

Wavelet Analysis for Frequency Disturbance Characterization in an Electric Vehicle

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ABSTRACT

Reduction of CO₂ emission is a mandatory objective for every actor in the field of automotive transport, and electric vehicles (EV's) are increasingly becoming an effective option for both OEMs and customers. However, components development and vehicle integration for EV's present new challenges that must be faced and new issues which need to be solved. In particular electric motor control systems are developed to achieve the same comfort conditions as in conventional vehicles. IDIADA developed a prototype electric commercial vehicle in which both the motor and driveline were integrated. The electric motor output shaft delivers the torque to the transmission under a certain level of load variation and with torque irregularities that must be smoothed out in the transmission components. This paper studies the results of the testing of the prototype vehicle carried out to improve the overall NVH behavior of the powertrain. The test results revealed that abrupt change in frequency content must be limited in order to avoid torque irregularities from the motor to the transmission. The abrupt change in current from the inverter to the motor was also studied by means of the wavelet analysis to reduce a given frequency range of load irregularities. This methodology permits a very accurate study in the frequency and time domain allowing the detection of the changes in time of the signals even for slight deviations and helps to properly specify the motor control characteristics. This study enabled the definition of the powertrain specifications and the electric motor control system for the entire vehicle speed range.

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INTRODUCTION

Recently, IDIADA developed its own electric light-duty vehicle. The main advantages of electric LDT's (Light-duty Trucks), namely lower running and maintenance costs, zero-emissions and eco-friendly image heavily outweigh their disadvantages: higher charging time compared to ICE (Internal Combustion Engine) vehicle refueling and shorter range. These advantages make electric LDTs viable due to the fact that they are compatible with the driving cycle requirements of fleet customers.

The noise level generated by electric LDTs is generally expected to be lower than that of conventional powertrains. However, other noise components that are usually masked by the ICE are clearly perceived, as the overall noise is lower. Interior and exterior noise can be characterized by high-frequency noise components that are usually subjectively perceived as unpleasant or annoying by the vehicle's occupants. Similarly, high-frequency load contribution which is unusual in ICE powertrains can appear in mechanical parts

and jeopardize the life of mechanical components; presenting new challenges in electric vehicle integration, NVH and durability at design phase.

Hence, in the development of the LDT particular care was taken to smooth out the effect of high-frequencies in noise and vibration. An analysis using different motor loads and conditions was carried out in order to verify noise and vibration content. The field weakening strategy for the torque control caused abrupt change in the current at a specific speed and the corresponding torque variation effect had to be smoothed out to avoid possible comfort and reliability issues. Hence, the calibration of the inverter was analyzed and modified in order to improve the motor working conditions both for vibration and noise and to lower the effect of the torque control on the NVH performance.

ELECTRIC LIGHT-DUTY VEHICLE DRIVELINE

Vehicle Description

After detailed benchmark analysis, IDIADA electrified a light-duty truck. One of the project targets was to maintain the maximum number of carry-over parts in order to control the development cost and the project timing; and, for this reason, Body-in-White, rear axle, propshaft and engine mount positions were maintained. A virtual model of the vehicle with the main components is shown in [figure 1](#).

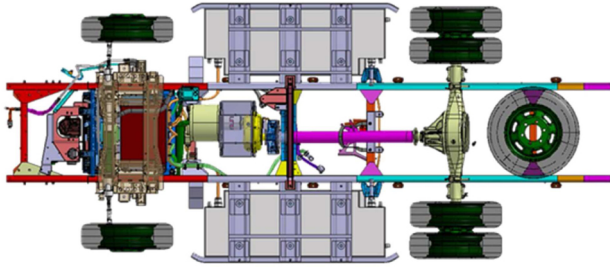


Figure 1. vehicle virtual lay-out

All control functions were integrated in the E-drive Control System (a specific in-house-developed control unit for EV's). The software was developed using Simulink and makes use of automatic code generation.

The electric motor was a three-phase Permanent Magnet Brushless Synchronous Motor of 400 Nm and 145 kW that allowed regenerative braking, fed with operating voltage range of 300 to 420 VDC and input current limitation at 500A. The power was provided by the same supplier's inverter with PWM control and IGBT module power device working at 12.5 kHz switching frequency. A torsional damper was installed in the output shaft to reduce torque ripple effect and isolate vibrations. A single stage reducer (ratio 2.678) was installed in order to combine the gradeability target (30%) with the maximum speed target of 80 km/h. [Figure 2](#) shows the motor subframe, the motor, the motor brackets, the torsional damper and the motor mounts with the reducer.

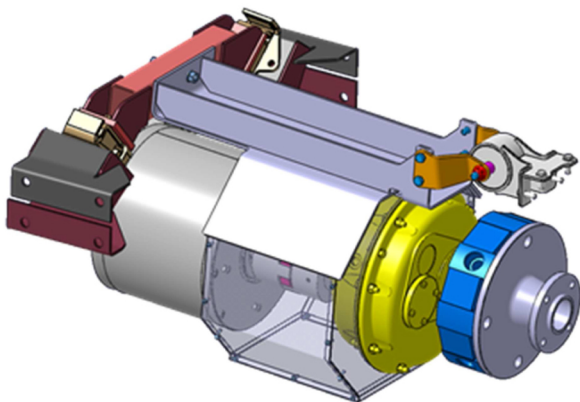


Figure 2. powertrain virtual lay-out

An overall positive evaluation was obtained during the validation process when the electrified truck was compared to the ICE, whereas during the evaluation process, some of the evaluators stated that some high-frequency tonal components were slightly annoying, especially at medium vehicle speeds. Considering that this vehicle is aimed to be driven mainly in cities, this exterior noise was judged as important as, together with low speeds, medium speeds are the most used due to the fleet cycles. The low-frequency content was judged as acceptable due to the lower level obtained in comparison with the ICE.

Measurements

After the evaluation, interior and exterior noise were measured in order to determine the annoying frequency components and to try to reduce their contribution to the perceived noise. Acceleration of mechanical components was also measured to determine whether the high-frequency acoustic components noticed in the overall evaluation also appeared in the form of vibrations. For this purpose, two different inverter switching strategies were tested to study the influence of the inverter calibration on the high-frequency noise and vibration.

To perform the tests, the vehicle was placed on the roller test bench in IDIADA's hemi-anechoic chamber as shown in [figure 3](#). The use of the hemi-anechoic chamber also allowed the isolation of the powertrain noise from other contributions such as aerodynamic noise or road noise that should remain at the same level as in ICE vehicles. The tests performed on the roller test bench were ramp accelerations from 0 to the maximum vehicle speed in about 45 seconds for two different inverter calibrations.



Figure 3. vehicle a hemi-anechoic chamber

For the purpose of this study, a microphone was placed close to the electric motor to evaluate the noise radiated by this element, an accelerometer was also placed on the motor to measure the vibration and, finally, ring amperometric clamps were placed on the inverter outputs in order to

measure the current delivered by each phase to the engine. All the signals were measured synchronously with a sampling frequency of over 65 kHz to allow study and correlation of high-frequency phenomena. Figure 4 shows the microphones installed close to the motor. The proximity of these microphones to the noise source allows the origin of the annoyance and the relation with the exterior noise to be identified.

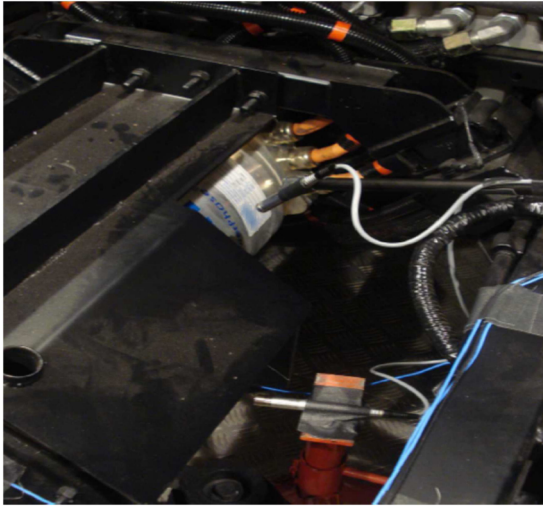


Figure 4. microphone and accelerometers instrumentation

Previous Results

An analysis presented by Iturbe J. *et al.* [1] of the current signal for the first software configuration hereby defined as “0” (see figure 5 below) shows that the main orders present are the order 9th and 27th. Some harmonics are present in the current signal such as 18th, 36th, 45th, 54th and further higher content. Current delivered by the inverter shows a transition line at around 3500 rpm. For motor speeds higher than this value, the harmonic content is higher than at lower speed.

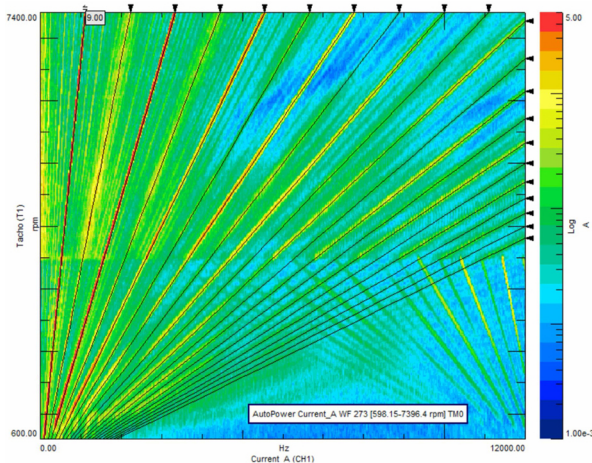


Figure 5. current spectral map for conf. 0 (rpm vs. Hz)

In figure 6 the spectral map of the noise signal shows that the orders 9th, 27th and 54th are clearly present and contribute to the annoying frequency. This is due to in the 9 pole pairs three-phase motor characteristics.

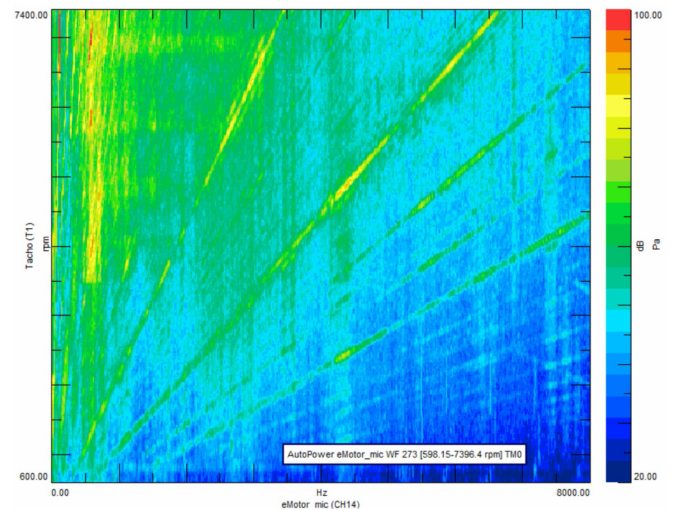


Figure 6. noise spectral map for conf. 0 (rpm vs. Hz)

The spectral map of the accelerometer signal in figure 7 shows particularly orders around the 27th and 54th and some resonance between 3000 Hz and 3500 Hz.

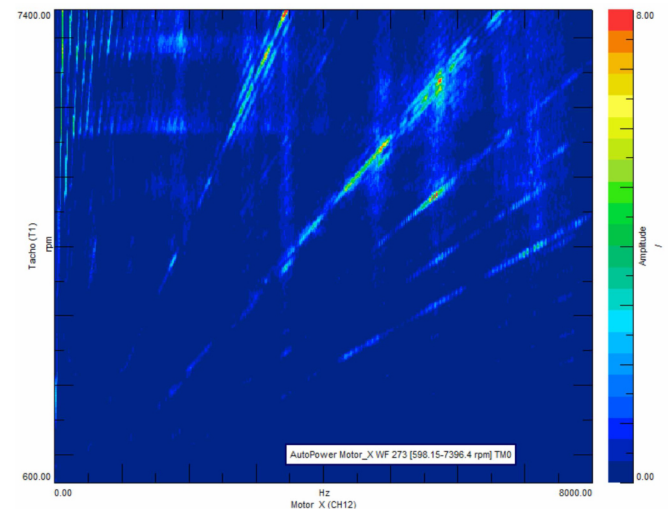


Figure 7. vibration spectral map for conf. 0 (rpm vs. Hz)

The effect of the discontinuity of the motor control on the noise and vibration signal is quite difficult to infer from the order analysis. Some more energy content can be observed starting from around 3500 rpm only in the current main orders and resonance frequencies.

Therefore, in order to deepen the study of the transition in the motor control, a specific tool was used. The wavelet transform is able to detect abrupt change in a signal both in the frequency and in the time domain. The characteristic of

the discontinuities in the current and their possible effect on noise and vibration of the motor are then studied in the next paragraphs.

WAVELETS

Continuous wavelet transforms are relatively recent mathematical tools which allow decomposition of signals into both time and scale. As detailed by Farge in [2] the scale decomposition is based on a convolution of a set of functions formed by dilation (l) and translation (τ) of the chosen mother wavelet (Ψ) with the signal as evidenced in [equation 1](#) and shown in Appendix A [figure A1](#).

$$\psi_{l\tau}(t) = \frac{1}{\sqrt{l}} \psi \left[\frac{t - \tau}{l} \right] \quad (1)$$

A particular wavelet well-suited to quantitative analysis of time series is the Morlet mother wavelet which is a sine wave of frequency k modulated by a Gaussian envelope of unit width as evidenced in [equation 2](#), where i corresponds to the imaginary unit and shown in Appendix A [figure A2](#).

$$\psi(t) = e^{ikt} \cdot e^{-(t^2/2)} \quad (2)$$

As it is a progressive complex-valued wavelet, the phase shift between its real and its imaginary parts allows the wavelet's oscillations when visualizing the wavelet coefficients power to be eliminated.

It can be noted that, due to only dilation or compression transform, the shape of the wavelet never changes in time domain, but its time duration and its amplitude does. Whereas, in frequency domain, its spectrum is a Gaussian-like function that is centered at higher frequency with increasing frequency range support while reducing the scale.

This is the reason why the continuous wavelet transform is well-suited to analyzing the local differentiability of a signal and for detecting and characterizing possible singularities. At the same time it is not very accurate in frequency domain especially due to its increasing spread at lower scales. It is therefore a potentially useful tool for detecting and identifying transient information in non-stationary signals and signals having time-dependent spectral characteristics, but it is not so well suited for performing order analysis. A detailed analysis of the different transform comparison is depicted in [Appendix A](#).

WAVELET APPLICATION

The Morlet continuous wavelet transform from [equations 1](#) and [2](#) yields a two dimension complex number transform from a one dimension signal. Hence the information is split in time and frequency at the same time. Generally the absolute value of the resulting complex number is used and eventually the phase of the complex number is studied too. In this post-processing of the wavelet transform just the power, that is the

squared absolute value as defined in [equation A1](#), is evidenced in the two-dimensional colormap plots. [Figure 8](#) shows the wavelet transform power coefficient of the current signal with motor speed [rpm] in abscissa and frequency [Hz] in y axis for software configuration 0. The order 9th of the current is evidenced throughout the ramp with a power spread around the main 9th order's frequency. The spread in frequency, as commented before, is due to the wavelet frequency content spread at lower scales. This phenomenon is more and more evident at increasing frequencies, for instance, the orders between 45th and 63rd are spread in the frequency range between 3000 Hz and 6000 Hz in the ramp during the acceleration from 3500 rpm. It can also be noted the fixed frequency of 12500 Hz during the first part of the ramp that corresponds to the switching frequency of the inverter.

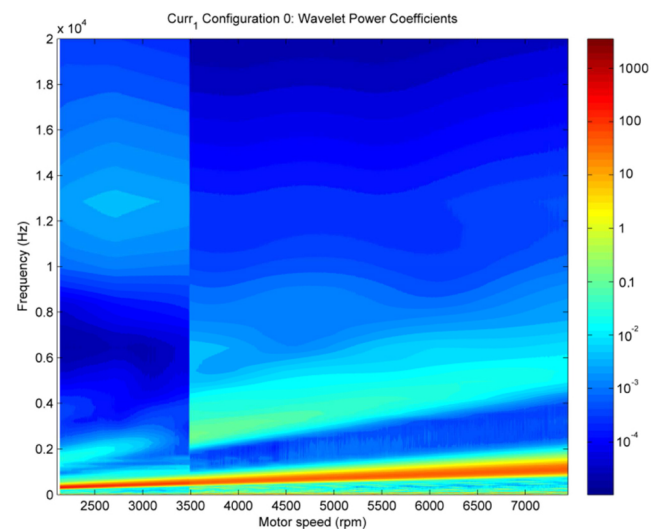


Figure 8. wavelet transform power coefficient P (Hz vs. rpm) for current signal in software configuration 0

The transition corresponding to 3500 rpm, speed at which the torque control system changes to field weakening commutation, can be clearly observed. In fact, for motors used for electric drive, at increasing speed the torque must be limited and the field weakened when the phase voltage reaches its nominal value. For a permanent magnet motor, reducing the field is not trivial and relatively complex approaches allow field weakening to be performed. The concept is generally to weaken the total field by injecting a negative field current in the direct axis that opposes the fixed excitation from magnets via the controller system [3]. The software of the torque control system of the first application, called configuration 0, had the characteristics that are evidenced by the wavelet transform of [figure 8](#) corresponding to a given noise and vibration content that must be improved. The paper deals with what happens in the current during the passage to field weakening commutation for two different

software controls as well as in vibration and noise as a consequence of the torque that was not measured directly.

Figure 9 shows the wavelet power coefficient of the current intensity signal for the second configuration of the software of the torque control.

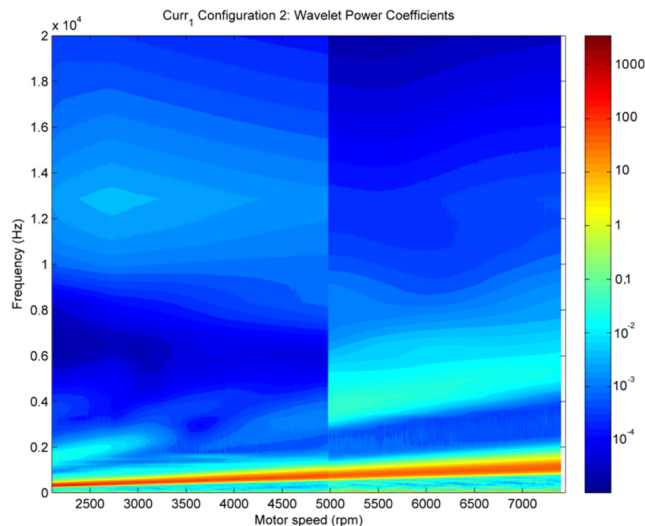


Figure 9. wavelet transform power coefficient P (Hz vs. rpm) for current signal in software configuration 2

It can be noted that the transition occurs in this case at 4975 rpm, and for the medium speed range there is less power content in the frequency range between 3000 Hz and 6000 Hz. After the commutation to field weakening strategy at 4975 rpm, the spread at around 54th order was noted for configuration 0 is also observed. In both cases even the lower frequencies of the 9th order receive more power in the field weakening area than before, whereas the switching frequency of 12500 Hz continues to be present until the commutation speed and almost disappears after. Further post-processing is needed to extract the maximum information: in Appendix B the different quantities that were calculated from the wavelet transform coefficient are explained in detail.

Figure 10 shows the comparison of the energy content obtained by integrating the power coefficients in time as defined in equation A2. The maximum energy content is in both software configurations at around the 9th order.

At lower energy levels it is possible to detect 3000 Hz and 6000 Hz peak in both cases but at higher value for configuration 0 at 3000 Hz. Due to the fact that the time integration emphasizes the duration of a given phenomenon, the calculation of the power (eq. A3) as “average” of the energy against time is proposed in figure 11 where the frequency content around 3000 Hz is confirmed to be noticeable for the configuration 0 after the 3500 rpm speed corresponding the field weakening commutation transition.

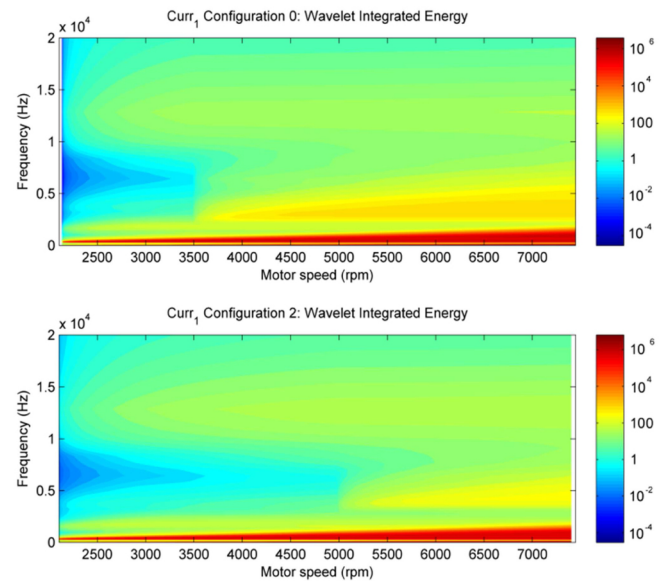


Figure 10. wavelet transform energy coefficient E

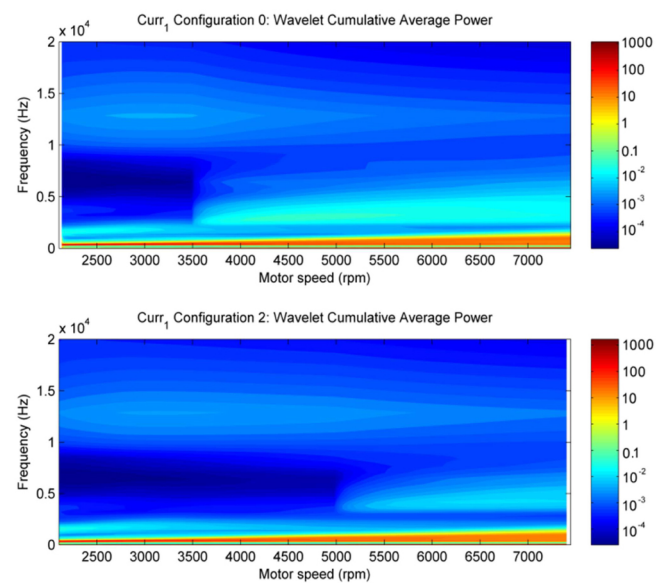


Figure 11. wavelet transform average power coefficient (Hz vs. rpm)

Finally, the direct comparison of the power wavelet transform between configuration 0 and 2 is shown in figure 12 via the ratio of the values at corresponding speed and scale (eq A4).

The higher value of instantaneous power for configuration 0 in the ramp between 3500 and 4975 rpm is very evident in the frequencies lower than those of the 9th order (525 to 750 Hz), and frequencies between 3000 Hz and 6000 Hz, while for speed lower than 3500 rpm and higher than 4975 rpm the ratio is close to 1. The red and brown areas show ratios higher than 5 times while the blue and cyan areas show the complementary frequency range where the configuration 2