

High Speed Reluctance Machine Designed With IES-Field Analysis Programs

Dr. Hans K. Asper, Silphenix GmbH, Switzerland

About Dr. Hans Asper

Dr. Hans K. Asper was born and raised in Zurich, Switzerland. He received his diploma in electrical engineering from ETH (Swiss Federal Institute of Technology in Zurich). After two years of experience with Swiss industrial companies, Hans Asper immigrated in 1956 to the US, where he joined the microwave instrumentation division of Hewlett Packard Company in Palo Alto, California. In 1961, he transferred to the Radio Astronomy Institute of Stanford University. After returning to Switzerland, he started in 1965 his work towards a PhD (1971) at the ETH, where he subsequently formed the ETH Radio Astronomy Research Group developing a computer controlled solar radio telescope. In 1980, Hans Asper left the field of radio astronomy and started the ETH Energy Storage Research Group engaged with the development of high speed, fibre composite flywheel systems. Since 1988, he successfully used field analysis program for the development of new high-speed electrical machines. In July 1992, Hans Asper started his own engineering and consulting office with activities in the areas of high-speed electrical machines, magnetic bearings, and electromagnetic field analysis.

Introduction

In the context of the author's professional experience in the field of flywheel energy storage systems during his research activity, at the ETH Zurich, the focus was on compact high-speed flywheel systems for day storage of solar photovoltaic energy in the order of 0.5 to 5 kWh usable energy storage. Important constraints for energy day store are extremely low losses per day e.g. – 1% per hour. This means, that the idling losses have to be less than 5 W and 50 W for a 0.5 kWh and a 5 kWh unit respectively. Minimising the idling losses requires not only operation in a vacuum environment but in addition also: Low bearing losses (→ Magnetic Bearings) , Low Eddy Current losses (→ Reluctance Machine) and Low Drag Losses (→ Cylindrical Rotor Surface).

Most important design tools were the IES* field analysis programs MAGNETO 2D and AMPERES 3D, which enabled the modelling of both magnetic bearings and the reluctance machine. Particular features of these IES programs are the exceptional ease of geometric modelling and the interactive use of MAGNETO 2D and AMPERES 3D to create the geometric model and the currents in the stator coils. Using parametric solver mode the force values axial rotor position with respect to the magnetic bearings and the torque values versus the rotor angle versus the rotor angle are obtained.

* Integrated Engineering Software, Winnipeg, Mb, Canada

Magnetic Bearing

The passive magnetic bearing (Dual Ring Pair) as shown in Fig. 1 chosen consist of two ring pairs with repulsive magnetisation in both radial – and axial direction.

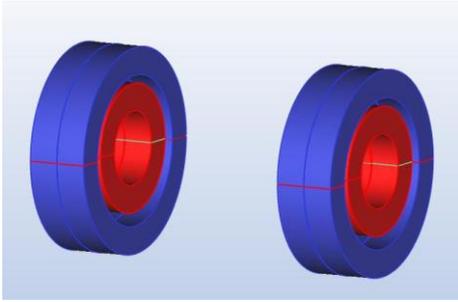


Fig. 1 Passive Magnetic Bearing Dual Ring Pair Ne 45, Repulsive magnetisation in both radial (x,y) direction and in the axial direction (z). The motor axis coincides with the z-coordinate.

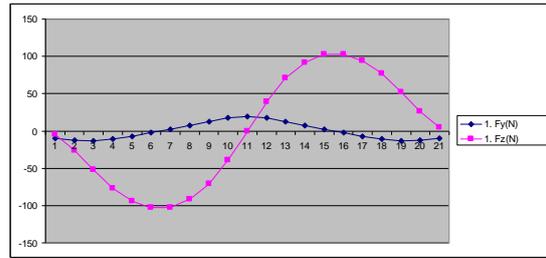


Fig. 2 Restoring Forces of a two pair passive magnetic bearings (Fig.1) for a radial rotor displacement of $dy = -0.5$ mm and an axial rotor displacement in the range of of -5.0 mm $< dz < +5.0$ mm using the parametric solver mode of AMPERES

For a horizontal orientation of the motor axis the forces have been computed with the parametric solver mode of AMPERES for an axial rotor displacement dz between -5.0 mm and $+5.0$ mm as shown in Fig.2. In the axial center position (#12) the radial force $F(y)$ is positive providing a restoring force compensating the rotor weight. The axial force $F(z)$ near the center position (#11) is zero with while at $dz = -0.5$ mm point (#10) $F(z) = -39.4$ (N) indicating axial instability, which has to be confined mechanically in both directions e.g. with a flat precision ground steel disk inserted at the end of the rotating axis against a small stationary steel sphere on both ends. Therefore the actual mechanical bearing losses depend on a low axial destabilisation force Fz obtained by (1) manually adjusting the axial air gap and (2) the optimum material choice (e.g. high grade ceramics) for both the disk and the sphere.

Alternatively an axial active magnetic bearing can be used requiring low power for stabilisation (Ref: Jan Fremerey). The radial restoring force Fy for a radial displacement of -0.5 mm is 19.4 Newton (#11). For a rotor mass of 1 kg (9.81 (N)) the radial restoring force is reduced to 9.7 Newton as shown in Fig 3. If a higher radial restoring force were needed, the geometry of rings or the number of ring pairs could be altered.

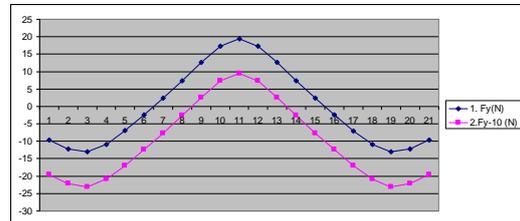


Fig. 3 Radial restoring force $Fy = 19.4$ (N) in the axial center position of the bearing (#11). The rotor weight of 1 kg (10 N) reduces the radial restoring force to $Fy = 9.7$ (N), which is amply sufficient for a well balanced rotor.

Reluctance Motor

The choice of a reluctance motor has been made due to the inherent low eddy current losses and the absence of both permanent magnets and rotor coils. The geometry of stator, rotor and the coils have been successfully modelled using MAGNETO and AMPERES interactively. The torque has been calculated with MAGNETO yielding torque values for a rotor length of 1000 mm. For a rotor length of 15 mm the torque values are normalised by a factor of 15/1000. The torque can also be computed with AMPERES requiring more computing time. However, the results obtained with either program are within comparable limits.

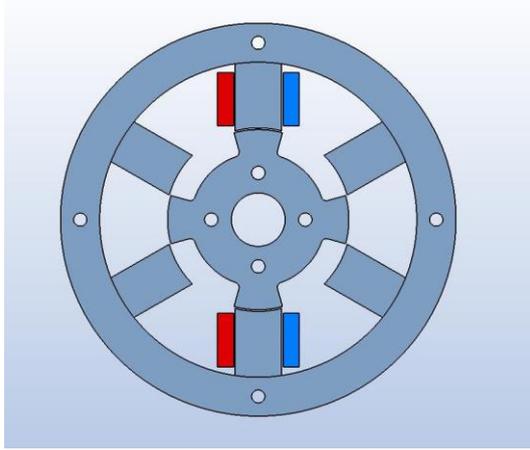


Fig.4 The reluctance motor geometry designed with MAGNETO has salient poles for both rotor and stator. A preferred choice is 4 rotor poles and 6 stator poles with three stator coil pairs.

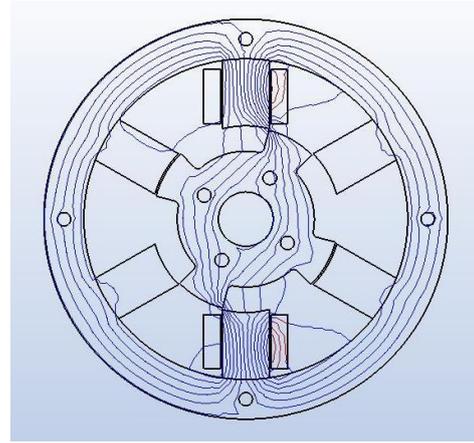


Fig.5 The field lines of the reluctance motor shown with the rotor in the -30 deg position with maximum reluctance obtained with MAGNETO with current flow in one coil pair only.

Rotor and Stator have salient poles of unequal numbers as shown in Fig.4. The torque is generated through the physical phenomenon of reducing magnetic reluctance. When one stator coil pair is energized, a rotor torque is generated as shown in Fig.5. The nearest rotor pole is pulled from the nonaligned position (e.g. -30 deg) towards the aligned position (0 deg). When the three stator coil pairs are connected to a 3-phase variable frequency current source the rotor follows the rotating field. The phenomena of magnetic reluctance can be visualized by pictorially replacing the field lines (Fig.5) with rubber bands, which exert a maximum restoring torque (i.e. maximum reluctance) on the rotor in the non aligned position (e.g. - 30 deg) and a zero torque in the center position (i.e. minimum reluctance)

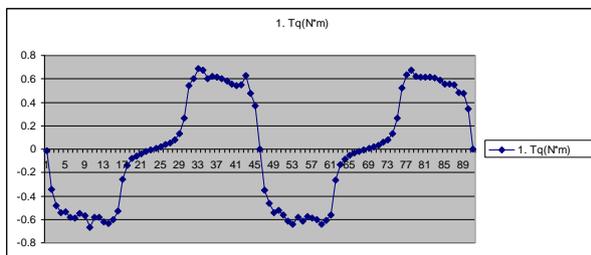


Fig 6a Over a rotor rotation of 180 degrees (#1 to # 90) there are two negative torque ranges (generator mode) and two positive torque ranges (motor mode) for the 4 salient pole rotor.

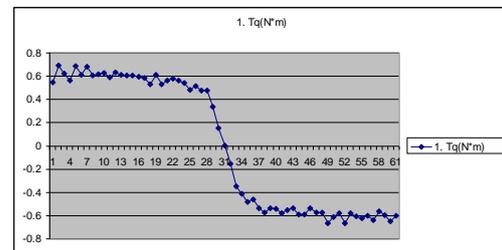


Fig.6b In the positive torque range (# 1 to # 31) the magnetic reluctance decreases (motor mode) while in the negativ torque range (#31 to #61) the reluctance increases (generator mode) .

Cylindrical Rotor Surface

Special attention had to be given to minimize the drag losses of the rotor with its four salient magnetic poles as shown in Fig. 7a and Fig 7b. In order to obtain a smooth cylindrical rotor surface, 4 sectorial elements have been integrated into the salient rotor. The five rotor elements can be fastened with the two supporting discs and 12 screws into a compact cylindrical rotor with a cylindrical surface. However in order keep the radial stress of the rotor within its design limits several layers of carbon filaments (0.3 mm radially) have been added to the cylindrical surface reducing the actual air gap to 0.7 mm, which is still within the radial operation range of the magnetic bearing.

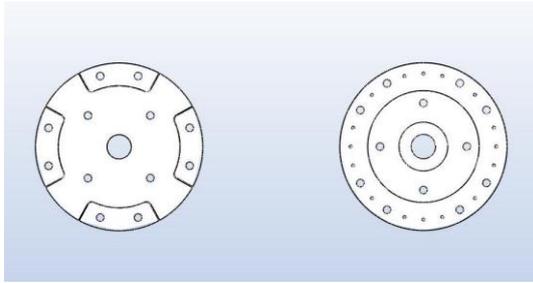


Fig. 7a The 2D geometry of the salient rotor with its 4 sectorial sections and the rotor mounting disk have been designed with MAGNETO 2D

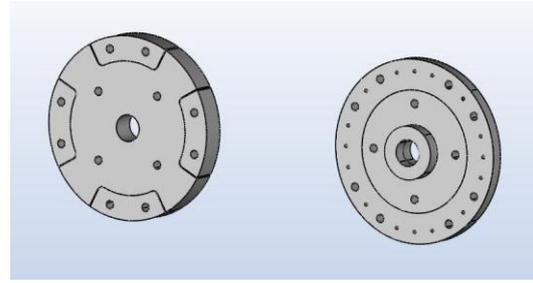


Fig 7b The 3D geometry of the salient rotor with its 4 sectorial sections and of the rotor mounting disks have been generated with AMPERES 3D

The rotor geometry has been with MAGNETO in 2D as shown in Fig 7a . The holes for the axis and for the rotor mounting screws are added. Next the 2D rotor elements are loaded with AMPEES 3D. The volumes of all rotor parts with the four sectorial sections, two mounting disks, the hub for the rotor axis and the mounting holes are then generated using the “**sweep mode**” of AMPERES as shown in Fig. 7b. Furthermore, the “**object mode**” allows a total – or partial exploded view of the reluctance motor. The model of the reluctance motor is shown in Fig 8. When all the components of the reluctance motor had been completed with AMPERES, all the data were transferred as drawings and in addition as “step-mode” files to the machine work shop in the Fig. 9 shows the completed Reluctance Motor.

All the supporting structures for the stator and the magnetic bearings have been designed using MAGNETO and AMPERES interactively. The assembly of system components has been greatly facilitated using the “**object–mode**” of AMPERES. This mode allows a number of useful options e.g. display of all the motor - and magnetic bearing components or exploded view of the motor components. In particular, individual system components can be singled out and modified, if necessary.

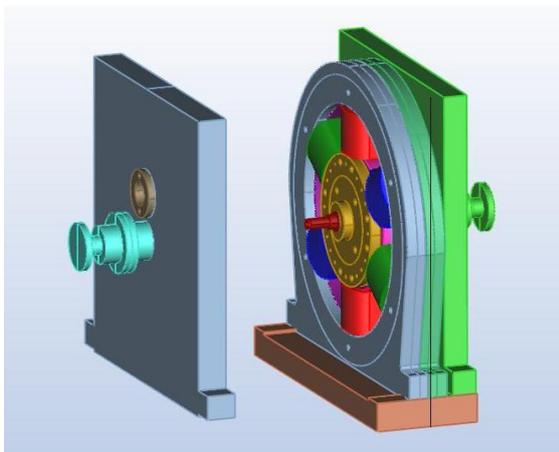


Fig 8 Reluctance Motor MAGNETO model with 2 passive magnetic bearings, 3 coil pairs, 2 stator supporting structures and the rotor.



Fig. 9 Reluctance Motor completed in the machine work shop of the ETH in Zurich.

An opto-electronic sensor above the magnetic bearing (Fig. 9) had to be added to measure the rpm during run down, since no electric stators signals are then available. The radial air gap of only 0.7 mm requires an excellent dynamic rotor balancing and a fine adjustment of the axial rotor position. First test runs are planned in the coming months.

Acknowledgement

The author is grateful for the continuous support of IES with updated versions of AMPERES and MAGNETO. Working with MAGNETO and AMPERES is rewarding. The commands of the programs are structured to generate the geometry of the different system components with increasing ease and speed, reflecting the professional engineering logics of MAGNETO and AMPERES. It is a real pleasure to discover all the potential design feature of the IES electro-magnetic programs.

Zurich, April 9, 2018

Dr. Hans K. Asper