G2E lab
Grenoble Génie Electrique
Grenoble Electrical Engineering

Energy efficiency oriented

Highlights 2014

Materials, Machines and Advanced Electromagnetic Devices

Grenoble INP

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Foreword

MADEA: Materials, Machines and Advanced Electromagnetic Devices

The MADEA team has multidisciplinary activities, aiming design of innovative systems through material knowledge and their potential applications in Electrical Engineering. Its research field covers from materials to applications and associated phenomena analysis, modelling and experimentation.

The researches of the MADEA team are structured in three axes:

- ***Study of functional materials for Electrical Engineering***
  MADEA is working on magnetic materials, superconductors and magnetocaloric materials. It involves improvement and optimization of these materials and apprehension of behaviour laws taking into account material physics.
- ***Research on innovative electromagnetic devices for energy conversion and processing***
  The approach is based on rational use of materials, especially magnetic materials, and study of new device structures exploiting the full potential of these materials.
- ***Design of innovative electromagnetic devices for information conversion and processing***
  MADEA team works on magnetic field sensors and physical quantity sensors (electric current, position, torque, etc.).

Contents

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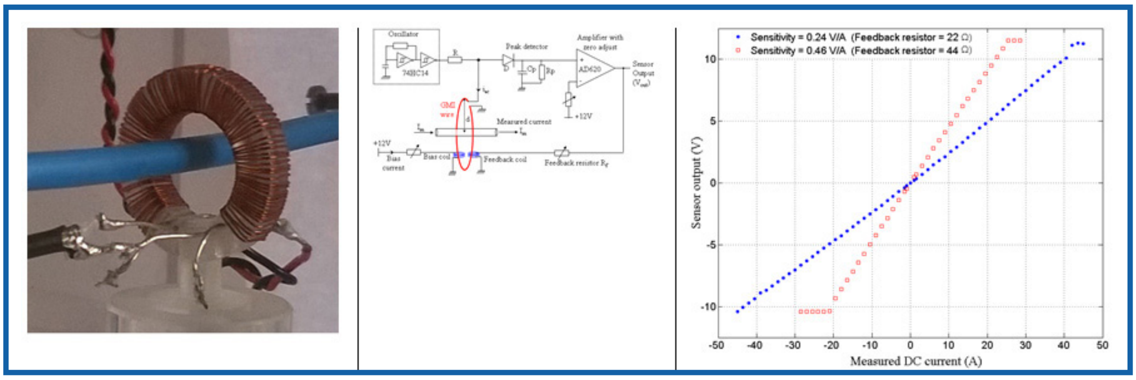
Giant Magneto-Impedance (GMI) sensors for contactless measurement of electric current

The Giant Magneto-Impedance (GMI) sensor is a new category of magnetic sensors that may offer several advantages over conventional and commercially available technologies of magnetic sensors (Hall effect, fluxgate, magneto-resistance sensors…). The key advantage is the expected high sensitivity and large bandwidth. This advantage, combined with low cost, low power consumption as well as small size of the sensitive element suggest that these devices have a promising future in the realization of magnetometers and sensors for measuring a variety of physical quantities (electrical current, force, position, torque…). This is why the MADEA team explores the potential of the GMI sensors for all these applications.

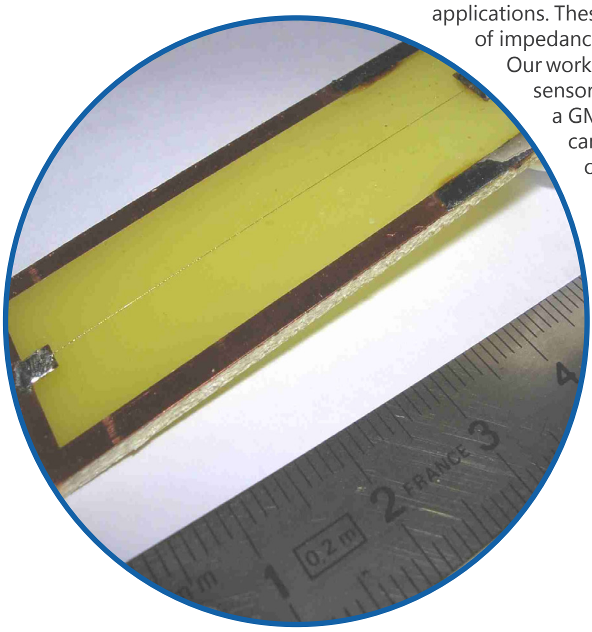


A GMI current sensor. The GMI wire has only one spire curled to a toroidal core. The measured current crosses the tore; the windings around the tore are used for the polarization and feedback.

The GMI is a large change of the high frequency impedance of some softs ferromagnetic materials (such amorphous thin wires or ribbons) when they are subjected to an external magnetic field.

Since its discovery in the mid-90s, the GMI effect has attracted international research for the development of a new category of magnetic sensors, adapted to a wide domain of applications. These new sensors are based on the measurement of the significant change of impedance of the amorphous sensitive element with the external magnetic field. Our work is currently focused on the development of a contactless electric current sensor for industrial applications. The principle of current measurement using a GMI sensor is relatively simple: a current produces a magnetic field which can be measured by a GMI magnetic sensor. Several prototypes of GMI current sensors has been developed and investigated. They show a promising potential for a large palette of applications.

Given the very good characteristics of sensitivity and bandwidth of these new sensors, they should be well suited in Power Electronics, Electromagnetic Compatibility (EMC) measurement, energy systems as well as for biomedical applications.



A typical GMI wire in the middle axis of the PCB

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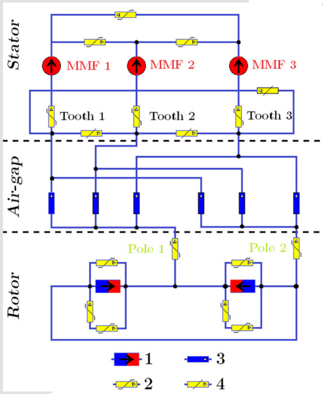
FURTHER READING

A high dynamic range GMI curent sensor
Journal of Sensor Technology, 2012, 2, 165 - 171
Doi:10.4236/jst.2012.24023

MADEA

Design Optimization of Permanent Magnet Synchronous Machines for Electric Vehicle

Due to the use of permanent magnets in the rotor, Permanent Magnet Synchronous Machines (PMSM) have the highest power density and efficiency among all types of motors. Therefore, PMSM have found wide attention in designing machines for a lot of high performance industrial applications as in transportation and Electric Vehicle (EV). In the same time, specifications of such applications present severe constraints and the challenge of designers is to find the best machines giving the best performances.

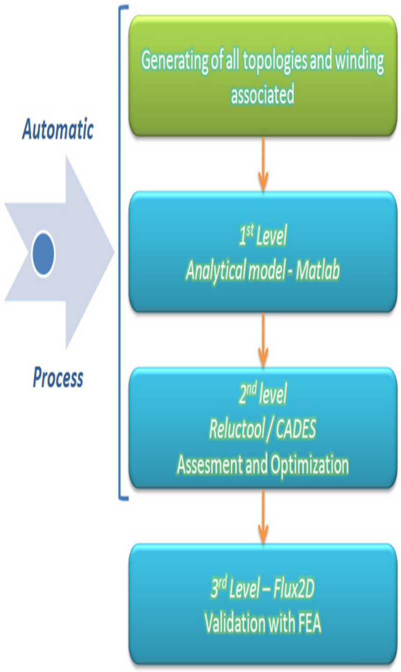


Reluctance Network model

In terms of design, modeling is a key point. For an optimized design approach, each modeling level has to be considered in different manner during the design process (Multi-level). Analytical models, giving very fast but coarse results, will be used in the first step of design and choice of machine's topology will be greatly facilitated [1].

Then, semi-analytical models as Reluctance Networks (RN) are particularly appropriated for first machine's optimization. Indeed, RN modeling has the advantage of owning a good compromise between computation speed and accuracy. It provides the possibility to takes into account the magnetic saturation, the slotting effects, the harmonics and the gradient of output parameters thanks to the software RelucTOOL. Therefore, sensitivity analysis and very fast (less than one minute) optimizations can be performed with deterministic methods as SQP provided by the software CADES [2].

Last stage concerns the validation of the results obtained with Finite Element Analysis (FEA) thanks to the software Flux2D. Finally, parameters of machine's geometry are also readjusted before the production of the first prototypes.



Multi-level approach for machine's design

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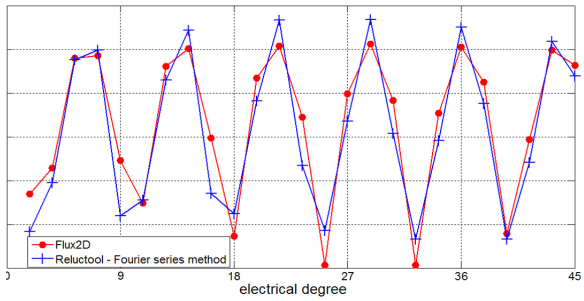


Validation results between ReluCTOOL & Flux2D

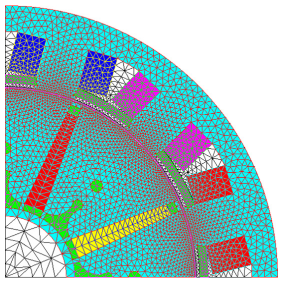
Further reading

[1] Analysis of Slots-Poles Combination of Fractional-Slots PMSM for Embedded Applications
H.Dogan, F. Wurtz, A. Foggia and L. Garbuio
IEEE Aegean Conference on Electr. Machines & Power Electronics, ACEMP'11, Istanbul, Turkey, Sept. 2011

[2] Multistatic Reluctance Network Modeling for the Design of PMSM
H. Dogan, L. Garbuio, H. Nguyen-Xuan, B. Delinchant, A. Foggia and F. Wurtz
IEEE Conference on Electromagnetic Field Computation, CEFC'12, Oita, Japan, Nov. 2012

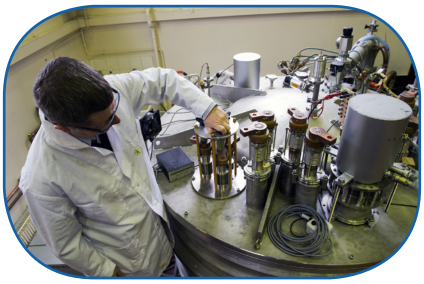
Industrial partners:

Valeo LEROY SOMER Vesta System

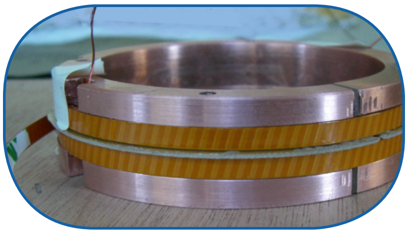


Finite Element Model

HTS magnets: opportunities for SMES

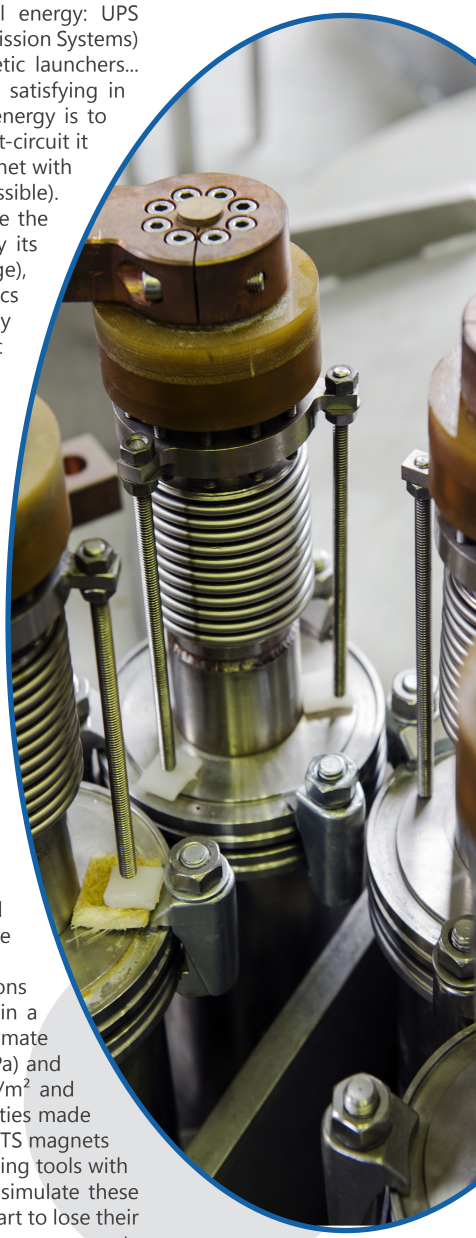


Upper flange of the SMES with the current leads and the cryocoolers



YBaCuO coil with outstanding performances: 1000 MA/m² under 18 T and hoop stress of 700 MPa

Many applications require pulse or transient electrical energy: UPS (Uninterruptible Power Supply), FACTS (Flexible AC Transmission Systems) to improve the operation of power grids, electromagnetic launchers... Existing solutions, capacitors in general, are not always satisfying in terms of weight and volume. An original way to store energy is to inject a current in a superconducting magnet and to short-circuit it on itself. The energy is recovered by discharging the magnet with excellent energy transfer efficiency (higher than 97 % possible). Superconductors not knowing Joule effect can then store the energy of magnetic origin on long durations. Known by its acronym SMES (Superconducting Magnetic Energy Storage), this storage system shows very favourable characteristics for pulse/transient applications. Several SMES very successfully operated on industrial sites, but no economic development followed due to the high cost of this technology and the lack of decisive advantages. These SMES used low critical temperature superconductors (LTS) that limit their performances. The today mass energy record is 13.5 kJ/kg. The development of high critical temperature superconductors (HTS) changes the data. The operation at higher temperatures reduces the cost of cryogenics (investment and operation). HTS magnets are much more stable than the LTS magnets. Being much less sensitive to unavoidable external disturbances this is an important advantage for industrial applications. But HTS can enhance above all and significantly the energy density of SMES and thus bringing a real advantage. These new elements challenge the conclusions about LTS SMES all the more since the demands of pulse/transient energy increase.
A major outcome of these researches is to have shown that energy densities of 20 kJ/kg, and even higher, are possible with a HTS SMES storing energies higher than a few MJ using 2nd generation YBCO coated conductors. The performances of SMES increase indeed with the energy value. Furthermore we experimentally proved that these materials show performances far beyond those necessary to achieve 20 kJ/kg.
Several HTS small coils tested under representative conditions in the unique facilities at LNCMI (DC fields up to 18 T in a 160 mm bore in our case) showed significantly higher ultimate performances (1000 MA/m² and a hoop stress of 700 MPa) and no degradation in the conditions for 20 kJ/kg (400 MA/m² and 400 MPa for energy of 5 MJ with a solenoid). These activities made possible to develop the technology to realize successful HTS magnets with very high mass energy performances. Several modelling tools with some experimental validations have been developed to simulate these magnets especially in the very critical phase where they start to lose their superconducting state. These simulations, as dedicated measurements confirm that HTS magnets are much more stable than conventional LTS ones. The energy required to really quench (no recovery) the magnet is very large, several orders of magnitudes compared to LTS magnets.



Disconnectable current leads of the SMES

These works have been carried out with Institut Néel, LNCMI, CEA-SACM and Nexans in the context in particular of the ANR project "Super SMES".

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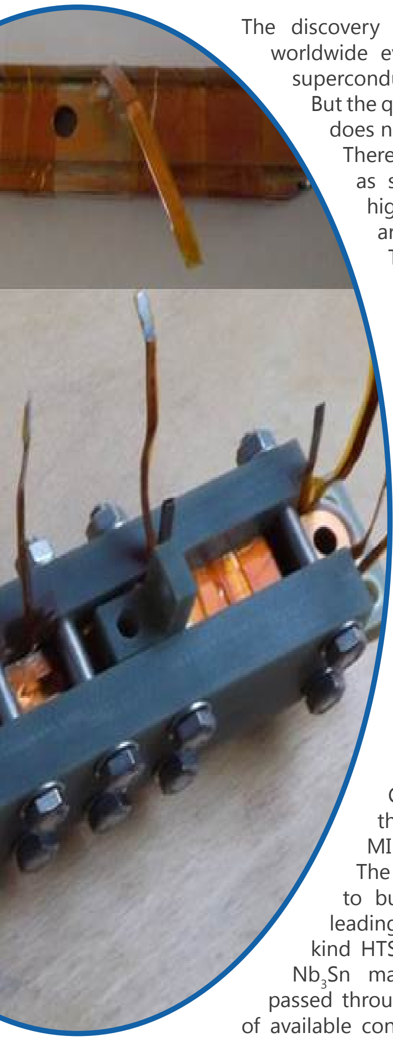
FURTHER READING

HTS magnets: opportunities and issues for SMES
B. Vincent, P. Tixador, T. Lecrevisse, J.-M. Rey, X. Chaud, Y. Miyoshi
IEEE Transactions on Applied Superconductivity vol 23 5700805.

HTS magnets: opportunities for very high field magnets



The discovery of the Higgs boson in 2012 was a worldwide event, possible thanks to the LHC, the superconducting collider at CERN.

But the quest for the fundamental laws of Universe does not stop.

There are numerous unsolved questions, such as super symmetry, for which colliders of higher energy, thus higher magnetic fields, are required.

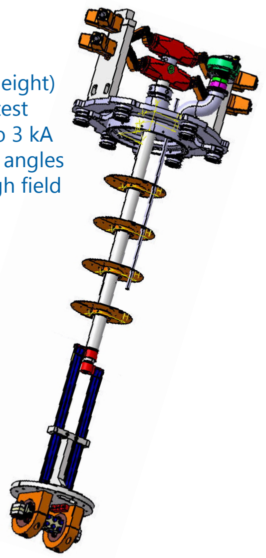
The constraints on superconducting (SC) accelerator magnet design are severe: very high current densities (higher than 300 to 400 MA/m^2) due to space constraints, outstanding field quality for a suitable beam optics... The electromagnetic stresses are huge on SC conductors since they experience both high current densities and magnetic flux densities. The field limit for low critical temperature superconducting magnets is about 15-16 T. But the outstanding current transport properties of high temperature superconductors at low temperatures open the road to higher magnetic fields. YBCO coated conductors show an overall current density higher than 1000 MA/m^2 at 4 K under a longitudinal magnetic flux density of 35 T. Within the EC EuCARD project, coordinated by CERN, the G2ELab with Institut Néel led the "high field" task, in cooperation, LNCMI and CEA among others.

The possibility of using YBCO conductor to build an insert dipole was investigated, leading to the development of a 1st of a kind HTS dipole that will be tested in an outer Nb_3Sn magnet under development. The activities passed through several steps, from characterizations of available conductors to modelling work focused on stability and quench. Several instrumented HTS solenoid insert coils have been developed especially in Grenoble, which gave the Grenoble team a very valuable understanding and know-how, allowing the design of the dipole insert coil. A preliminary instrumented pancake coil made by CEA was successfully tested under 10 T at LNCMI, using a dedicated high current probe. The quench energy measurements have confirmed the high stability of such HTS magnets. These preliminary and pioneered works are continuing under the EC project EuCARD[2].

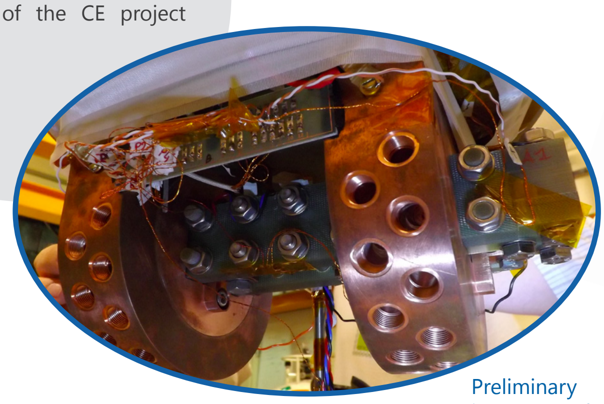
These works also concern the development of superconducting very high field magnets. Grenoble has always been at the forefront in the domain of high fields with the LNCMI. The Grenoble hybrid magnet (superconducting outsert and resistive insert) kept the highest worldwide DC field amplitude for many years. Resistive magnets show outstanding performances with the Grenoble developments among others but also show huge electrical consumption: 20 MW are required to produce 30 T in addition to a few hundred kW for the water cooling system. The significant increase in the cost of electrical energy represents a big issue in the future in addition to the very little sustainability of these magnets. It is very difficult or impossible to make a productive use of the considerable Joule energy dissipated in the magnet. High critical temperature superconductors, YBCO coated conductors in particular, with their outstanding current capacity under very high fields open the way for very high field sustainable magnets. The superconducting magnet energy overall consumption (cooling and power supply) is lower to that of the resistive magnet system by a factor of 100 to 1000. Works are carried out by G2Elab, Institut Néel and LNCMI to develop the required technologies to develop very high field superconducting magnets and to progress in the understanding of these magnets behaviour, in particular when they lose their superconducting state. Understanding such events is a key issue they induce severe temperature increase and mechanical constraints that can damage the magnets. In order to control these events and mitigate their effect, the behaviours of all types of YBCO conductors should be understood, in the magnet extreme operating conditions. We succeeded building small coils with outstanding ultimate performances (1000 MA/m^2 under 18 T with a hoop stress of 700 MPa). A preliminary model of the dissipative state between the current sharing and critical temperatures has also been developed with some experimental validations. The way remains long to develop a user compatible 30/40 T fully superconducting magnet but the technical and scientific developments successfully started.

Preliminary dipole YBCO insert pancake made by CEA with Grenoble support for high energy physics.

These works have been carried out with Institut Néel, LNCMI, CEA-Saclay and CERN in the context in particular of the CE project "EuCARD".



Probe (1.8 m height) developed to test pancakes up to 3 kA under variable angles in a LNCMI high field magnet.



Preliminary dipole YBCO insert pancake in the probe.

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Nanocrystalline Magnetic Materials for EMC filters applications

MADEA

The More Electrical Aircraft Systems require the development of electrical converters with higher power density when operating at high temperature. In the scope of ISS Power&Control Project involving) Hispano Suiza society, AMPERE electrical engineering lab at Lyon and G2Elab (are joined), new integrated magnetic components for EMC filter applications overcoming EMC DO160 requirements and temperature issues are studied.

Nanocrystalline materials cores (FeSiBCuNb aka Finemet) are widely used in Common Mode Chokes (CMC) required in EMC filters. For these applications, a large attenuation of CM noise up to several MHz is often achieved by the use of tape wound cores of nanocrystalline ribbons with a large relative permeability (over 30,000). The question that occured was how to achieve a complete EMC magnetic filter, effective for both Common Mode (CM) and Differential Mode (DM) disturbances exploring nanocrystalline materials and their high temperature stability.

According to that, three different inductors topologies were selected thanks to a literature and patents review followed by an optimized design approach. Improvements of the modelling tool led to consider a CMC design in which the DMC was obtained thanks to a magnetic bypass over the tape wound core as shown in Fig 3. The aim was therefore to model the frequency behaviour of the CMC taking into account the manufacturing constraints in an optimized design approach. Thanks to the specific know-how of TCT Company in impregnation, cutting and coating nanocrystalline cores the device has then been successfully implemented.
On the other hand, the design of an integrated CMC into the Print Circuit Board was studied. The nanocrystalline alloys are closely related to the amorphous materials, due to their manufacturing process needing very rapid solidification of 20 µm thin ribbons. The good mechanical cutting ability of the precursor amorphous state allows meander topology to be designed as depicted in Fig.1. When the ribbons are cut, they need to be nanocrystallised by an annealing at medium temperature (1h @ 500 - 550°C). To achieve a flat hysteresis shape, i.e a low and constant permeability over a wide frequency range, transverse anisotropy should be induced within the material. This is performed thanks to a field annealing in which the magnetic field is applied in the transverse direction of the ribbon, i.e perpendicular to the practical field direction in the final use. As a consequence, a specific device was designed to apply this magnetic field inside the annealing furnace as shown in Fig.2. Results have led to consider a design in which the DMC is obtained by a magnetic bypass between two superposed CMC in meander topology. Further improvements are now conducted to fully design a CMC integrated into a double layer PCB!

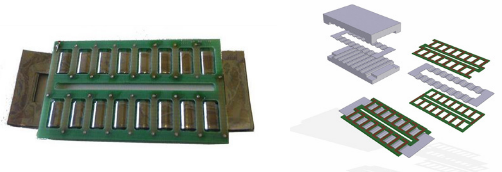

Figure 1 : View of the meander topology : stamping molds, meander magnetic core and up and bottom Print Circuit Board (Aperam Imphy Alloys / G2Elab) and PCB integrated prototype.

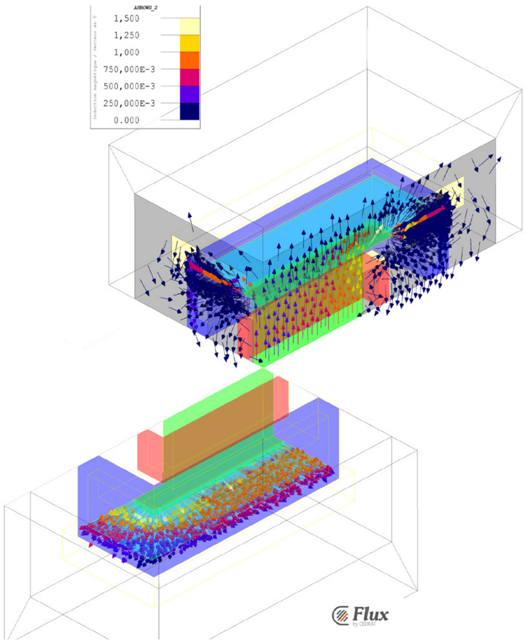

figure 2 : Flux 3D (Cedrat) simulation results (Magnetic Flux Density (Tesla) related to the specific device designed to apply magnetic field inside the furnace.

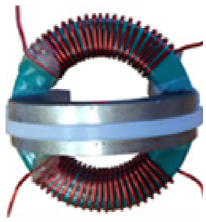

figure 3 : Prototype of integrated Common-Mode and Differential-Mode Choke with magnetic bypass over a tape wound core

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3D Analytical calculation of permanent magnet systems: magnetic field components of force torque, energy and interaction

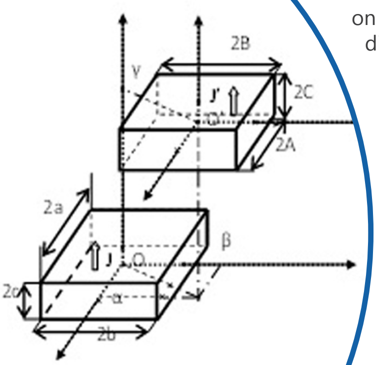

Figure 1 : Permanent magnet configuration

Permanent magnets own a rigid magnetization. They can be represented by magnetic charges on their poles: charges «+» on the North Pole and charges «-» on the South Pole. These charge distributions allow calculating of the magnetic field created by magnets, by fully analytical expressions. The basic element is the magnetized parallelepiped, with the direction of magnetization parallel to an edge (Figure 1).

The analytical expressions are relatively complicated; Figure 2 show the simpler case: the 3D interaction energy. If the magnetization is not parallel to an edge, it can be made by projecting the magnetization on the edge axes and by summing the contributions.

Recently, all the three component of the interaction force and all the three components of the torque have been calculated between two parallelepiped magnets with 3D fully analytical expressions, whatever the magnetization directions are.

For more complex magnet shape, the calculation can be made by decomposing the volume in elementary parallelepipeds. As everything is linear, the total field is the sum of the contribution of each parallelepiped element.

The analytical expressions are very difficult to obtain because it is a very high level mathematical calculation, but then their use is very easy: direct calculation of magneto-mechanical systems, calculation of electromagnetic systems, optimization of these systems, integration in numerical methods, etc.

Today we are always working on the improvement of analytical methods:
- Calculation of the magnetic field created by a 3D triangular surface. By adding the contributions of each of the faces we know now calculate the magnetic field created by a polyhedron magnet (Figure 3).
- Mutual inductance calculation between two coils
- Interaction force between a magnet and a thick coil to design VCM actuators.

$$E=\frac{J\cdot J'}{4\pi\mu_0}\sum_{i=0}^{1}\sum_{j=0}^{1}\sum_{k=0}^{1}\sum_{l=0}^{1}\sum_{p=0}^{1}\sum_{q=0}^{1}(-1)^{i+j+k+l+p+q}.\psi(U_{ij},V_{kl},W_{pq},r)$$

$$\psi(U,V,W,r)=\frac{U(V^2-W^2)}{2}\ln(r-U)+\frac{V(U^2-W^2)}{2}\ln(r-V)+UVW\cdot tg^{-1}\left(\frac{UV}{rW}\right)+\frac{r}{6}\left(U^2+V^2-2W^2\right)$$

Figure 2 : Example of analytical expression, the calculation of the interaction energy between two magnets (one of the simpler analytical expression)

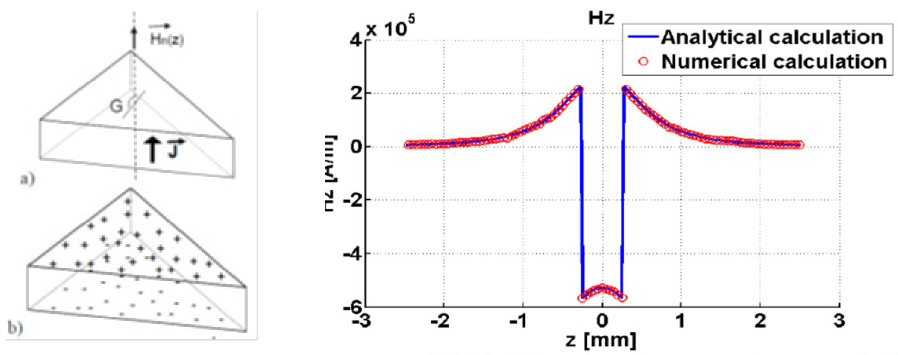

Figure 3 : Field created by a prismatic triangle magnet

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FURTHER READING

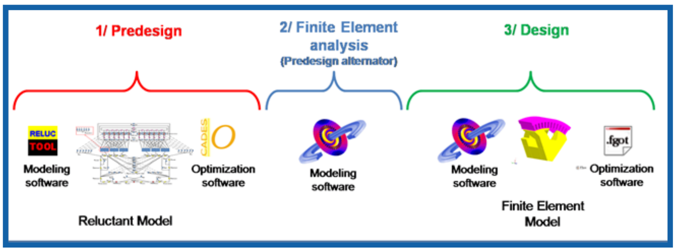
Three-Dimensional Analytical Calculation of Permanent Magnet Interactions by "Magnetic Node" Representation
J.-P. Yonnet and H. Allag
IEEE Transaction on Magnetics, Volume 47, n° 8, Aug 2011, p. 2050 – 2055

Analytical Calculation of Magnet Systems: Magnetic Field Created by Charged Triangles and Polyhedra
C. Rubeck , J-P. Yonnet , H. Allag , B. Delinchant, and O. Chadebec
IEEE Trans on Magn, Vol. 49, No. 1, Part 1, January 2013, p. 144 – 147

Optimal Sizing of Claw-Pole Alternator Without Magnet - Contribution of FeCo alloys

MADEA

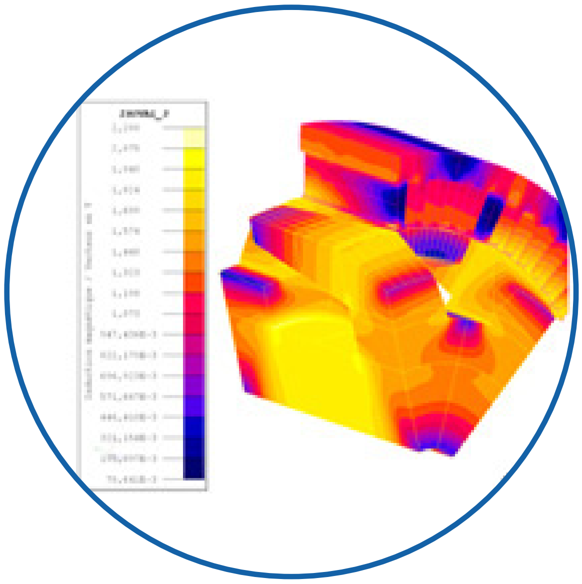
Claw-pole alternators are often used in automotive industry. Permanent magnets like NdFEB are currently integrated to increased the power density of claw-pole machine. However their higher price and their availabilities brings into question their usage. This tight context implies finding new technical solutions to keep the same power density without NdFeB magnets. The solution adopted consists to evaluate the potential of gain with different soft magnetic materials and more especially FeCo family (AFK18, AFK1 et AFK502).



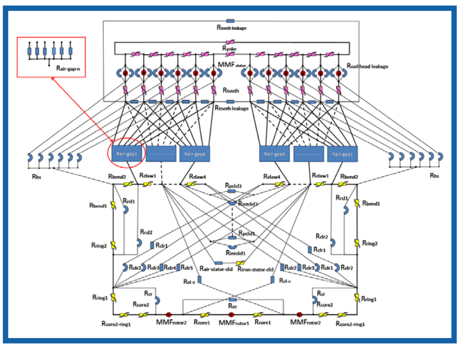
Multi-level Conception Strategy : Predesign and Design

FeCo material offers high saturation polarization and high permeability but their higher price imposed us to use it with moderation and smartness. In this study, we have evaluated their usage and shown that FeCo core alternator can reach the same performances of initial structure [1]. Unlike conventional electrical machines, claw-pole machine is characterized by its unsymmetrical shape of poles along the rotor that induces a 3D flux path. In this context, a model based on a magnetic equivalent circuit (MEC) is established to perform optimizations under constraints including short time simulation and high parameters number. In our case, the model accuracy is about 30 % but it was adequate to achieve predesign of the alternator. Results demonstrate the CoFe ability to increase the output current at low speed. Alternator predesigns achieved with the MEC model showed that using solid CoFe rotor should increase the current flow of 30% to 70 % at low speed.

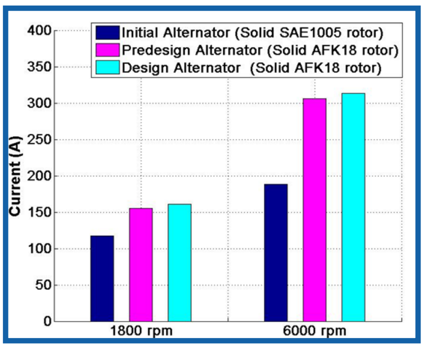
In optimization aspect, this work is based on an adapted design methodology including two modeling level (magnetic equivalent circuit model and finite element model) in order to obtain a good compromise between time computation/accuracy [2].



Optimization of a Claw pole generator : a 3D problem



Reluctance Network Model for wide and complex optimization problem



Improvement of output power with optimal FeCo core (FEM results)

Industrial partners: Valeo aperam

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Perez S., Garbuio L., Foggia A., Kedous-Lebouc A. and Mipo J-C
SMM 2013, Budapest, Hongrie, 2013

[2] Modeling of claw-pole alternator with a global reluctance model based on improved equivalent magnetic circuits with objective of robustness
Perez S., Garbuio L., Foggia A., Kedous-Lebouc A. and Mipo J-C
IEEE Conference on Electromagnetic Field Computation, CEFC'12, Oita, Japan, Nov. 2012

MADEA

Superconducting Fault Current Limiter for meshed HVDC grids

Meshed High Voltage Direct Current (HVDC) grids are foreseen as an economical, suitable and very efficient solution for the transfers of large amount renewable energies through submarine cables or/and on long distances: offshore wind generation farms and desert solar energies. Nevertheless this attractive technology faces the technical hurdle of managing fault currents. In DC it is no more possible to take advantage of the AC current zero-crossing in order to clear a fault. Whereas it is possible to fix this issue in today point-to-point HVDC transmissions by interrupting the current on the AC sides, it becomes a difficult task and significant lock in meshed HVDC grids. The control of the voltage converters does not allow handling the fault currents due to the diodes connected anti-parallel across the controlled switches. The estimations of the fault currents in meshed HVDC grids overstep the switching and clearing capacity of the state of the art DC circuit breaker and destroy the diodes of the converter.

This very annoying problem could be solved by using Superconducting Fault Current limiters (SCFCL) whose first medium voltage devices are installed in grids. G2Elab and Institut Néel have long experience and know-how on SCFCL design and grid integration.

Figure 1 : Eccoflow 24 kV – 1 kA SCFCL to which G2Elab participated

Recently they participated to the Eccoflow EU project (figure 1), one of the most ambitious project worldwide on Superconducting technologies applications. The SCFCL is based on the intrinsic highly non linear voltage versus current characteristic of a superconducting element. Under a given DC current the voltage across it is nearly undetectable making it invisible for the grid. On the other hand, as soon as a current oversteps this given current a high voltage develops itself automatically and naturally, which limits the fault current amplitude without any external action. A circuit breaker is required to isolate the superconductor and avoid its damaging. The superconducting length can be favourably used to show an inductance to limit the fault current rise. In DC systems, this superconducting inductance does not introduce any voltage drop in normal and steady state operation.

Investigations have been carried out at G2Elab in the context of the Twenties EU project. Through a suitable design of SFCL it is possible to limit the fault currents in the diodes to two times their rated current thus avoiding any damage to them. The simulations take into account the propagation, the cable model versus the frequency and a very accurate model of the components (IGBT) of the converter with its control. Figure 2 shows the meshed HVDC grids with the SFCL. In figure 3 we can see that the SFCL really limits the fault current which can be interrupted within 4 ms after the short-circuit considering a 15 kA breaker. The SFCL has also a very positive effect on the current rise in the diodes by slowing it down: the diode current reaches 2 p.u. after 2.16 ms without SFCL but 4.95 ms with an optimized SFCL (Figure 3). With this delay a DC breaker with a clearing capability of 15 kA meets the requirements for the diodes since it opens within 4 ms (Figure 3). In this HVDC example the SFCL represents the only possible solution to cope with fault currents with the today state of the art of the DC breakers.

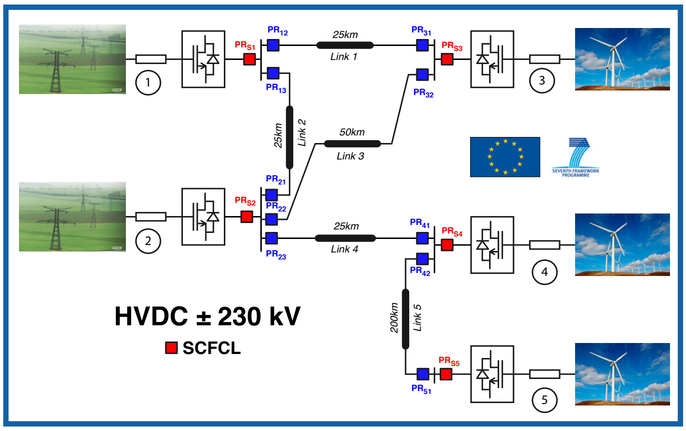

Figure 2 : Studied HVDC grid for wind farm connexions (Twenties EC project)

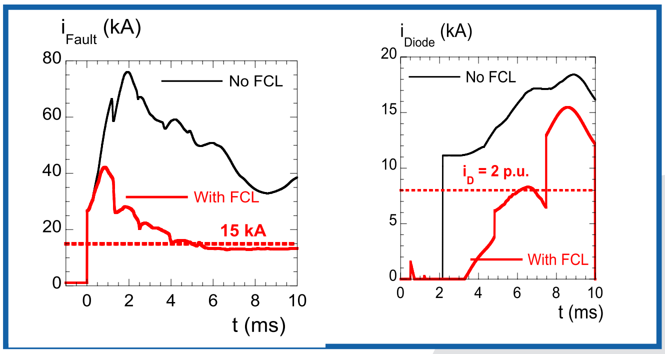

Figure 3 : Line and diode fault currents versus time with and without SFCL for a fault.

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Further reading

Innovative distribution networks planning integrating superconducting fault current limiters
C. Gandioli, M.-C. Alvarez Hérault, P. Tixador, N. Hadjsaid, D. M. Rojas Medina
IEEE Transactions on Applied Superconductivity vol 23

Design and production of Eccoflow Resistive Fault Current Limiter
A. Hobl, W. Goldacker, B. Dutoit, L. Martini, A. Petermann, P. Tixador
IEEE Transactions on Applied Superconductivity vol 23

Protection system for meshed HVDC network using superconducting fault current limiters
J. Descloux, C. Gandioli, B. Raison, N. Hadjsaid, P. Tixador
IEEE grenoble powerTech 2013

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