Design of Electrical Machines

This is a course compendium on design of electrical machines EIEN20V16. On the following pages you find a collection of various items related to the design experiences over the past years. The text of this document is not carrying the science of linguistics or charming everybody that they could become brilliant designers, design is like learning – the competence and experience grows, if you let it. The content of this work refers to free knowledge – Wikipedia, free and excellent computation tool - FEMM and shears the design experience freely with you.
1 Introduction to Electrical Machine Design

Design covers the wide span of practical efforts from an initial sketch or a plan to well detailed drawing, a prototype or an installation. Design is something between an idea and product. Word ‘design’ can describe the process as well as a state of the process. The design can have specific orientation or a sight of improvement such as design for manufacturability, electromagnetic compatibility, reliability and so on. Similar to the design process, the learning process is the action of taking something apart in order to understand and study it, an opposite process, which results in a new creation and maybe an improvement. The goal of the design process is to develop and to formulate the understanding of the functionality of an electrical device. It is more important to establish a good understanding on the energy conversion process that is related to certain geometry than to find an optimum of a mathematical model that incorrectly describes the energy converter. There is a trade off between the exhaustiveness and the time spent of creating the model and the modeling itself. The target is that the model is accurate and fast enough. If anything could go wrong with computer based design [13] then:

1. the expectations of the results are more than code can ever deliver,
2. the wrong data is supplied or the problem specification is erroneous,
3. the procedures used in the software are not accurate enough,
4. the assumptions inherent in the procedure are too approximate,
5. the user does not have enough knowledge to interpret the results or misuses the software.

A software user’s/designer’s knowledge is decisive in the design process. The successful solution of an energy converter and fully understood functionality of the conversion process are often not yet the triumph for a complete designed product. It is important to understand the objectives additional to the functionality such as controllability, manufacturability, reliability and so one [13][15].

Design as a process involves a number of choices and motivations, and can take many forms depending on the object being designed and the individual or individuals participating. Designing normally requires considering the design requirements and to look for the best solution, which is additionally an optimization process where a target such as a light-weight construction, cost, efficiency, reliability or some other requirements are focused on.

1.1 Design for electromagnetics

The electrical machine design does not concentrate only on the rotating electrical machine and how the machine is constructed – analyzing it and taking the machine in parts. The course introduce computation tools and models for design that are applied on a number of devices where the electromagnetic energy conversion is used such as actuators, rotating and linear machines, chokes, transformers and induction heaters.
Power of imagination and power of understanding are the basis for the creativity. The purpose of Figure 1.1 and Figure 1.2 is both to improve the ability to observing, analysing and understanding. Figure 1.1 demonstrates the geometric transformation from a shell type of transformer to three phase tooth less machine. Every step of this chain the geometric freedom of the inner electromagnet is increased until it can freely rotate. The placement of the coils in space gives the freedom to induce voltages displaced in time that is the basis for the three phase system. Figure 1.2 shows the rotation of the inner electromagnet from the magnetizing position (on the left) to the position where the maximum torque can be produced when both rotor winding and the vertically placed stator winding are carrying the electric current.

The electromagnetic design is not just the geometric arrangement that is able to give the maximum torque density at certain speed in an electrical machine or the maximum energy density at certain frequency in a transformer. There are direct continuations from the first conceptual sketch toward to a more complete design where the energy losses and thermal management likewise the practicalities related to production and assembling is included.

**Design in nutshell**

Both rotating electric machines and transformers are taking advantage on the presence of the magnetic field when converting energy. Electrical machines are using the rotating magnetic field and transformers the alternating magnetic field. Therefore the peculiarity of the machine is that the windings are arranged to provide rotating magnetic field for the electromechanical energy conversion, while transformer takes advantage of strong magnetic coupling between the excitation (primary) and the load (secondary) winding. The magnetic core is regularly used as it facilitates the energy conversion. The core has a distinguishable air-gap between stator and rotor in rotating electrical machines. In case of transformers the input and the output is electrical energy that is conditioned to the voltage requirement and provides galvanic insulation. The shaft of the rotating electrical machines is the mechanical terminal from where the mechanical energy is transmitted. The magnetic forces are created due to magnetic attraction and interaction and are often referred as reluctance and excitation forces or torque, respectively. This excitation is either induced in conductors or stored in permanent magnets or supplied externally. Therefore the principle of transformers and also induction machines is based on mutual induction. Concerning to energy conversion in electromagnetic devices the primary interest is related to magnetic coupling and forces – converted or stored energy while the secondary concern is the irreversible thermal energy, cooling and temperature rise.

From energy conversion point of view the device is often described in terms of inputs, outputs and intermediate relations such as voltages, currents, flux linkages, torque and speed. The connection between the conversion and construction is defined by the limits of electric field intensity and breakthrough voltage, current density, flux density, force density and stresses. The design for manufacturability resolves the device, which is among transformers, actuators, rotating electrical machines or some other types of electromagnetic energy converters, and the most suitable production and assembling alternatives. There can be more options involved in the design that makes it more complete and mature (Figure 1.3).

![Figure 1.3 Overlapped goals and criteria that influence the design: three examples showing the variety of key factors](image)

### 1.2 Guidelines for machine design

The main goal for the machine design is to evaluate conceivable ideas, realizable production steps and product layout proposals and provide functional and manufacturable product – an electric machine. The design can be partly optimal but it should prevent overvaluation and oversight – a mistake resulting from inattention.
Most of the design work can be advanced by the help of computers. Computer aided design (CAD) is used to design and to develop products, tools and machinery that are used in turn to manufacture the designed products. CAD is used throughout the engineering process from drafting, conceptual design and layout, through detailed engineering and analysis of components to definition of manufacturing methods (Figure 1.4). The purpose of computer-aided engineering analysis (CAE) is to analyze the robustness and performance of the components and assemblies. It encompasses simulation, validation and optimization of the products and the manufacturing tools. This includes numeric field modeling tools such as finite element analysis (FEA), computational fluid dynamics (CFD) etc. Computer-aided manufacturing (CAM) refers to the software used to generate the instruction codes for a computer controlled manufacturing tools in order for it to cut out a shape designed in a computer-aided design (CAD) system. It saves the development time when a device structure can be specified quickly according to set of parameters that are specified for the type of the device construction. It is also convenient to use the common data formats (STEP, IGES, STL, etc) when transferring the geometric data between CAD/CAE/CAM tools, which is a bridge between ideas and experience such as a rapid prototype.

Typically the analytical model is the fastest but too approximate and the experimental work is too costly, which is due to the need of process time and resources, for the device development. The computer simulation establishes an advantage of a design and an evaluation approach, which is relatively inexpensive and rapid. At the same time the reduced scale experiments, which can be even a tiny detail from the full scale, give a valuable input of manufacturing and validate the models.

Computer aided design (CAD) bases on a design model or a number of parallel models that incorporates the optional choices. The design model joins together the main goals of the design of an electromagnetic device and formulates its’ performance according to the dimensions, sources and materials. CAD includes often CAE tools such as numeric field modeling in order to evaluate the characteristics of the electrical device. The evaluation of physical phenomenon and processes (in this course material) bases on a set of simple equivalent circuits (EC) or a more complex finite element (FE) model. The model(s) describes the magnetic, mechanic and thermal behavior. The output from the equivalent circuit is considered as a rough estimation. Nevertheless, it is necessary that the equivalent circuits are able to account correctly the changes in the device construction, and to give realistic results in a wide range of input variables. The
purpose of the rough estimate is to find out ‘optimal’ relations in the device construction and sources according to the design criteria, which could be an input to a more exhaustive numerical modeling method as FE analysis (Figure 1.5).

The device design is a process loop of different tasks that usually use different software’s. It is important that this loop is able to operate without user interaction. In an example of this course material the design tool is often operated from Matlab. This command script specifies the input data to the finite element analysis, does the model administration and analyses results and visualizes the output. Animations are often used as it is useful for a fast visual evaluation process. The FE analysis, which is performed by different software than Matlab, is used in conjunction with the Matlab programming language in order to perform automated simulation and performance analysis of a device. Instead of an exhaustive and ‘correct’ optimization the designed device is entered into upgrading analysis such as sensitivity study in order to improve the initial characteristic of the device.

Figure 1.6 shows a design flow chart for evaluation and development of ideas, which is continued with component or a constructional element and product development. The starting loop is a drafting that basically evaluates how a component in an electric machine such as a core or a winding is to be constructed and how this contributes to the energy conversion i.e. if the component is functional and rational. This evaluation loop requires topology generation as an input and leads to the visible solutions. This is not just dimensionless sketching as it determines the first layout for the machine element such as core or winding layout in the slot. This layout is a groundwork for functionality evaluation, which is based on a set of analytic models, empiric expressions or/and experience. This layout is also the starting point for construction study where the manufacturers experience is used to validate the practical realization and assembling possibilities for the component(s).

The second loop contains practically a number of sub optimization loops where the best materials and dimensions for the drafting layout are chosen for the improved functionality and more rational manufacturability. The importance of these calculation loops (of a number of simplified 2D finite element (FE) models) is to determine not only the strengths but also weaknesses of concepts and topologies. The simplicity of the 2D FE models is achieved by

- the reduced geometric size: a magnet or a core, a slot, a cooling channel etc
- simpler formulation of physical problems: linear around operation point
- reduced amount of degrees of freedom: mesh, uncoupled physics

The attractive outcome from the geometric modeling is used as the foundation on the early estimation on machine performance and manufacturability analysis. The performance estimation is basically the completion of the C-coals such as characterization of the concepts and topologies. There is no additional flow chart for production analysis and that is why the selection of an optimal layout or promising concept is considered subjective here.

The visible solutions with promising characteristics become as inputs to 3D structure modeling. In this case the 3D structure is either defined in CAD software with the production orientation or in FE software with simpler control for field computation. The later is for the sake of meshing and obtaining quick and valuable results. The structure modeling focuses basically only on a single component in a system and studies different types of loads.

In continuation the assembling of the stator and whole machine gains importance. There is CAD for prototyping in parallel to performance evaluation models. The calculation models can be rather general 3D FE to analyze the outcomes of integration or rather specific with the focus on special issues relating to assembling and tolerances.
Parameterization
- Geometry (W, H, proportions)
- Material properties (coil, core, )
- Loads (duty, current, flow)

Parametric change
- Rough sizing
- Operation point sweep
- Sensitivity study

Geometry (2D)
- Draw cross-sections, model initialization, analytic/empiric models, realisation visibility

Material properties
- Coils and conceivable ideas

Loads (duty, current, flow)
- Geometry (W, H, proportions)
- Material properties (coil, core, )
- Loads (duty, current, flow)

Geometric modeling (2D)
- Draw cross-sections, model initialization, analytic/empiric models, realisation visibility

Early estimation of machine performance vs manufacturability
- Peak operation, visibility vs vulnerability, subjective analysis of production

Structure modeling (3D)
- Draw complete component or a structure in the machine,

3D FE multiphysics
- Voltage across terminals
- Cooling conditions along
- Cooling surfaces
- etc

Theoretical specification of machine performance and production
- Detailed construction vs functionality estimation, production methods, cost, tolerances

Assembly modeling (2D and 3D)
- Complete evaluation of the design vs detailed study on manufacturing issues

2D FE electromagnetics
- \( \nabla \times (1/\mu(\partial) \times \mathbf{A}) = J - (\mu 0 \sigma) \mathbf{A} - \sigma \nabla V \)
- Heating power \( q = \nabla \cdot \mathbf{J} \)

2D FE heat transfer
- Temperature distribution
- \( \rho \nabla \cdot \mathbf{u} + \rho \cdot u \cdot \nabla \vartheta = \nabla (k \nabla \vartheta) + q \)

2D FE fluid flow
- \( \rho \frac{\partial \mathbf{u}}{\partial t} + \rho \cdot (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \eta \nabla^2 \mathbf{u} + \mathbf{F} \)
- Cooling power \( q = \mathbf{u} \cdot \mathbf{n} \rho c \)

Figure 1.6 Design flow chart for evaluation and development of ideas continued with product development

The design flowchart, which is presented here in Figure 1.6, is as an example. In this experience the conceptual sketch, which does not need to be complex at all, is drawn as a parameterized geometry. This geometric layout gives not only the first reality impression but also is used to study the effects on electromagnetism, mechanics, heat transfer or fluid dynamics alone. Later the geometric complexity is increased as well as multiphysics problem modeling is involved where different fields are coupled and dependencies on material properties included. Once again design process is alike to learning process. The learning process prioritizes establishing a good understanding in analysis, development and synthesis of an electromechanical device rather than creating excellent computer based functions. The computer based functionality has importance to improve the power of understanding and imagination, and to shorten the design process.