Design of an electrical machine with integrated flywheel

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Abstract

A kinetic energy storage unit has been optimised regarding energy content, power and losses within the machine. The machine design is a permanent magnet synchronous machine with an outer rotor arranged as a Halbach array. This design minimises the losses particularly within the rotor. The stator losses are reduced to the mere copper losses. The outer rotor has been integrated into the flywheel, forming one unit instead of a machine with an attached flywheel. Thus the air gap circumferential speed of the machine may reach higher values than usually. The torque of the machine is calculated dependent on the geometry and the magnetic flux. In the presented version the power of the machine has been optimised, considering the electromagnetic parameters and the rotor strength both together. The highest power can not be combined with the highest possible energy density. Therefore depending on the requirements other design goals like energy density or energy to power ratio must be taken into account for a total design optimisation as well. The burst behaviour of the rotor has been considered as another main design criteria. A proper design of the composite rotor helps to reduce the forces onto the containment to an acceptable level.

Introduction

A typical concept of flywheel energy storage for mobile application usually consists of an electrical machine with an attached flywheel. Both components are in general optimised independently. The machine must among other requirements supply the specified power with minimised losses. The fly-wheel has to be designed for sufficient energy content and a controllable burst behaviour with an acceptable safety reserve within the speed range of the machine. Both components with the bearings and the containment are assembled together and form the system.

The principal demands for a flywheel energy storage system are the amount of stored energy and the power rate. Beyond this the burst behaviour and the power losses, especially within the rotor, strongly influence the usability of the design.

In this paper a design of an integrated machine/flywheel concept will be discussed. The machine is based on a tubular multipolar magnet array which produces a high field concentration in the inner part of the rotor with no need to enforce the flux concentration by additional iron. The magnets form the outer rotor of the machine. The air gap may thus be increased without suffering a significant reduction of machine performance. The advantages of this machine concept is an increase in efficiency having losses only in the copper winding and no additional iron losses. High speed machines of the presented concept gain significantly.

The flywheel consists of the rotating parts of the machine reinforced with a rim of a high strength carbon fibre reinforced composite. Thus, the permanent magnets add to the moment of inertia, and the air gap circumferential speed is maximised and thus the power of the machine as well.

Concept consideration

The evolution of the flywheel drive technology has led to an integrated system. The system is no longer considered to be an electrical machine with an attached flywheel. The goal of increasing the energy density leads to highest rotational speed. The rotor of the electrical machine has to withstand extreme high centrifugal forces. That ideally leads to a concept which combines the flywheel with the rotor, where the flywheel acts as a support structure for the spinning part of the electrical machine. An external rotor motor is the natural choice for this kind of an application.

Beside the energy density the losses determine the concept:

- gas friction losses on moving surface
- bearing losses
- copper losses
- hysteresis losses in iron parts
- eddy current losses on rotor and stator

All these losses grow with the increase of the rotational speed. A design is required to minimise these effects. The common choice for the drive are permanent magnet synchronous machines. They combine the advantage of high exploit with absence of electrical excitation and low rotor losses. The latter is achieved with a large air gap. An air gap winding prevents eddy current losses due to air gap slotting. The copper losses are not as important since they do not show while the drive is idling. Furthermore they can be further reduced by a proper layout. The gas friction losses are nearly eliminated by evacuation of the containment. Magnetic bearings eliminate the mechanical contact and therefore the largest part of the bearing losses. If the size of the rotor does not constrain the use of conventional bearings at the target speed they may be the better choice. Compared to the bearing losses the hysteresis losses are significantly higher. Therefore a reduction of the bearing losses makes sense only if the hysteresis losses are reduced as well.

Hystereris losses may be reduced by using iron with very soft magnetic properties. These materials are still under development and are improving their performance. However they are expensive and not easy to handle.
Another approach for eliminating these inherent losses is to choose an ironless machine. Since the utilisation factor for an ironless machine with conventional permanent magnet (PM) design is very

poor, the so called ”magic array” of Klaus Halbach [1] may be used to overcome this penalty. The magnetic array is magnetised in such a way that the maximal induction inside the ring is achieved. As there is no magnetic flux outside the array the energy produced by the PM is entirely focused into the region carrying the motor current. Furthermore having inherently a large effective air gap the reaction of the armature (voltage drop and eddy currents in the PM) is reduced.

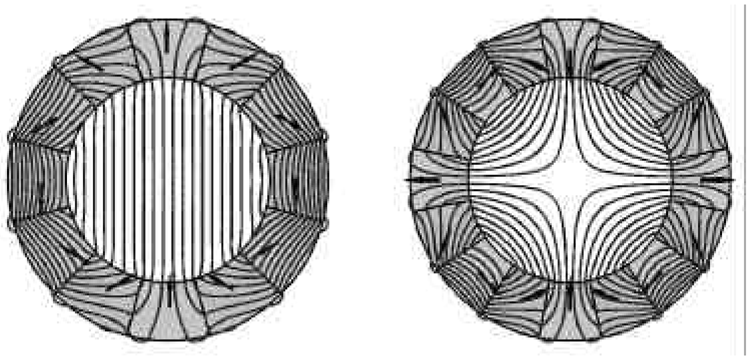

Fig. 1: Field lines of multipolar array with p=1 and p=2 calculated by FEM

The windings of the electrical machine can be designed in different ways. Compared to conventional windings the conductors are not placed in slots. The winding has been designed as a full pitch winding arranged in two layers (Fig. 2).

The PM external rotor ironless machine using a multipolar magnet array according to the proposal of [1] is shown in Fig. 2. The carbon fibre composite acts as a support structure for the PM elements. Both together form the inertia for the kinetic energy storage.

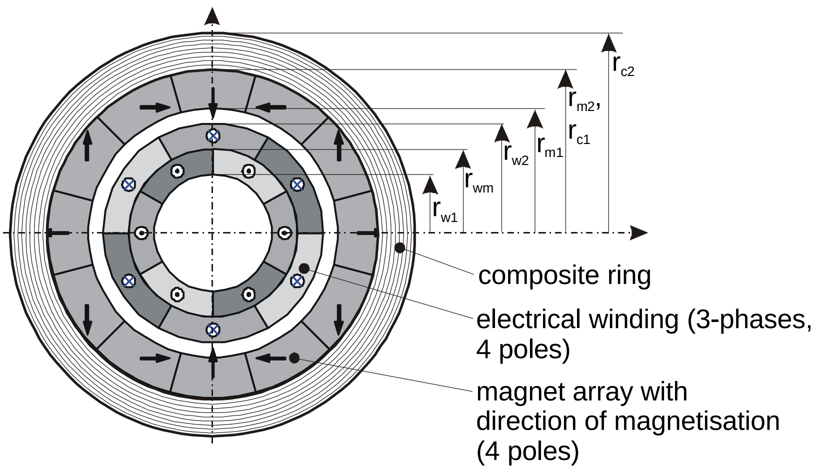

Fig. 2: Cross section of the ironless concept (p=2)

The used dimensions are as follows:

$\mathbf{r_{w1}}$, $\mathbf{r_m}$, $\mathbf{r_{w2}}$	inner, mean and outer radius of the stator winding
$\mathbf{r_{m1}}$, $\mathbf{r_{m2}}$	inner and outer radius of the magnetic array
$\mathbf{r_{c1}}$, $\mathbf{r_{c2}}$	inner and outer radius of the composite ring

An ideal sinusoidal distribution of the magnetic flux is achieved inside the magnet ring when the magnetisation varies continuously along the circumference of the ring. However, a more economical way is to use a segmented ring. Furthermore this segmentation helps to overcome the poor strain capabilities of sintered magnetic materials. The following calculations are based on a flux distribution of the ideal ring as an adequate approximation.

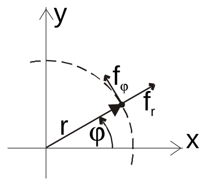

Fig. 3: Polar coordinates: radial (f_r) and circumferential (f_φ) component

The field inside the ring is described in polar coordinates by

$$\begin{aligned} B_r &= B_{\max}\cos(pj) \\ B_j &= -B_{\max}\sin(pj) \end{aligned} \qquad (1)$$

with:

$$B_{max} = \begin{cases} B_0 \ln\left(\dfrac{r_{m2}}{r_{m1}}\right) & \text{for } p > 1 \\ B_0 \dfrac{p}{1-p}\left(\dfrac{r}{r_{m1}}\right)^{p-1}\left[1-\left(\dfrac{r_{m1}}{r_{m2}}\right)^{p-1}\right] & \text{for } p > 1 \end{cases} \qquad (2)$$

p is the number of pole pairs of the electrical machine, r_{m2} and r_{m1} are the radii of the construction (Fig. 2), B_0 is the remanence flux of the used magnetic material.

Optimisation machine

The several design parameters of the flywheel system have to be optimised. There's a choice of different goals:

- maximal power output for a given magnet volume
- minimal overall volume or mass for a requested energy or power
- maximal efficiency constraint by a given volume or mass

First the relation between the output power per machine length and the geometrical dimensions of the magnetic ring will be analysed. Then the torque for a given cross section will be calculated. Depending on the inner radius and the height of the magnet ring, the maximal allowed speed must be determined. Finally the output power is derived as the product of both values.

The number of pole pairs and the number of phases are included in the optimisation. However, both of them are usually constrained by arguments beyond those of the machine design. The effort for the power electronics will limit the number of phases. Higher pole numbers increase the supply frequency of the machine for a given rotational speed. As discussed above the losses are a central concern of energy storage and higher frequencies will increase nearly all the mentioned losses.

Torque

The calculation of the torque is done according Fig. 2. The current loading is homogeneously distributed in the single winding segments and contributes to the torque relative to its radial position.
The torque is calculated as follows

$$M = \iint_A l\, r\, B(r, j, t) J(r, j, t)\, r\; df\; dr \tag{3}$$

where *B(r, j, t) and J(r, j, t)* are time and location dependent values of flux and current density in the segments. Using *q*-phases with a phase lag of *2p/q*, the time dependency of the torque will disappear. The integration across the segments and the summation of the phases gives the following formula for the torque

For *p*=1:

$$M = \frac{\sqrt{2}}{3} q l J_{eff} \sin\left(\frac{p}{q}\right) B_0 \ln\left(\frac{r_{m2}}{r_{m1}}\right)\left(r_{w2}^3 - r_{w1}^3\right) \tag{4}$$

and for p>1:

$$M = \sqrt{2} q l J_{eff} \sin\left(\frac{p}{q}\right) B_0 \frac{p}{(p-1)(p+2)}\left[r_{m1}^{\;1-p} - r_{m2}^{\;1-p}\right]\left(r_{w2}^{p+2} - r_{w1}^{p+2}\right) \tag{5}$$

J_{eff} is the effective value of the current density under consideration of the feasible filling factor. The current density is assumed to be constant, only depending on the cooling capabilities of the machine. The minimal inner radius of the winding is constraint by mechanical requirements. The air gap (r_{m1}-r_{w2}) is assumed to be small compared to the radii. The formulas allow a variation between a thick magnet and reduced winding radii or thin magnets with low induction but a larger lever for the torque generating current. Either $r_{m2}=r_{m1}$ or $r_{w2}=r_{w1}$ will result in no torque.

Strength

The speed of the machine and the flywheel will be limited only by the strength of the material. Both the power of the machine and the stored energy of the flywheel will increase with the speed of the rotor. The maximal speed of a thin rim can be defined by the specific strength of the material. An additional centrifugal loading of the rim caused by permanent magnets without considerable strength will result in a pressure onto the composite rim. As the magnets will be segmented anyway the strain ability of the two different materials is no concern here.

The stress distribution $\sigma_\varphi(r)$ and $\sigma_r(r)$ in a rotating rim made from a coiled composite material with the material properties E_φ and E_r as parallel and normal Young's modulus, $\nu_{\varphi r}$ as Poisson's ratio, ρ as density and ω as angular velocity is

$$s_j = r w^2 \frac{3+n_{jr}}{9-l^2}\left[\begin{array}{l} l\left[\dfrac{k^{-l-1}-k^2}{k^{-l-1}-k^{l-1}}\left(\left(\dfrac{r}{r_{c2}}\right)^{l-1}\right)\right]+ \\ l\left[\dfrac{k^{-l-1}-k^2}{k^{-l-1}-k^{l-1}}-1\right]\left(\left(\dfrac{r}{r_{c2}}\right)^{-l-1}\right)-\dfrac{l^2+3n_{jr}}{3+n_{jr}}\left(\dfrac{r}{r_{c2}}\right)^2 \end{array}\right] \tag{6}$$

$$s_r = r w^2 \frac{3+n_{jr}}{9-l^2}\left[\begin{array}{l} \left[\dfrac{k^{-l-1}-k^2}{k^{-l-1}-k^{l-1}}\left(\left(\dfrac{r}{r_{c2}}\right)^{l-1}\right)\right]- \\ \left[\dfrac{k^{-l-1}-k^2}{k^{-l-1}-k^{l-1}}-1\right]\left(\left(\dfrac{r}{r_{c2}}\right)^{-l-1}\right)-\left(\dfrac{r}{r_{c2}}\right)^2 \end{array}\right] \tag{7}$$

with the relative ratio of the composite rim radii

$$k = \frac{r_{c1}}{r_{c2}} \tag{8}$$

and the ratio of the orthotropic material stiffness

$$l = \sqrt{\frac{E_j}{E_r}} \tag{9}$$

Similar the stress due to pressure from the inside of the rim is

$$s_j = -s_{r1}\left[\begin{array}{l} l\left[\dfrac{1}{k^{-l-1}-k^{l-1}}\left(\left(\dfrac{r}{r_{c2}}\right)^{l-1}\right)\right]+ \\ l\left[\dfrac{1}{k^{-l-1}-k^{l-1}}-1\right]\left(\left(\dfrac{r}{r_{c2}}\right)^{-l-1}\right)\end{array}\right] \tag{10}$$

$$s_r = -s_{r1}\left[\begin{array}{l} \left[\dfrac{1}{k^{-l-1}-k^{l-1}}\left(\left(\dfrac{r}{r_{c2}}\right)^{l-1}\right)\right]- \\ \left[\dfrac{1}{k^{-l-1}-k^{l-1}}-1\right]\left(\left(\dfrac{r}{r_{c2}}\right)^{-l-1}\right)\end{array}\right] \tag{11}$$

As the magnets are segmented, no circumferential stiffness within the magnets is assumed. The magnets behave like an ideally distributed mass. The internal stress from the magnets with a density ρ_m is

$$s_{r1} = \frac{-p\left(r_{m1}^2 - r_{m2}^2\right)}{2p\, r_{m2}} r_m w^2 \left(\frac{r_{m1} - r_{m2}}{2}\right) \tag{12}$$

Together with the material properties and an appropriate failure criteria the maximal allowed speed of the rotor with a given magnet rim has been calculated. In the following example this rotor speed has been determined for a TENAX HTA standard fibre composite, using the Tsai-Wu failure criteria [2] and applying a safety factor of 1.5.

Power

The power P is calculated from the torque of the machine multiplied with the ultimate speed ω of the rotor

$$P = M * w \tag{13}$$

As an exclusively torque optimised machine does not necessarily run with the fastest possible speed the power has been considered as an overall optimisation criteria.
The following calculation example is based on constant copper losses, which leads to a smaller winding thickness with increasing air gap radius. The cross section area of the magnets has been used as an additional parameter.

Figure 4 shows that the maximum power is reached with a high cross section of magnets and therefore a comparatively slowly spinning rotor. Higher radii reduce the maximum speed, smaller radii reduce the resulting torque. A larger magnet area increases the flux but reduces the ultimate speed.

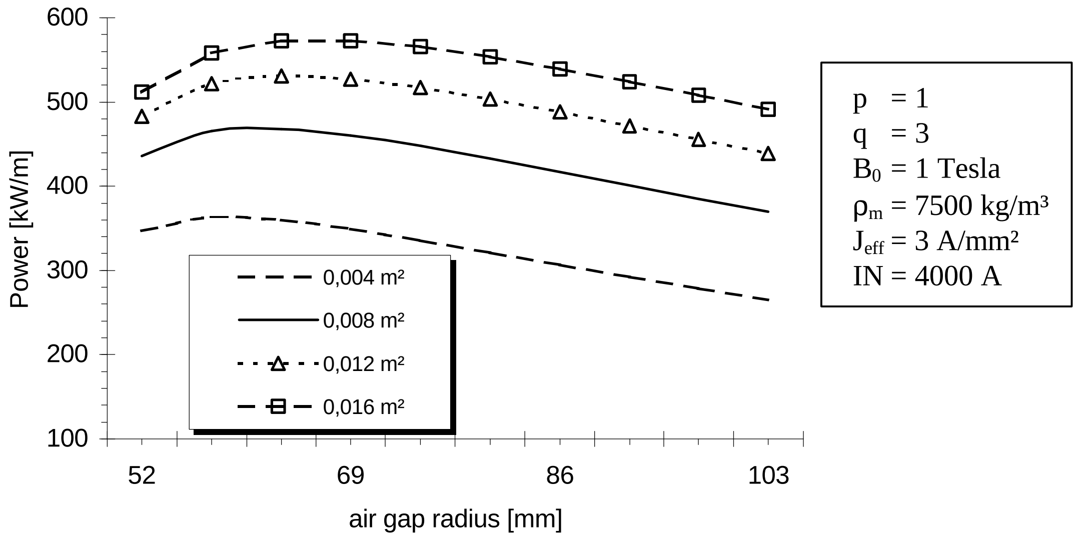

Fig. 4: Power depending on air gap radius and magnet volumes for a given winding area

Additional optimisation criteria may thus be the energy to power ratio, energy to volume ratio, power per magnet volume ratio etc. and must be weighted according to the specific requirements of the intended use of the storage system.

Burst Behaviour

When a car is to be equipped with a potentially dangerous device such as a flywheel, safety precautions will have a very high priority from the beginning. A controllable burst behaviour is among the top concerns to be considered.

To achieve a benign burst behaviour the stored energy should remain rotational energy as long as possible. The size and dimensions of the fragments produced in a burst are therefore essential [3]. With composite materials two different failure modes can be achieved. Depending on the stress distribution either fibre or matrix failure predominates. With a carefully designed matrix failure mode the rotor breaks into fragments of very long circumferential and of small radial dimension (Fig. 5).

These fragments contain mainly rotational energy which will be converted via friction into heat during a relatively slow process. In numerous burst tests conducted so far no crucial radial or penetration forces beside the inevitable torque forces due to the spin preservation have been observed.

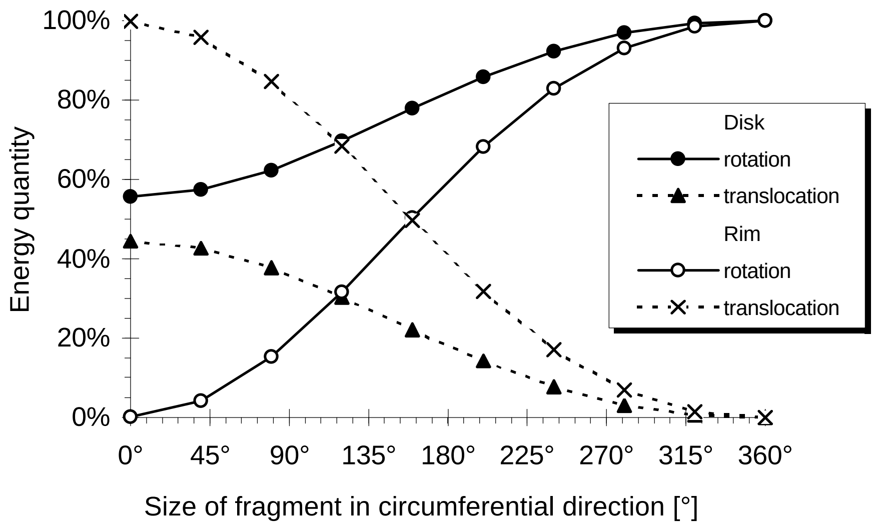

Fig. 5: Energy quantity of burst fragments

Different researchers have reported huge axial forces beside the forces acting within the rotating plain. The resulting forces from the deflection of a cloud of burst debris and/or due to an increase in volume of the debris may be able to destroy a containment [4]. This concern has to be addressed with both a proper design of the containment and of the flywheel. Tentative measurements of forces acting on the containment during a burst show promising results so that a containment with reasonable weight seems to be feasible.

Conclusion

The ironless concept is a favourable choice for drives with lowest rotor and idling losses. Using multipolar magnet arrays, despite the absence of ferromagnetic material, a remarkable magnetic flux can be obtained. The mechanical and electrical parameters of the drive are interdependent. The paper presents a method calculate the power under consideration of all given geometrical and material parameters. By variation of these parameters an optimisation according the specific requirements can be done. Since different applications will call for different optimisations there is no final solution of how to design a storage system.

The goal of highest speeds can not be reached concurrently with highest power densities. The stress load due to the magnetic material penalises the circumferential speed. The interacting of the two parameters leads to the final machine performance.

The presented optimisation results in the maximal power for a given current area and a constant magnet volume leading to an optimal geometrical configuration. Attention should be paid to the energy density of such a design. The magnet thickness reduces the maximal speed considerably. An additional composite rim could be attached around the machine optimised on its own for maximal energy density.

As magnets are still expensive, a design with minimised magnetic volume might be of interest. The presented ironless concept is not favouring this context particularly. However, the presented optimisation can be used for other machine concepts with conventional flux production as well.

The geometry of the rim, the material and the size of the permanent magnets must be chosen in a way to achieve interlaminar failure where the fibres have areas with sufficient strength reserve for a benign burst behaviour.

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