Electromagnetic energy conversion

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Summary

The research at the Institute of Electrical Machines (IEM) in Aachen (Germany) aims at developing innovative application fields for all kinds of electrical machines. The IEM has got a large expertise in design, modelling and optimization of the stationary and dynamical operation of electrical apparatus, ranging from a few μW to several GW. Finite-element software is developed at the IEM for 2D/3D applications, which is able to consider eddy currents, mechanical couplings (motion, vibrations and acoustics) and effects due to magnetic properties of the materials in the electrical machines. Thanks to well-equipped workshops, the IEM has facilities to build prototypes and perform experimentations in-house. Customers of the IEM are major manufacturers of electrical machines and actuating systems, automotive companies, manufactures of electrical steels, as well as electro-heating industries in Europe. This paper presents an overview of techniques and methodologies that have been successfully applied at the Institute of Electrical Machines of the RWTH Aachen University, for the design and analysis of modern electrical devices of various natures.

1 Introduction

Design of electrical machines might be the branch of numerical modelling in industry that features the largest number of coupled phenomena:

- Electromagnetism, field radiation,
- material effects, iron losses,
- heating, fluid interactions (cooling),
- power electronics, drives, control,
- mechanical load, motion, deformations,
- vibrations, acoustics...

On the other hand, numerical modelling is at a turning point. Now that single-domains techniques have reached maturity, people active in Computational electromagnetism have, in order to go any further, to face numerous important and new questions concerning:

- *Definition of couplings*: How should the interfaces between different anal domains be specified? Is the exchange of solution files between single-don packages sufficient, or is it necessary to devise specific multi-domain co and algorithms?
- *Accuracy*: Does more computational power always lead to a greater accuracy in typical multi-domains problems? In which conditions is it worth investment? By which techniques can the accuracy still be estimated controlled?
- *Materials*: How could advances in material science be exploited in applications or turned into technical innovation? How do simplifications uncertainties in material laws affect the accuracy of modelling?

This paper illustrates those questions in the field of electrical machine design, presenting a panorama of the approaches and methodologies that are develo and applied at our institute to model real-life multi-domain applications [1].

2 Staged Modelling

The design of electrical machines is an iterative process. To reduce costs development times, prototyping is more and more replaced by simulations. Sin domain Finite Element techniques have reached a high level of precision. Howe to fully replace prototyping and measurements, all physical effects have to regarded accurately. This requires appropriate models, which, in order to rem tractable, need to be organised efficiently and subdivided into several tasks. T methodology is called staged modelling [2].

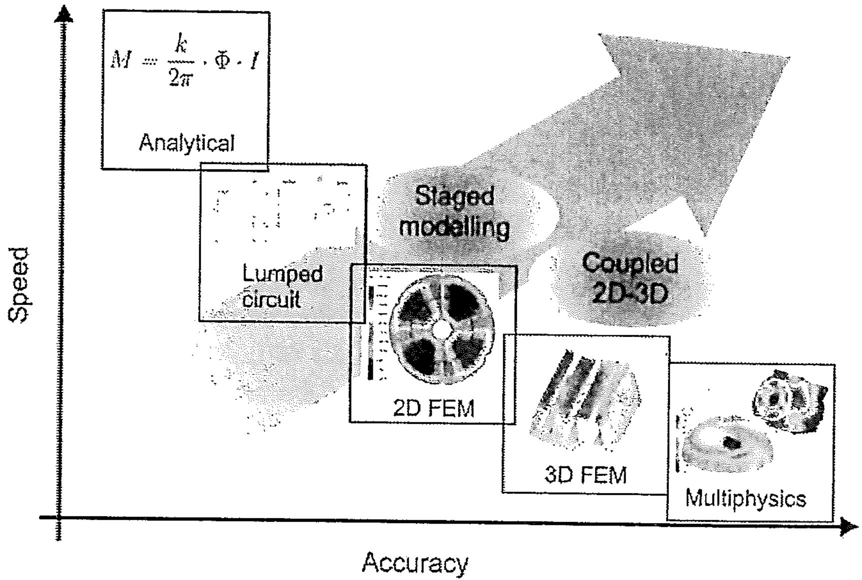

Fig. 2.1. Trade-off between accuracy and computation speed and the trend of staged modelling.

Classical numerical techniques can be considered as having a roughly const speed–accuracy product, i.e. the faster the computation, the lower the accura They can therefore be placed on a hyperbolic curve in the speed-accuracy plane, depicted in Fig. 2.1. The purpose of staged modelling is, by combining the advantages of different techniques, to increase the speed-accuracy product, so as to leave the hyperbolic locus of non-mixed approaches.

In general, technical *specifications* of electrical devices concern non-electromagnetic quantities (thermal, mechanical, acoustic), whereas design *parameters* (geometry, winding, magnets, materials...) are electromagnetic quantities. This clearly advocates for a global modelling approach. On the other hand, engineers think, even in the presence of complex systems, in terms of a quite limited set of observable variables. The purpose of *design* is to build (or modify) a system in order to make the relations between those significant variables match predefined specifications. Now, the *model* is the exploratory tool that must help in doing so, i.e. a reliable way to obtain, in a reasonable time, a good picture of the coupled dynamics of the whole system. It should be noted that this picture need not necessarily be from the beginning a highly accurate one, because one is, at the R&D stage, still essentially concerned with quantitative questions, incomplete, not yet fixed or inaccurate data.

The general idea of this approach, which we call *staged modelling*, is to combine the conciseness and intuitive virtues of classical analytical models, with the accuracy of numerical models. For that purpose, the coupled system must be decomposed into a network of sub-systems that interact only through well-defined and controlled channels. Usually, this decomposition implies doing some ad-hoc simplifications, the modelling challenge being to find simplifications allowing a decomposition into meaningful sub-systems, with controllable communication channels, without deteriorating too much the accuracy.

Our experience indicates that efficient staged models exist for large classes of applications. This is not surprising if one considers that electrical devices are purposely conceived to convert energy. The energy flow is quite structured in the device and the purpose of the staged modelling is to identify that structure and to match it as closely as possible with the structure of the model. Very often, the effective simplifications are very similar to the ones made to obtain classical analytical models (equilibrated phases, no eccentricity...).

As an example, the dynamic multi-domain staged models of Brushless DC or Permanent Magnet machines is now described. The proposed approach is more generally applicable to all electrical machines of the synchronous type.

The *flux plot* is by definition the flux embraced by the coils of the reference phase, as a function of rotor position and stator currents. It represents the interface between the magnetic field and the coils, which are connected to the supply. Assuming an equilibrated system, the three phases are equivalent, up to a phase shift, and only one needs then to be analysed. Represented by a look-up table, the flux plot is associated with a given geometry of the cross section of the machine and is computed by static finite element (2D or 3D) computations, imposing $\{I_R, I_S, I_T\} = \{I, -I/2, -I/2\}$. A few side parameters (stack length, number of turns...) can be taken into consideration without recalculating the table.

Because of the big difference in scale between one electrical period and the tim needed by the motor to reach its nominal speed, a classical transient analysis woul require several ten thousands of time steps, and be inefficient. The dynamic analysi is therefore advantageously split up into two nested loops. The inner loop consists i calculating *over one electrical period* the periodic stationary current and voltage wav shapes, assuming fixed speed and fixed temperatures. The inductances, resistance and back-emf's of the phases (plus possibly extra voltages and resistances due t the electronic components) and the switching strategy of the inverter bridge are take into consideration. From this, the mean torque, ripple torque and the losses, includin the Fe-losses, are estimated. The outer loop is the *transient dynamic and therma analysis*, with a much larger time step, computing the acceleration and heating up o the machine. This time scale splitting is another typical simplification of the stage modelling.

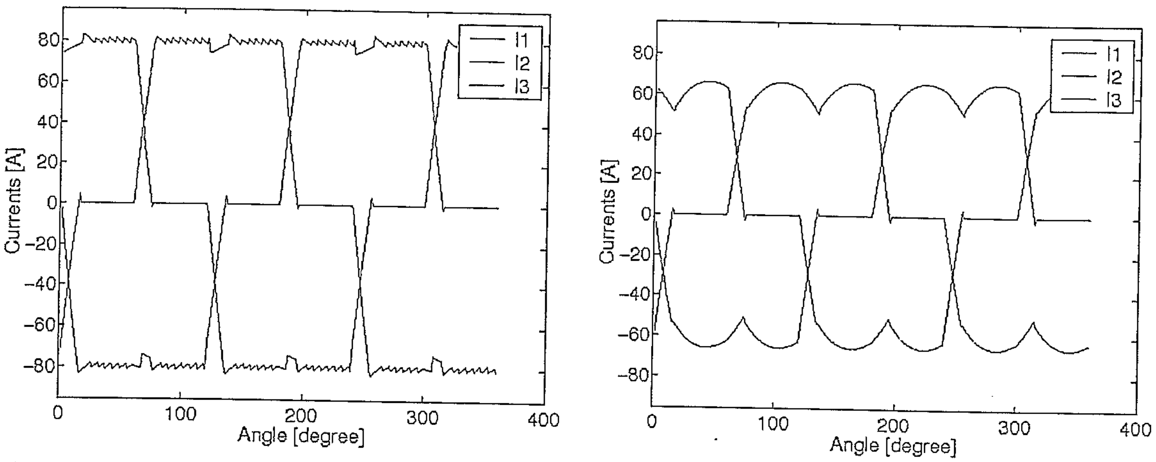

Fig. 2.2. Wave currents computed by the "over one period analysis" with a B6 bridge supply at 1000 rpm (left) and (2500 rpm (right).

A staged model is not a computation run. It is rather a growing set of organised information, similar to an expert system. When the sub-system structure has been identified, the interfaces are characterised, and their description stored. The dynamic multi-domain behaviour of the system is then computed by means of a specific programme (C++, Matlab...) that manage with maximum efficiency and versatility the interaction between the sub-systems, performing all required operations (time stepping, integration, etc...). The model can so evolve progressively, from the low accuracy/low computational time model of early design, up to a very complete and well-argued representation of the system. C++ classes or pieces of code (efficient algebraic/differential management of "over one period" solutions for instance) that have been written for one specific model are usually widely reusable or easily adaptable to other models.

3 Defect diagnosis, noise reduction

The identification of hidden defects in a device on basis of acoustic noise measurements is a kind of inverse problem. The usual way to solve such problem would be to modify input parameters of the corresponding direct problem, here the construction parameters of the machine, and solve repeatedly until a good agreement is obtained between the computed output parameters and the measured output parameters. In the case of the noise generated by an induction machine, the direct problem is however far too complex to allow any inverse approach like this [3]. The system under consideration is indeed a multiphysics system with three levels: electromagnetics (type of magnets, geometrical effects...), structure dynamics and acoustics. Moreover, the coupling term between the electromagnetic level and the structure dynamic level, i.e. the mechanical work delivered by the Maxwell stress as the stator structure deforms, is quite intricate and require enormous computational effort to be modelled in an acceptable way.

It is therefore worth trying to pose the problem another way. We wish to probe an electrical machine for hidden defects that induce abnormally high audible noise and we have all freedom to decide which kind of measurements is best suited to this aim. The methodological question is then: can the two ends of this identification process, i.e. defects and measurements, be linked more directly and more efficiently? In other words, do `signs' of the hidden defects exist that could be captured by appropriate measurements without unnecessarily generating a complete knowledge of all physical fields involved?

In the case of electrical machine analysis, frequency spectra can play this role. As the mechanical structure of the machine, i.e. the stator stack, which is the part mainly responsible for the radiation of acoustic noise, is not dissipative, the frequency spectrum of the excitation (Maxwell stress tensor) is nearly identical with the one of the response (vibrations). This is the fundamental assumption of our methodology.

So, on one side, the FFT of the measured noise gives reliable information about the frequency spectrum of the vibrating motion of the machine's surface, whereas the frequency spectrum of the Maxwell stress tensor can be determined analytically or by finite element analysis under different assumptions concerning possible hidden defects. By comparing the computed and measured frequency spectra, one may identify correlations and then make a diagnosis, i.e. to identify the kind of defect that is likely responsible for the abnormal noise generation. This approach has also to take into account the relevant parameters of the materials used in the machine.

Fig. 3.1 (left) represents the structure-borne noise measured on the terminal box and on a side rib and shows clearly the mechanical eigenfrequencies of the system. Those frequencies do however not appear in the measured acoustic noise spectrum, Fig. 3.1 (right), which indicates that the sought defect is not of mechanical origin. A common resonance peak at 1730 Hz is however found between the vibrations measured at the terminal box and the acoustic noise. It is due to the vibration of the terminal box, probably due to a loose fixing of the latter.

Fig. 3.2 represents the measured acoustic noise in the range [0, 800] Hz range, for two machines generating different levels of noise. The peaks that are present in the spectrum of the noisy machine and not in that of the other one are due to the sought defect. In order to determine the cause of those extra peaks, the expected air gap field spectra are calculated by means of analytic models under different assumptions:

saturation, static and dynamic eccentricity. The corresponding spectra for the radial forces acting on the stator teeth, is then derived. Comparing the measured spectrum with the different calculated ones, it turns out that the largest peak, which appears for both machines, is due to the stator slotting. The extra peaks can be attributed to a dynamic eccentricity of the rotor, which has been confirmed after dismantling the machine.

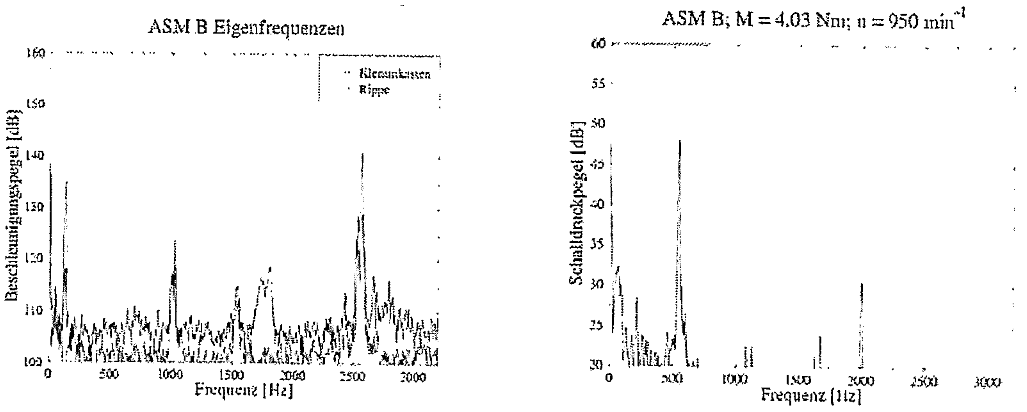

Fig. 3.1. Measured structure-borne noise (left) and acoustic noise (right) in the frequency range [0,3000] Hertz.

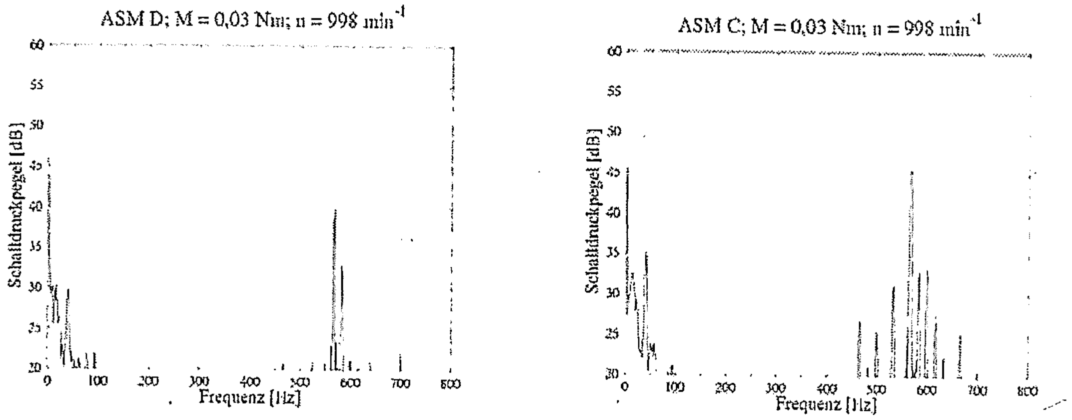

Fig. 3.2. Measured acoustic noise measured in the range [0, 800] Hz range, for two machines generating different levels of noise.

4 Material laws

Whether desired or not, all energy conversions occurring in a system must be addressed by the model. In particular, iron losses in magnetic electrical machines core are commonly disregarded although they may have a significant effect on the performance of the machine in sustained operation.

A dynamical vector hysteresis model based on a local energy balance has been developed at the institute [4]. The model can be considered from the point of view of a mechanical analogy of the pinning of Bloch walls phenomenon by a friction force. The dissipation functional associated with this force is not differentiable and must be

handled with the tools of convex analysis. This non-differentiability is however only a theoretical feature as it reduces to a simple if-statement in the implementation.
Contrary to the Jiles-Atherton model, for which the magnetisation is decomposed into a reversible and an irreversible part, the applied magnetic field is in this model decomposed into a reversible part and an irreversible part. Unlike the models of Preisach and Jiles-Atherton, this model is readily vectorial and dynamic and it is therefore able to represent rotational hysteresis. The magnetic material in an electrical machine undergoes locally a quite different magnetization behaviour: circular, elliptic or linear B vs.H characteristic. The model is able to represent internal loops and minor loops (Fig. 4.1) and exhibits the memory effect and the wiping-out property. Unlike the model of Jiles-Atherton, the number of parameters is not limited. Fig. 4.2 shows the agreement obtained between the numerical model with 15 parameters and measurement.

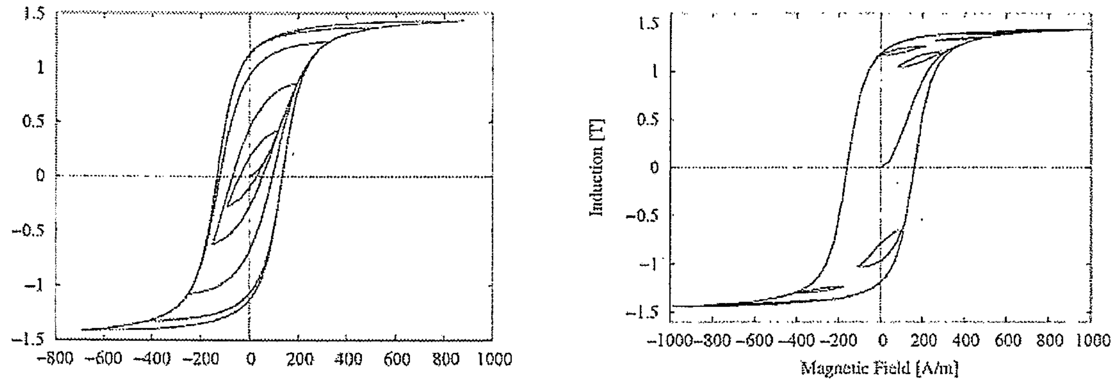

Fig. 4.1. Internal loops and minor loops.

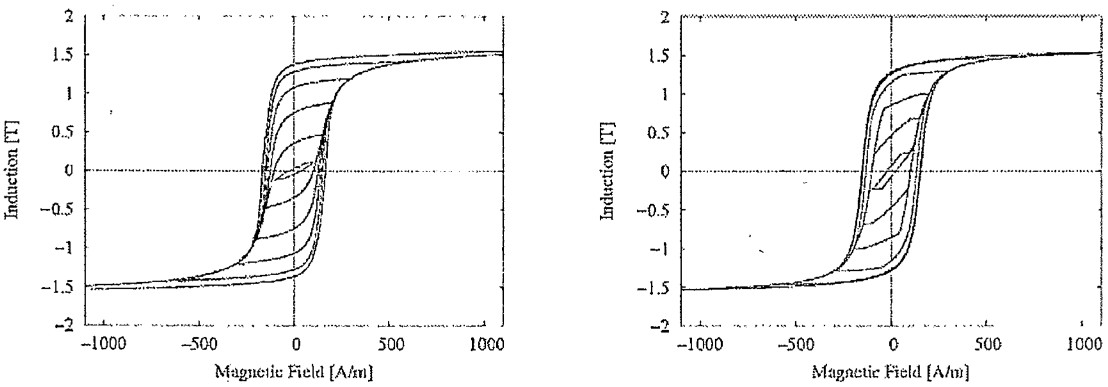

Fig.4.2. Agreement between model and measurements with 15 parameters.

5 Evaluation of material effects

Material aspects include on the one hand the development of models, which take better into account the real behaviour of the material and on the other hand the evaluation of the material effects. The first includes the consideration of the magnetizing behaviour of the material in the electrical machine as well as of the resulting specific magnetic losses of the used material. The second concerns the interplay of geometric data, operating conditions and magnetic data of the materia for an electrical machine with given basic data (power, speed, frequency, number of pole pairs...). In particular, modelling techniques have been developed

- to evaluate the effects of substituting one type of electrical steel with another in a given electrical machine on the energetic parameters in the case of asynchronous machines with a power of 1 to 100kW,
- to calculate an effective B vs. H characteristic of the magnetic material in an electrical machine based on the measurement of the U vs. I characteristic of the finished machine. Comparison with the primary B vs. H characteristic of the used magnetic steel (Epstein frame data), this enables a better estimation of the fabrication steps for the manufacturing of a magnetic component on the resulting magnetic properties [5],
- to describe the resulting noise in magnetic cores including the magnetic contribution to the noises.

6 Conclusion

In modern electrical machine design, numerical models must address at the same time all aspects of the system under analysis. Moreover, in order to be really effective in a development process, the computation time should not exceed a few hours and the model should nevertheless be accurate and reliable. Classical methods cannot fulfil satisfactory this whole set of requirements. Innovative methodologies and techniques still need to be devised and developed in the domain. This paper has proposed a few examples.

References

[1] D. van Riesen, F. Henrotte, Ch. Schlensok, K. Hameyer, "Coupled simulations in the design of electrical machines", Int. Conf. on Computational Methods for Coupled Problems in Science and Engineering COUPLED PROBLEMS 2005, M. Papadrakakis, E. Oñate and B. Schrefler (Eds), Barcelona 2005.

[2] F. Henrotte, I. Podoleanu, K. Hameyer, "Staged modelling: a methodology for developing real-life electrical systems applied to the transient behaviour of a permanent magnet servo motor", Compel, Vol. 22, Nb. 4, 2003

[3] C. Schlensok, D. van Riesen, T. Küest, G. Henneberger, "Acoustic Simulation of an Induction Machine with Squirrel-Cage Rotor", Proc. Of ICEM 2004, Krakow, Polen.

[4] F. Henrotte, K. Hameyer, "A dynamical vector hysteresis model based on an energy approach", IEEE Transactions on Magnetics, VOL. 42, NO. 4, 899-902, APRIL 2006.

[5] F. Henrotte, J. Schneider, K. Hameyer, "Influence of the manufacturing process on the magnetic properties of iron cores in induction machines", presented at this conference.