1 Introduction

With the beginning of the age of electromobility, the automotive manufacturers and their suppliers face new challenges. Customers think differently and demand new mobility solutions. This changes previous requirements for the construction of automobiles. The components are different, as well as the way of vehicle manufacturing and the vehicle system itself. The electrical drive solutions influence the perception of the Electrical Vehicle (EV), based on the drive performance, fuel feed, as well as the sound intensity of the drive. These facts lead to new requirements for electrical vehicles, which entail special challenges regarding acoustic requirements and new analysis opportunities. Before starting the electrical drive system and analysis, it is necessary to understand the construction of an EV.
The EV example in Fig. 1.1, shows that the combustion engine in the front area of a vehicle is changed to an electrical machine (3). High voltage wires (orange) connect the electrical machine (3) with the inverter (2). The inverter (2) is connected to the battery (1), which replaces the gas tank. For the inverter control system, the 12V battery is connected to the inverter with the low power supply cable (black). The EV needs to have an electrical brake booster (4), which is connected to the mechanical brakes via hydraulic tubes (turquoise). Finally, the electrical control unit (5) controls and communicates with the electrical drive and all of its system components (magenta).

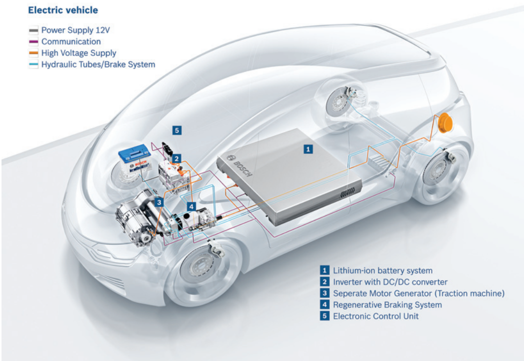
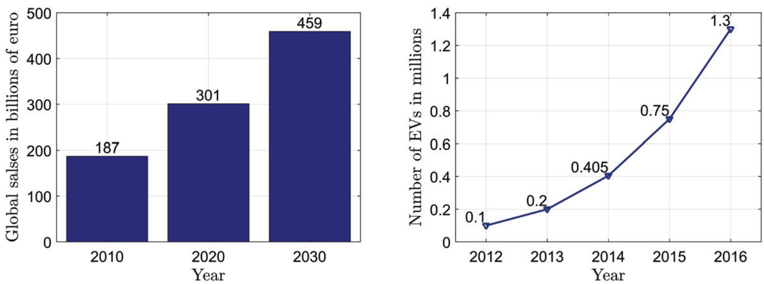


Figure 1.1: Construction of an Electrical Vehicle (EV)

Market potential and importance of the EVs

There are advantages as well as disadvantages in electromobility solutions. From the economic point of view, the forecasts for global sales and worldwide inventory development of EVs, diagrammed in Fig. 1.2, shows a high market potential. In these forecasts, the market for electromobility will increase drastically and fast. Till the year of 2030, there shall be mainly EVs or plug in EVs moving in our streets. The rapid expansion of EVs also entails risks. The countries' electrical energy system and infrastructure need to be adapted to a higher demand in electrical power. However in the long run, electromobility involves lower operational emissions, lower noise emissions and lower local particulate matters [Ele12]. This in turn can also help countries achieving their climate target. In addition, the production of the EVs produce more emission in comparison to conventional vehicles, highlighting the battery production [Sch14].



(a) Forecast of global sales of electric vehicles from 2010 to 2030 [McK11]

(b) Worldwide inventory development of electric cars in the years 2012 to 2016 [ZSW16]

Figure 1.2: Statistics of electrical vehicles

Electrical drives as multi-objective optimization

To fulfill the customer needs for acceleration, end speed, operating range and costs as well as comfort, the electrical drive and especially the electrical machine can be designed in a multi-objective optimization [NZE05; Ram+16]. With this design method, the priorities for the design characteristics are given to the optimizer in order to achieve a fast, cost-effective and highly requirements-matching electrical machine and drives design (Fig. 1.3). The technical design of the electrical drive often shows less focus on Noise, Vibration and Harshness (NVH) optimization in the early design phase, whereas the fundamental operational requirements are prioritized higher. With these priorities, NVH requirements are often not fulfilled. Thus, this work aims to simulate the harmonics in early design phases and shows how to change and optimize the control system of the inverter and electrical machine to achieve a cost-effective software solution fitting all customers needs.

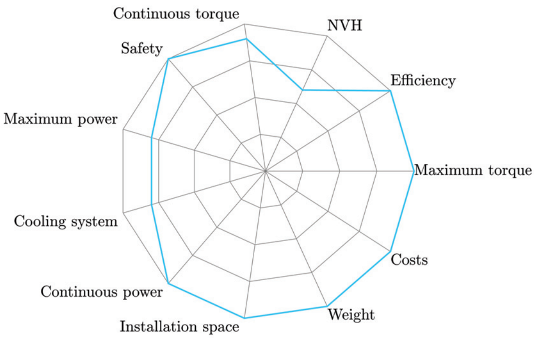


Figure 1.3: Example for priority of design characteristics of multi-objective optimization

Application of induction machine (asynchronous machine) drives

In former times, with a few minor exceptions, induction machines were mainly used in industrial applications, because of their reliability, low-maintenance and low costs [MP06; MVP08]. With the beginning of hybrid electromobility, permanently excited synchronous machines (PSMs) were applied. With the age of full electric vehicles a new discussion about the application of PSM and induction machine drives started. The difference of these electrical machines is mainly on the rotor side. Whereas PSM have permanent magnets in its rotor, the induction machine, has a squirrel cage, which in traction applications is built with copper bars to improve efficiency. These facts have a direct influence on efficiency and performance. The PSM shows a higher average efficiency, where in the partial load area, especially in efficiency cycles, the induction machine can partially achieve higher efficiencies. PSM drive systems show higher torque densities, but are more critical with the demagnetization of their magnets when heating up. For high performance applications with bigger machines, the induction machine can show a better average performance, because of the scaling effects of the power losses and its control strategy in the field weakening area. Induction machines also have advantages for the safety system, where the induced voltage and with it the induction machine drive can be turned off. The squirrel cage induction machine drives dispense with permanent magnets. Furthermore, it reduces costs and the consumption of toxic or rare materials. With all of this information, the induction machine is still an alternative to the PSM, which is shown in the latest electrical vehicle applications [Rip07; Lam18].

Causality chain from voltage excitation to acoustic noises

Getting more and more into the detailed analysis of electrical machines and drives, as well as the acoustics of electrical drives, the causality chain from the voltage excitation to the acoustic noises can be diagrammed in a rough scheme, shown in Fig. 1.4 [vdGie11; Boe13; Gar+97; VBG92; GWC06], and is inspired by the construction of this work.

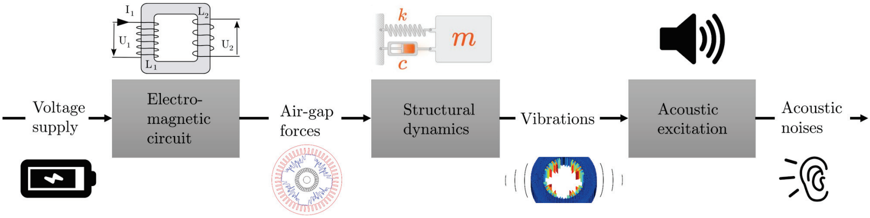


Figure 1.4: Causality chain from voltage excitation to acoustic noises

In chapter 2, the fundamentals for the acoustic analysis and signals processing as well as the inverter and machine control are explained. In this case, the inverter is the voltage supply, feeding the electromagnetic circuit, the induction machine, with voltage.

In chapter 3, the electromagnetic modeling of induction machines, is explained how the electromagnetic circuit creates air-gap forces. The electromagnetic circuit can be seen as a load drawing currents from the voltage source, creating a magnetic flux density. The magnetic flux density and subsequently the electromagnetic forces are creating tangential forces and radial forces directed to the stator and rotor, which produce electromagnetic torque and noise excitation.

These air-gap forces directed to the stator are described in chapter 4 on structural dynamic modeling. Projecting the forces on the stator and calculating the surface vibration response based on a structural dynamics model, the acoustic noises based on the surface vibration are computed.

After the calculation of the surface vibration, the electrical drive can be optimized for its NVH behavior with the findings from the previous chapters: The first approach is to change the electrical machine in its operating point, shown in chapter 5. This chapter shows the dependency of the machines operating strategy for best efficiency in conflict to best NVH behavior.
The second approach concerns to the elimination of harmonics in the currents and surface velocity, shown in chapter 6, injecting voltage harmonics in an open and closed looped system as well as showing the NVH- advantages and disadvantages.

Approach for efficient NVH simulations of induction machines

In order to optimize the analysis process for NVH simulations, the calculation path can be split up into two parts, shown in Fig. 1.5. The first part is the so-called 'offline' path, which can be seen as a pre-calculation, including the modal analysis of the mechanical structural dynamics and condensing it into a processable modal force matrix. After this pre-calculation, the 'online' part can be performed starting with the system simulation, calculating the inverter timings and currents for the electromagnetic model. This model includes the air-gap forces, which are used for estimating the air-gap forces and for the NVH-synthesis, where the structural dynamic are coupled to the electromagnetic [Kot+17b; Boe13].

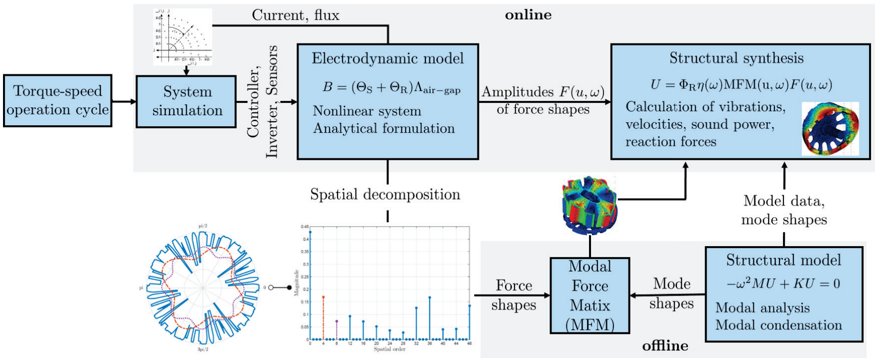


Figure 1.5: Simulation path for efficient NVH simulations (based on [Kot+17b; Boe13])

Introduction of the investigated electrical drive

The investigated electrical drive consists of an insulated-gate bipolar transistor (IGBT) inverter and a three-phase squirrel cage induction machine with aluminum, unskewed rotor bars and a distributed, zoned stator winding (App. A). The voltage level of the electrical drive is 180V to 250V with a maximum phase current of 500A. With the machines pole pair number of two, the electrical drive can provide a maximum torque of 133Nm and a maximum power of 70kW, where the power decreases to a continuous power of 35kW. The maximum speed of the machine is limited to 18000rpm with an axial length of 112mm and a stator outer diameter of 166mm. The induction machine has a mechanical one-sided air-gap of 0.6mm with 48 stator and 36 rotor slots. The inverter is mainly used with a switching frequency of 10kHz and with a space vector pulse width modulation scheme.

For the detailed analysis of the harmonics excitation, in chapter 3 and 4, especially the pole pair number, the number of stator and rotor slots as well as the switching frequency in relation to the rotor speed are the region of interest. With the number of pole pairs the order of the air-gap force excitation can be directly deviated. In case of the investigated electrical drive, the 0th, 4th and 8th force excitation are the dominant spatial orders. With the multiples of the stator and rotor slots, the temporal harmonics of the spatial forces can be roughly estimated, where the one-sided air-gap gives a hint on the electromagnetic damping of the system. Finally, the 10kHz of inverter switching frequency, the voltage modulation scheme and the stator frequency depending side bands of the interaction between the inverter and the electrical machine complete the picture.

2 Fundamentals

Before starting with modeling the electromagnetic and structural-dynamic behavior of electrical drives in chapter 3 and chapter 4, it is necessary to understand the general terms and definitions of electrical drives acoustics. In section 2.1 the noise emissions of drives are explained and the noise sources of electrical drives are presented. Section 2.2 shows the basics of waves and vibrations, as well as the calculation path from vibrations on the surface of the electrical drive to its sound power radiation. The acoustic analysis and its signal processing are shown in section 2.2.2 in order to show the different analysis methods, that are used in electrical drives acoustic analysis. The last section in this chapter treats the inverter control schemes and shows a rough implementation of the machine control system.

2.1 Noise Emissions and Noise Sources in Electrical Drives

Noise emissions have a huge influence and are surrounding us in our daily life [FSD12]. Especially noises in public have a huge influence on our sense of well-being and and cannot be directly influenced by oneself. One of the potential sources of these noises are vehicle. In particular, drives influence these noise emissions in public roads.

Too silent for pedestrians

Humans are familiar with the sounds of conventional vehicles through the daily use of cars. New generations of drives, especially electrical drives, change the picture of surrounding sounds. In fact, if pedestrians are distracted, electrical traction drives at low speeds can be too silent for their perception. Thus, pedestrians are terrified of EVs moving behind them or suddenly crossing their ways. To prevent these situations and to protect pedestrians, the European Union (EU) and the United States (US) view the possibility of new regulations for electromobility [Mas14; Com10]. One obvious solution is reviewed adding a sound generator to the electrical vehicle for the time of familiarization with the electrical vehicles and their electrical drives.

Not noisy but annoying

Comparing the noise emissions of electrical drives against conventional drives, the electrical drives have the potential of being less noisy, but also of being annoying in particular [BTM14]. The electrical machines are operating and inclining to tonal noises at higher frequencies. The conventional combustion engines have a more broadband noise and operating in the lower frequency range [Kön07]. Figure 2.1 shows the noise emissions of the vehicles components and their valence. It is shown, that the sound pressure of the vehicle should be as close as possible to the blue curve. The horizontal lines show the frequency components of the vehicle. In addition the electrical drive is diagrammed, in order to show the increased annoyance starting at around 1000Hz. The amplitude of the signals can also have a major influence, but in the test of [Kön07], noises don't have to be particularly loud to be annoying.

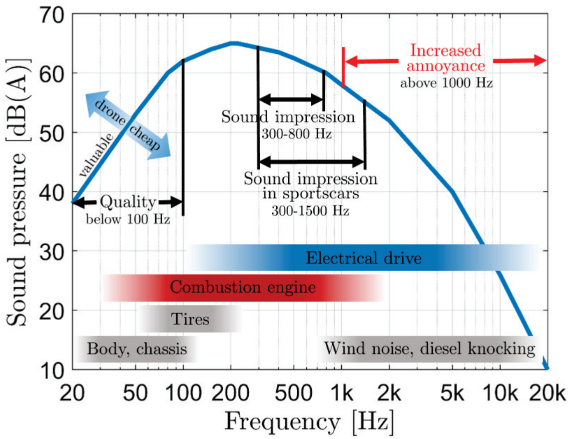


Figure 2.1: Noise emission of automobiles (based on [Kön07])

Noise sources in electrical drives

In order to understand the different noise sources of electrical drives, it is necessary to distinguish between noises of electromagnetic origin, mechanical origin, the interaction of mechanical and electrical origin, and the aerodynamic origin [Boe13; GWC06], shown in Fig. 2.2. Highlighting the mechanical and electromagnetic source, because these effects are only there in case of a non-ideal realistic electrical machine and have their origin normally in the manufacturing of the machine, affecting the electromagnetic and mechanical noises at the same time. Where the mechanical harmonics mainly include the bearing and friction noises and the electromagnetic harmonics mainly include the radial forces, torque ripple and inverter switching. The transmission path of noises can be very different, where the main paths are the stator, housing and auxiliaries. From these transmission paths the structural borne noises are transmitted to acoustic noises, also including the aerodynamic noises from cooling and slotting effects. Noises of aerodynamic harmonics and mechanical harmonics, not effecting the electromagnetic behavior, are mainly not in scope of this work.

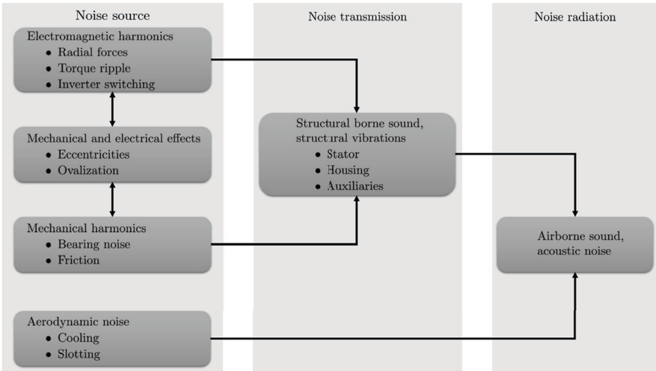


Figure 2.2: Noise sources in electrical drives

2.2 Terms and Definitions for Machine Acoustics

This section introduces the mathematical and physical expressions, which are needed for the general understandings of machine acoustics. Subsection 2.2.1 defines the general terms of waves and vibrations. Subsection 2.2.2 outlines the signal processing tools for acoustic analysis.

2.2.1 Definition of Waves and Vibrations

Vibrations are defined as oscillations on mechanical equilibrium points. It can be expressed as shown in (2.1), with its amplitude $\hat{y}$, time t, angular frequency ω and temporal harmonic order n [MM04]. The temporal harmonic order n is related to the angular frequency ω, thus $|n| = 1$ represents the fundamental vibration [MP06].

$$\boxed{y_\mathrm{n}(t) = \hat{y}\sin(n\omega t), \text{ with } n \in \mathbb{Z}} \tag{2.1}$$

Waves are defined with a temporal part $n\omega t$ and its spatial part $\nu k\alpha$. The sign of the spatial part defines the direction the wave moves. Waves are hereby, not like vibrations, oscillations on mechanical equilibrium points, shown in equation (2.2), with the spatial velocity k, the spatial points α and the spatial harmonic order ν. The spatial harmonic order ν is related to the spatial velocity k, thus $|\nu| = 1$ defines the fundamental wave with its temporal distribution parts n. A spatial wave can herewith oscillate temporal with order n, but keeps its spatial distribution ν. A special form of the wave is the standing wave, which occurs due to the contrary movement of two waves with the same amplitudes. This special form will play an important role in chapter 4 [MP06].

$$\boxed{y_{\mathrm{n},\nu}(\alpha,t) = \hat{y}\sin(n\omega t \pm \nu k\alpha), \text{ with } n,\, k \in \mathbb{Z}} \tag{2.2}$$

2.2.2 Signal Processing and Acoustic Analysis

In order to analyze the signal behavior of electrical drives, it's necessary to define the constraint and characteristics of the signals in subsection 2.2.2.1 and the transformation methods in 2.2.2.2. Subsection 2.2.2.3 shows the display formats the of fast Fourier transformations (FFTs) and finally the discretized filters in subsection 2.2.2.4, that are used in this work.

2.2.2.1 Signal Constraint and Characteristics

This subsection defines the requirements on the signal in time and space in order to transform it into its frequency domain [Boe13].

Periodicity

Time signals must have at least one period of a constant amplitude in order to transform into the frequency domain. Speed run-ups are performed, so that this condition is fulfilled in comparison to the relevant frequency. With this, quantities in the air-gap of the rotating induction machine are always periodic and stationary in one period.

Discretization

Time signals have to be sampled in order to discretize the signal and to analyze their behavior. The sampling of this signal has to occur in equidistant steps. Beforehand the time signal has to be filtered with at least half of the highest relevant signal frequency content [Nyq28]. The filter methods and their discretizition are shown in subsection 2.2.2.4.