed from a material with a density ρ and a tensile strength σ is given by;

$$E = \frac{\sigma}{\rho} k \qquad \text{J/kg} \qquad (1)$$

where k is a 'shape factor' which relates the stored energy to the theoretical maximum that can be stored in a uniformly stressed disc-shaped flywheel. Table 1 compares the specific energy capabilities of candidate flywheel materials [2], whilst Fig. 1 shows the influence of the geometry of a flywheel on its energy storage capability [3]. Clearly, fibre composite materials offer significant advantages, since their high tensile strength to density ratio facilitates a high specific energy capability, whilst their anisotropic nature makes them appropriate for a simple annular rim flywheel geometry. Thus, despite having a relatively low shape factor, a fibre composite rim arguably offers the greatest potential for peak power buffer applications. Further, such a geometry can be supported by integral passive and active magnetic bearings, which facilitate operation in a vacuum so as to minimise aerodynamic loss, and can incorporate a highly efficient permanent magnet brushless motor/generator for kinetic energy to electrical energy conversion. In order to minimise electromagnetic losses in the rim,which is a major consideration when operating in a high vacuum, since heat dissipation from the rim is essentially only by radiation, a soft magnetic composite can be used for the rotors of the active magnetic bearings, whilst a hard magnetic composite may be appropriate for the rotor of the electrical machine.

Material	Tensile Strength (MPa)	Density (kg/m^3)	Specific Energy (J/kg)
Aluminium alloy	600	2730	220
Maraging steel	2000	7850	254
Carbon fibre	7000	1780	3933
S-glass	4800	2520	1905

Table 1: Specific energy storage capabilities of various materials [2]



(a) (b) (c) (d)

(a) uniform stress disc, k =0.93
(b) flat disc, k=0.61
(c) thin rim, k=0.5
(d) flat pierced disc, k=0.31

Fig.1 Influence of flywheel geometry on energy storage capability [3]

Since flywheel peak power buffer units may become a key enabling technology for all-electric and hybrid-electric vehicles, as manufacturers strive to produce non-polluting and more energy efficient vehicles whilst meeting consumer expectations regarding performance, the paper considers one concept for such a unit based on a high speed carbon fibre composite rim, as well as the application opportunities for both hard and soft magnetic composites.

FLYWHEEL PEAK POWER BUFFER UNIT

Fig. 2 shows a schematic of a flywheel unit which is being developed for use as a peak power buffer in the drive-train of electric and hybrid vehicles [4]. The carbon fibre composite flywheel rim is supported by two active radial magnetic bearings and two passive axial magnetic bearings and incorporates an integral permanent magnet brushless motor/generator. The rim rotates within an evacuated enclosure, so as to minimise aerodynamic loss, the inner and outer containment ensuring safety in the event of failure of the rim. Mechanical back-up/touch-down bearings provide support for the rim in the event of failure of the active magnetic bearings, when external disturbance forces exceed the bearing electromagnetic force capability, and when the flywheel is not in use. The maximum rotational speed of the rim in the concept demonstrator is around 60,000rpm, and the energy storage capacity is ≈ 400Wh. The continuous peak power rating of the electrical machine ranges from around 28kW to 5kW, dependent mainly on the remanence of the permanent magnet material which is used for the rotor. In practice, it is only feasible to maintain this power capability down to around half speed, ie. 30,000rpm, otherwise the low speed torque requirement, and hence the active space envelope of the machine, would be unacceptably high, and the resulting power capability at maximum speed would not be utilised.

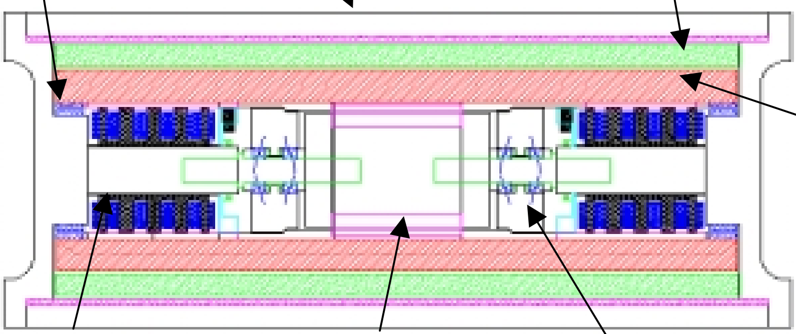


Fig. 2: Flywheel peak power buffer

THE FLYWHEEL RIM

The carbon fibre composite flywheel rim is produced using the filament winding process, a combination of hoop (winding angle relative to rotor axis $\phi \approx 90^o$) and helical ($\phi < 90^o$) windings being used to obtain the required strength and stiffness in the circumferential and axial directions, which are proportional to $\sin^4(\phi)$ and $\cos^4(\phi)$, respectively [5]. Since the stiffness of the rim in the radial direction is determined primarily by the epoxy, such a fibre composite rim exhibits strongly anisotropic mechanical properties, and has to be operated within stricter mechanical limits when compared to a steel equivalent. As well as storing kinetic energy, the rim also carries the soft magnetic rotors of the active magnetic bearings, and the permanent magnet rotors of the passive magnetic bearings and the brushless machine, and its inner bore is interfaced to back-up silicon nitride ceramic ball bearings via non-magnetic stainless steel touch-down surfaces. Since these are relatively high-density materials, 7000-8000 kg/m^3, they could exert a significant radial stress at the bore of the rim. Thus, the volume of these materials is limited by the tolerable radial stress, and thereby strongly influences the performance capabilities of the motor/generator and the magnetic bearings.

PERMANENT MAGNET BRUSHLESS MOTOR/GENERATOR

In the flywheel peak power buffer unit shown in Fig. 2, a brushless electrical machine is incorporated within the bore of the flywheel rim, which must, therefore, either incorporate or accommodate permanent magnet material to enable it to act as the external rotor of the machine. The machine itself must be capable of operating at its maximum continuous power rating over the operational speed range from 30,000 to 60,000 rpm , so as to achieve a consistent vehicle performance, with minimal losses during both generating (ie. when the vehicle is accelerating) and motoring (ie. when the vehicle is regeneratively braking) modes, at a round-trip efficiency greater than 90%. Thus, the motor/generator must have an efficiency exceeding 95% when operating at rated power. This would be very difficult to achieve with a conventional iron-cored permanent magnet machine, due primarily to iron losses. However, since the continuous torque requirement of a peak power buffer for a small urban electric/hybrid vehicles is relatively low at such high rotational speeds (eg. at 30,000rpm: the torque is 9,5Nm for a power of 28kW), it is feasible to employ an air-cored machine topology, which eliminates stator iron losses. The absence of stator iron also minimises unbalanced magnetic pull, and thereby alleviates the demands on the magnetic bearing system. The favoured air-cored machine topology employs a multipole Halbach magnetised rotor [6], since this also eliminates the need for rotor back-iron and results in zero leakage field in the exterior region, as illustrated in Fig. 2. The conductors of the 3-phase stator winding are disposed as shown so as to maximise the flux-linkages with the permanent magnet rotor. They are encapsulated in an enhanced thermal conductivity resin, in which water cooling ducts are located in close proximity to the conductors in order to dissipate the heat which is generated as a result of stator copper loss. Since the conductors are exposed to a high fundamental frequency magnetic field (e.g. 3kHz for a 6-pole machine rotating at 60,000rpm), eddy current losses are minimised by the use of 'Litz' (ie. multi-stranded insulated) wire. Although the high fundamental operating frequency could be reduced by adopting a lower pole number design, which would reduce the switching loss in the associated power electronic converter, this would significantly reduce the power density of the motor/generator, as will be evident from Fig. 3.

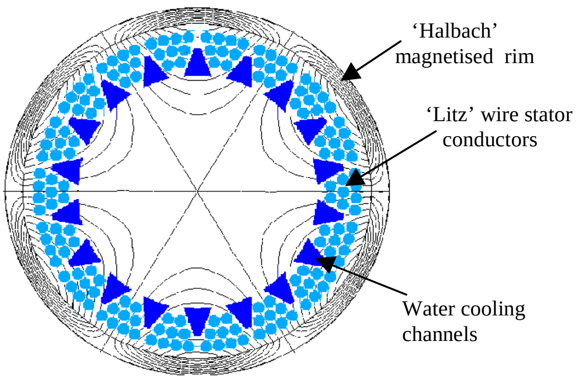


Fig. 2 6-pole Halbach magnetised, 3-phase, air-cored, permanent magnet brushless machine

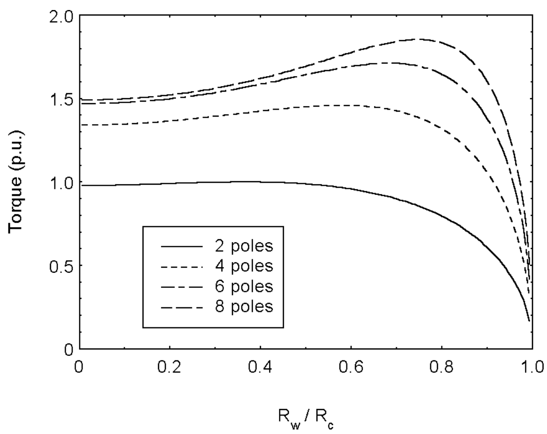


Fig. 3 Variation of electromagnetic torque with pole number and ratio of inner radius R_w to outer radius R_c of stator winding – constant copper loss

By way of illustration of the merits of employing an air-cored brushless dc machine equipped with a Halbach magnetised rotor, Table 2 compares its performance with that of a conventional external rotor, iron-cored machine equipped with radially magnetised magnets mounted adjacent to the airgap. Both machines are water-cooled and are designed for the same maximum power capability and the same space envelope, and use sintered Sm_2Co_{17} magnets, the stator of the conventional machine having 0.1mm thick $Fe_{49}Co_{49}V_2$ laminations.

Parameter	Iron-cored, radially magnetised permanent magnet machine	Air-cored Halbach magnetised permanent magnet machine
Power @ 30000 rpm	28kW	28kW
No-load loss @ 30000 rpm	210W	21W
Efficiency	96%	98%
Unbalanced magnetic pull for 50µm rim axis displacement	14N @ No-load	0.7N @ Full-load

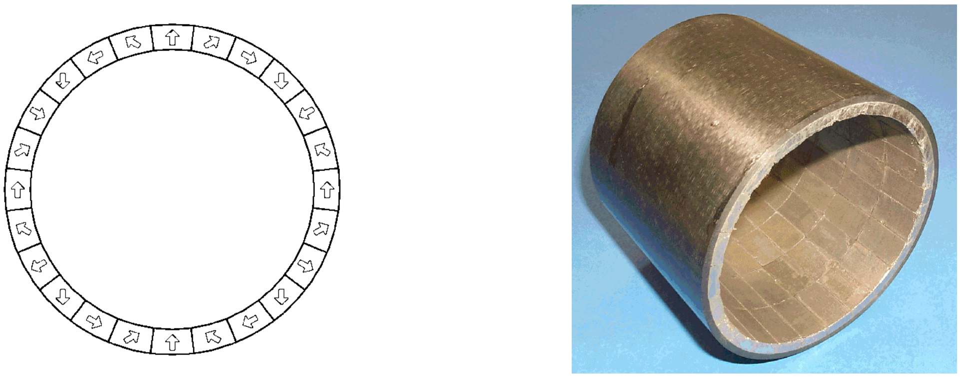
Table 2: Comparison between conventional iron-cored and air-cored Halbach magnetised, 6-pole permanent magnet machines

Hard Magnetic Materials

Two techniques have been explored for producing the permanent magnet Halbach magnetised rotor, viz. (a) by attaching either sintered, injection moulded or compression moulded rare-earth magnets to the inner bore of the flywheel rim, and (b) by impregnating rare-earth powder directly within the rim. In each case, due to the projected temperature rise of the rim, and concerns regarding the thermal stability of neodymium-iron-boron, only samarium-cobalt materials were considered. Clearly, the magnet properties (i.e. maximum energy product, remanence, and coercivity), and, therefore, the specific torque and power capability of the electrical machine, depend on the grade of permanent magnet material.

Sintered Samarium Cobalt Magnets

The 6-pole Halbach magnetised rotor can be fabricated by affixing an appropriate number of oriented and magnetised anisotropic Sm_2Co_{17} magnet segments to the rim as shown in Fig. 4. However, in order not to unduly compromise the self-shielding properties of the Halbach magnetisation distribution, at least 4 magnet segments per pole are required.



(a) *schematic of 6-pole Halbach array using discrete magnet segments*

(b) *Prototype rotor for 6-pole permanent magnet brushless machine*

Fig. 4: Halbach magnetised rotor fabricated from magnet segments

An obvious advantage of employing sintered magnets is that they are fully dense and, therefore, have the highest remanence (1.07T), which is conducive to a high specific torque. On the other hand, they have a relatively high electrical conductivity, and are, therefore, prone to induced eddy currents as a result of stator current harmonics. In this regard, although circumferential segmentation is required primarily to approximate the Halbach magnetisation distribution, it is also an effective method of reducing the induced eddy current loss.

Injection and Compression Moulded Magnets

Up to ≙65% and ≙85% by volume of rare-earth permanent magnet powder can be combined with resin by injection and compression moulding, respectively. However, the magnetic properties are correspondingly diluted, compared with those of sintered magnets, and the specific power capability of the machine is reduced accordingly. A virtue of such bonded magnets, however, is their high electrical resistivity, which is conducive to a low rotor eddy current loss.

Magnetically Loaded Carbon Fibre Composite

The Halbach magnetised rotor can also be realised by incorporating rare-earth permanent magnet powder directly into the fibre composite rim without significantly affecting the overall mechanical properties of the fibre. However, the maximum magnetic loading density is limited to around 20% by volume [5]. The magnetically loaded composite rim can then be multipole impulse magnetised to impart the required Halbach magnetisation distribution. By way of example, Fig. 5 shows a micrograph of a carbon fibre composite with 20% volume loading of samarium-cobalt powder, whilst Table 3 shows various compositions of magnetically loaded composite. The corresponding demagnetisation characteristics, which result after magnetisation to saturation, are shown in Fig. 6. As will be evident, even with 20% by volume loading of samarium cobalt, which is the maximum without compromising the integrity of the structure, the remanence is significantly lower than for injection/compression moulded and sintered magnets.

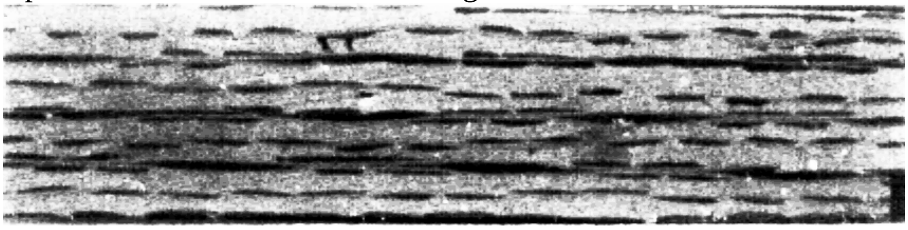


Fig. 5: Micrograph of fibre composite loaded with 20% samarium-cobalt powder

Sample	% volume fibre	% volume epoxy	% volume magnetic powder	calculated density kg/m^3	measured density kg/m^3
A	24	51	25	3221	3033
B	24	56	20	2876	2935
C	32	53	15	2563	2344
D	39	51	10	2246	2148

Table 3: Magnetically loaded carbon fibre composites

Nevertheless, the combined magnetic and mechanical properties of magnetically loaded composites can still be exploited, albeit the electrical machine having a significantly reduced continuous specific power capability. This will be seen in Fig. 7, which shows how the continuous power capability of a 6-pole Halbach magnetised brushless machine, of given dimensions and having a specified maximum stator winding temperature, varies with the remanence of the rotor permanent magnet material, over an operational speed range from 30,000 to 60,000rpm. In this particular example, 1 p.u. power corresponds to 28 kW.

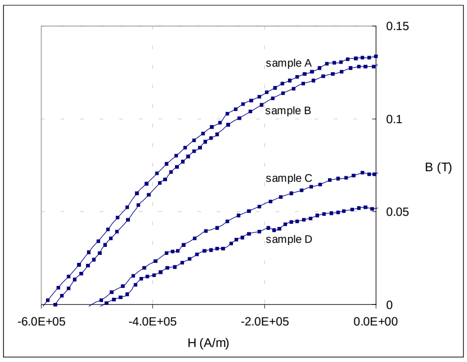


Fig. 6: Demagnetisation curves for magnetically loaded composites

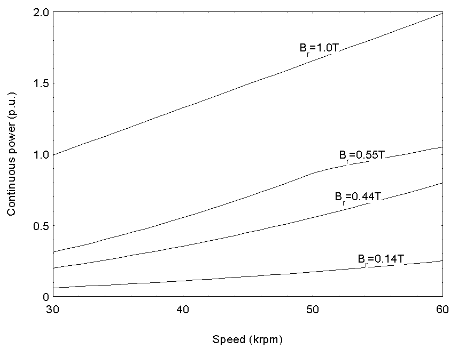


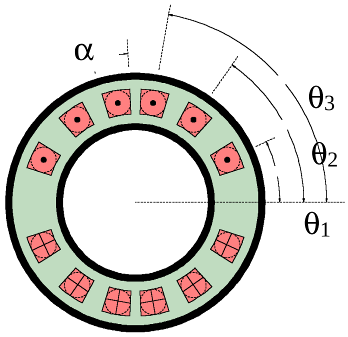
Fig. 7: Continuous power capability over 2:1 speed range

Clearly, the weaker the permanent magnet material the lower will be the peak power capability of the flywheel unit. However, the use of magnetically loaded fibre composite can allow the rim to operate at a higher rotational speed (e.g. up to 100,000 rpm), since lower density material on its inner surface will reduce the hoop stress and, at the same time, will provide additional structural strength to the rim. Consequently, a higher energy storage capacity is possible, and rather than acting as a peak power buffer, such a flywheel unit might be employed as an energy store, either to complement or replace electrochemical batteries.

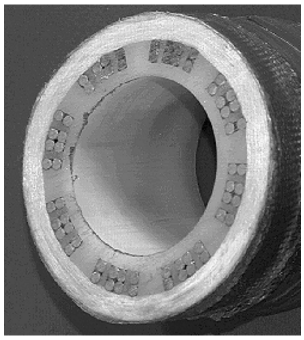
One potential method of increasing the power capability of a machine which employs a magnetically loaded fibre composite rotor would be to orientate the impregnated magnet powder during the filament winding process, such that anisotropy is imparted which is compatible with the subsequently applied Halbach magnetisation distribution.

Multipole Impulse Magnetisation

For both a magnetically loaded carbon fibre composite rim, and, an injection/compression moulded annular permanent magnet rotor, the multipole Halbach field distribution has to be imparted by an impulse magnetisation fixture. The required magnetising field distribution is realised by employing a fixture in which the disposition of conductors is optimised, so as to eliminate low-order harmonics in the magnetising field distribution, as illustrated in Fig. 8. With k magnetising conductors under each half-pole, all having the same cross-section and current density, their angular disposition can be optimised to eliminate the first k harmonics in the magnetising field [6].



(a) Disposition of conductors(θ_1,θ_2, θ_3) to eliminate first 3 harmonics in 2-pole Halbach magnetising field



(b) Cross-section of 6-pole impulse magnetising fixture

Fig. 8: Disposition of magnetising conductors to impart Halbach magnetisation distribution

ACTIVE RADIAL MAGNETIC BEARINGS

In a vehicle-mounted flywheel, the main demands on the bearing system arise from gyroscopic torques generated by the rotational motion of the vehicle in pitch, roll and yaw. In turn, these depend on the orientation of the flywheel on the vehicle. The peak power buffer unit shown in Fig. 2 is intended to be mounted horizontally and transversely in a vehicle, since a longer flywheel rim can then be accommodated, which facilitates a wider spacing between the magnetic bearings at each end of the rim, which, therefore, reduces the required electromagnetic force capability. The gyroscopic torques then arise only from roll and yaw motions of the vehicle, and result in essentially radial bearing forces. At the maximum operational speed of 60,000rpm the gyroscopic torques result in peak forces on the radial bearings of up to 1500N on the vertical axis and 800N on the horizontal axis. In addition, axial disturbance forces result from transverse linear acceleration of the vehicle, although these are comparatively low. Therefore, high force, high stiffness active radial magnetic bearings are employed, in combination with inherently lower stiffness, passive axial magnetic bearings. Since the active radial magnetic bearings act directly on the flywheel rim, its inner surface must carry an annulus of soft magnetic material. Although it is possible to employ a stack of annular electrical sheet steel laminations, this constrains the bearing to have the heteropolar magnetic circuit topology shown in Fig. 9, since the magnetic flux paths must be in the plane of the laminations. Given that the peak force capability of active magnetic bearings is ≙0.9N/mm^2 of pole-face area, a total pole-face area of ≙2000mm^2 is required per electromagnet, which translates into an active length of 100mm. It will be noted that, despite the lower force requirement on the horizontal axis, the electromagnets on both the vertical and horizontal axes have the same pole-face area, since the maximum thickness of the yoke was limited by the need to accommodate the water coolant supply, electrical power cables and sensor connections in the central hub.

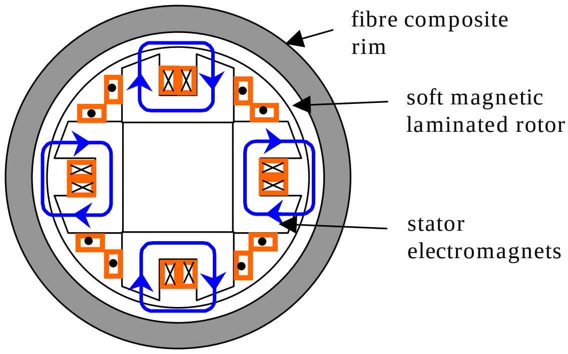


Fig. 9 Schematic of heteropolar active radial magnetic bearing

An alternative is to employ an annulus of magnetically isotropic soft magnetic composite material, which then enables the bearing to have the homopolar magnetic circuit topology shown in Fig. 10. The electromagnets can then be dimensioned to cater for the different peak force requirements in the horizontal and vertical axes. As a consequence, the required pole-face area is achievable with an active length of only 80mm.

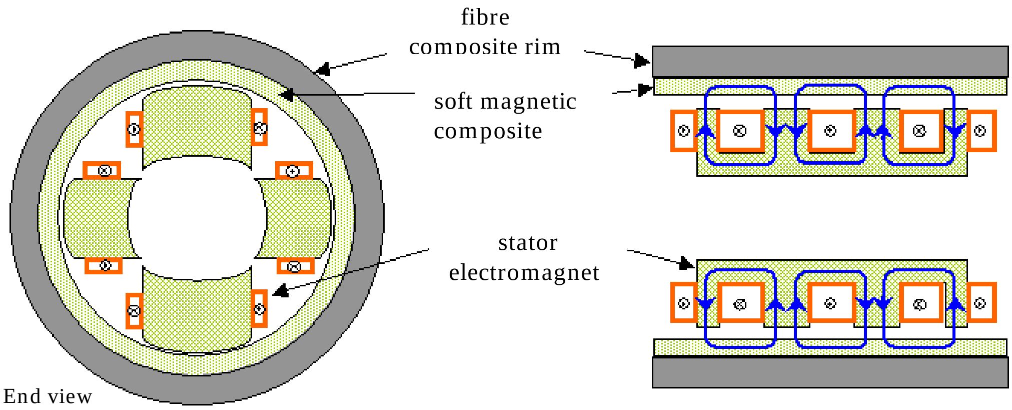
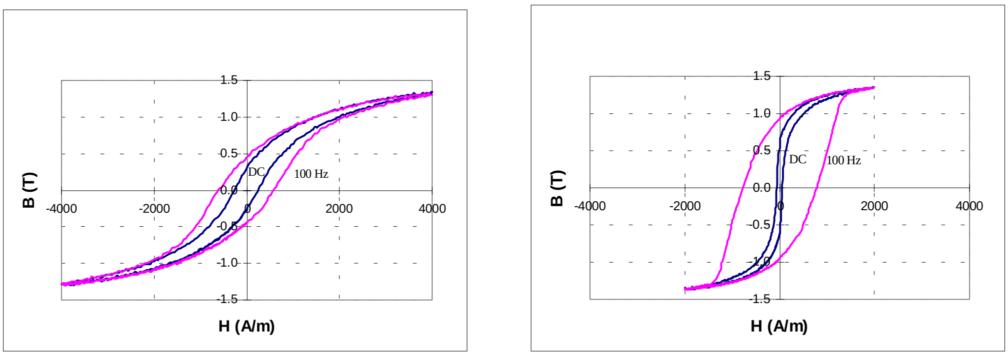


Fig. 10 Schematic of homopolar active radial magnetic bearing

The soft magnetic composite may be formed either from fine iron powder bonded with resin [7], or from small grains of iron which are compressed such that they interlock [8]. In both cases, the composite comprises around 97% iron by volume, the interface between the particles imparting mechanical strength and providing an insulating layer. However, since they are not fully dense, they have a relatively poor permeability ($\mu \approx 600$) compared with that of laminated materials. The dc and ac hysteresis loops, and the associated iron loss which results when the soft magnetic composite and the laminated materials are exposed to time-varying magnetic fields, also differ markedly, Fig. 11. As will be evident, under bipolar flux excitation the soft magnetic composite exhibits a significantly higher hysteresis loss per cycle, whilst the laminated material has a very much higher eddy current loss, particularly at high excitation frequencies. However, as will be seen from Fig. 12, the hysteresis loss in the soft magnetic composite under unipolar flux excitation is comparable to that in the laminated material under bipolar excitation. As a consequence, the total rotor loss in the homopolar magnetic bearing equipped with the soft magnetic composite is significantly less than in the laminated rotor of the heteropolar bearing.



(a) Soft magnetic composite ('Accucore') (b) Si-Fe laminations (Transil 335)

Fig. 11 Typical dc and ac hysteresis loops for soft magnetic composite and laminated materials

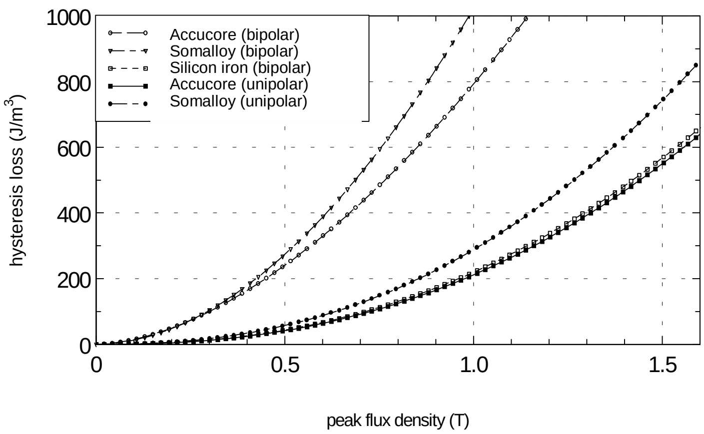
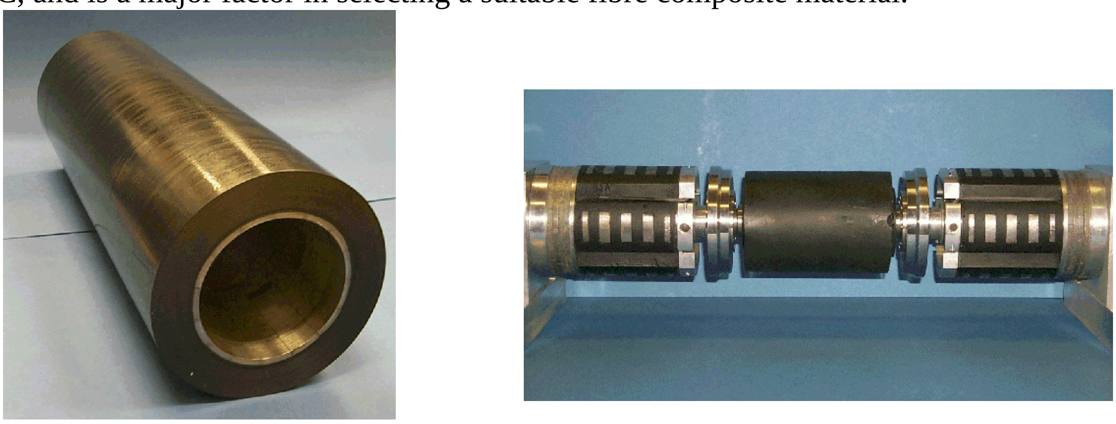


Fig. 12 Hysteresis loss in soft magnetic composite and Si-Fe lamination materials

Demonstrator Peak Power Buffer Flywheel

Fig. 13 shows the carbon fibre composite rim and the central hub, comprising the stationary parts of the bearing system and electrical machine, of the demonstrator flywheel unit, whilst Fig. 14 shows the predicted temperature distribution in the rim when the motor/generator is operating at rated power, 28kW, and there is a loss of 50W in its rotor, as well as 50W in each rotor of the two active radial bearings. The maximum temperature rise is predicted to be ≈180°C, and is a major factor in selecting a suitable fibre composite material.



(a) Carbon fibre composite rim (b) Central hub

Fig. 13 Rim and central hub of prototype flywheel unit

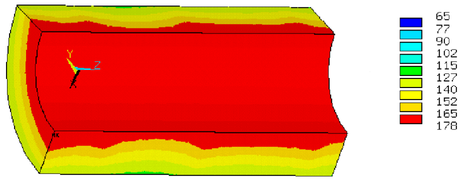


Fig. 14 Predicted temperature distribution in composite flywheel rim at 60,000rpm 28kW

CONCLUSIONS

There is considerable potential for employing fibre composites in high-speed flywheels, for which permanent magnet ‘Halbach’ magnetised machine is particularly appropriate for efficient kinetic energy to electrical energy conversion. It has been shown that by magnetically loading the fibre composite, the permanent magnet rotor of such a machine can be integrated with the flywheel rim, whilst a soft magnetic composite can be employed to advantage in a homopolar active magnetic bearing topology.

ACKNOWLEDGEMENTS

The research on the flywheel peak power buffer which has been described in the paper has been funded by the EU under the BRITE-EURAM and JOULE-THERMIE Programmes. The authors acknowledge the contribution of other partners in the project, viz. BMW, Centro Ricerche Fiat, Renault, Bertin, Elettronica Santerno, Ansaldo Recherche, VTT Chemical Technology, Dresden University and AKA.

REFERENCES

1. Howe D, Peel D and Mellor P H, “High speed electro-mechanical energy storage systems for electric vehicles”, *Proc. PowerTech’95*, 1995, pp. 50-56.

2. Post R F, Fowler T K and Post S F, “A High-Efficiency Electromagnetic Battery”, *Proc. of the IEEE*, Vol.81, No.3, March 1993, pp.462-474.

3. Acarnley P, “Advanced Components for Electrical Drive-Trains”, Proc. *UK Magnetics Society Seminar on Electric and Hybrid Vehicles*, University of Warwick, 16th July 1997.

4. Howe D, Mason P, Mellor P H, Wu Z Y and Atallah K, “Flywheel Peak Power Buffer For Electric/Hybrid Vehicles*”, To be presented at Proc. IEMDC Conference*, Seattle, May 1999.

5. Buckley J M, Atallah K, Bingham C M and Howe D,”Magnetically Loaded Composite For Roller Drives”, IEE Colloquium on New Magnetic Materials, London, UK, 28th May 1998.

6. Atallah K, Howe D and Mellor P H, “Design and analysis of multipole Halbach (self shielding) cylinder brushless permanent magnet machines”, *Proc. EMD’97*, 1997, pp. 376-380.

7. Persson M, Jansson P, Jack A G and Mecrow B C, "Soft magnetic composite materials - use for electrical machines", Proc. IEE Electrical Machines and Drives conference, Sept. 1995, p242-246.

8. Krause R F, Bularzik J H and Kokal H R, "A new soft magnetic material for ac and dc motor applications", Intermag conference, Seattle, USA , 1996.