Concepts for increasing the efficiency and the power per volume of Electrical Machines

Kay Hameyer
RWTH Aachen University
Institute of Electrical Machines (IEM)
Schinkelstrasse 4
D-52056 Aachen, Germany

Summary

The appropriate design of a tailor-made electric machine for a mobile propulsion application is strongly depending on the material characteristics and properties of the ferro-magnetic materials used. Next to the magnetic properties, the mechanical and thermal material parameters are important to consider. In this paper particular attention will put to this discussion.

It is obvious, that vehicles are operated in a very wide range of speed and that the ferro-magnetic material properties are varying with the motor's speed. This has to be considered by applying drive cycles to evaluate the most used magnetisation frequencies, which depend on the speed and / or saturated points of operation of the material used. E.g. the drive cycle in urban environment is significantly different when compared to the drive of a vehicle on a highway. This contribution will show and discuss the described context of ferro-magnetic material properties in electric motors for the increase of efficiency and power density.

Introduction

It can be noticed that the specific interest in electrical drive trains for the propulsion of all possible types of vehicles is strongly increased over the last years.

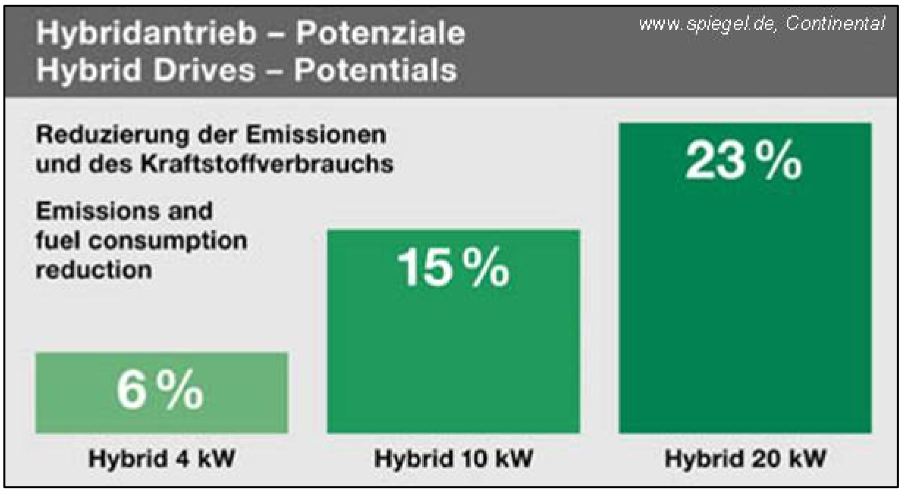


Fig. 1: Estimated fuel consumption reduction for hybrid electrical vehicles.

Applications of hybrid cars and the full electric vehicles are of particular interest because of their specific constraints. Fig. 1 illustrates the motivation to increase the electric propulsion power in hybrid vehicles. The main issues concerning such mobile drive systems are power density, weight and of course efficiency. Such constraints are driven by the requirement of an energy source, e.g. battery in the drive system. For full electric vehicles, the limiting factor of the battery's capacity forces the design of the electric drive to be very efficient, of low weight and to reach a maximum in power density. In cars operated by combustion engine, an extra of 100 kg weight in the car results in an additional fuel consumption of approximately 0,3… 0,34 litre. Therefore low weight is a key issue in mobility.

Having met such requirements for the motor drive system delivers the maximum range and function of the vehicle. In hybrid cars e.g. the strongest limitation is the space available for the components of the electric drive train. This paper focuses on the issues concerning the electric motor to meet the described properties and requirements and here in particular, the context of the ferro-magnetic material used in the motor. It will be shown, that the most appropriate motor design strongly depends on the chosen ferro-magnetic material with its parameters. A different material characterisation for mobile electric propulsion applications is given. The regularly used non-linear BH character together with some loss versus flux density diagrams is not appropriate for the specific designs of such motor drives. In the paper it will be discussed what parameters should be used instead.

To increase the power density of electric motors the knowledge of the mechanical properties is required to design a tailor-made motor drive solution. E.g. the mechanical power of an electrical motor is defined by:

$$P_{mech} \sim Volume \cdot speed \tag{1}$$

If we assume that the motor's volume is proportional to the weight of the machine and consider a very high speed of e.g. 30.000 min^{-1} , the motor reaches a very low ratio of power to weight thus a high power density, which is proportional to the 1/speed:

$$\frac{weight}{P_{mech}} \sim \frac{1}{speed} \tag{2}$$

High-speed rotating electrical machines need to be carefully studied in this respect to estimate maximum allowed speeds limited by the mechanical forces acting at the rotor material of the machine.

On the other hand, the power density of a motor is determined not only by the speed of the rotor but as well by the thermal properties of the materials used. The electrical machine must be designed in such a way, that the heat generated by the particular losses inside the motor is transferred out of the machine. The electromagnetic losses are the ferromagnetic iron losses and occur in the volume of the ferro-magnetic circuit, thus in the iron parts of the machine. The motor's windings with its ohmic copper losses due to the machine's current are arranged inside the iron core as well. All such losses have to be transferred out of the machine. Therefore, the thermal properties of the electro lamination must be considered carefully to ensure the thermal heat flow. A motor design with larger losses, respectively lower efficiency, can be more appropriate for a particular application in the case that the thermal conductivity of the iron lamination is large when compared to another application I which the efficiency is larger but the losses can not be transferred out of the motor due to low thermal conductivity of the ferro-magnetic material.

Electric machines for mobile applications

The electric machine used in mobile automotive applications can be found generally in the power range of 10 kW up to approximately 100 kW. Drive trains with larger motor powers are found in specific applications, e.g. the electric sports car TESLA. In this contribution we will focus on such powers because in this segment most of the ferro-magnetic material will be employed in the future. It can be expected that the produced numbers of motors dominantly in this power range will grow. Therefore it is thinkable that tailor made materials are developed and produced in the future to provide those applications with the appropriate ferro-magnetic material.

Next to electric drive train we have board net components in the traditional combustion motor operated cars, which have to be enhanced in their quality with respect to efficiency and power density. Here, the automotive claw pole generator can be named in particular. Every extra kW of generated electrical energy consumes approximately additionally 1,7 litre of fuel.

Another important development which is under scientific study at the moment, are electric generators for the application as range extender. Full electric vehicles are due to the performance of the drive's battery limited in their range of operation. To travel longer distances, the battery charging costs still a significant amount of time. To surmount this difficulty, it is appropriate to install in the vehicle a small and light weight combustion engine together with an especially for this purpose designed small and as well light weight electric generator. The set consisting of the small combustion engine and the electric generator is called the range extender. To reach the aim of small and low weight, it can be expected that the combustion engine a swell as the generator will operate at high speed. Therefore, the same argumentation as for the propulsion motor or the integrated electric motor for the hybrid vehicle applies and the ferro-magnetic properties will play an important role for the design of the generator.

As it was mentioned in the introduction, the power density of the electrical machines has to be increased, it is expected that the speed, the number of poles in the machine and as a consequence that the supplying frequency of the motor's current and voltage will increase. The efforts to minimise the motor's volume and weight will force the designs to be efficient at higher frequencies as well. The iron losses must therefore be minimised for high frequencies, which can reach values up to approximately 10 kHz. However, measured material characteristics for such conditions are nowadays hardly available to the motor's design engineer. Due to this reason, one of the still open questions is to say if it is required to develop a better ferro-magnetic quality of the motor's lamination regarding the magnetisation, or to increase the efforts to develop and manufacture motors with thinner lamination to decrease eddy current losses at higher frequency. Probably the combination of powder metallurgy with electro lamination is another way to match the requirements of modern efficient and power dense electric machines. With this paper we want to contribute to this discussion and support the idea to strengthen the efforts to investigate in particular detail the context between the ferro-magnetic material, the motor's application including the drive cycle and the resulting machine design.

Basic context of ferro-magnetic material versus electric motor design

In this section we will discuss the fundamental dependencies between the machine parameter and quantities, such as pole pair number, mechanical power, iron- and ohmic losses, efficiency etc. and the ferro-magnetic material characteristics.

We can say that the magnetisation frequency f_m is given by the pole pair number p and the speed of the machine n.

$$f_m = p \cdot n \qquad (3)$$

The mechanical output power of electrical machines is determined by the current density A and the magnetic air gap flux density B:

$$P_{mech} \sim A \cdot B \qquad (4)$$

This eq.(4) shows the dependency of mechanical output power on the properties of the magnetic circuit. The air gap flux density depends on the magnetisation of the ferromagnetic parts of the magnetic circuit. Characteristics such as the non-linear magnetisation curve, the BH-characteristic (Fig. 2), can be used to determine $B=B(H(\sim i),f)$. The value of field strength H depends on the field exciting current i and B with this on the frequency f and H. Such magnetisation characteristics are often measured for the DC case, or in the AC case for a frequency of 50 Hz. In this case the current wave form is controlled in such a way that the resulting flux density is of sinusoidal shape. However, in reality the magnetisation inside electrical machines is different from that. There, we have not only AC magnetisations, but also rotating magnetisations, which can significantly contribute to the iron losses (Fig. 3). In addition, usually there are field harmonic contributions, which distort the flux density and change the BH-characteristic significantly [1].

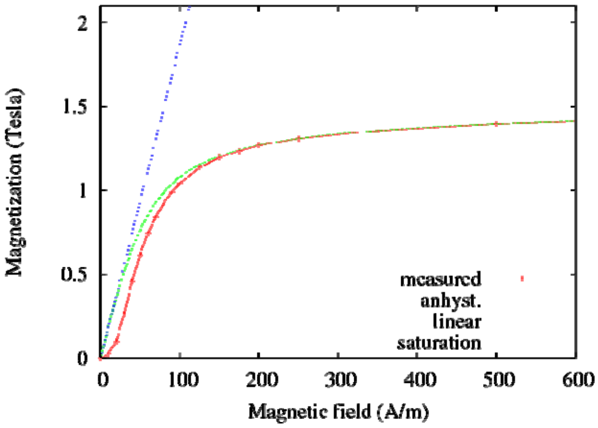


Fig. 2: Non-linear ferromagnetic BH-characteristic.

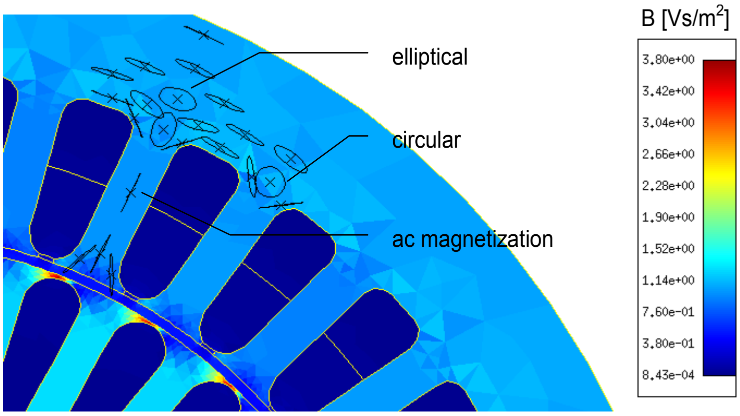


Fig. 3: Part of a stator yoke of an induction machine with indication of magnetisation type.

Figure 3 indicated on which locations inside a magnetic circuit various rotating and AC magnetisations can be found. It is obvious, that with the usually available motioned data of the material's properties, an accurate simulation and therefore prediction of the field quantities is erroneous. Accurate and useful models are required to characterise the material inside electrical in an appropriate way. Therefore, the materials are required to be characterised especially for the application in electromagnetic energy converters.

Measured material characteristics cannot in general be directly used in Finite Element program packages to model the ferro-magnetic material's behaviour. A parametric iron loss model must first be determined, of which the free parameters are identified by correlation with the available measurements.

Estimating the efficiency η of electrical machines delivers eq.(5). P_{el} represents the electric input power of the motor. Regarding the losses, we can determine the sum of all losses as there are mechanical losses such as friction, the iron losses consisting of eddy current and hysteresis loss, the cupper winding losses and the excess losses.

$$\eta = 1 - \frac{\sum P_{loss}}{P_{el}} \tag{5}$$

Regarding to the magnetic field quantities of the machine, which determine the iron losses, we have to consider the eddy current loss P_{ec} and the hysteresis loss.

$$P_{ec} \approx k_{ec} B_n^{\,2} (f)^2 \tag{6}$$

In eq.(7) the contribution of the rotational losses to the hysteresis loss is estimated by the parameter c [2].

$$P_h \approx k_h \left(1 + c(r-1)\right) B^2 f, \quad c = \frac{B_{\min}}{B_{\max}} \tag{7}$$

From the eq.'s(6) and (7) it can be seen that the iron losses have to be estimated by $P=P(B,f)$ characteristics valid for various frequencies and a large range of B. However, the same problematic as with the BH-characteristic applies here.

A further weakness in the simulation models and therefore in the design process of efficient and power dense electrical machines is the influence of the manufacturing process on the magnetic parameters. Mechanical stress e.g. changes significantly the ferro-magnetic properties of the material. Punching, stamping etc., thermal processes etc. and mechanical pressure generating mechanical stress inside the lamination are such effects just to name some of them. Usually they are not an integral part of consideration during the design of a motor or generator.

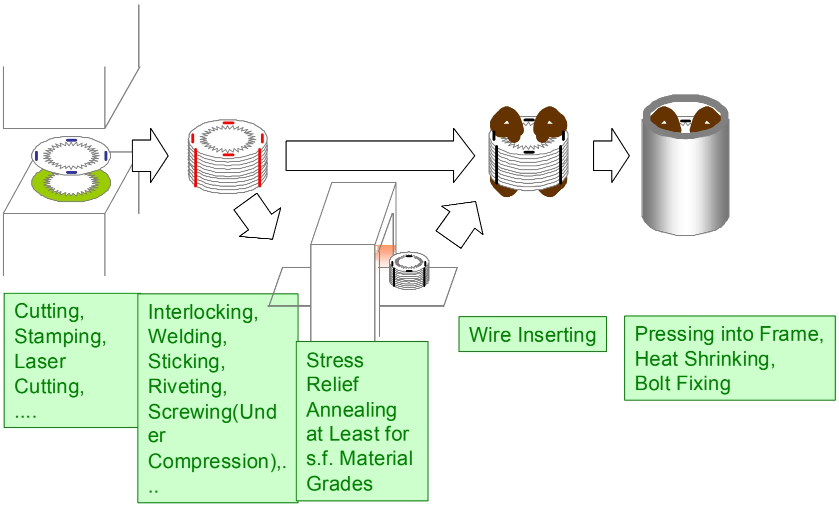


Fig. 4: manufacturing process influencing the material's properties.

Duty cycle / operation of the machine

To optimise the electrical machine regarding its best point of operation, the duty cycle or the most frequent used points of operation during operation have to be evaluated. Regarding hybrid or full electric cars, the actual operation of the electrical machine determines the overall efficiency. Already during the design phase of the machine the duty cycle has to be considered to achieve the best overall efficiency. A high efficiency in a single point of operation is not sufficient. Fig. 5 illustrates this with the torque-speed diagram of an electrical traction drive. As parameter in the diagram the efficiency is plotted. It can be seen that in the example for working points in the speed range of 4000 1/min at a torque of about 50 Nm the highest efficiencies present.

Assuming now the machine is operated more frequent in the low speed-high torque range of the diagram; the level of flux density has to be high to be able to generate the demanded torque. To achieve this, initial permeability and saturation magnetization of the ferro-magnetic have to be large. Assuming to operate at higher speed, the iron losses are dominant. Therefore lamination with particular thin steel sheets is desirable to have low iron losses at high magnetization frequency. In addition, due to the high speed, the material has to provide sufficient mechanical strength to cope with the mechanical forces acting at the rotor's surface.

As a standard, the Toyota Prius is equipped with NO FeSi electrical steel lamination of thickness 0,35 mm (Fig. 6). However, the trend is going to thinner laminations, such as 0,25 or even to 0,2 mm due to increasing motor supply frequencies respectively to higher motor speeds. Figure 6 collects some iron core loss data of TKS FeSi alloys with varying Si content and lamination thickness.

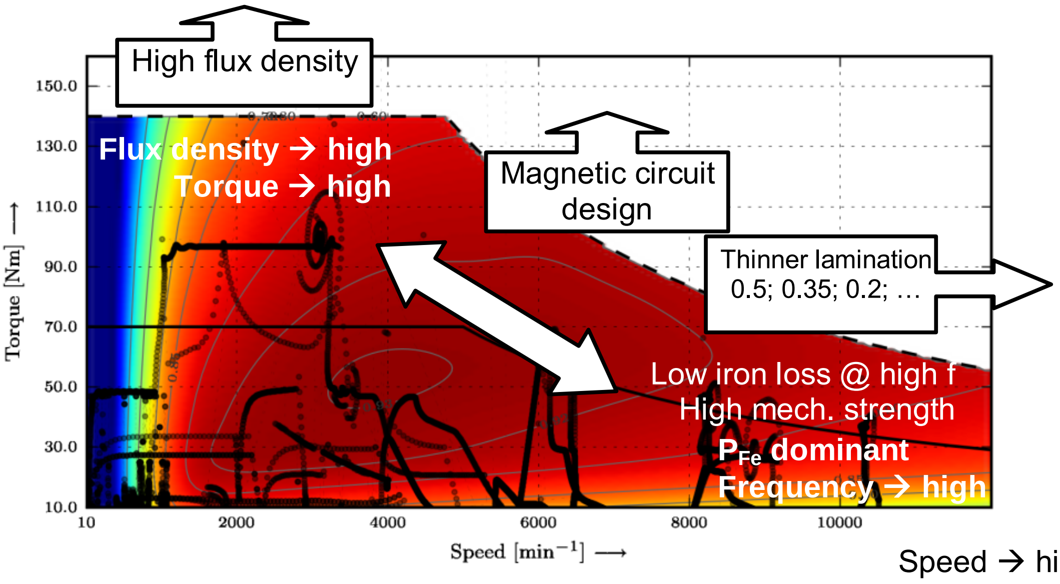
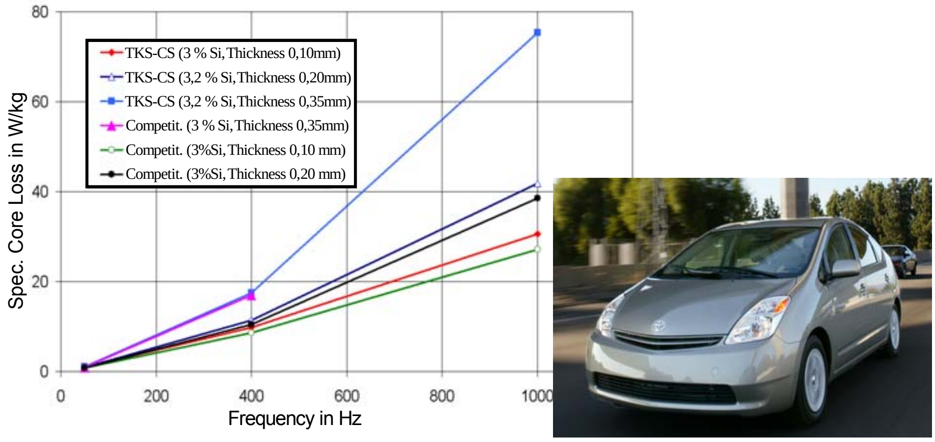


Fig. 5: Efficiency map of a traction drive indicating desired ferro-material properties.



Material Grades with Thickness ≤ 0,35 mm for Machines with Higher Basic Frequencies and Other Specific Application

Hybrid Vehicle „Prius" of Toyota: PM-SM Machine;
NGO-Material Grade with Thickness 0,35 mm

Fig. 6: Typical iron losses of FeSi alloys with varying lamination thickness.

It can be noticed, that recent developments of the material manufacturers are aiming in the same direction to produce electro steel with better eddy current behaviour.

There are improved material grades with thickness of 0,35 mm available:
P1.5 (50Hz) ≤ 2.1 W/kg (NSC, TKS, ArcelorMittal)
P1.5 (50Hz) ≤ 1.9 W/kg (ArcelorMittal – 2008)

Mainly employed material in hybrid vehicles nowadays is the P1.5 (50Hz) ≤ 2.5 - 2.7 W/kg iron losses. There are several developments for FeSi electro band of 0,1; 0,15 and 0,2 mm and a Si content of >3% in process to further reduce eddy currents.

Since such machines are not operated at one particular operation point but at a complete range of operation points, they must be designed with regard to the intended application. Thus, in a first step the operating range of these machines are estimated in view of the future application.

The frequency distributions of the operation points resulting from vehicle simulations (Fig. 7) and the driving cycles must be determined (Fig. 8). In this multiphysical simulation model all possible aspects such as vehicle mass, mechanical transmission gear, the battery with its charging control strategy are considered. Fig. 7 shows further sub-models for the simulation of hybride-vehicles including the tank as energy source and the car associated combustion engine.

In a next step, the electrical machine must be designed in such a way, that the range of best efficiency meets the range of most frequent used operation points [4], i.e. the average overall efficiency must be maximized in order to improve the energy balance and reduce the vehicles fuel consumption.

The requested frequent used operation points are, as mentioned, delivered by the results of the entire vehicle simulation assuming a particular vehicle concept. Figure 9 collects the simulation results for a series- and a parallel-hybrid vehicle concept applied to the drive cycles given in Fig. 7.

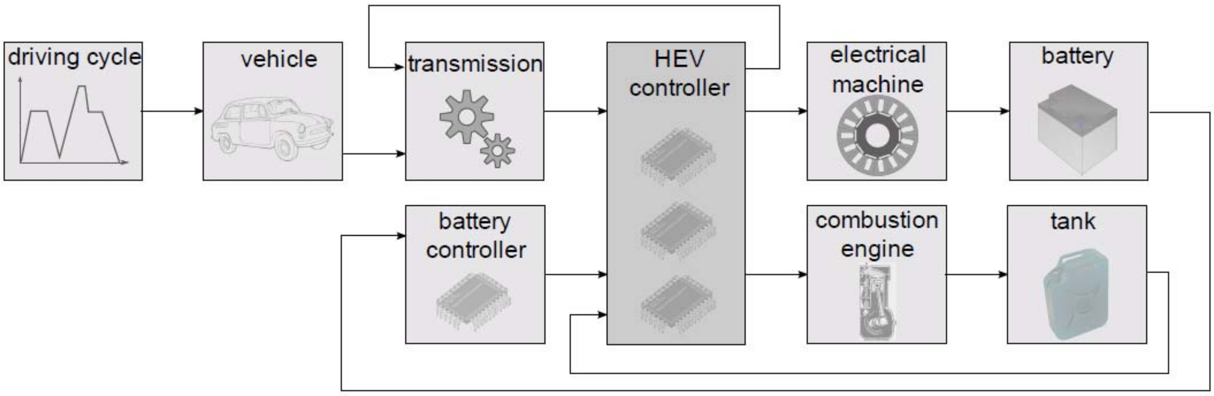
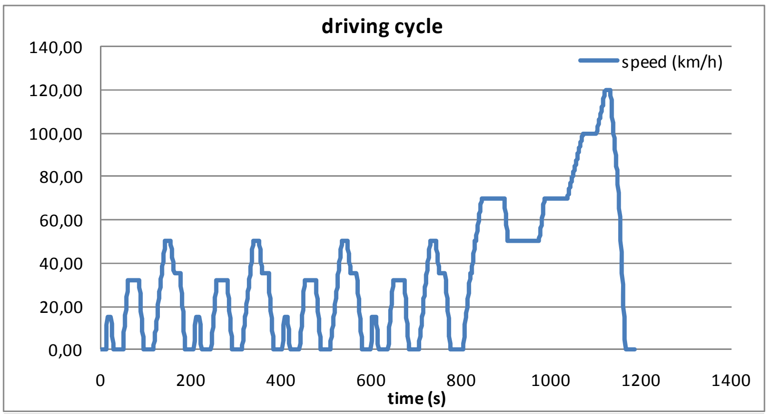
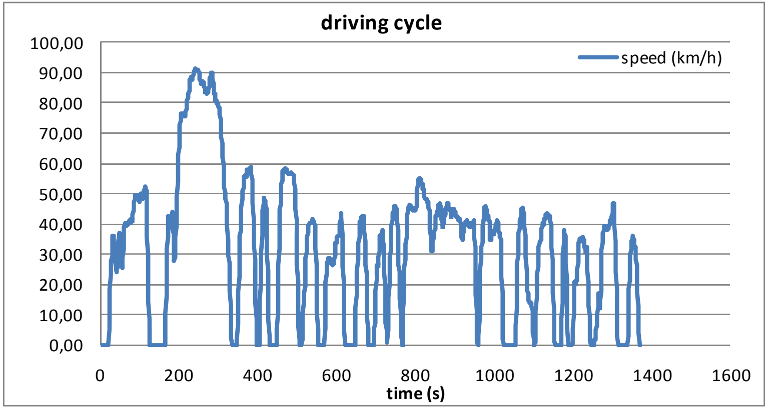


Fig. 7: Vehicle simulation model considering the drive cycle.

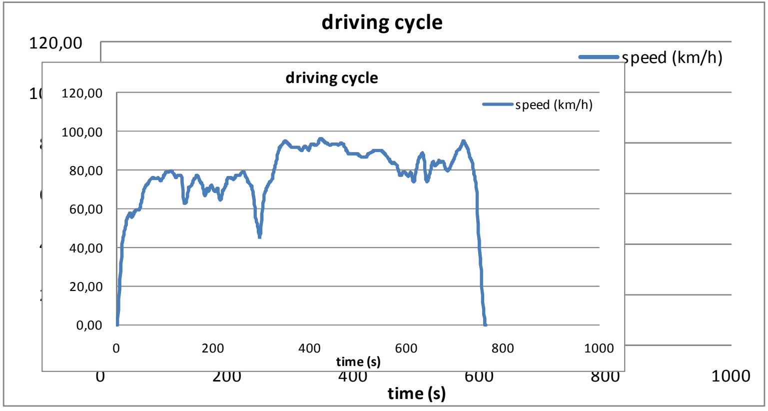
Referencing now to the aspects discussed concerning Fig. 5, it is obvious, that the choice of the most appropriate ferromagnetic materials depend strongly on the application with its drive cycle. As a conclusion of the simulated results together with the torque-speed characteristic of Fig. 5, it can be taken that the different drive cycle and vehicle concept requests for different materials. Therefore, vehicles operated in urban environment will have different ferro-magnetic material requirements as the high speed vehicles operating mainly on the motor way (Fig. 5). What was not mentioned yet, is the aspect that the appropriate choice of motor type is depending on the drive cycle as well. Figure 10 shows the evaluation of highest motor efficiency indicating the best area of torque and speed.



New European Driving Cycle (NEDC)
time : 1184 s
distance : 10.93 km
max. speed : 120 km/h
avg. speed : 33.21 km/h
max. accel : 1.06 m/s^2
max. decal : -1.39 m/s^2



Urban Dynamometer Driving Schedule (UDDS)
time : 1369 s
distance : 11.99 km
max. speed : 91.25 km/h
avg. speed : 31.51 km/h
max. accel : 1.48 m/s^2
max. decal : -1.48 m/s^2



EPA Highway Fuel Economy Cycle (HWFET)
time : 765 s
distance : 16.51 km
max. speed : 96.4 km/h
avg. speed : 77.58 km/h
max. accel : 1.43 m/s^2
max. decal : -1.48 m/s^2

Fig. 8: Various standardized EU and US drive cycles.

Physical material models, an example for the BH characteristic

It is well known that various conditions can vary the ferro-magnetic behaviour of e.g. electric steel. There are mechanical stresses, the magnetization, the influence of higher magnetization frequencies and influence of the manufacturing process for the electrical machine.

The purpose of this section is to show how the influence of the manufacturing process on the magnetic characteristics of stator and rotor core laminations can be *a posteriori* assessed from a voltage-current characteristic measured at no load on the finished machine. The implementation of this inverse problem is described at the example of an induction machine. The obtained model allows evaluating manufacturing effects on the resulting magnetic properties of the magnetic steel.

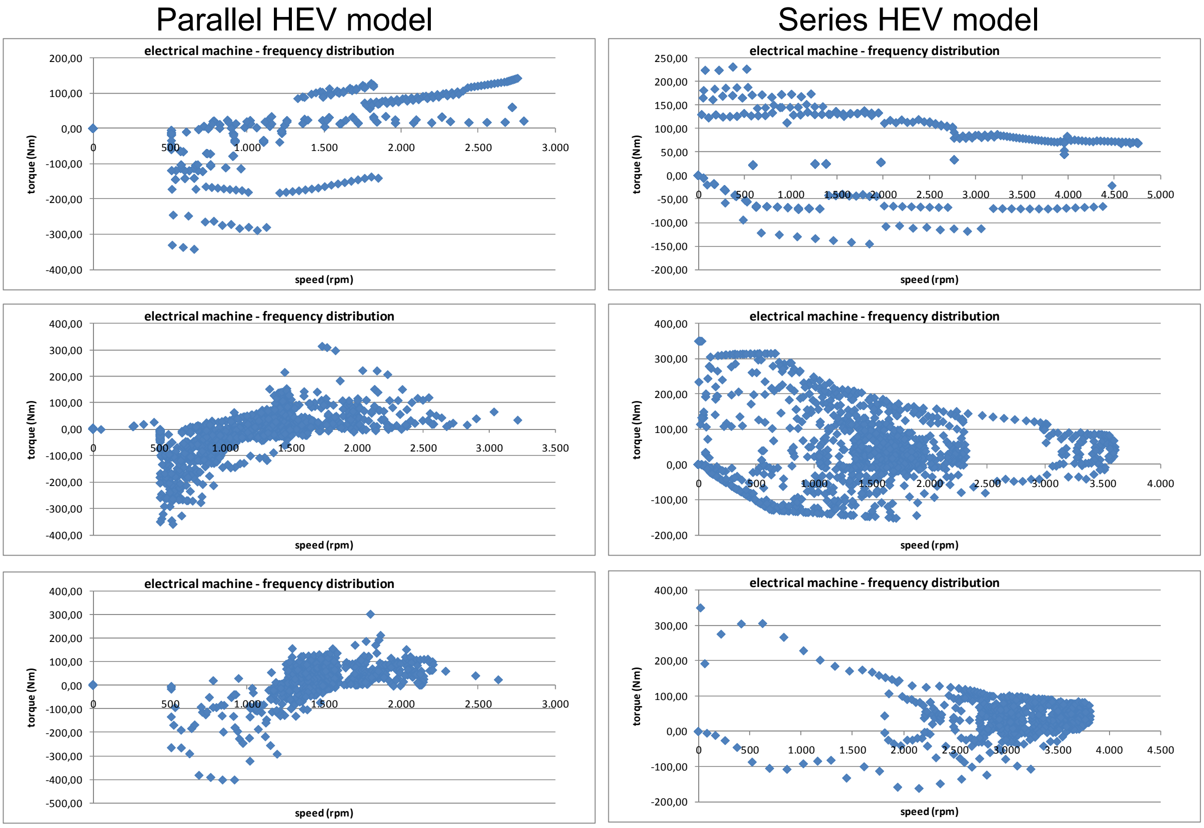


Fig 9: Most frequent used operation points applying parallel and series HEV models to the various drive cycles.

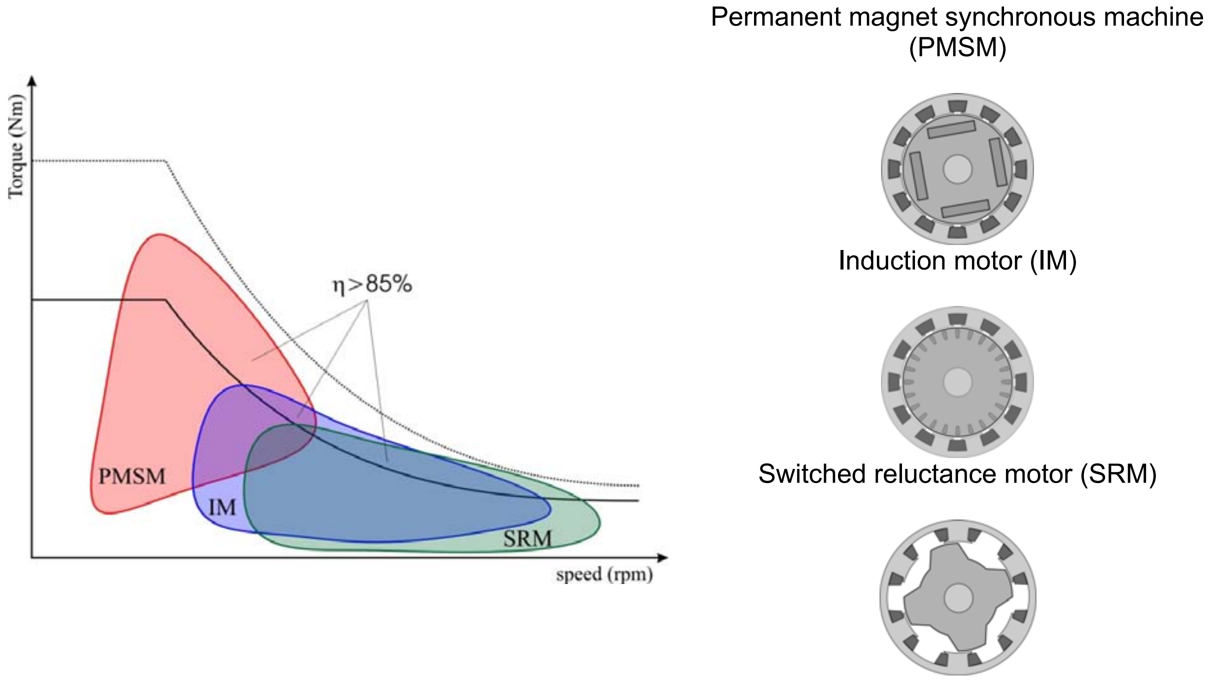


Fig. 10: Motor type versus drive cycle indicating torque and speed range of best efficiency.

We are interested in the calculation of effective *B-H* characteristics of processed (punched, stamped, cut…) laminations in induction machines, on basis of voltage *U* and current *I* measurements performed on the manufactured machine. The objective is to be able to compare a calculated effective *B-H* characteristic with the ideally measured reference *B-H* characteristic of the unprocessed material. The latter is usually measured with an Epstein frame and provided by the manufacturer (Fig. 11).

To this end, a tool is built to determine the resulting *B-H* characteristic of the steel in the machine that, when used as material characteristic in the analytical model of the machine, delivers a *U-I* characteristic matching the measured one. On the other hand, this approach can help motor designers to take into account the effects expected from the manufacturing process, when they decide on the best material, the optimum design and the fabrication methods in the given application.

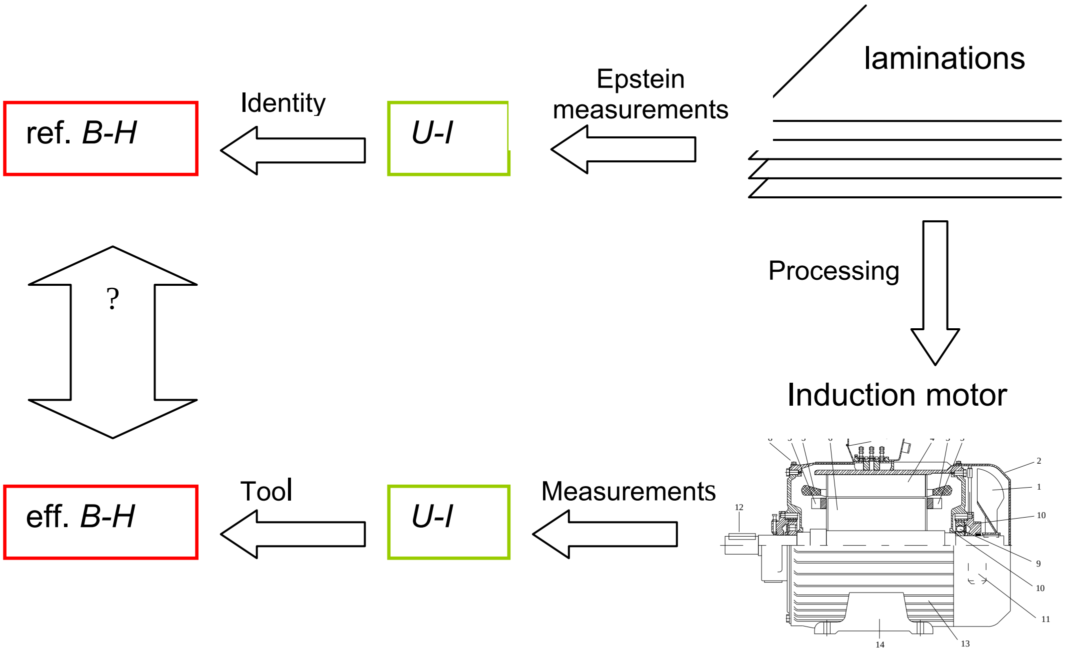


Fig. 11: Block diagram describing the project. This approach allows generating an effective *B-H* characteristic that can be compared to the reference *B-H* characteristic measured under ideal conditions in an Epstein frame.

It should be noted that the *reference B-H* characteristic (Epstein frame measurement) is also derived from a *U-I* measurements, exactly as we intend to do for the *effective B-H* characteristic of an electrical machine.

The *B-H* curve deduced from Epstein measurements is a useful representation of the magnetic material for magnetic field calculations based on conventional models or using FEM. It is precisely what (analytical or numerical) models neglecting hysteresis and eddy currents in the magnetic cores need as a material description. The resulting characteristic of the Epstein measurements for the specific magnetic losses *P* of the regarded magnetic steel as function of the maximum value of the induction *B* at a given frequency is mostly used in the calculation of the Fe-losses of the regarded electrical machine. The calculation of Fe-losses is generally done in the post-processing of magnetic field calculation results.

As the Epstein frame is an experimental set-up for the determination of the *B-H* characteristics and the magnetic losses of magnetic materials, it is conceived in such a way that the relation between the measurable quantities (*U* and *I*) and the measured quantities (*B* and *H*) is as close as possible to an identity (Fig. 11). To this point is the enforcement of the sinusoidal-*B* condition of importance, i.e. the current *I*(*t*) imposed to the excitation coil is controlled in such a way, that the voltage *U*(*t*) induced at the terminals of the measurement coil, is sinusoidal. This allows monitoring directly B_{peak} and H_{peak} :

$$\begin{aligned} B_{peak} &= \frac{U_{peak}}{2\pi f \cdot S} \\ H_{peak} &= \frac{N \cdot I_{peak}}{L} \end{aligned} \tag{8}$$

where *f*, S, N and L are respectively the frequency, the cross section of the measured sample, the number of turns of the excitation coil and the average magnetic path length of the field lines in the magnetic core of the Epstein frame made up from Epstein strips. The procedure is repeated for different magnitudes of the excitation current, so as to generate the complete B_{peak}-H_{peak} characteristic, which is called simply *B-H* characteristic (anhysteretic or virgin curve) in the following. The material is demagnetised before each measurement.

Magnetic circuit model. The analytical model for magnetic field calculation that is used to represent asynchronous machines is described in [5, 6]. It applies to rotating asynchronous machines in the range from 1 to approx. 100 kW. The purpose of this model is not to provide a descriptive model of the asynchronous machine, but rather to evaluate, on basis of basic geometrical and design data of the machine, the effects of substituting one magnetic steel material with another on the energetic properties of the considered machine.

In principle, one pole of an induction machine can be considered as a magnetic circuit with three independent loops (see Fig. 12). The main loop carries the flux linkage ϕ which links with both stator and the rotor currents and crosses twice the air gap. The two other loops carry respectively the stator and rotor leakage fluxes $\phi_{\sigma 1}$ and $\phi_{\sigma 2}$. The purpose of the model of Hameyer and Müller [5, 6] is to extract the relation between the flux linkage ϕ and the corresponding magneto-motive force $V = I_1 + I_2$.

If *D* is the diameter of the air gap, the pole pitch, i.e. the arc length of the air gap spanned by one pole of the *p* pole pair machine, is defined by $\tau_p = \pi D/2p$. The flux linkage is then by definition $\phi = B_m \tau_p L$, with *L* the length of the machine and B_m the average induction over one pole of the machine. The flux linkage flows in magnetic materials only, except when it crosses the air gap. It is the quantity that is the more tightly linked with the *B-H* characteristic of the magnetic cores.

If higher spatial harmonics are neglected, one has the relation $B_m = 2\,B_{fsw}/\pi$ between B_m and the amplitude B_{fsw} of the fundamental spatial induction wave in the air gap. This simplification disregards the contribution of the higher odd order spatial harmonics (5, 7… in a three-phase machine). The error granted this way on the flux linkage is smaller than 10% (1/25+1/49+1/121+1/169+…).

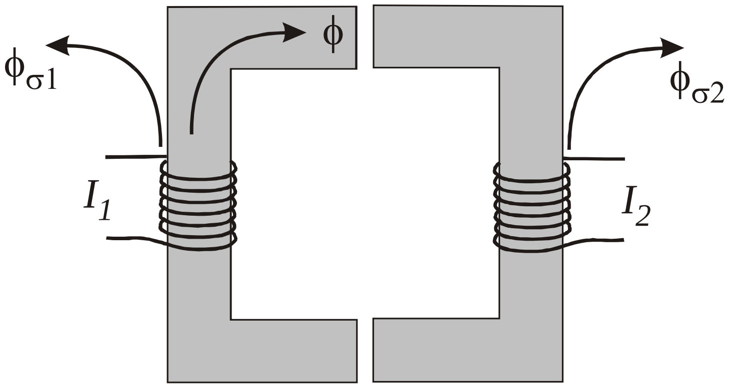


Fig. 12: Magnetic circuit of one pole pair of an asynchronous machine.

One now needs a link between B_{fsw} and the amplitude $B_{\max}$ of the induction field in the air gap because peak values are the relevant quantities as look-up variables in *B*-*H* characteristics. One states that $B_{\max} = \alpha\, B_m$ where α is an empirical factor. The above described procedure may be also generalized for the case of different values of B_m in the yoke and the teeth.

***U-I* measurements and the parameters of the new model.** The ϕ-V relation calculated by the Hameyer-Müller model can be also obtained for a real machine by means of a no-load experiment. At the no-load experiment, the machine is supposed to be in equilibrium. The equivalent circuit of one phase of an induction machine in no-load operation is given in Fig. 14.

The measurable quantities are the phase voltage U, the line current I, the supplied power P and the phase resistance R. Joule losses are then defined by $P_{\mathrm{Cu}} = 3\, R\, I^2$. The curve P–P_{Cu} in function of U^2 is nearly a straight line. Friction losses P_{Rb} are estimated by intersecting this curve with the $U^2=0$ axis. Iron losses are defined by $P_{\mathrm{Fe}} = P - P_{\mathrm{Rb}} - P_{\mathrm{Cu}}$. As the stator phase leakage inductance $L_{\sigma 1}$ is assumed negligible, the voltage at the terminal of the magnetisation branch of the equivalent circuit is $U_\mu = U_1 - R_1 I_1$.

The resistance representing the iron losses in the equivalent circuit is defined by $R_{\mathrm{Fe}} = 3\, (U_\mu)^2 / P_{\mathrm{Fe}}$. In order to determine the main reactance X of the machine, one proceeds as follows. The total impedance of one phase of the machine at no-load seen from the supply terminals is

$$Z = R + \frac{X^2}{R_{\mathrm{Fe}}^2 + X^2} R_{\mathrm{Fe}} + j \frac{R_{\mathrm{Fe}}^2}{R_{\mathrm{Fe}}^2 + X^2} X \tag{9}$$

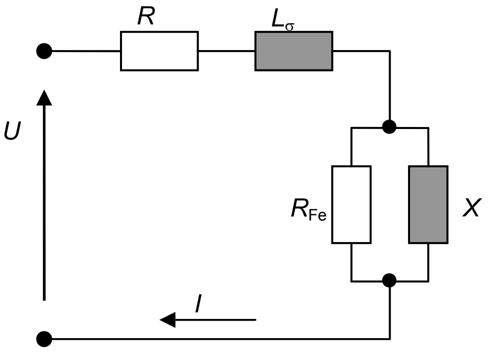


Fig. 14: One phase electric equivalent circuit diagram of an induction machine.

The active power delivered to the machine is then

$$P = P_{\text{Rb}} + 3\Re(Z)I_1^2 = P_{\text{Rb}} + 3\left(R + \frac{X^2}{R_{\text{Fe}}^2 + X^2}\right)I_1^2 \tag{10}$$

from where follows after elementary calculations

$$X = R_{\text{Fe}}\left(\frac{3R_{\text{Fe}}I_1^2}{P_{\text{Fe}}} - 1\right)^{-\frac{1}{2}} \tag{11}$$

The magneto-motive force *V* and the flux ϕ in the main magnetic loop of the induction machine can now respectively be defined as

$$\begin{aligned} V &= \sqrt{2}\; nI_\mu = \sqrt{2}\frac{nU_\mu}{X} \\ \phi &= \sqrt{2}\frac{U_\mu}{pn\omega}10^6 \end{aligned} \tag{12}$$

where *n* is the number of windings per pole pair and per phase. The √2 factors arise from the fact that *V* and ϕ are peak values, whereas U_μ and I_μ are effective values.

In order to find the relation between the flux linkage ϕ and the magneto-motive force *V*, the magnetic field *H* is integrated along the field line corresponding with that maximum amplitude of the air gap field.

Calculation of effective B-H characteristic. The problem of determining effective *B-H* characteristics from *U-I* measurements seems at first sight to be what Mathematics calls an inverse problem and what engineers call non destructive testing, i.e. the class of problems that aim at retrieving from surface measurements relevant information about the internal constitution of a given system. There are however considerable differences between the problem as posed here and the standard classes of inverse problems:

- In impedance tomography and most medical imaging inverse problems, one tries to identify regions with considerably modified physical characteristics (magnetic permeability, conductivity, dielectric permittivity…). In this case, we have to detect a small deviation (a few percent) with respect to the *B-H* characteristic of the unprocessed steel.
- Standard inverse problems deal with linear systems, whereas electrical steel has a strongly non-linear *B-H* characteristic and is usually operated precisely in the range where this non-linearity is most visible.
- The engineering problems of tomography and non-destructive testing consist mainly in determining how many probes are required and where they should be positioned for an optimal reconstruction. In this case, the measurement set is entirely fixed from the beginning and consists in the *U-I* no-load characteristic measured on the finished machine. This amounts to probing the main flux path in the machine, which consists of well-defined teeth and yoke pieces. The measurement set is then quite poor and incomplete. In particular it does not allow identifying individually different *B-H* characteristics, found at different places along this path.

Inverse problems are a class of optimisation problems. One must here find an effective *B-H* characteristic that minimises the error between measured and calculated *U-I* characteristics.

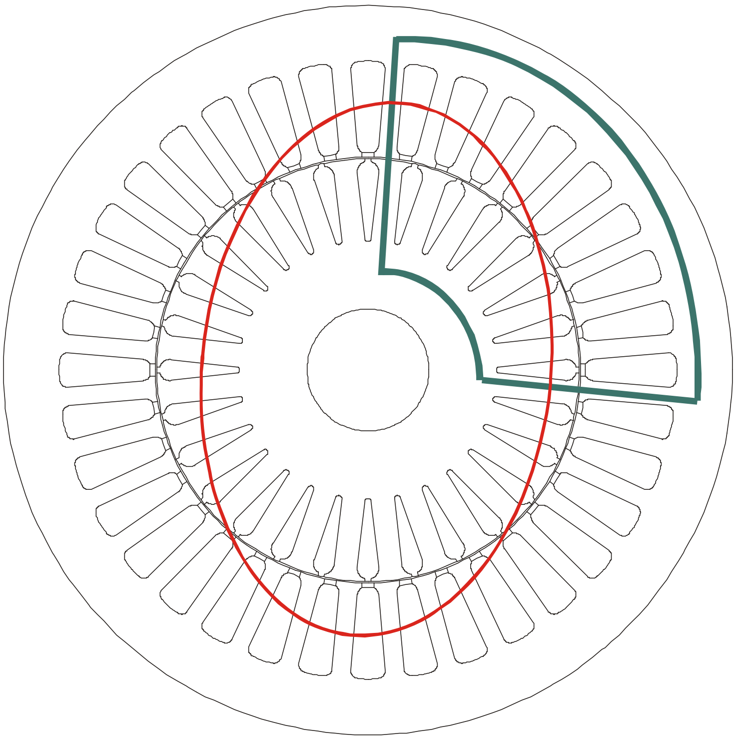


Fig. 13: Cross section of a 2p=2 pole pair induction machine. The distance between the ellipse and the air gap represents the magnitude of the air gap field. The thick line represents the path over which the magnetic field is integrated to obtain the magneto-motive force.

Conclusions

The magnetic circuit of electrical machines is constructed by ferromagnetic materials. Non-oriented magnetic steel is used in rotating machines. Various parameters determine the appropriate choice of the material. To list only some of the most important parameter: the type of machine, the range of operation of the flux density, the ferromagnetic losses, the geometry of the machine, its operational conditions, range of speed respectively the frequency, etc, etc.

It can be stated, that the properties of ferro-magnetic materials influence the design of the drive train of electric vehicles, such as hybrid- or full electric cars, significantly. Next to the inherent important material quantities, all physical properties, the thermal conductivity, the thermal capacity, the mechanical properties such as weight, maximum mechanical stress etc are of particular importance for the motor type and its design.

However, the most appropriate choice for a ferro-magnetic material applied to vehicles containing a significant electrical power for the traction is very difficult. Data available from the material manufacturer are not sufficient to provide sufficient help to the motor designing engineer. Due to the request of designing high efficient motors with a large power density, the required data have nowadays changed when compared to the data used in the designs for stationary drive systems. E.g. due to power electronic circuits, supplying the speed variable and torque controlled motor, parasitic effects, such as field harmonics imposed to the iron core of the motor have to be considered. High speed rotors require mechanical stable rotor constructions and ferro-magnetic material, which does not change its good magnetic properties due the mechanical stress imposed by the centrifugal forces. A traction motor can have a higher power density when the thermal property, the thermal conductivity, of the ferro-magnetic material is better when compared to the material with higher permeability, for example.

The material data for the iron losses and the magneization of the material for nowadays motor designs must consider higher frequencies, extra losses by particular magnetizations, e.g. circular or elliptical magnetizations, and data for all this at higher field strengths.

The measurements nowadays deliver only standardized data for relatively small flux densities and low frequencies. However, measurements at elevated frequency e.g. are difficult to obtain because of the large electrical power required and thermal loss generating high temperatures inside the measurement probes.

To surmount such difficulties it is suggested to define novel data sets which can supply newly developed physical material models. Such models can then be used in numerical tools or other motor models to accurately consider the material properties in the design phase of the drive motor. This will say that measurement and mathematical material model can be coupled to provide data for the simulation of the electrical machine to meet the strong specifications of variable speed drives [7, 8, 9].

As an example an approach to evaluate the effective *B-H* characteristic of magnetic cores in an induction motor from *U-I* measurement performed on the finished machine has been discussed. This approach helps machine designers to take alterations due to the manufacturing process into consideration when they have to decide on the best-suited electrical steel, the design and the best fabrication methods.

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