Development of electromagnetic compatibility tests in a simulated environment

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ABSTRACT

With the continuous advancement and integration of various electronic systems in the automotive segment, it is increasingly necessary to pay attention to aspects of electromagnetic compatibility (EMC), since these electronic modules can interact causing problems with each other, which can impair the system's operation. Although there are correction and prevention techniques, such as filters and shields, the development of these protections depends on several, often complex, aspects related to EMC, and vary according to the applied techniques and range of action. Regulatory norms are imposed by international entities to limit the level of electromagnetic noise allowed, which are applied by vehicle manufacturers in their electronic products. Laboratory tests in general have high price when it comes to certification during the development phase. In this context, the implementation of an EMC analysis by simulation, still in the product design phase, allows the reduction of validation and re-design costs, identifying beforehand points of improvement in the design. Therefore, the purpose of this work was to develop some tests such as conducted emissions with the help of Ansys Electronics Desktop software, to carry out analyzes and check design variables.

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INTRODUCTION

The implementation of electronic systems in passenger and commercial vehicles, due to automation and electrification of systems, is increasing. Aspects of electromagnetic compatibility (EMC) become relevant, especially when it comes to design of circuits, connectors, cables and the like, since these electronic modules can interact causing electromagnetic compatibility problems, interfering with each other. Although there are correction techniques and protection such as filters, shields, layout and arrangement of electronic components, the development of solutions depend on several aspects that are often complex related to electromagnetic compatibility and vary according to the techniques and operating ranges [1]. This makes it difficult to identify problems and their root cause, which can impair the functioning of systems. Thus, regulatory standards are used to limit the level of electromagnetic noise allowed [2].

For the automotive segment, the main regulation is CISPR 25 for automotive modules. Therefore, it is important that, during the development of electrical and electronic equipment, the possible sources of electromagnetic emissions are identified. Late identification of sources of interference, often during the test phase, leads to high costs for design changes and delays in product delivery. The implementation of an EMC analysis by simulation, still in the product design phase, allows a more accurate view of the electromagnetic compatibility and susceptibility cases, enabling design changes to be made at lower costs. For these reasons, the simulation of EM-emissions generated by electronic devices is the subject of several studies, in which methodologies are sought that can reliably and adequately predict the fields generated and voltages induced by these systems, the same way it allows an assessment of the device to external disturbances [1].

Currently there are several commercial electromagnetic simulation software that use various numerical methods such as Finite Element Method (FEM), Boundary Element Method (BEM), in addition to other solvers such as IE (Integral Equation), SBR (Shooting Bouncing Ray) which approximates the wave propagation in terms of radius, transient simulation and eigenmode solver [3]. These softwares discretize geometric models, Computer Aided Designs (CAD), and for high frequency electromagnetic simulations use the characterization of these systems through the scattering method, where it is possible to obtain the S parameters of high frequency circuits. Thus, it is possible to perform numerical modeling and simulation of electromagnetic fields generated by electronic devices.

To reduce certification costs of the development of electronic modules, and consequently reduce the number of tests in laboratories, models of conducted emissions were developed. The selected software was Ansys Electronic Desktop (AEDT). This work covers the methodology used for the development of the conducted emissions models, as well as the comparison between the results of a case study and laboratory measurements. It is expected a reduction of up to 60% of the tests in laboratories, only the tests for certification being necessary, as well as a reduction in the number of samples, development time and reduction of failures, as shown in the figure 1.

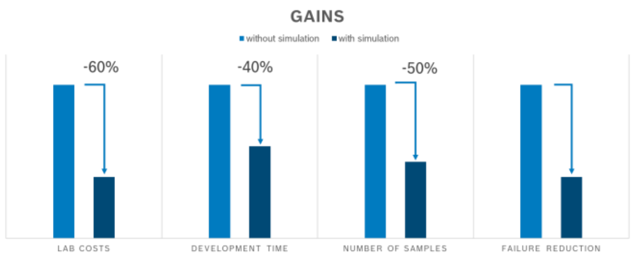


Figure 1. Possible gains with EMC test simulation

ELECTROMAGNETIC INTERFERENCE

Electromagnetic interference (EMI) is the process by which unintentional disturbances generated by electronic systems propagate to other equipment and impair its functioning. Electromagnetic compatibility (EMC), on the other hand, is associated with whether a system or group of systems is electromagnetically compatible. Thus, a system is considered electromagnetically compatible when it meets the following criteria [4]:

- Does not cause interference above defined limits.
- Not troubled by emissions from other systems.
- Does not interfere with itself.

The susceptibility to external disturbances is related to propagated fields that couple in input and output wires, being conducted to the interior of the unit. The main receivers are transmission lines, critical electronic components like some Integrated Circuits (IC) and sensitive adjacent printed circuit board (PCB) traces or cables [2]. In this scenario, tests such as conducted emissions and radiated emissions are applied, in which CISPR 25 standard defines the emission limits for modules used in vehicles.

Interference coupling can be radiated or conducted (inductive and capacitive coupling respectively), as shown in Figure 2. Historically, the most important problem of EMI appeared with the invention of high-density electronic components [1]. Almost all electronic functions are implemented digitally, for the benefit of increased switching speed and miniaturization of IC. This means an increase in noise density and expansion of the range of spectral content (faster signal switching). Especially in electronic systems, high power switches can generate significant interference [3].

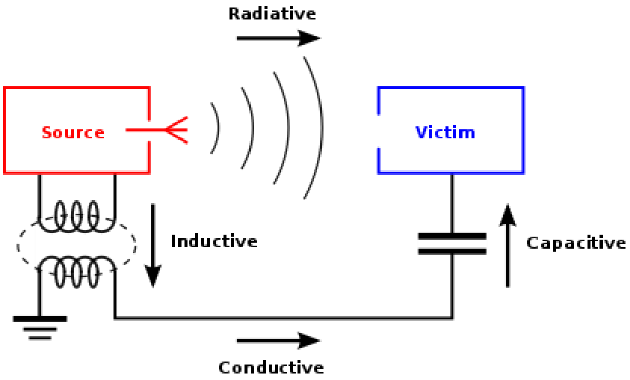


Figure 2. EMI representation

One way to evaluate both compatibility and electromagnetic interference resistance is by developing numerical models for the systems of interest, for example: populated PCBs, mechanical structures such as antennas, connectors, and others. The analysis of electromagnetic models starts with an evaluation of the power part of the electrical circuit because it is where the highest levels of voltage and current occur. Where there are sources of variable – periodic or non-periodic – electrical signals with high amplitude, there can be a source of interference [1].

However, for many practical problems it is not possible to compute the integrals analytically, being necessary to start with numerical models, either to reduce the computation of the domain in finite elements, or to solve the integrals numerically. Although numerical methods give approximate solutions, the solutions are accurate enough for engineering purposes [4].

CHARACTERIZATION OF HIGH FREQUENCY ELECTRICAL CIRCUITS

The characterization of high frequency electronic systems is performed differently from Thevenin's methods, as phenomena related to the reflection behavior of the signals begin to impact the result. The method consists of characterizing the system through the scattering matrix [5]. Figure 3 shows a two-terminal electronic component, and the characterization of the input and output signals, as well as the coefficients for the composition of the matrix. Power inputs, electronic components and structures can be modeled as ports. The scattering indicates what fraction of an applied voltage wave is transmitted or reflected at each port.

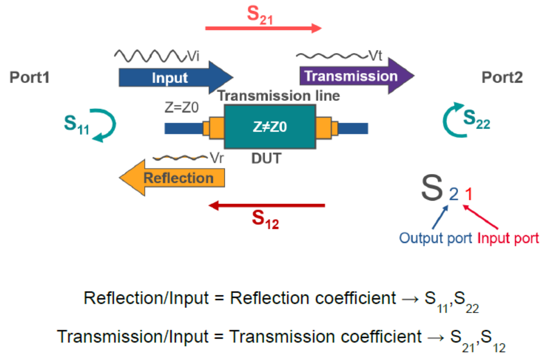


Figure 3. HF characterization of electrical system

In practice, these results are obtained with VNA (Network Vector Analyzers), which sweeps the frequency with sinusoidal signals of constant amplitude and phase and evaluates the reflection and transmission characteristics of the ports of interest [5]. Through the network theory (quadrupole), the electrical characteristics of traces, via, components and geometries are computed. Both the scattering matrix theory and the VNA compose the response of the system of interest with the characteristics of each port, the coefficients contain information such as impedance, both magnitude and phase values. Thus, with the characteristic values of each coefficient, it is possible to obtain the dynamic behavior of HF electrical systems [4].

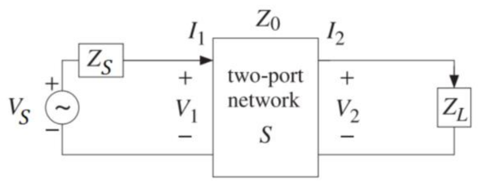


Figure 4. Quadruple representation of HF electrical system

In Figure 4, there is a representation of a 2-port network, where Z represents the impedance, I current and V voltage and the sub-indices referring to each port.

HIGH FREQUENCY ELECTROMAGNETIC SIMULATION

As previously mentioned, the software chosen for the development of the models was AEDT. As described in the previous sections, the characterization of HF electrical systems stems from the scattering method, that is, the AEDT, discretizes through the analysis by distributed parameters, using numerical methods, and composes the scattering matrix, with the ports defined in the model.

The values of the frequencies (module and phase) responsible for the excitation of the device and the time step of the simulation are configured. The model discretization, mesh and response directly depend on these adjustments. For most applications, the FEM solution in the frequency domain is sufficient to obtain the response of the fields. The maximum frequency of interest must be defined at the beginning of the modeling, because it is associated with refinement parameters of the mesh and consequently the discretization and response of the system [7].

To test the real conditions of the system it is necessary to carry out a co-simulation of the circuits involved, in the software in question there is a module for the simulation of the circuits, which uses the S parameters computed in numerical analysis. With the state-space behavior of the system under study, it is possible to carry out analyzes of the dynamic behavior of electronic systems, considering different geometries and materials, applied in the configuration setup.

With the simulation of the S parameters and the electrical circuit, it is possible to carry out excitations of the signals, to represent the real conditions of the model. Here the main conditions of electromagnetic compatibility tests, such as conducted and radiated emissions, can be represented, either in a simplified way or with maximum detail.

To provide the excitation of the electronic device under analysis, the model needs gates, which for the characterization of electrical/electronic systems are components and structures that are part of the device. The methodology applies the quadrupole analysis method, which has the advantage of using the same reference or ground. In this case what matters is the voltage difference between two elements, so instead of creating 4 ports to prescribe the input reference, only 2 ports are needed. An example is presented in figure 5, which represents a PCB trace. The same goes for the representation of two terminal electronic components, where only one port is needed, considering of course the polarity. This simplifies the model and maintains a good representation [4].

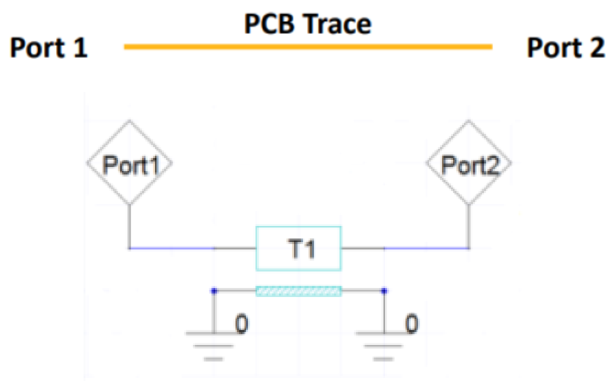


Figure 5. Example characterization of a PCB trace [7]

With this workflow it is possible to extract the S parameters from the CAD model of the test setup, emulate the conditions with the real operating signals and carry out the measurements of the conducted emissions test.

To validate the model, parametric variations were performed with the objective of evaluating the behavior of the emission pattern, the analyzes were variation of the rise time and fall time, of the load, and of the duty cycle. Comparing the results obtained through the simulations and laboratory measurements, it was possible to verify a similarity with the values of the electric fields emitted by the electronic device, proving the effectiveness of the proposed methodologies.

MODELS

Simulated conducted emissions tests were performed in accordance with the CISPR 25 standard, whose setup is shown in figure 6, with remote ground configuration. The simulations were also performed with the configuration described by the development team that was in the laboratory during the period of the tests.

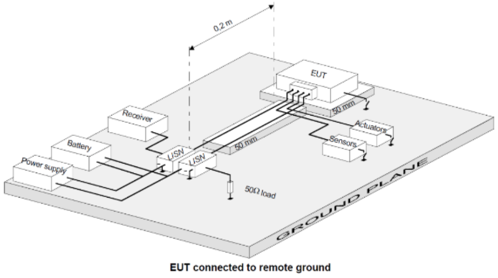


Figure 6. Conducted emissions – Example of test setup for EUT (Equipment Under test) [8]

The developed methodology is based on the modeling described in [7], and in the discretization of the model following the procedures adopted for capturing the signal, according to the filters applied in the standard and in the EMC detector. Therefore, some assumptions were adopted to elaborate the model.

The method for the model development method was:

- Analysis of the schematic.
- Identification of the power circuit.
- Obtainment of components' SPICE[1] models
- Identification of power circuit components in ECAD[2] and CAD files.
- Neglection of coupling impedance of component terminals and solders.
- Excitations modeling of electronic components.
- Definition of boundary conditions.
- Definition of initial conditions.
- Characterization of materials and dimensions.
- Circuit Simulation.
- Definition of the maximum simulation frequency.
- Discretization to compose the model according to the standard.
- Results analysis.

The conducted emissions test aims to assess how much electrical interference in a frequency range is conducted from the EUT (Equipment Under Test) to the external environment. For this, a LISN (Line Impedance Stabilization Network) is used to standardize the impedance and filter only the range of interest and ensure that the only source is the EUT [8]. Therefore, all models were evaluated on the positive output of the LISN, in order to be able to compare their results with the real measurements.

The tested device is part of an electronic module, and its main function is to drive four resistive loads, controlled by transistors. The module consists of a PCB and a mechanical structure, which acts as a heat sink for the transistors, and which ends are the terminals for the wiring harness connector. Much of the current flows through the area of this mechanical structure. As it is possible to extract the S parameters from the geometric characteristics, as well as the characterization of the materials used and to test the behavior, four models were elaborated:

1. The module model (PCB plus structure).
2. Module plus setup of CISPR25 conducted emissions.
3. Model of the mechanical structure of the module plus measurement setup carried out in the laboratory.
4. Complete model plus measurement setup carried out in the laboratory.

The device was tested in accordance with an internal standard for measuring conducted emissions, in which the limit frequency is 87 MHz. The models were discretized according to the EMC detector used, following the discretization of the sampled signal in the test receiver standard, as shown in the table 1. The results were evaluated from 100 kHz up to 87 MHz

Table 1. Analysis range and scan configuration used during actual measurements.

Range	Step	Detector
100 kHz – 300 kHz	4 kHz	Average
300 kHz – 530kHz	4 kHz	Average
530kHz – 2 MHz	4 kHz	Average
2 MHz – 5,9 MHz	4 kHz	Average
5,9 MHz – 6,2 MHz	4 kHz	Average
6,2MHz – 26 MHz	4 kHz	Average
26 MHz – 30 MHz	4 kHz	Average
30 MHz – 68 MHz	40 kHz	Average
68 MHz – 87 MHz	40 kHz	Average

In addition to this range, the representation of the model at low frequency was considered, as it operates at a low frequency [7]. For representation and optimization of

[1]SPICE - Simulation Program with Integrated Circuit Emphasis

[2]ECAD - Electronic Computer Aided Design

computational cost, the following discretization of the models was defined.

Table 2. Model discretization.

Range	Step
0 Hz – 100Hz	1 Hz
100 Hz – 100 kHz	5 kHz
100 kHz – 300 kHz	4 kHz
300 kHz – 600 kHz	5 kHz
600 kHz – 10 MHz	15 kHz
10 MHz – 30 MHz	15 kHz
30 MHz – 70 MHz	15 kHz
70 MHz – 87 MHz	50 kHz

RESULTS

All models were co-simulated in an AEDT circuit simulation module, that is, with the S parameters and the SPICE model of the electronic components. Circuit simulations were carried out with the real operating characteristics, such as supply voltage, characteristics of the load, control voltage of the gates of the transistor, all presented in the table 3. The objective of the analysis of the circuits was to evaluate the signal integrity, the relation of input and output electrical values and operation characteristics to consider the real condition in the 3D model.

Table 3. Conditions of the device considered in the modeling.

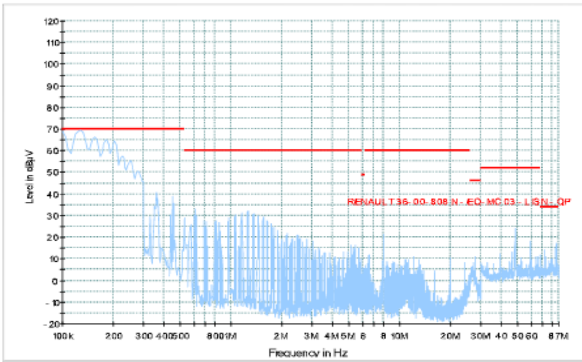
Initial conditions		
Input voltage	V_{in}	13.5 V
Switching frequency (PWM)	f_s	32 Hz
Load resistance	R_heater	560 mΩ
Gate voltage control	V_g	24 V

Analyzing the circuits with the S parameters of the model is a way to ensure that the model is working correctly. After validating the characteristics of the model signal, according to the excitation points, it was possible to perform the conducted emissions measurements.

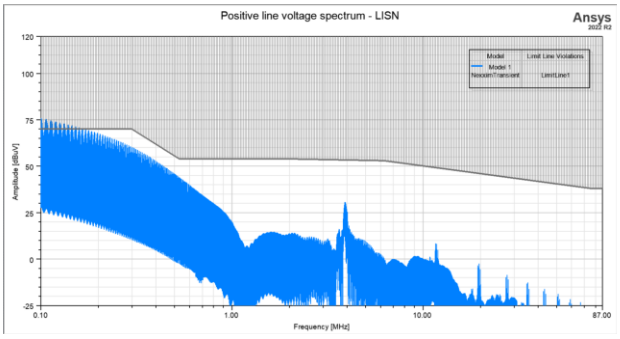
MODEL 1 – To simplify the test, as high frequency models tend to have a high computational cost, only the CAD files – mechanical structure and PCB – were considered. It was assumed that the main source of emissions is the device itself, that is, the influence of cables and laboratory equipment was not considered, considering only the S parameters of the device in question. In practice, it is known that cables and power supplies in the laboratory of real measurements impact the result, due to the possibility of signal coupling by the cables.

In the model, all components of the power circuit, such as resistors, capacitors and power supply connection were defined ports for model characterization.

Even though this is a simplification, that is, not considering the cables or the geometry of the LISN and power supply, the attenuation rate per decade is similar until up to 1 MHz, as presented in figure 7.



(a) LISN positive line emission spectrum – Quasi-peak. Real measurement



(b) LISN positive line emission spectrum –Simulated measurement

Figure 7. Comparison of the real measurement (a) in LISN and the result of model 1 (b)

MODEL 2 – Model 2 uses the CISPR25 remote ground configuration. All the components of the power circuit were modeled, with the difference that it was considered the ports in the geometry of the LISN and the load simulator, as shown in figure 8.

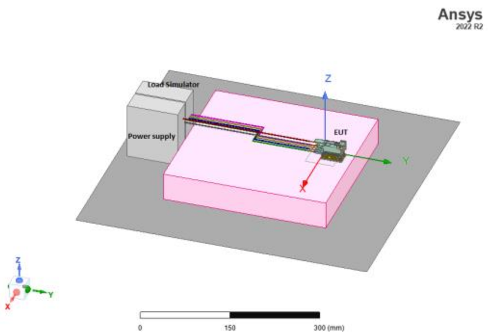
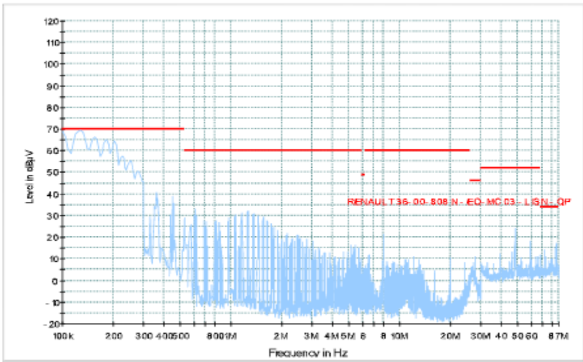
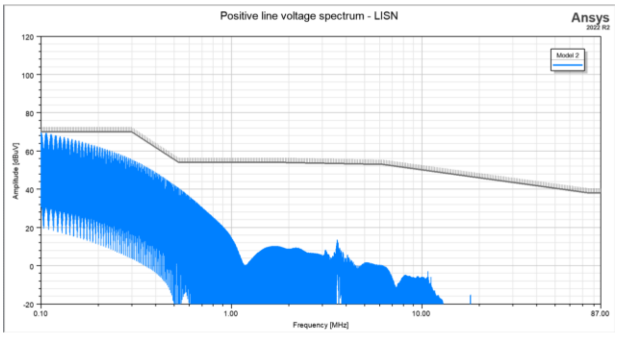


Figure 8. Setup of model 2

In this model, it is noticed that there were reductions in the values at high frequency, above 1MHz, since the impedance coupling of the cables is considered.



(a) LISN positive line emission spectrum – Quasi-peak. Real measurement



(b) LISN positive line emission spectrum –Simulated measurement

Figure 9. Comparison of the real measurement (a) in LISN and the result of model 2 (b)

MODEL 3 – Model 3 is a simplification since the circulation of high current levels occurs only through the mechanical structure.

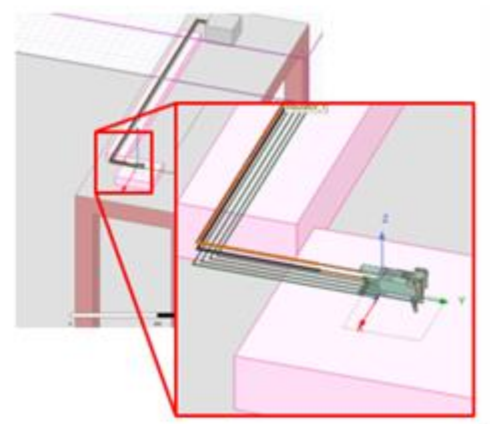
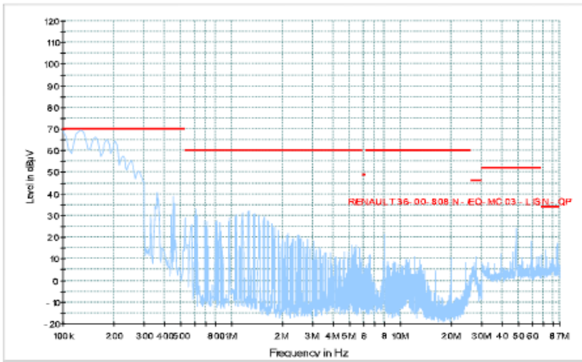
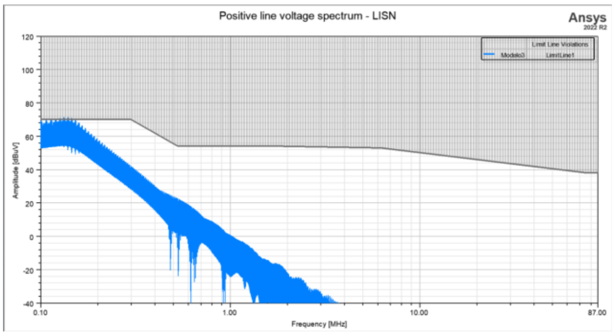


Figure 10. Setup of model 3

In this model, the greatest contributions of the geometry are at low frequencies, which in this case means the spectrum below 1 MHz.



(a) LISN positive line emission spectrum – Quasi-peak. Real measurement



(b) LISN positive line emission spectrum –Simulated measurement

Figure 11. Comparison of the real measurement in LISN (a) and the result of model 3 (b)

MODEL 4 – Model 4 showed similar amplitude levels consistent with the real measurements. The model also considered PCB plus mechanical geometry, besides power supply and LISN geometries, with the ports defined in these geometries. In addition to the table configurations, the characteristics of the grounded and conductive table and floor were added, with the same values as the actual laboratory specification.

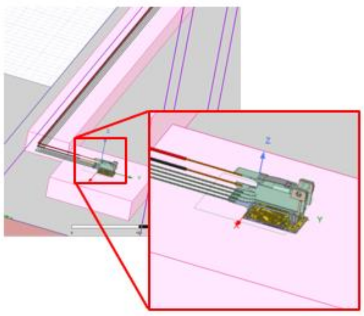
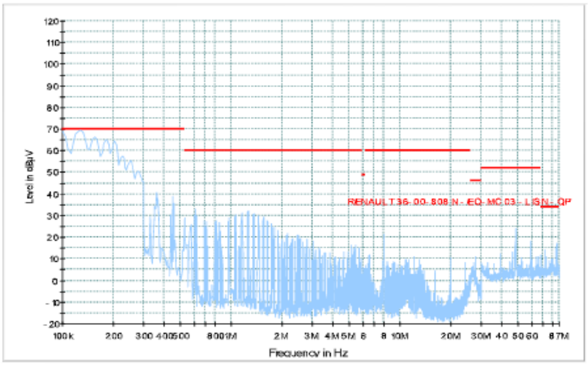
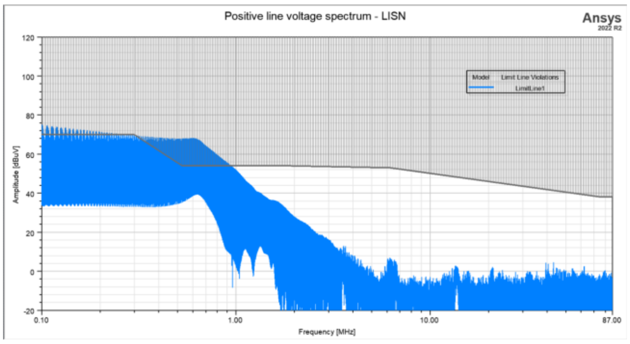


Figure 12. Setup of model 4

As can be seen, the results, in terms of amplitude, of the values for frequencies above 1 MHz were closer to the actual measurements, which indicates that the coupling of cable dimensions in the model impacts the response at higher frequencies. More analysis must be done to understand the differences, but it is evident that the correct characterization of the wiring harness cables impacts the response at frequencies above 1 MHz.



(a) LISN positive line emission spectrum – Quasi-peak. Real measurement



(b) LISN positive line emission spectrum –Simulated measurement

Figure 13. Comparison of the real measurement in LISN (a) and the result of model 4 (b)

VALIDATION

RISE AND FALL TIME – To observe the behavior of the model and evaluate real conditions, some test variables were defined, one of which was the rise time and the fall time. These characteristics are known to influence the device emission, the shorter the time interval of the voltage variation (higher dV/dt), the greater the emission. By figure 14 it is possible to notice that the spectrum is following this behavior. The average signal energy difference between the longest and shortest time is approximately 8 dBμV.

Another interesting aspect was the envelope characteristic in the spectrum, a modulation characteristic of the signals in the frequency, in which the shorter the rise time, the greater the envelope frequency. Another feature observed in the model is that it is more sensitive to variations in the rise time than the fall time.

It was defined to use a percentage of the real value of the rise time and the fall time ranged from 30% to 130%, that is, the smaller the percentage, the shorter the time.

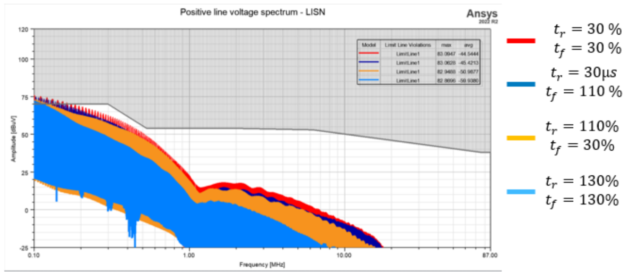


Figure 14. LISN positive line emission spectrum – Simulated measurement. Rise and fall time variation.

LOAD VARIATION – Another variable investigated was the load variation, in which the greater the current, the greater the amplitude of the emission spectrum should be, and again the model proved to be consistent with real measurements. It was noticed that the load variation impacts more in the low frequency range. The analysis varied the load from 20% to 150% of its nominal value.

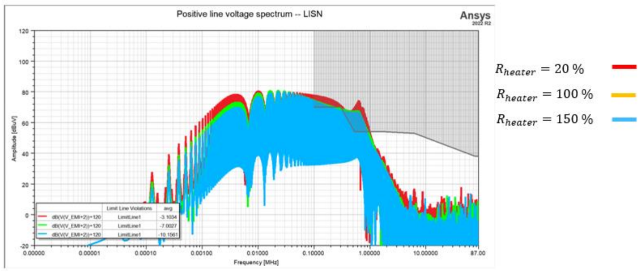


Figure 15. Result from the analysis of load variation

DUTY CYCLE – The duty cycle was also varied, and it was verified that in the condition where the greatest voltage variation occurred, there was greater energy in the spectrum of conducted emissions.

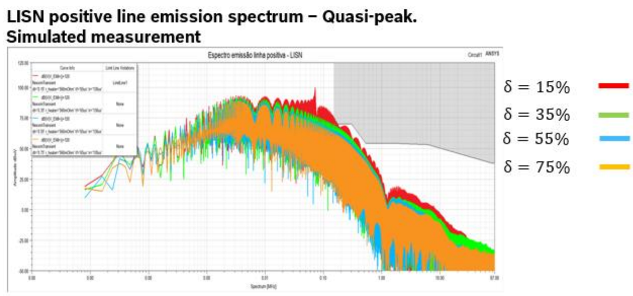


Figure 16. Result from the analysis of the variation of the duty cycle

Given the characteristics of the load, with lower duty cycles, there is a greater current variation, which results in higher levels of emissions.

INDUCTANCE OF CABLES – One of the main behaviors observed in the models was the poor similarity of the curves above 1 MHz, which was investigated with the simple representation of the impedance of the cables, for both the power supply and the load cables, in addition to the detection algorithms, which use specific filters for frequency ranges. Disconsider the behavior of the quasi-peak detection algorithm, the influence of the real inductance of the cables was investigated.

With the software the inductance of the cables was evaluated to be around 300 nH, and according to real measurements, the inductance is close to 5 µH. By adding this inductance to the circuit simulation, a difference in the spectrum at high frequencies was observed (figure 17) showing that there is a considerable portion of signals being coupled via cable, thus changing the behavior of the emission spectrum for test conditions.

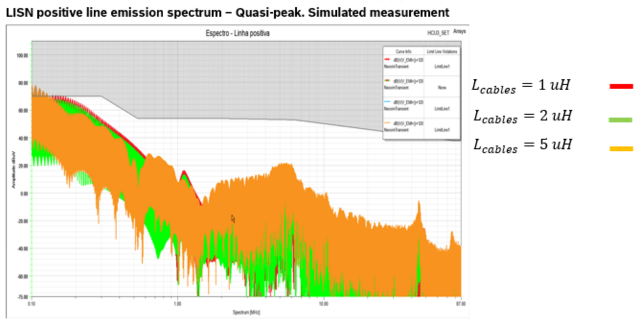


Figure 17. Result from the analysis of the real addition of the inductance of the cables

Varying the inductance from 1 µH to 5 µH, significant changes were observed in the conducted emissions spectrum, as shown in the graph above (figure 16). This behavior is expected since the magnitudes that most influence the behavior at frequency are the capacitive and inductive characteristics, which couple conducted and radiated signals.

CONCLUSION

Analyzing the results obtained, it is noted that all models are close to the real measurement, with satisfactory values to perform preliminary analysis. It is worth noting that the differences in the results of the simulated and measured models are due to several factors, the first obviously being the method of applying the Fourier transform, while in the laboratory peak and quasi-peak filters are applied in specific frequency bands, in the simulation the Fourier transform is applied in the simulated period, that is, it does not show the frequency bands of interest, according to the standard. The second aspect is the coupling of impedances not considered. It is worth also mentioning the uncertainties of measuring equipment.

More measurements will be needed to validate the models, or even the development of new models for comparison purposes, since the amplitude and behavior of the models studied in this report are close to real measurements.

Evidently, these preliminary results demonstrate that for tests of conducted emissions, the results are pertinent to evaluate the behavior and characteristics of electronic systems, in addition to all the characteristics of the geometries it is possible to extract impedance, behavior of circuits in time and frequency domain, as well as evaluating the main design conditions.

In future projects, simulations like these can be used to validate PCB layout, as well as to assess the entire design behavior under time and frequency domains conditions. Reducing project completion time, costs involved in laboratory tests and improving the sensitivity and robustness of electronic systems developed.

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