# MAGMOLIB

## Modelica® library of detailed magnetic effects in rotating machinery

### State of the art – Background

Electrical motors use is spreading in new fields and they are replacing other actuators because of their performance, power, torque density and reliability. However, in order to integrate these new components into a system engineering design process, the models of electrical machines must be pre-evaluated and designed for specific uses.

In the past years several issues have changed the panorama regarding electrical machines typology. Regarding motors using magnets: appearance and proliferation of Surface Mounted Permanent Magnet Synchronous Motors, internal Permanent Magnet Motor Family, emerge and intensive development due to magnet's price raises (substitution of rare earth magnets by ferrite magnets) and increased power density requirements (keeping rare earth magnets in geometrical configurations meant to achieve high airgap flux). Regarding externally excited Synchronous Machines [1]-[2], its ability to work in four quadrants and to work under very high temperatures (where magnet motors get demagnetized) made them resurge in micro generation, both in land and aviation fields. These new appearances did not pull back Induction Machines because of, as in Switched Reluctance Motors, its low construction and operation costs are still an advantage [3].

The electrical machine design process has also changed due to the reduction of FEA costs and high demand of motors for specific purposes. Both phenomena made it possible to start developing specifically optimized motors out of catalogue increasing the added value of small companies.

Not only design process has changed, but its implementation and tests before construction. The introduction of systems engineering design in Product Lifecycle Management requires parametrized models of all its components. Modelica not only fits in that spot but also allows multi-parametric, multi-physics implementation of such models for both: steady state and transient simulations [4].

The work presented is the first Modelica implementation of pre-design tool able to provide the data required to create such models in order to integrate the specific machine size and properties into system models and is intended to work under Clean Sky [5] European Initiative.

Therefore the library along with help files, and manuals are free to use. This novel tool in the Modelica society also leaves a possibility to be used with other already developed open and commercial libraries i.e. outputs of pre-design sizing algorithms can be passed as inputs to electrical machines advanced and complex models such as the Actuation 2015 project [6].

In the cases where, in a system model, an electrical machine is required, the user is force to select from pre-designed models (with restricted electro-mechanical sizes) or manually calculate the machine parameters for the purpose he is modelling for. With this new tool, added to the Modelica chain, and given designer's specifications, insert the specific machine he needs to work with.


[1] M. R. Kuhn, A. Griffo, W. Jiabin, and J. Bals, "A components library for simulation and analysis of aircraft electrical power systems using Modelica," in Power Electronics and Applications, 2009. EPE '09. 13th European Conference on, 2009, pp. 1-10.

[2] M. R. Kuhn, "Advanced generator design using pareto-optimization," in Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on, 2011, pp. 1061-1067.

[3] J. Yang, "A novel modelica based design platform for switched reluctance drive systems," in Electrical Machines and Systems (ICEMS), 2014 17th International Conference on, 2014, pp. 3302-3308.

[4] C. Kral, A. Haumer, and R. Wöhrnschimmel, "Extension of the FundamentalWave Library towards Multi Phase Electric Machine Models," ed, 2014.

[5] The Clean Sky Joint Technology Initiative. Available: http://www.cleansky.eu/

[6] (2015). Actuaction2015. Available: http://www.actuation2015.eu/


### Objectives

First, a predesign tool for electric machines has been implemented with a GUI for guided model design from geometric motor considerations and torque and power targets.

In this way the basic pre-design tool includes the following machines: Asynchronous Induction Machine [IM], Surface Magnet Permanent Magnet Synchronous Motors [SMPMSM], Internal Permanent Magnet Synchronous Motors (in three variants: Spoke, V-shape and Planar) [IPM], Synchronous Reluctance Machine [SRM], and Synchronous Machine [Sync]. This tool uses a table of inputs in order to generate

Second a multi-physics (electrical, magnetic, thermal) model of a SMPMSM based on reluctance networks and thermal lumped parameters. By means of thermo-reluctance network a detailed thermo-electro-magnetic dynamics taking into account discrete distribution of windings, stator and rotor slotting, magnetic steel saturation, skewing, demagnetization and non-sinusoidal currents will be modelled. Therefore spatial and time harmonics in the magnetic flux distribution and torque ripples have been reflected in the great level of precision, providing a singular, realistic, computationally efficient equivalent circuit model which virtually facilitates the enhancement of classic control and diagnosis strategies and paves the way for the new ones.

In this sense the objectives can be synthetized as follows:

- To characterize and classify operational and constructive machine parameters regarding their effects on flux distribution and thermal behavior.

- To identify and formalize models and expressions to be developed and included in new libraries, identifying the most appropriate program structures to include the programs scripts and the interface to the human operator.

- To fill the machine-type oriented FEM-DB by FEM simulations, and to manage the obtained data by means of Multi-Dimensional Data Set Processing

- To obtain the performance of the constructed motor, that is, torque-speed capabilities, torque-current characteristics, mechanical, electrical and magnetic losses, thermal behaviour and efficiency curve.

- To validate the developed Modelica library by comparison of the demonstrative motor experimental performance results and the performance results obtained by means of the developed Modelica library. Also, data from the real motor and from FEM simulations will be taken into account.

- To generate a complete Report including qualitative relationships used, databases, Modelica libraries and interfaces, GUIs and User Manuals.

- To define and deploy a proper Dissemination Plan, that will be aimed to achieve a maximum visibility of project and ensure that activities and relevant results reach the target stakeholders and audiences, through appropriate dissemination channels.

## Description of work

As a way to improve existing Modelica Machine models on regards to spatial harmonics, it is foreseen to consider non-sinusoidal stator winding and rotor magnet distribution and rotor saliency, including iron and teeth shapes. Single layer windings schemes, dimensional details (air-gap, rotor and back iron thickness, teeth and magnets,…) and constructive parameters.

By using functionalities of this tool, torque and flux profiles are obtained and studied, and electrical, mechanical and thermal machine properties are estimated. Parameters considered for this basic design and generated data are then used to tune the Modelica Library Model by filling with them the corresponding tabs. Iterative process with manual adjustment is performed, up to behaviour of the motor responds to expectations, and final dimensional and constructive data of the motor developed is obtained. These data are then used to run FEM simulations of the motor, and data are acquired and operated to find characteristics of the motor, i.e., torque profiles, flux distributions, Back – EMF, and so on.

## Results

The main results of project can be summarized as follows:

R1. Working code in Modelica for the basic design of rotating machines, specifically:
- SRM Machine:
- Asynchronous Machine
- Synchronous Machine
- IPM Machines
- SMPMSM Machine

R2. Full Reluctance & Thermal Network Model for a SMPMSM design and evaluation

During the elaboration of the code of the V-shape (ready to deliver) several issues were faced and solved, such as:

1. Inductance calculation

2. Rotor geometrical characterization

3. Mechanical properties identification (Moment of Inertia, mass of each region)

4. Flux leakages (quantitative approach)

5. Flux concentration (quantitative approach)

7. Demagnetization (qualitative approach)

This led to a new more flexible method of pre-design for rotating machines because of the rotor complexity. The new methodology takes into account the aforesaid issues. Given the method is extensible to V-shape, a new whole package for rotating machines was supplied.

A detailed study of MMF shape generation based on geometry has been performed, as well as an intensive work on determination of the proper point location to generate an accurate reluctance network because of the necessity of speed in execution of the aforesaid implementation. The airgap flux path model for proper and reluctance network has been also studied and developed.

Winding detailed winding is very important for a correct MMF definition. We have developed A function able to predict MMF shape based on currents per slot in single layer winding has been developed and included into the software model. Also, the tooth reluctance network has been developed and included into the Modelica environment.

Finally, the reluctance and thermal networks developed in Modelica in the project have been validated against simulation and experimental data.

### a) Timeline & main milestones

The Project started October 2013 and ended November 2015.

The main milestones and its achievements are:

- Modelica Programs for each machine type (i.e., asynchronous and synchronous machines, IM, PMSM, and BLDC), and Library levels structure.
- Modelica programs for fine-tuning of lumped reluctances and thermal networks using data contained in FEM-DB.
- Interactive Development Tool Modelica-Based for Electric Machines.
- Publication of Project Web Page: http://magmolib.upc.edu/en

### b) Environmental benefits

The project will have a high contribution to the European competitiveness with a potential for a reduction of energy consumption and environmental pollution.

The project appears to be in line with the environmental targets of the SRA of ACARE. On the other hand, the Clean SKY SGO initiative aims to meet the increasing social demand to reduce fuel consumption, emissions and noise through the adoption of a new approach when designing systems.

The project is in line with this general objective as it aims to develop a design tool optimized for electric motors. More specifically, SGO environmental objective consists in the reduction of $CO_2$ emissions (between a 5 and 9% of reduction) through an improved energy management.

The project aims to develop a design tool optimized for electric motors, which allows a more rapid design, with better performance than the approximate packages used hitherto. Machine design optimized from the point of view of behaviour and losses allows better use of energy. This energy performance improvement occurs both by improving motor efficiency during normal operation for the improved design, as by the increased life expectancy for better treatment of loss and oscillations caused by electromechanical pairs not covered at the stage design when using existing Modelica tools.

The Modelica tool has as target the improvement of the overall engine efficiency of around 2.5% in 20kW engine, which, in turns, implies a saving of 12 kWh per day of operation, if we compare this with the classic design not FEM used so far, despite the major advantage of the new tool is the is the optimal tradeoff between design time and accuracy of results.

### c) Maturity of works performed

The currently available Modelica libraries for electrical machines has been greatly improved, in two ways:

1- No pre-design tools are available in commercial software with such a wide range of machines able to perform a simple pre-design in minutes including efficiency maps. Modelica is yet to implement such a rich featured SMPMSM model and compatible with the pre-design tool.

2- The basic pre-design and the reluctance network model are fully modeled and perform their calculations under Modelica environment, using Dymola. This is what is called the sizing core of the product, i.e. the set of elements and functions that perform the sizing calculations: geometrical, electrical, magnetic and mechanical. Sizing core includes no GUI or data preparation. This method allows to export and setup the sizing core in any environment letting the designer incorporate it to a bigger project or use it as a tool in an optimization process getting rid of all GUI and data treatment code, making the sizing core smaller, faster and more robust. Modelica data is saved in a matrix structure that can be read inside Modelica or exported to a text file to evaluate with any third-party software.

In order to properly use the sizing core, a GUI interface has been developed. This graphic interface includes four sub-modules one for each of any GUI of these characteristics must perform. The first layer is the GUI itself, i.e. the code necessary to make a visible dialog to introduce the input data.

This first layer shares functions among all machines like load and save but has a particular input layout for each machine. The second layer is the data translation from the input data to the input file required for the sizing core to run, as long as a script to call Dymola and perform the sizing operation. The third layer performs the inverse process than the second layer. Once Dymola has ended the sizing process returns control to the GUI which takes the output data and converts it in order to let GUI show the results. The final layer is a set of tools in order to let the designer evaluate the generated data: scaled cross section (full or symmetrical sector), scaled axial section, design iteration graphic (depends on machine), and Torque vs. Speed. Efficiency chart (not for all machines), as long as the output data: geometrical, electrical and mechanical. This disposition is shown in Figure 1. For the current work the GUI was designed and implemented in Matlab and runs by means of a standalone executable file for windows platform that only requires Matlab Runtime Compiler (MRC), which is free.

MAGMOLIB ended 2015 providing such a tools verified by FEM the first part and with an actual prototype, tested in the detailed test bench, the second and until now is following the progression as scheduled.

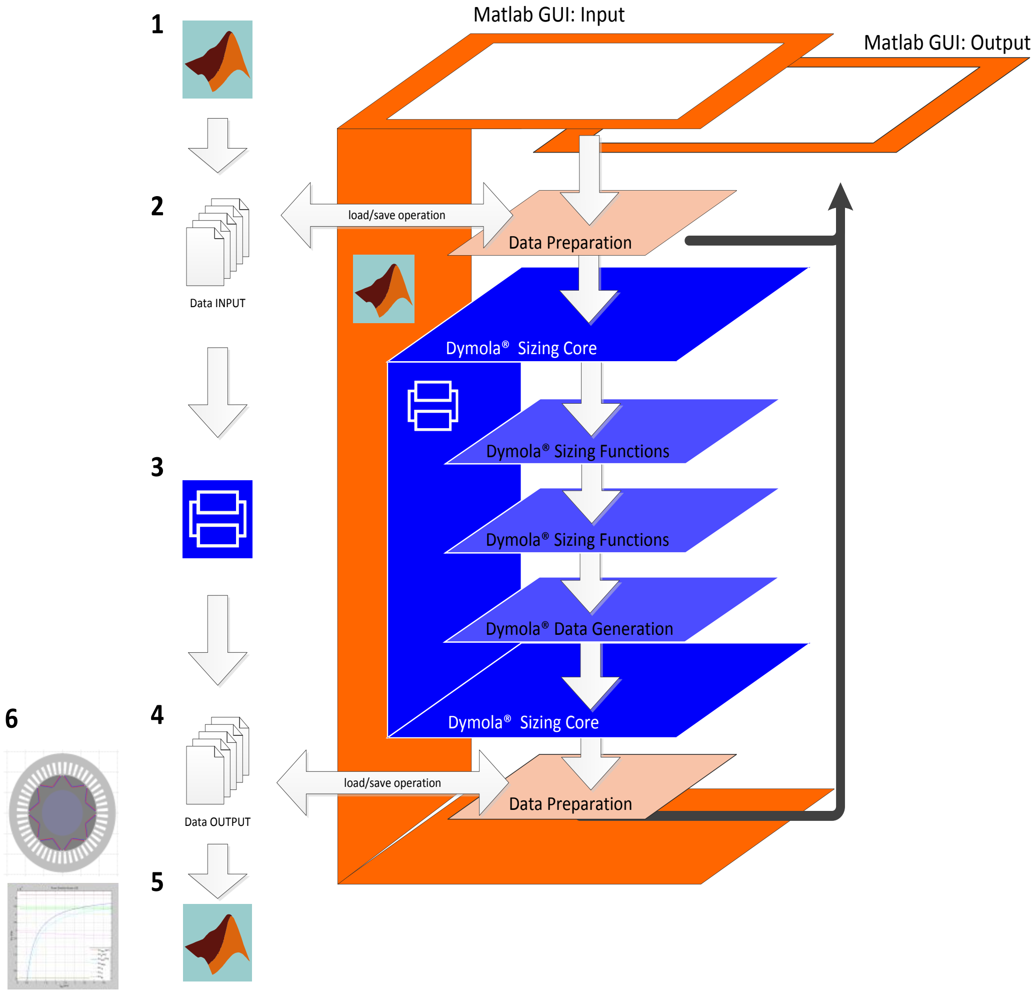


Figure 1. Schematic layer chart of the pre-design mechanism with the two tools used, Modelica for the Sizing Core and Standalone Matlab GUI for the interface.

***Project Summary***

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| Acronym: | MAGMOLIB |
| Name of proposal: | Modelica library of detailed magnetic effects in rotating machinery |
| Technical domain: | Electric motors |
| Involved ITD: | Systems for Green Operations |
| Grant Agreement: | 620087 |
| Instrument: | Clean Sky JU |
| Total Cost: | 246,056.80 € |
| Clean Sky contribution: | 180,496.06 € |
| Call: | SP1-JTI-CS-2013-01 |
| Starting date: | 01/10/2013 |
| Ending date: | 31/10/2015 |
| Duration: | 25 months |

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