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M. Papadrakakis, E. Oñate and B. Schrefler (Eds)

THE DIFFERENT LEVELS OF MAGNETO-MECHANICAL COUPLING IN ENERGY CONVERSION MACHINES AND DEVICES

A. BELAHCEN, R. KOUHIA AND K. FONTEYN

Aalto University
POBox 13000, FI-00076 Aalto, Finland
E-mail: anouar.belahcen@aalto.fi, reijo.kouhia@aalto.fi, katarzyna.fonteyn@tkk.fi
Web page: http://sahkotekniikka.tkk.fi/en/, http://buildtech.tkk.fi/en/

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Abstract. This paper reviews the methods for coupling the magnetic and mechanical problems in magnetic materials and their application to electrical machines. The reviewed methods include both the material models and the computing methods as well as the methods for computing the magnetic forces. The paper shows that there are different levels of coupling the magnetic system with the mechanical one and that the use of a method or another depends on the application and the level of accuracy aimed at. The paper also clarifies some terms and concepts related to the coupling terminology such as strong, weak, local, global, direct and indirect coupling and put these terms in a coherent context. Most of the examples are related to the two dimensional analysis but some three dimensional ones are also shown.

1 INTRODUCTION

Energy conversion devices refer to these devices that convert mechanical energy into electrical one or vice-versa by the media of a magnetic field. Such device could be an electric motor or generator but it could be also an actuator or in some cases even a sensor although there is very little energy conversion in this latter case.

In the case of a motor or generator, the energy conversion occurs so that the current flowing in the windings of the machine, connected to a voltage source, generates, in accordance with the Ampere law, a magnetic field in the core and the air gap of the machine that exerts magnetic forces and torque on different parts of the machine and thus produces motion of the rotor or any other moving part. Thus the electrical energy in the form of voltages and currents at the terminal of the machines is converted into mechanical energy in the form of motion and torque at its shaft or vice-versa. In the case of actuators the electrical energy is converted into mechanical one either through a rigid motion of a plunger or through an elastic deformation of the actuating part under the effect of the magnetic field e.g. magnetostrictive deformation. Fig. 1 shows a cross-section of an electrical motor and illustrates the power flow from the electric supply to the mechanical load. Fig. 2 schematically shows a simple electromagnet and illustrates the related power flow. Fig. 3 shows a schematic view of a magnetostrictive actuator and illustrates its operation and power flow. The energy conversion is always accompanied with power losses in different parts of the devices and only part of the input power is converted to the output.

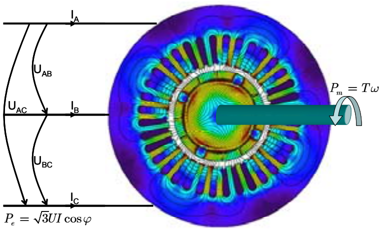

Figure 1: Illustration of the power flow in an electric motor. The electric power is converted into mechanical power through the magnetic field and the torque it produces. Part of this power is dissipated in the device.

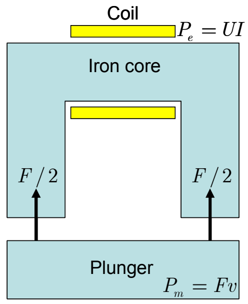

Figure 2: A schematic view of an electromagnet. The input electric power, which depends on the position of the plunger, is converted into mechanical power in the form of motion and force on this later one.

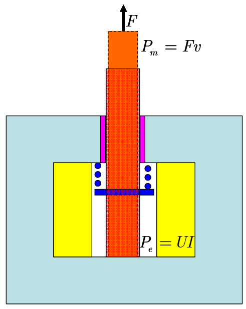

Figure 3: Schematic representation of a magnetostrictive actuator. The magnetic field in the actuating part causes its deformation, which is transmitted as mechanical output to the surrounding

Besides their operation as energy converters, the above devices are prone to parasitic phenomena such as vibrations and acoustic noise as well as wearing. The vibrations and noise occur due to the magnetic forces and the magnetostriction. Indeed, the time dependent magnetic field in the core and the air gap of the machine produce time dependent magnetic forces and induce magnetostrictive strains under the effect of which the structure of the device starts vibrating and emits acoustic noise. The acoustic noise is also produced by fluid flow in the machine and its surrounding as well as by pure mechanical effects such as contacts between parts or rolling of the bearing balls. In some cases, the acoustic noise is not generated in the structure of the machine but rather in some surrounding of it as the vibrations of the machine are transmitted to the surroundings.

On the other hand, the operation of the energy conversion device depends on the magnetic properties of the underlying material of its core, windings and permanent magnets. These properties such as the magnetization characteristics of the permanent magnets and the core material or the resistivity of the winding material or even the magnetostriction of the actuating parts strongly depend on the temperature or the mechanical stress level in the material or both. Fig. 4 shows e.g. the measured hysteretic magnetization curves of alloy steel under different levels of applied mechanical stresses at room temperature [1] and Fig. 5 the magnetostrictive strain of an electrical steel grade at different mechanical stresses and as function of the magnetic flux density [2]. Also, the rigid motion of different parts of an energy conversion device contributes and is a decisive factor in determining e.g. the current drawn from a voltage source by the device. This phenomenon can be appreciated when comparing the current of an electrical machine or an electromagnet in the case when the rotor or the plunger is under motion with the case of blocked rotor or plunger for example.

The design of efficient energy conversion devices and the prediction of their operation under different load and fault conditions as well as the minimization of the parasitic phenomena caused by these devices require not only simulation models from different fields of science vis. electromagnetism, mechanics etc. but also in most cases a coupling methodology between these models. In this paper we will focus on the magneto-mechanical or magneto-elastic models and the way they are coupled. In some examples the electromagnetic coupling is also handled.

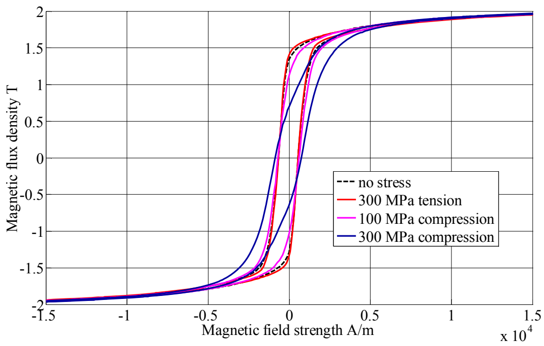

Figure 4: Measured quasi-static BH-loops of alloy steel at different applied stresses. The stress state in the sample is different from the applied one due to the magnetostriction. The frequency is 0.01 Hz.

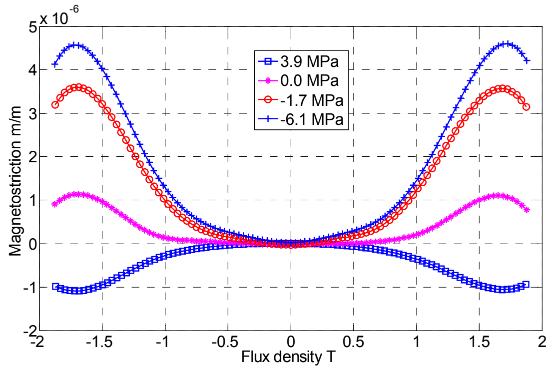

Figure 5: Measured magnetostrictive elongation of electrical steel under different applied stresses. The stress and the magnetic field are in the same direction and the measurement frequency is 5 Hz.

In Section 2 we will first establish a general context in which the coherent definition of different terms used to specify the nature of the coupling and its methodology is possible. In Section 3 we will review and explain the different levels of magneto-mechanical coupling and how they have been used in the recent literature. Section 4 clarifies the methods for magnetic force computation as well as the magnetostriction and the ways to deal with it. Last, in Section 5 we present some challenges and open issues in the magneto-mechanical modeling.

2 CLARIFICATION OF TERMS AND CONCEPTS

If one goes through the published literature dealing with the coupled problems in general and the electro-magneto-mechanical coupling in particular, he/she will find a multitude of terms used to specify the nature of the coupling methodology for solving a given problem. Such terms as direct or indirect coupling as well as strong and weak coupling are deliberately used and seldom explained. In this section we will first clarify these terms.

We propose a separation between the physical or phenomenological aspect of the coupling and its computational methodology or implementation aspects. In this respect, the physical coupling could be either strong or weak depending on the level of interaction between the fields or in other words how the change in one field say the magnetic field e.g. affects the change in the other field say displacement field e.g. It is obvious that this definition is a subjective one and depends on the accuracy at which we are aiming. Yet another terminology related to the phenomenological aspect is the concept of global and local coupling. By global coupling we mean an interaction between the field quantities without effects on the constitutive relations of the underlying materials, whereas the local coupling means the participation of the materials constitutive relations to this interaction. These concepts of weak vs. strong and local vs. global can be combined in pairs to specify the level of coupling both from its strength and its nature point of views. E.g. a problem can present strong global coupling and weak local coupling as is the case when modeling the operation of an electrical machine without interest in its vibrations. The strong global coupling here describes the coupling between the rotor motion and the magnetic field and the weak coupling describes the fact that in these conditions single-valued stress-independent magnetization properties are used to model the magnetic material and that the magnetostriction can be ignored.

The terms implicit, explicit, direct and indirect coupling should be reserved for the computational or implementation level. One speaks about explicit coupling when the governing equations for the quantities from different fields are written in a closed form, whereas the implicit coupling relates to governing equations that are written for each set of quantities separately but with the awareness that each set of equations includes parameters that have to be solved or updated from the other set. In both cases the equations can be formulated and solved either simultaneously and one speaks about a direct method or sequentially and we are speaking about an indirect method. Fig. 6 illustrates the intended use of these terms with some examples. It should be noted here that the explicit coupling is possible only in very special cases where some assumptions on the geometry of the problem or the properties of the materials are to be made. The explicit coupling also results in large system matrices with lower level of sparseness, which usually makes the solution of such problems slow. It is also to be noted that in most cases the solution of a coupled problem requires an iterative procedure regardless of the computational methodology used.

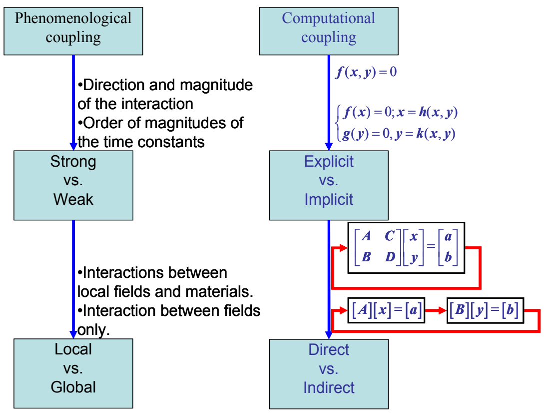

Figure 6: Proposed terminology for coupling methodology. ***x*** and ***y*** are hypothetic fields. ***f***, ***g***, ***h***, and ***k*** are functions or operators defining the governing equations of the fields. ***A***, ***B***, ***C*** and ***D*** are matrices or sub-matrices, which in conjunction with the load vectors ***a*** and ***b*** define the algebraic equations to be solved. These vectors and matrices are in general depending on the fields and the problem is generally nonlinear and requires an iterative solution procedure.

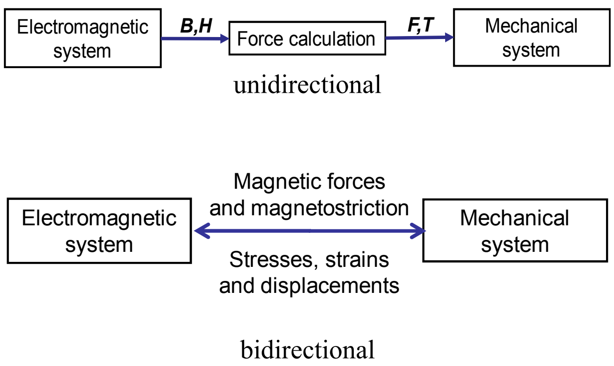

Figure 7: The Flow charts of the unidirectional and bidirectional magneto-mechanical coupling. ***B*** and ***H*** are the magnetic flux density and the Magnetic field strength. ***F*** and ***T*** are the magnetic forces and the torque. In some cases the magnetic vector potential ***A*** and the scalar electrical potential ***Φ*** are used instead of ***B*** and ***H***. The unidirectional coupling takes only the effect of electromagnetic system on the mechanical one whereas the bidirectional coupling is simultaneous and all the phenomena happen at the same time in both systems.

3 THE DIFERENT LEVELS OF MAGNETO-MECHANICAL COUPLING

Now that the terminology is explained we will proceed with the different levels of coupling starting from the simplest one and in a bottom-up fashion evolving to the most general case and concentrating on the magneto-mechanical phenomena only.

3.1 Unidirectional coupling

The flow chart of the unidirectional magneto-mechanical coupling is shown in Fig. 7. From the phenomenological point of view such a coupling method suites a weak coupling, where there is no effect of the mechanical displacements on the magnetic field or the underlying magnetic materials. In such a methodology the nonlinear Maxwell equations governing the magnetic field in the device are solved assuming that the magnetic material properties such as the permeability of iron or the relation between $\boldsymbol{H}$ and $\boldsymbol{B}$, are not depending on the mechanical state of the material i.e. the mechanical stress. Such an assumption is usually possible due to the low level of stresses in the core of the machine and also due to the fact that the mechanical displacements are very small, except when a rigid motion is involved. The rigid motion is possible to handle separately. The one directional coupling is the most popular way of calculating the vibrations and noise from rotating electrical machines [3]-[6]. It allows for a complex and accurate electromagnetic modeling such as coupling the circuit equations of the machine windings and the electrical supply e.g. the frequency converter with the magnetic problem in the machine either in a 2D or 3D approach as well as for complex and accurate material modeling e.g. magnetic hysteresis [7]. It also allows for a complex modeling of the mechanical problem by the use of a detailed 3D geometry and updated FE model parameters [3], [5]. The coupling quantities in this approach are the magnetic forces that may or may not include the magnetostriction [2], [6], [8], [9]. The different methods for computing the magnetic forces and magnetostriction are explained later in Section 4. However, the most common ways to transfer the forces from the magnetic problem to the mechanical problem in this kind of coupling are either the so called teeth forces or the rotating stress waves in the air gap of the machine [2], [10]-[12]. Both methods are based on the Maxwell stress tensor as will be seen in Section 4. Fig. 8 shows a plot of the teeth forces for the stator of a 37 kW induction motor at a given time and Fig. 9 shows a spectral plot of the 2D Fourier decomposition of the Maxwell stress in the air gap of the same machine. Both forces are calculated from the 2D time stepping solution of the magnetic field in the cross section of the machine. The generalized nodal forces can also be used to couple the magnetic problem with the mechanical problem. The computation of these forces will be explained in Section 4.

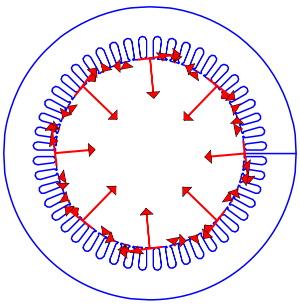

Figure 8: Normalized teeth forces of a 4 poles 37 kW induction machine at a given time. The direction and amplitude of the force vectors are time dependent.

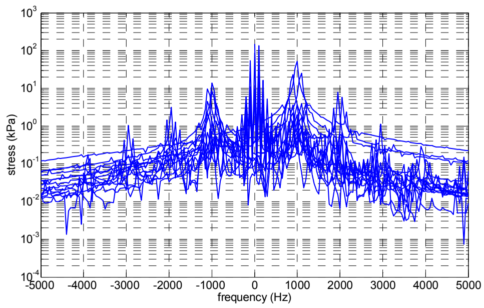

Figure 9: 2D spectral decomposition of the radial Maxwell stress in the air gap of the 37 kW machine. Each line corresponds to a spatial harmonic. Negative frequencies mean that the wave is rotating in opposite direction to that of the rotor.

3.2 Two directional coupling

In a two directional coupling it is possible to model both the effect of mechanics on magnetism and that of magnetism on mechanics. Such kind of coupling, suites best for phenomenological strongly coupled problems. This is the kind of coupling at which, most of the recent papers on the subject are aiming. Indeed, the solution of the magnetic problem requires knowledge of the material magnetic properties, which are stress dependent (see Fig.

4). On the other hand the solution of the elastic or mechanical problem requires knowledge of the load forces and the magnetostrictive strains, which depend on both the magnetic field and the stress of the material (see Fig. 5). Further, any change in the computed stresses and displacements will reflect on the computed magnetic forces through a change in the magnetic field and any change in the computed stresses and displacements or strains will reflect on the magnetic field through either the material properties or the geometry of the problem. These considerations are better understood from the flow chart presented in Fig. 7 above.

It should be understood that the coupling between the different phenomena is simultaneous and occurs in a continuous process rather than in a discrete or sequential one. This also means that the separation between the causes and consequences is rather artificial and should be used only for visualization purposes in view of a better understanding of the phenomena considered so that it could be used for the derivation of possible simplifications when needed.

In addition, the magneto-mechanical coupling is affected by the electric system, which is usually the source of the magnetic field. A load torque e.g. at the shaft of a machine connected to a voltage source will result in increased current withdrawn by the machine, which in turn will change the magnetic field configuration and further the force and the mechanical strains and displacements. Here again, the separation between the causes and the consequences is rather artificial and all these phenomena occur simultaneously. Reference [13] presents an example of this electro-magneto-mechanical coupling, where the coupling methodology seems to have some effect on the results of the computations. In the study, the motion of the plunger of an actuator, like the one in Fig. 2, has been modeled with time stepping and with its terminals connected to a voltage source. It was noticed that the current of the actuator was depending on whether the coupling was implement as direct or indirect.

The magneto-mechanical coupling can be modeled in different manners depending on the nature of the coupling and the aim of the investigation. The vibrations of an electrical machine can be computed with reasonable accuracy with a unidirectional approach and without accounting for the effect of mechanical stresses or any other mechanical quantity on the material magnetic properties and the geometry of the machines. However, the computation of the hysteresis energy losses e.g. in the iron core of the machine requires knowledge of the stresses in the core of the machine as the losses are very much affected by these stresses [14]-[16]. The additional losses due to the stress affect the current withdrawn by the machine and the torque it produces and thus affects the stress state. The methodology to carry out such an analysis as well as the results of its application to an electrical machine has been presented in [17]. The methodology consists of presenting the reluctivity of electrical steel as a function of the magnetic flux density and the mechanical stress and solving the magneto-mechanical problem with an implicit approach and in an iterative fashion. In such analysis the magnetostriction of iron was ignored and the iron losses were computed in a posteriori manner which result in their effect on the current being ignored.

The magnetostriction of iron has been also modeled with equivalent magnetic forces acting on the structure of the machine [6], [9]. The computation method of these forces are presented later in section 4.3 and discussed altogether with other methods. It is worth notice that the approach adopted in the implementation of the problem is again implicit although the algebraic systems of equations have been solved simultaneously.

After time and space discretisation, the equations to be solved has the form

$$[\boldsymbol{P}]\begin{bmatrix}\Delta\boldsymbol{A}_{k+1}^{n}\\ \Delta\boldsymbol{u}_{k+1}^{r\ n}\\ \Delta\boldsymbol{i}_{k+1}^{s\ n}\\ \Delta\boldsymbol{u}_{k+1}^{n}\end{bmatrix}=\left[\boldsymbol{R}_{k+1}^{n}\right] \tag{1}$$

With $\boldsymbol{P}$ the Jacobian matrix for the coupled magneto-elastic system, $\Delta\boldsymbol{A}_{k+1}^{n}$ the vector potential increment, $\Delta\boldsymbol{u}_{k+1}^{r\ n}$ the rotor bar voltage increment, $\Delta\boldsymbol{i}_{k+1}^{s\ n}$ the stator current increment, $\Delta\boldsymbol{u}_{k+1}^{n}$ the displacement increment and $\boldsymbol{R}_{k+1}^{n}$ the residual at time step k+1 and iteration n [2]. As far as the phenomenological coupling is not very strong, the off-diagonal sub-matrices associated with the magneto-elastic coupling can be set to zero resulting in a sparse matrix but a lower convergence rate of the solution. When the coupling is strong due to material properties, the coupling terms could not be avoided.

3.3 Coupling through the material

The coupling procedures and methodologies presented in the previous section were implicit coupling in the sense that the equations for the magnetic and mechanical systems are written separately and the coupling is implemented through the magnetic and magnetostrictive forces. The equations of each system are then discretised and the solution is achieved through an iteration process that updates the material properties according to some rules or equations.

In [18], the coupling methodology is quite different. Here, the constitutive equations of the material are written in a coupled form, which is derived from energy considerations. Thus the coupling procedure is explicit and does not require separate modeling of the magnetostriction e.g. as a set of equivalent forces as will be discussed later. The explicit coupling, which requires coupled constitutive equation for the material, is the correct way to model magnetostrictive materials used in actuators. The explicit coupling presents also the possibility of modeling the so-called delta-E effect if the constitutive equations are well elaborated. However the explicit coupling required the energy functional to be parameterized and even though resulted in large system matrix with low level of sparseness as explained above. This is a natural property of the explicit coupling that requires coupling terms in the Jacobian matrix for the solution to converge.

The constitutive equations in [18] are written in terms of the stress tensor $\boldsymbol{\tau}$ and the magnetic field strength vector $\boldsymbol{H}$ as functions of the strain tensor $\boldsymbol{\varepsilon}$ and the magnetic flux density vector $\boldsymbol{B}$. Additional parameters α_i are used to write the energy functional ψ of the magneto-mechanical system in terms of six invariants I_i, from which the constitutive equations are derived. Further, in defining the stress tensor it was assumed that the stress is the sum of the electromagnetic stress and an elastic stress $\boldsymbol{\tau}=\boldsymbol{\sigma}_{elastic}+\boldsymbol{\tau}_{m}$ where the electromagnetic stress tensor is defined in terms of the magnetic flux density $\boldsymbol{B}$ and the magnetization $\boldsymbol{M}$ vectors as

$$\boldsymbol{\tau}_{m}=\mu_0^{-1}\left(\boldsymbol{B}\otimes\boldsymbol{B}-\frac{1}{2}\left(\boldsymbol{B}\cdot\boldsymbol{B}\right)\mathbf{I}\right)+\left(\boldsymbol{M}\cdot\boldsymbol{B}\right)\mathbf{I}-\boldsymbol{B}\otimes\boldsymbol{M} \tag{2}$$

The space and time discretisation of the governing equations follows similar approach as in the implicit coupling and results in similar matrix equations.

4 METHODS FOR MAGNETIC FORCE COMPUTATION

The computation of magnetic forces from the solution of the magnetic field in a given geometry has been a subject of many discussions and publications. The main problem, was the fact that different computation methods ware giving exactly the same total magnetic forces but the force distribution were different from one method to the other [19]. These differences were mainly present in magnetized media such as the iron core of an electrical machine. Lately, methods based on the principle of virtual work seem to gain confidence among the researchers and the application of these methods is somehow established especially in conjunction with the FEM.

In this section we present the main methods for force computation and explain how they can be used in coupling a magnetic system with a mechanical one.

4.1 Lorentz force

Consider a current carrying conductor with a constant permeability μ_0. The force density within the coil is given by the classical Lorentz formula

$$\boldsymbol{f}_j = \boldsymbol{J} \times \boldsymbol{B} \tag{3}$$

Where $\boldsymbol{J} = \nabla \times \boldsymbol{H}$ is the current density in the conductor and $\boldsymbol{B} = \mu_0 \boldsymbol{H}$ is the magnetic flux density in the conductor. $\boldsymbol{H}$ is the magnetic field strength. This formula can be used whenever the conductor has a constant permeability and is currying a current. The resultant force acting on the conductor is naturally the integral of the force density over the volume of the conductor.

In magnetized media, the conduction current is usually zero and the Lorentz force equation results in null force density. However, the magnetized media can be represented at least in three different manners; surface magnetic pole distribution, surface current density, or a combination of both. In all cases, a local use of the Lorentz force distribution combined with the definition of magnetic moments, will result in a given force distribution either on the surface of the iron or inside it. A summary of these distributions is given all together with their discussion and consequences in [19].

4.2 Maxwell stress tensor

Starting from the Lorentz force formula, Maxwell derived a general purpose stress tensor that can be used to compute the force on any part on a device either magnetized or not

$$\boldsymbol{\sigma} = \frac{1}{\mu_0}\left(\boldsymbol{B} \otimes \boldsymbol{B} - \frac{1}{2}\boldsymbol{B} \cdot \boldsymbol{B} \boldsymbol{I} \right) \tag{4}$$

The force on any volume V bounded with the surface S is then calculated as

$$\boldsymbol{F} = \int_V \boldsymbol{f} \mathrm{dV} = \int_V \nabla \cdot \boldsymbol{\sigma} \mathrm{dV} = \oint_S \boldsymbol{\sigma} \cdot \boldsymbol{n} \mathrm{d}S \tag{5}$$

Where $\boldsymbol{n}$ is the normal vector to the surface element dS directed outwards of the volume element dV and $\boldsymbol{f} = \nabla \cdot \boldsymbol{\sigma}$ is interpreted as a force density, which result into

$$\boldsymbol{F} = \oint_S \left(\frac{1}{2\mu_0}(B_\mathrm{n}^2 - B_\mathrm{t}^2)\boldsymbol{n} + \frac{1}{\mu_0} B_\mathrm{n} B_\mathrm{t} \boldsymbol{t} \right) \mathrm{d}S \tag{6}$$

Although no mathematical or theoretical evidence is given, the terms under the integral are interpreted as a normal and tangential surface stresses or surface force densities. Such an interpretation has been the subject of a large number of publications.

If we accept this assumption (see Fig. 10 and 11), and in conjunction with rotating electrical machines, the stress can be developed into two dimensional Fourier series (space and time) and used as input or load for the mechanical system in the unidirectional coupling approach. A spectral plot of the radial component of the Maxwell stress in a 37 kW induction machine has been shown in Fig. 9. The usefulness of such a method is that even without making any mechanical analysis one can already "*guess*" what are the expected noise and vibration frequencies and modes that can be generated in the machine. Of course, all the frequencies and modes are not likely to be excited. The Maxwell stress or in general the electromagnetic stress tensor can also be used in the more general coupling method as explained in [18].

4.3 Method of virtual work

The method of virtual work for force calculation is not only one of the oldest methods to compute the magnetic forces but also is the one that have seen many developments is the last decades. The conventional virtual work method consisted of computing the magnetic field at two positions of a given moving part while the current or the flux are kept unchanged, computing the magnetic energy or co-energy at these positions and calculating the magnetic force as the ratio of the change in the magnetic energy or co-energy and the displacement of the part under investigation. Such a method is very heavy as it required two computations of the magnetic field and the displacement needed to be of adequate size for accuracy aspects. Reference [20] came with a method that best fits the FE computation and needs only one field solution. In this method the forces are computed from the derivative of the magnetic energy too but the derivation is made using the numerical and analytical properties of the FEM. However, the method was intended for the computation of total forces and torque of electrical machines and did not answer the critical question of force distribution. Reference [21] used the concept presented by [20] and applied it to the nodes of an FE mesh. In this way the author could resolve what he called "*generalized nodal forces*". These forces do not represent the force distribution in the material. They rather give a combined method to transform the force distribution into a local total forces acting each on a given node of the mesh and representing the force on a volume around that node. The volume itself cannot be defined with this method neither the force distribution. However, the advantage of the generalized nodal force concept it that it allows for a coupling between the magnetic and the mechanical systems when they are treated with finite element method. They also allow for the use of the same FE mesh for the magnetic and elastic system and avoid the problem of projection from one mesh to the other. The computation routine for the nodal forces although originally present in terms of the magnetic vector potential has been extended to the general case of magnetic flux density and also could be derived from the Maxwell stress tensor as in [22]. These methods were using linear finite elements. Methods using higher order elements and methods to reconstruct the force distribution from the generalized nodal force have been presented in [23], [24]. Other projection methods related to the generalized nodal forces have been presented in [25]. A plot of the generalized nodal force in the stator of a 3 MVA synchronous machine is shown in Fig. 10. For comparison purpose a plot of the surface forces from the Maxwell stress tensor is shown in Fig. 11. In both figures the field solution and the force computation have been carried out with linear triangular finite elements. Note that the scaling of the force vectors is not the same in the two figures but the shapes of the *force distributions* are similar and the absolute values are close to each other. This is due to the fact that the iron is saturated and the forces are concentrated on the surface of the iron [26].

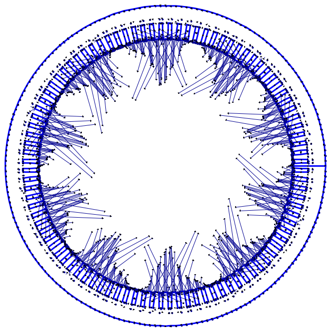

Figure 10: Generalized nodal forces in the stator of a 3 MVA synchronous machine.

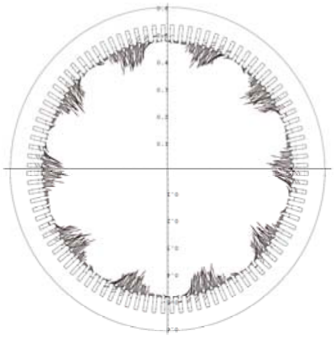

Figure 11: Maxwell force distribution on the stator of a 3 MVA synchronous machine.

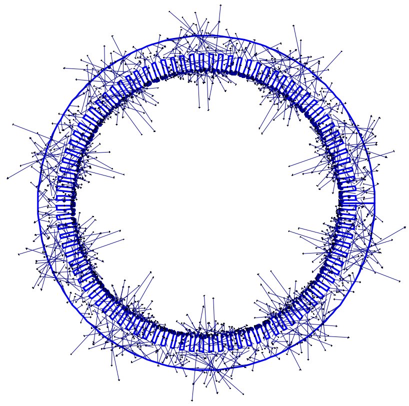

Figure 12: Magnetostrictive forces in the stator of a 3 MVA synchronous machine.

4.4 Magnetostriction

The magnetostriction is the phenomenon by which a sample of magnetic materials deforms under the effect of a magnetic field. Such a deformation is not due to the existence of external magnetic forces, it is rather the result of the internal stresses and strains in the material, which are due to the rearrangement of the magnetic domains and their interactions with the material lattices.

The magnetostriction has been traditionally accounted for through sets of equivalent forces, which are computed from either the magnetostrictive strain [6] or the magnetostrictive stress [8]. A plot of the magnetostrictive forces computed from the magnetostrictive stress in the stator of the 3 MVA synchronous machines is shown in Fig. 12.

However, the magnetostrictive stresses or strains are themselves dependent on the total stress in the material as shown in Fig. 5. Such a behavior could be simulated with stress dependents magnetostrictive forces [2] but it does not reproduce the actual stress behavior in the material when the materials boundary conditions are taken into account [2]. In this respect, the magnetostriction is better modeled within the material coupling methodology presented above [18]. In this methodology the magnetostriction is included in the magneto-elastic coupled constitutive equation through a relation between the stress, strain and magnetic flux density, which has been derived from energy considerations and measurements analysis. The fact that the magnetostriction is already in the constitutive equations makes it difficult to visualize it from complex computations which is the consequence of the fact that in real life the magnetic and mechanical coupling happen simultaneously and there is no way to separate them. Some attempts to find out how different phenomena in the magneto-mechanical coupling could be separated are still presented in [18].

5 OTHER CHALLENGES

In the previous sections, we handled the magneto-mechanical coupling as a separate problem from the electrical coupling and also from the mechanical load, which is usually connected to the shaft of electrical machines or the moving plunger of an actuator. We also assumed that the solution of the magneto-mechanical system is non-dissipative except for the dissipation in the resistive parts of the system. The other dissipations such as iron losses were estimated a posteriori.

The mechanical dissipation can be added to the system by additive mechanical damping [27] and the magnetic dissipation in the iron parts due to hysteresis and eddy currents can also be added through dynamic vector hysteresis models [7]. However, such additions to the different parts of the system result in non-coherent description of the energy, resulting in mathematically (and also physically) incorrect models. One challenge in the magneto-mechanical modeling is thus to include different dissipation phenomena at an early stage of the energy description, derive the dissipative constitutive equations for the material, and include these equations in the solution of complex systems such as electrical machines and actuators.

Most of the problems presented above have been implemented in two-dimensional analysis. This is due to the fact that the computational cost of these models is high and at the limit of what nowadays computation resources allow for. The computational resources are however developing very fast and already now one can carry out three-dimensional analysis of very complex systems within a reasonably short time. The development of the previous models and their adequacy for three-dimensional computations is then another challenge that has to be dealt with in the near future.

Last and not least, the characterization of the material and the identification of the models require experimental setups able to take measurements in three directions, whereas the existing setups are mainly designed for a single or at most two directional measurements.

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