Multi-Physic Analysis of Power Electronic Control Parameters in a Simulation Framework

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Abstract
Incorporating sound quality markers into optimization objectives is a new approach that aims to design more efficient and high-quality powertrains. In this paper, a digital framework, which combines different simulation environments, is proposed with the intent of investigating the influence of pulse width modulation strategies on vibroacoustic response and energy consumption of an electric drive unit. Different switching schemes and frequencies are relatively compared within this process. A high frequency, non-linear, 1D model of an electric drive unit is realized to estimate the phase currents and rotor position of a permanent magnet synchronous machine, for certain working conditions. These results are employed in a 2D electromagnetic FE model to estimate the magnetic forces in the air gap. The structural modes of the stator are calculated by means of finite element method. The vibration modes are used together with the magnetic forces generated previously to calculate a modal-based forced response. A vibroacoustic simulation generates the response up to 12.5 kHz for certain target positions. Finally, the acoustic spectral information is rendered in time domain and a sound quality assessment is performed on the synthesized signals using psychoacoustic metrics.

1 Introduction

Battery electric vehicles have gained significant popularity as a sustainable and efficient mode of transportation, offering several advantages over internal combustion engine-powered vehicles. These advantages include zero local pollutant emissions, simplified drivetrains and control algorithms, and reduced noise emissions. However, even with the overall noise emitted by electric drive units being lower in level than their ICE counterparts, the high-frequency components of the noise can still be perceived as annoying by the users. Therefore, it is crucial to prioritize vibroacoustic analysis and sound quality assessment during the early stages of electric drive development to ensure optimal sound quality levels. This work highlights the importance of such assessments and presents an efficient method that leverages multi-physics numerical models to achieve this goal. By exploiting the capabilities of these models, various aspects of the electric drives (e.g., noise and vibration, energy balance) can be accurately simulated and analysed. The proposed approach aims to enhance the development process of electric vehicles by effectively identifying and addressing potential noise-related issues, ultimately leading to improved sound quality and enhanced vehicle efficiency.

1.1 E-motor noise

The noise generated by a rotating electric machine can be separated into three different components: electromagnetic, mechanical, and aerodynamic [1]. It is widely acknowledged in the literature that the most relevant contribution is the electromagnetic noise [2], which is caused by the excitation of the machine's active elements by magnetostriction and reluctance forces (i.e., Maxwell stresses). If the effect of magnetostriction in noise generation may usually be neglected, the reluctance forces are the greatest contributors [3]. Maxwell stress is the formalization of how Maxwell forces arise from electromagnetic fields [4]. The net tangential reluctance force exerted on the rotor determines the average electromagnetic torque of the electrical machine. However, the presence of tangential and radial harmonics in this force can lead to unwanted vibrations and acoustic noise [1]. When the wavenumber of the magnetic forces along the airgap coincides with a structural mode of the stator, resonance occurs, resulting in a significant amplification of vibrations and acoustic emission [5]. Regarding the electromagnetic force, two distinct effects can be emphasized: (i) the slot-to-pole interaction, influenced by the machine's topology, and (ii) the generation of high-frequency harmonics in the stator currents, caused by the implementation of modulation control in the power electronics. This research primarily focuses on the latter effect.

1.2 Modulation techniques

Modulation techniques are employed to convert direct current power to alternating current power and to regulate the output voltage or frequency. The most used is the Pulse Width Modulation (PWM) technique. It involves varying the width of the pulses of a square wave to control the average value of the output voltage. By adjusting the duty cycle, the output voltage can be effectively controlled. Different modulation schemes can be employed in power electronics to achieve specific objectives. Some common modulation schemes include sinusoidal pulse width modulation (SPWM), space vector modulation (SVM), third harmonic injection (THPWM) and discontinuous schemes (DPWM1/2/3). Each scheme has its own advantages and disadvantages, such as harmonic content reduction, switching losses, and control complexity [6]. Another main parameter that influences the sound characteristics of the machine is the carrier frequency. It is an important parameter in modulation control as it affects the switching frequency and the overall performance of the power electronic system. The selection of an appropriate carrier frequency depends on factors such as the switching devices' capabilities, the desired efficiency, and the noise considerations. In this paper, the effect of switching frequency and schemes is assessed looking at the vibroacoustic behaviour and at the switching power losses.

2 Simulation framework

In this section, a multi-physic approach (Figure 1) that combines different simulation models is proposed to predict the effect of e-drive control parameters in terms of noise level, sound quality, and energy efficiency.

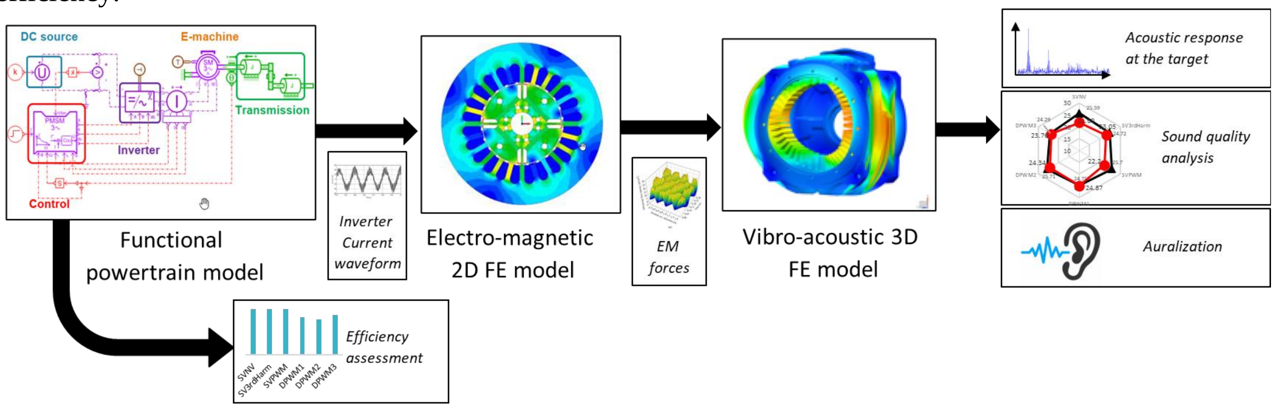

Figure 1: Simulation framework for a multi-physic analysis of e-drive control parameters

2.1 Lumped parameter model

A high frequency, non-linear, lumped parameter model of an electromechanical machine was realized in Simcenter Amesim 2020.2. The electromagnetic characteristics of the e-machine are modelled based on look-up tables of torque and flux linkage as a function of rotor angle and currents. This model considers all the non-linearity and the high-frequency behaviour associated with PWM current generation. A field-oriented motor control computes the voltage command according to the torque request. A space-vector PWM inverter control translates it into transistor commands. Additional sub-systems that complete the powertrain are the high-voltage battery and the vehicle dynamics model for reproducing the resistance loads applied to the motor according to the selected the driving condition (i.e., speed-torque values). Among the different quantities that can be efficiently calculated by this functional model, the key ones are, on the energy side, the losses caused by the switching components, while on the NVH side, the tri-phase current waveforms and the rotor angular position, necessary for the estimation of the electromagnetic forces that generate on the stator of the machine. These quantities are computed by a fixed step integrator with a resolution of 25 kHz.

2.2 Electromagnetic model

The three-phase current waveforms formed by the PWM control, and the rotor angular position are the inputs for the electromagnetic simulation to obtain the surface force density generated by the windings along the surface of the stator teeth as a function of the electrical angle and time. The method used for force calculation is based on the Maxwell stress concept [7, 8] which gives the stress, or force per unit area, directly in terms of the magnetic flux density. If B_n and B_t are the components of flux density normal and tangential to a surface, and σ_n and σ_t are the corresponding components of stress, then:

$$\sigma_n = \frac{B_n^2 - B_t^2}{2\mu_0} \tag{1}$$

$$\sigma_t = \frac{B_n B_t}{\mu_0} \tag{2}$$

Provided that the surface is closed, and passes entirely through air, the total force and torque may be determined by integrating the stresses over the surface.

For this specific study a 2D FE model of an Internal Permanent Magnet (IPM) synchronous motor was simulated using Simcenter Magnet 2021.1. The layout of the machine is shown in Figure 2.a, while its characteristics are listed in Table 1. The simulation consists in the calculation of the EM forces for different angular position with the aim of realizing a full rotation of the rotor. Rotational speed and torque are maintained constant during the simulation.

Rotor type	IPM with variable orientation magnets
Number of poles	8
Number of phases	3
Number of slots	48
Stator outer diameter	269 mm
Rotor outer diameter	162 mm
Stack length	50 mm
Air gap thickness	0.75 mm

Table 1: Salient characteristics of the IPM synchronous motor selected for the study

2.3 Vibroacoustic model

The aim of this simulation is to compute the acoustic response at exterior microphones placed around the component as shown in Figure 2b. The force field on stator teeth are exported from the EM model to the 3D vibroacoustic model that combine both the stator and the housing of the e-machine. The method used is the classic finite element combined with an Acoustic Transfer Vector (ATV). ATVs are arrays of transfer functions between surface normal velocity and acoustic pressure at field points. As a fast method for mapping vibration and vibroacoustic domains, it reduces the computation time under multiple operating conditions [9]. After mapping the electromagnetic mesh to the structural mesh with a Conservative Maximum Distance method, the EM forces are converted from time to frequency domain through a Fourier transform. The vibroacoustic solution provides both the displacement of the structure and the acoustic pressure levels at the target microphones. The software used for this analysis is Simcenter 3D 2206 [10].

2.4 Sound quality post-processing

The sound pressure computed at the targets is then processed to evaluate the simulation from a sound quality point of view. The first step consists in the audio synthesis of the spectral information. Assuming that the acoustic signal is periodic, since the simulation cover a full rotation of the rotor in constant speed condition, the signal can be repeated and transformed in time domain by applying an inverse FFT. The processed signals can be then listened to and post-processed to retrieve key indicators. The time-signal obtained is sampled at 44.1 kHz and repeated for 5 seconds. Finally, sound quality metrics are calculated by using Simcenter Testlab 2206.

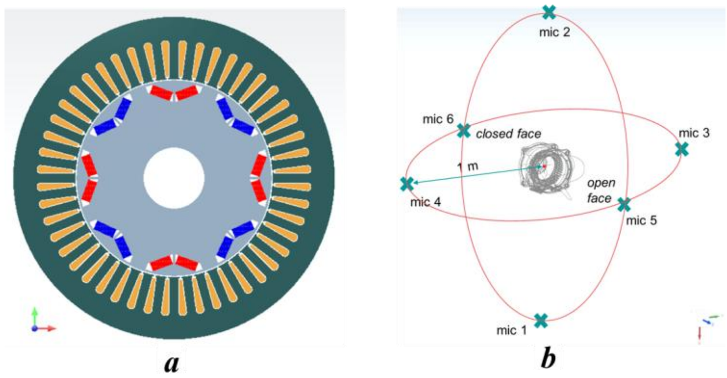

Figure 2: (a) cross section of the IPM motor, (b) position of the microphones around the structure: the open face is the one fronting the gearbox (not considered in the simulation).

3 Results

The effect of the PWM switching frequencies and schemes has been explored in a multi-physics analysis based on the described simulation framework, tackling modulation from an efficiency and a sound quality point of views. Different spectral quantities are presented in figure 3 up to 12.5 kHz to capture the effects of changing the carrier frequency of the modulated signal.

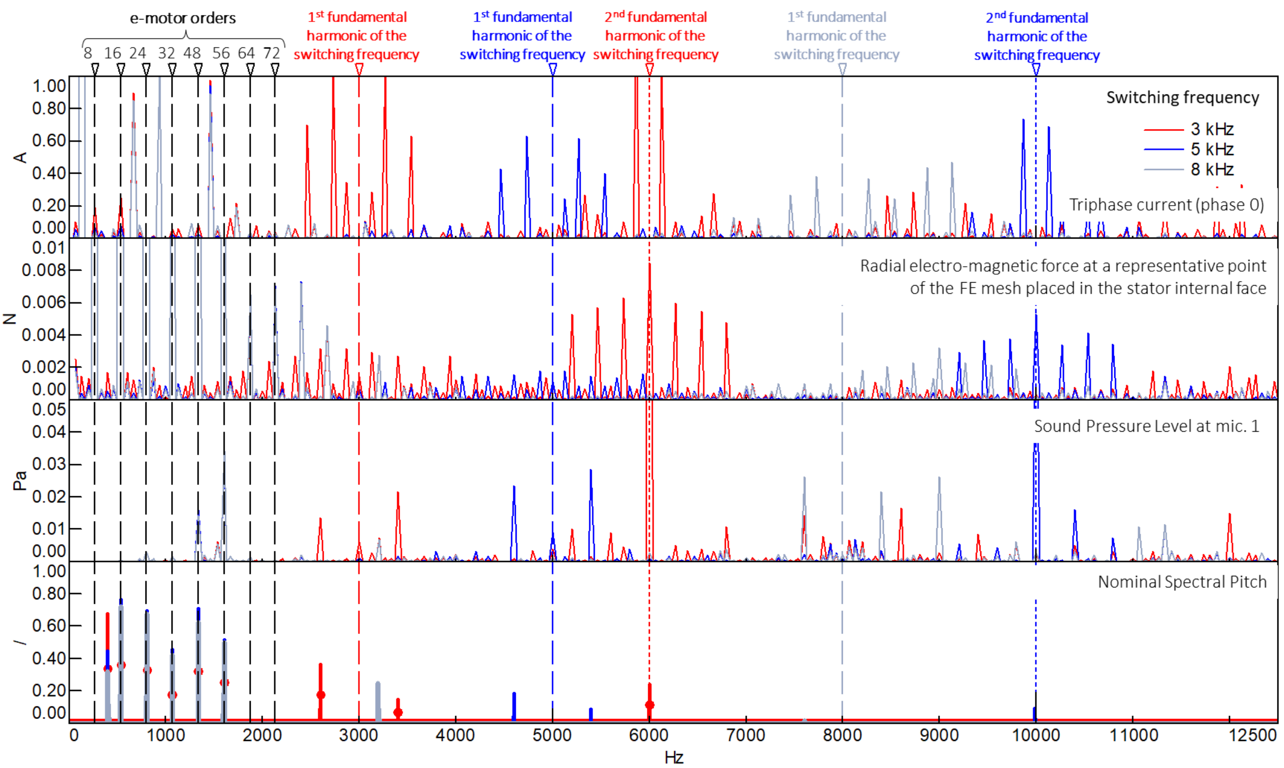

Figure 3: Comparison of results obtained by setting three different switching frequency. Speed is set to 2000 rpm, torque to 50 Nm, while the modulation scheme is the continuous space vector (SVPWM). Axes limits are set to highlight the effect of PWM.

First, the results show that changes in the switching frequency do not affect the order related to the topology of the machine (i.e., e-motor orders in Figure 3), as proved in literature [11]. Hence, order 8 and its harmonics present the same amplitude in terms of electromagnetic forces and sound pressure level in all the three cases. As expected, the presence of the PWM-related current harmonics is concentrated around the first and the second fundamental harmonic of the carrier frequency. It is worth to mention that for higher switching frequency corresponds a lower amplitude of the fundamental harmonic and related side bands. Besides a similar outcome, the radial force comparison shows the predominance in terms of magnitude of the side bands around the second fundamental harmonic over the harmonics related to the first fundamental.

As far as the acoustic pressure is concerned, the dynamic properties of the structure influence the response by filtering or enhancing the effect of the load in the whole spectrum. The second fundamental harmonics of the acoustic pressure are also the most prominent for all the switching scenarios.

Finally, the nominal spectral pitch provides a representation of the perceived sound: the metric confirms that the major role in the tonal contribution is played by the e-motor orders rather than the modulation harmonics. However, the effect of the first PWM fundamental harmonic and the side bands of the second one in the cases at 3 and 5 kHz, cannot be neglected.

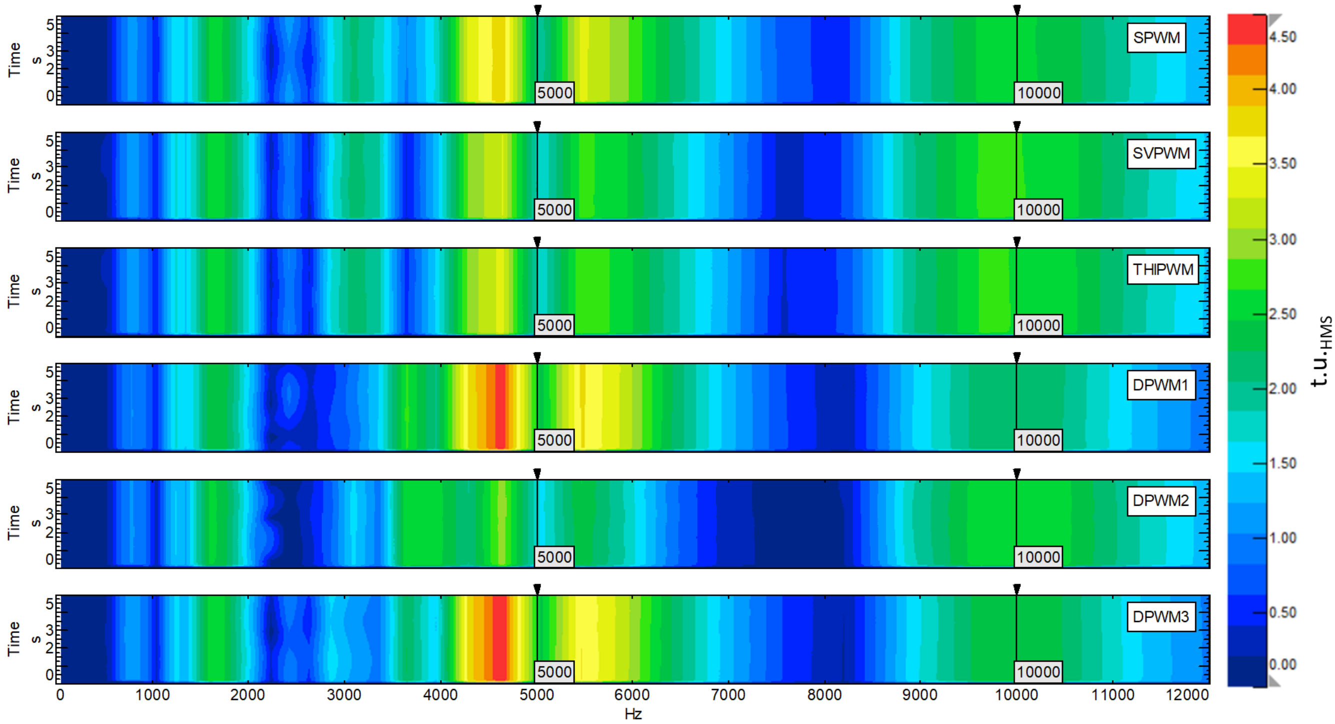

Figure 4: tonality of the synthesized sounds (mic. 1) expressed as function of frequency for different PWM schemes. Switching schemes compared are sinusoidal pulse width modulation (SPWM), space vector (SVPWM), third harmonic injection (THIPWM), discontinuous schemes (DPWM1, 2, 3). The switching frequencies is set to 5 kHz in all cases. Operational condition: 2000 rpm x 50 Nm.

Figure 4 shows the effect of different schemes on tonality (ECMA 74 An. G) as a function of frequency. Discontinuous schemes that generate higher harmonic magnitudes [12], show higher values of tonality around the fundamental harmonic of the PWM at 5 kHz.

At the same time, the effect of the same schemes can be evaluated in terms of energy consumption with the same simulation framework. A comparison in terms of switching losses is proposed in Figure 5. As expected, higher the switching frequency, higher the power losses related to modulation operations. In terms of schemes, the best results are achieved with discontinuous methods.

Finally, regarding the simulation duration, it is noteworthy that the total computation to run the whole processing and calculate the sound metrics necessitate approximately 20 minutes per combination of operating condition and parameter setting.

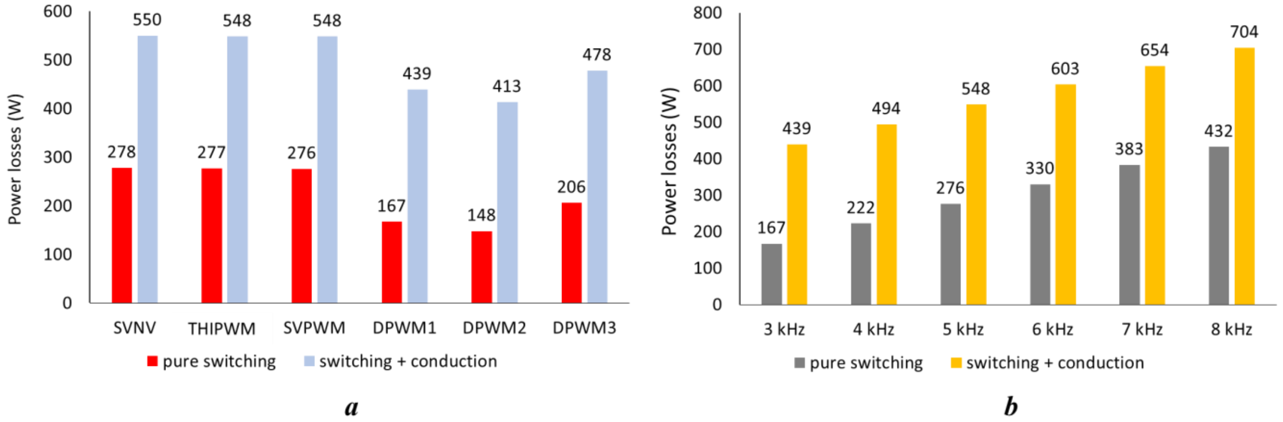

Figure 5: Results in terms of losses due to modulation. Comparison among different schemes (a) and carrier frequencies (b).

3.1 Conclusions

This paper introduces a digital framework that utilizes a multi-physics simulation approach to investigate the impact of PWM strategies on the vibroacoustic response and energy consumption of an electric drive unit. The study emphasizes the importance of incorporating sound quality markers into the optimization objectives for designing efficient and high-quality powertrains. By leveraging different simulation environments, the proposed framework accurately models electric and vibroacoustic physics of the machine, allowing for comprehensive analysis of noise and vibration, energy efficiency, and sound quality. The results of this study provide evidence that the choice of PWM switching schemes and frequencies has a substantial impact on the vibroacoustic behaviour and energy losses of the electric drive unit. It is observed that increasing the switching frequency theoretically results in lower amplitudes of the fundamental harmonic and its associated sidebands. However, it is important to note that the modal frequencies of the structure can significantly influence the overall impact of switching harmonics, by altering the acoustic emission characteristics. Furthermore, tonality comparison evidence some difference in the acoustic perception of selected modulation schemes. The results provide valuable insights for the development process of electric vehicles, enabling engineers to identify and address noise-related issues early on, thereby enhancing sound quality and optimizing powertrain efficiency. The authors are currently working on extending this approach from stationary to transient operating conditions.

Acknowledgments

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