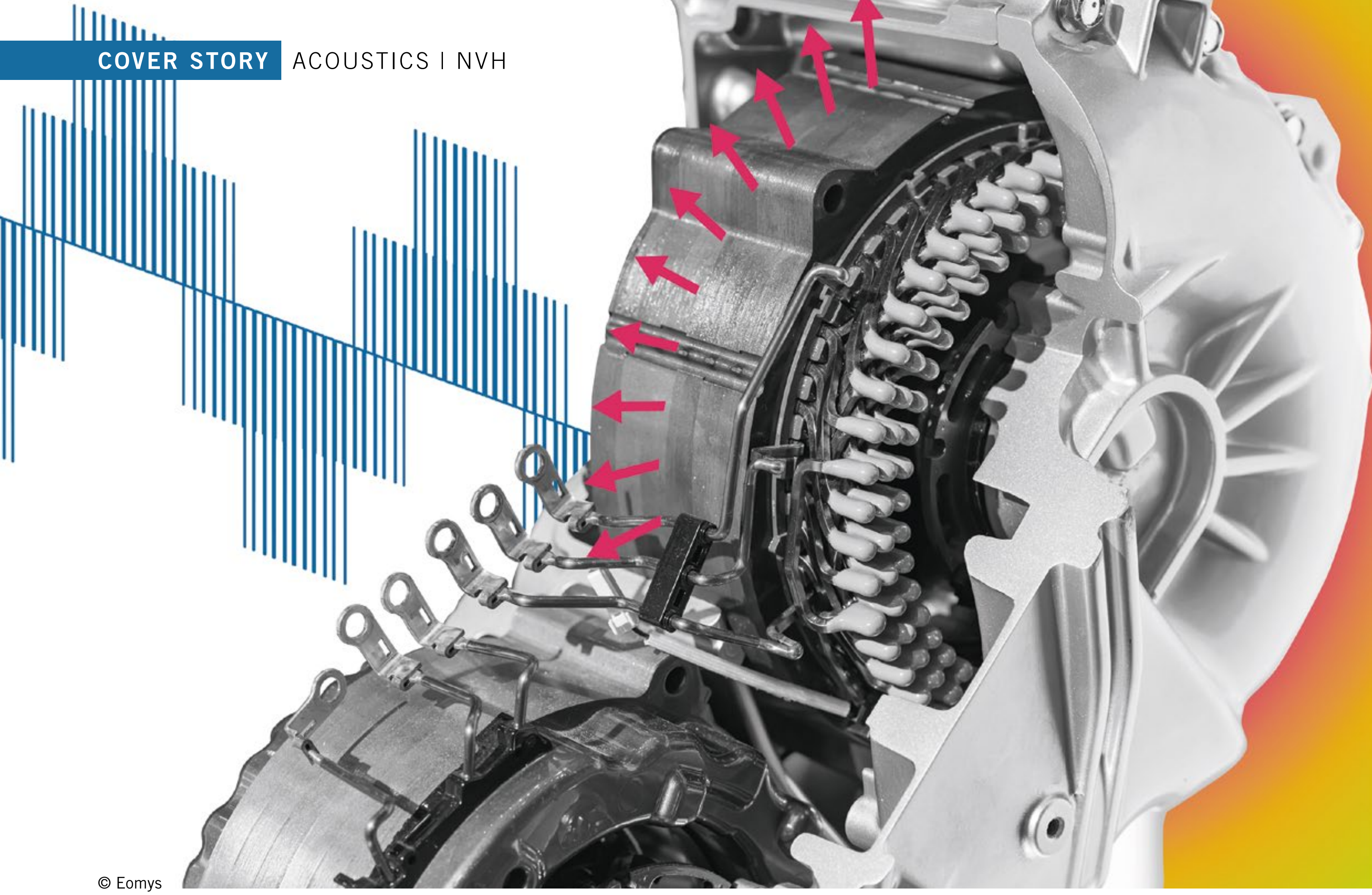


© Eomys

ADEQUATE NOISE LEVEL

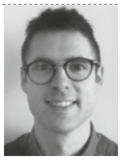
Acoustic noise sources in Hybrid Electric Vehicles (HEVs) or Electric Vehicles (EVs) must be controlled to guarantee an adequate level of acoustic comfort to both passers-by, drivers and passengers. Electric vehicle noise and vibration sources can be split into mechanical (for example tire/road, transmission), aerodynamic (for instance wind and fans) and electromagnetic (for example so-called airgap reluctance variations or electric motor slotting and inverter switching) origins.

In this article, Eomys focuses on often unpleasant switching noise caused by power electronics, also called Pulse Width Modulation (PWM) noise, which may be responsible for unpleasant sounds in Electric Drive Units (EDUs). First, the physics of the PWM sound generation principle is detailed, from voltage to magnetic excitation harmonics. Second, the sound spectrum characteristics of EV or HEV applications are derived analytically to make conclusions on sound quality aspects of switching noise. Finally, examples of sound measurements of commercial hybrid and electric vehicles are presented and interpreted.

NVH IN ELECTRICAL SYSTEMS

In recent years, there has been a growing interest in Noise, Vibration, Harshness (NVH) of hybrid and electric drives in HEVs or EVs due to several design challenges brought by electrification technologies. One of these so-called electric NVH challenges is the management of new excitation sources in electric drives, which are caused by electromagnetic forces as a result of mag-

AUTHORS

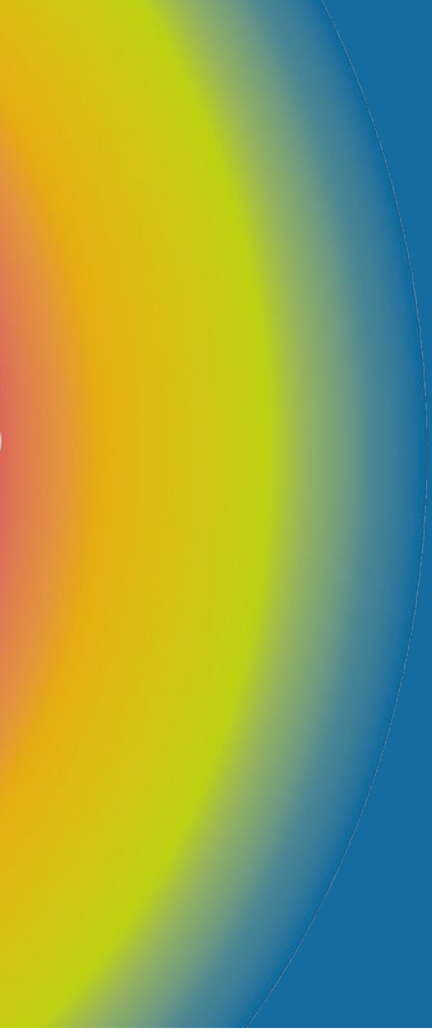


Dr.-Ing. Emile Devillers
is R&D Engineer in Electrical Engineering at Eomys in Lille (France).

Dr.-Ing. Paul Gning
is R&D Engineer in Electrical Engineering at Eomys in Lille (France).

Dipl.-Ing. Karine Degrendele
is R&D Engineer in Vibro-Acoustics at Eomys in Lille (France).

Dr.-Ing. Jean Le Besnerais
is CEO and R&D Engineer at Eomys in Lille (France).



Sound Quality Aspects of Electric Vehicles

Power electronics can cause unpleasant switching noises in hybrid and electric vehicles coming from the electric motor. To ensure comfort for passers-by, drivers and passengers, Eomys has conducted numerous tests on electric drives. The right choice of the inverter frequency can help reducing switching noise level according to the electric motor type.

netic field variations. Magnetic forces include Maxwell forces and magnetostriction forces, the latter being only significant in passive devices such as transformers. Based on Eomys' experience on more than 100 electrical machines, Maxwell forces are the driving electric NVH excitation sources in EV/HEV applications.

Electromagnetic forces tend to attract rotor and stator in electrical machines, similarly to magnets with opposite polarities. Two types of magnetic forces can be distinguished in electric motors: so-called slotting forces, coming from slot-to-pole interactions in Permanent Magnetic Synchronous Machines (PMSM), and switching forces, coming from current time harmonics induced by power electronics. Depending on their frequency and physical origin, magnetic forces are characterized by a particular shape along the airgap called wave number. One well-known magnetic excitation acting on both rotor and stator is called torque ripple; it corresponds to a pulsating force in tangential direction. Torque ripple is a peculiar magnetic force. It represents only one part of all magnetic force types present within the electromechanical conversion. Torque ripple and other possible excitation shapes are presented in **FIGURE 1**, which were generated using the Manatee software developed by Eomys.

Magnetic forces which apply to rotor and stator structures can be represented as traveling stress waves, written as couple $\{f, r\}$ where f is the excitation frequency and r the wave number. When the stator is submitted to such a force harmonic, normal deflection of the stator-housing assembly may occur, resulting in air-borne noise. Rotor magnetic vibrations may create structure-borne noise, especially in the case of $r = 1$ (unbalanced magnetic pull), **FIGURE 1**. Large vibration and noise levels can occur in case of resonance, when the magnetic force shape matches a stator or rotor modal shape and when its excitation frequency matches the corresponding natural frequency.

VOLTAGE AND CURRENT HARMONICS AS A RESULT OF PWM

As the shaft rotation speed is proportional to the fundamental frequency of Alternative Current (AC) motors (such as PMSM), variable speed traction applications require the generation of three-phase variable-frequency currents. Power electronics components do not include tunable frequency sine current sources; however, Direct Current (DC) voltage and switches (IGBTs) are available, and crenel shape voltage waveforms can be generated by switching from high voltage (generally provided by the battery of an EV/HEV) to zero voltage at some particular commutation times.

The PWM technique is often used in three-phase voltage inverters to create a quasi-sinusoidal current at a specified frequency in the stator winding of the electric motor. The aim is to create voltage pulses of different widths, **FIGURE 2**, which are based on the comparison of a carrier triangular waveform of frequency f_{swi} (switching frequency) and a modulating sinusoidal waveform of frequency f_{s} (stator current fundamental frequency). Due to the presence of inductances in the electrical circuit, voltage pulses are smoothed and current can increase sinusoidally as the sliding average of the voltage waveform increases and decreases.

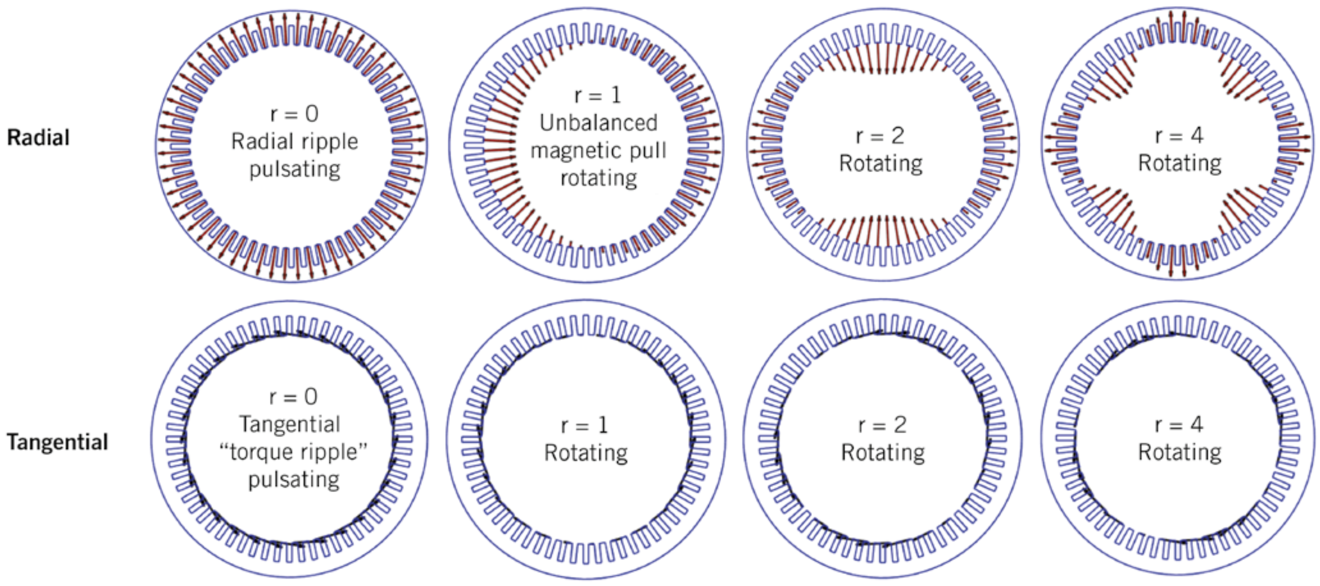


FIGURE 1 Examples of radial and tangential magnetic force types applied to the stator of an electric motor (© Eomys)

One can show that this modulation technique creates small-magnitude high-frequency harmonics in the voltage and current waveforms. For standard PWM strategies such as Sine PWM (SPWM) or Space Vectors PWM (SVPWM), the frequencies of these harmonics can be described by $f_{\mathrm{PWM}} = mf_{\mathrm{swi}} \pm nf_{\mathrm{s}}$ where m and n are integers with opposite parity, $n > 0$ and not multiple of number of phases q_{s}. As seen in **FIGURE 3**, the amplitude I of PWM current harmonics depends on modulation index D, which is the ratio of DC bus voltage to fundamental phase voltage [1]. Largest current harmonics occur at $2f_{\mathrm{swi}} \pm f_{\mathrm{s}}$ at starting and $f_{\mathrm{swi}} \pm 2f_{\mathrm{s}}$ in cruising mode.

HARMONICS OF THE PWM MAGNETIC FORCE

Maxwell forces are proportional to the square of flux density. In PMSMs, stator excitation field is proportional to the stator current, and rotor excitation is constant due to permanent magnets. Therefore, magnetic force harmonics due to PWM mainly come from the product of stator PWM flux harmonics and rotor fundamental flux.

Largest rotating flux waves due to PWM can be written as $\{f_{\mathrm{PWM}}, p\}$ where p is the number of pole pairs of the electric motor, while the rotor fundamental flux is $\{f_{\mathrm{s}}, p\}$. Assuming a symmetrical PWM strategy, the first order of magnetic forces induced due to PWM can be calculated combining these two flux harmonics. Wave numbers and frequencies of the magnetic force are obtained by adding/subtracting the ones of each flux density wave. PWM adds pulsating $r = 0$ and rotating $r = \pm 2p$ force wave numbers around multiples of switching frequencies. In case of an inner rotor PMSM with "high" number of pole pairs p (typically $p = 4$ in automotive applications), pulsating magnetic force harmonics dominate the NVH response, **FIGURE 4**, as vibration deflections of high wave number $2p$ tend to have lower magnitude and radiation efficiency.

This explains why in EV and HEV applications with standard PWM switching noise does not appear exactly at one switching frequency (only sidebands around it) but at twice the switching frequency. Besides at start, PWM noise is dominated by twice the switching frequency group modulated at $6f_{\mathrm{s}}$.

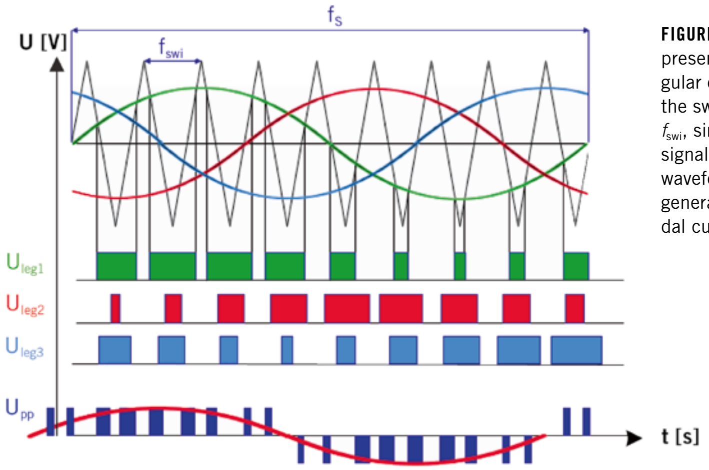


FIGURE 2 Schematic presentation of the triangular carrier waveform with the switching frequency f_{swi}, sinusoidal modulating signals and output voltage waveforms U_{leg1} to U_{leg3} generate the quasi-sinusoidal current U_{pp} (© Eomys)

SOUND QUALITY OF PWM NOISE

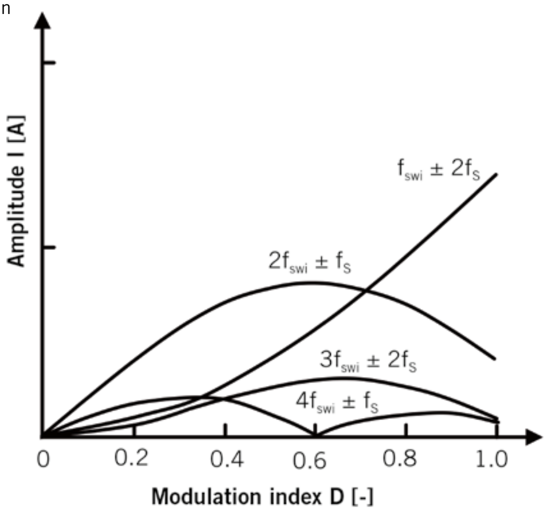
The switching frequency can vary from 250 Hz to 20 kHz depending on electric traction applications and converter current. The larger is the switching frequency, the higher are converter losses. In EVs, switching frequency tends to be minimized to improve electric drive efficiency, but maximized to lower

NVH and Electromagnetic Interference (EMI) impact.

PWM noise can sound unpleasant for several reasons. First, a part of switching noise is steady so it does not convey any driving speed information. Second, switching noise can be prominent at low driving speeds where wind and road noise are not playing any masking role. Then, PWM noise can sound like an annoying whistling noise, as it is characterized by high tonality and high prominence ratio.

Finally, PWM sound is characterized by strong roughness due to modulation effects. Roughness appears when the ear is not able to distinguish two close individual pure tones, typically when the frequency difference is between 10 and 300 Hz. A fluctuating envelop is then created, giving the unpleasant feeling of roughness. Roughness depends on the center or carrier frequency f_c (corresponding to f_{swi} or $2f_{swi}$ in PWM starting case), modulation frequency (corresponding to $6f_s$ in PWM starting case), and the modulation index m. For $m = 1$, roughness maximum is independent from switching frequency varying between 1 and 8 kHz. The roughness perception m is maximum when the modulating frequency is around 70 Hz [2].

FIGURE 3 Schematic presentation of the amplitude *I* of current harmonics in function of the modulation index *D* [1] (© Eomys)



EXAMPLES OF SWITCHING NOISE IN EV AND HEV APPLICATIONS

In NVH spectrograms, harmonics of an asynchronous PWM strategy appear as V-shape lines, as switching frequency is fixed independently of driving speed. In a synchronous PWM strategy, where the switching frequency is proportional to the rotational speed, more complex patterns appear.

FIGURE 5 shows spectrograms of two NVH test campaigns for EVs (Nissan Leaf) and HEVs (Hyundai Ionic) run by Eomys [3] where PWM noise harmonics are highlighted with white arrows. High frequency noise of Nissan Leaf occurring around 5, 10 and 15 kHz are due to PWM associated to an asynchronous switching frequency of 5 kHz. In agreement with theory, highest PWM noise harmonics occur at $2f_{swi}$ at start-

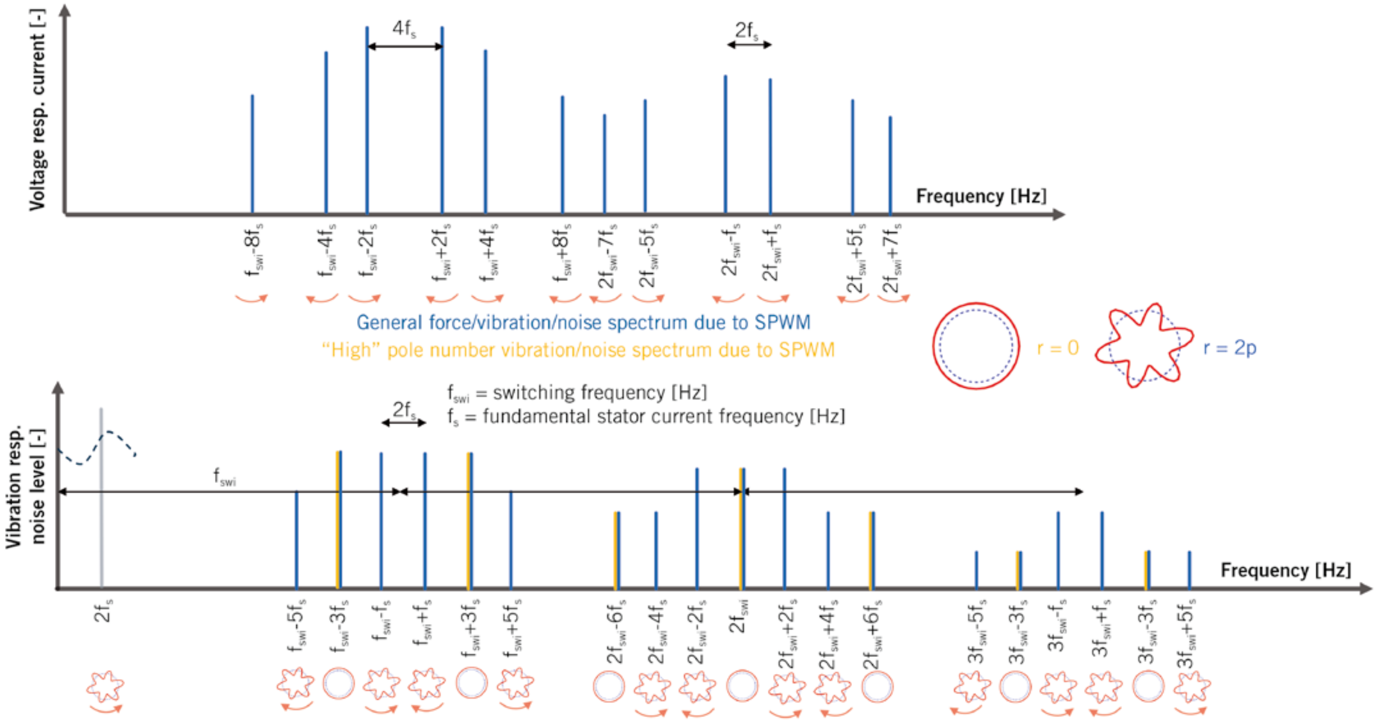


FIGURE 4 Schematic presentation of the spectrum of PWM voltage and current (top) as well as of the PWM electromagnetic excitation forces (bottom) (© Eomys)

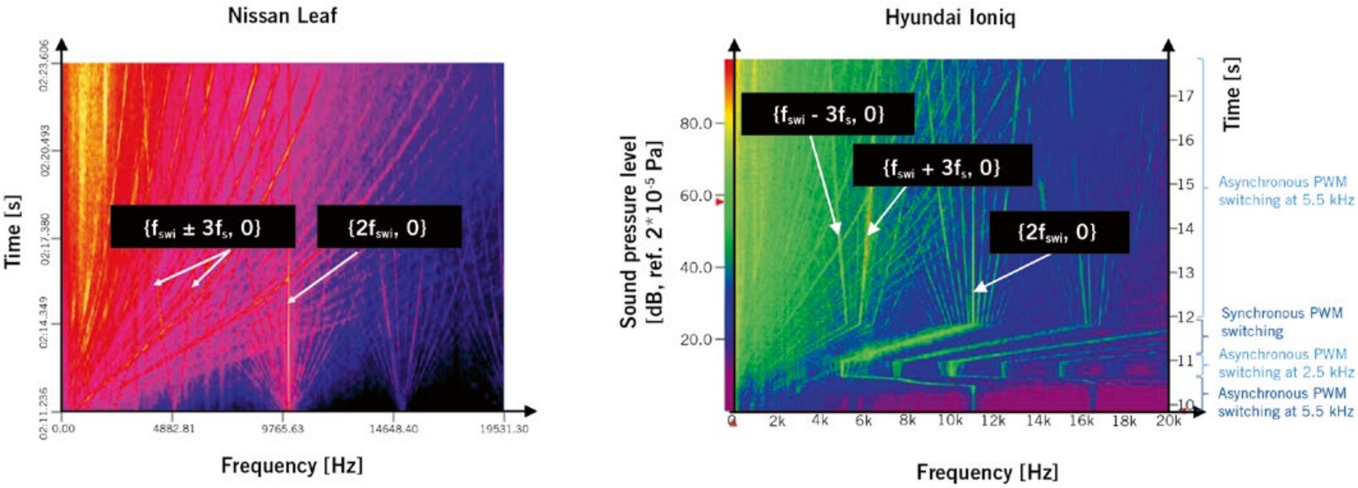


FIGURE 5 Sound pressure level spectrogram of an electric powertrain during run-up at maximum torque close to engine for the Nissan Leaf (left) and for the Hyundai Ionic (right) (© Eomys)

ing of the vehicle and $f_{swi} \pm 3f_s$ at higher speed.

In the Hyundai Ionic case, a more complex commutation strategy introduces sudden slope changes over speed; this particular strategy may be used to reduce switching losses or improve the NVH behavior. A resonance is visible in the acoustic spectrogram near 6 kHz which probably corresponds to the match between PWM pulsating forces and stator lamination breathing mode.

PWM strategies of these two vehicles as well as of other EV and HEV applications observed by Eomys are summarized in **TABLE 1**. It can be seen that the asynchronous PWM strategy predominates in the market.

CONCLUSION AND RECOMMENDATION

Power electronics modulate the supply voltage waveforms of variable rotational speed electric powertrains, resulting in additional current harmonics in AC motors. New electromagnetic forces are consequently introduced around multiples of switching frequencies associated to wavenumbers 0 and $\pm 2p$ where p is the number of pole pairs, resulting in a potentially unpleasant air-borne noise with strong roughness. The choice of switching frequency can help reducing switching noise level by avoiding resonances between electric powertrain (especially stator breathing mode) and magnetic forces, while the choice of the commutation strategy (for example with Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), Discontinuous Pulse Width Modulation (DPWM), General Discontinuous Pulse Width Modulation (GDPWM) and Random Pulse Width Modulation (RPWM), depending on the motor type) can help improving PWM sound quality.

It is highly recommended to assess switching noise issues in early design stage in order to avoid the application of acoustic temporary solutions in the late development phase, because this could result in additional weight, heat, cost and production delays. NVH design optimization can be carried along with electric powertrain virtual prototyping using combined electrical, electromagnetic, structural mechanics and acoustic numerical modeling as proposed by Manatee software solutions [4] from Eomys.

Car maker	Car model	Motor topology	PWM strategy	Switching frequency f_{swi} [kHz]
BMW	i3	HSM	Asynchronous	8.0
Hyundai	Ionic	PMSM	Variable	2.5 to 5.5
Nissan	Leaf	IPMSM	Asynchronous	5.0
Opel	Ampera	IPMSM	Asynchronous	10
Renault	Twizy	SCIM	Asynchronous	8.0
Renault	Zoe	WRSM	Asynchronous	10.0
Smart	Fortwo	IPMSM	Asynchronous	10.0
Tesla	X90D	SCIM	Asynchronous	5.5
Toyota	Prius 2004	IPMSM	Asynchronous	2.5
Volkswagen	E-Up	IMPSM	Asynchronous	9.0

TABLE 1 Summary of PWM strategies of multiple EV and HEV applications (HSM = Hybrid Synchronous Motor, PMSM = Permanent Magnet Synchronous Motor, IPMSM = Interior Permanent Magnet Synchronous Motor, SCIM = Squirrel Cage Induction Motor, WRSM = Wound Rotor Synchronous Motor) (© Eomys)

REFERENCES

[1] Ueda, S.; Honda, K.; Ikimi, T.; Hombu, M.; Ueda, A.: Magnetic noise reduction technique for an AC motor driven by a PWM inverter. In: Transactions on Power Electronics 6 (1991), No. 3 (July), pp. 470-475

[2] Fastl, H.; Zwicker, E.: Psychoacoustics. Facts and Models. Berlin, Heidelberg: Springer-Verlag, 2007

[3] Eomys Engineering (ed.): Audio files of electromagnetically-excited noise. WAV-Format, online: https://eomys.com/e-nvh/audio-files-of-electromagnetically-excited-noise/, access: March 23, 2020

[4] Eomys Engineering (ed.): Manatee. Magnetic Acoustic Noise Analysis Tool for Electrical Engineering. Software, version v1.09.01, online: http://www.manatee-software.com, access: April 20, 2020