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SUMMARY OF DOCTORAL THESIS

Comprehensive methodology for emission level prediction from magnetically coupled nonlinear circuits in automotive

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Metodologia prognozowania poziomu emisji zaburzeń promieniowanych w nieliniowych obwodach sprzężonych magnetycznie dla potrzeb przemysłu motoryzacyjnego

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Abstract

In radiated emission compliance tests of automotive components according to standard CISPR 25, the semi-anechoic ALSE chamber is used. It supports a good correlation with disturbances observed in a vehicle, yet it is expensive and time consuming in use. Therefore, a simple to apply alternative method is expected to provide a reliable assessment of radiated emission levels. This work proposes the comprehensive approach supporting that. This thesis focuses on accurately determining nonlinearities present in the analyzed circuits. Their effects are supposed to be introduced through the inductively coupled coils and observed as radiated disturbances. Firstly, the exact multilayered coil equivalents are introduced, supporting a reliable representation of the mass-produced inductors. Subsequently, the mutual coupling is analyzed for coils freely positioned in space. Next, the excitation voltage supplying a nonlinear part represented by the analog front end circuit is determined. In the following, a spectrum analyzer acting as a high dynamic range null detector supports obtaining its frequency and voltage-dependent impedance, and resulting nonlinearities. Prediction of radiated disturbances utilizes a complete model of the magnetic link. Required nodal quantities as system currents and voltages are obtained on their basis using the harmonic balance method. Finally, they are used in a complete structural model of the CISPR 25 measurement system, supporting estimation of the induced voltage in a rod antenna, the equivalent of radiated emissions. This dissertation extensively uses structural simulations and measurements in the ALSE chamber to verify the proposed methodology's correctness and accuracy.

Streszczenie

Zaproponowana metoda badawcza umożliwia prognozowanie poziomu emisji zaburzeń promieniowanych w nieliniowych obwodach sprzężonych magnetycznie, reprezentowanych przez cewki indukcyjne i współpracujący z nimi układ AFE (Analog Front End) stanowiący obciążenie części wtórnej obwodu. Nieliniowości tego układu analizowano uwzględniając selektywny charakter pracy oraz silne wysterowanie dochodzące do 20 Vpp. Amplitudy i fazy wzbudzonych sygnałów harmonicznych określono w zakresie częstotliwości od 100 kHz do 1,8 MHz wykorzystując dedykowaną metodę kompensacyjną. Na bazie uzyskanych charakterystyk częstotliwościowych, zależnych od aktualnego poziomu wzbudzenia, skonstruowano modele symulacyjne opisane zestawem nieliniowych równań różniczkowych oraz wielkosygnałowymi parametrami X.

Sprzężenie magnetyczne w obwodzie przeanalizowano dla dowolnej orientacji cewek w przestrzeni, w konfiguracji zawierającej cewkę powietrzną oraz cewkę z prętowym rdzeniem ferromagnetycznym. W tym celu skorzystano z metod analitycznych oraz symulacji 3D, których wyniki zweryfikowano wykorzystując dedykowany zestaw pomiarowy.

Stosując analityczną metodę balansu harmonicznych oraz modele cewek i układu AFE wyznaczono planarny rozkład prądów i napięć w obwodzie. Na jego podstawie zdefiniowano korzystny (pod względem poziomu dominującej trzeciej harmonicznej) zakres pracy całego obwodu, który następnie zweryfikowano pomiarami w komorze ALSE. Jednocześnie skonstruowano równoważny model symulacyjny układu pomiarowego zgodnego z normą CISPR 25, na bazie którego estymowano poziom zaburzeń promieniowanych. Finalnie uzyskano zbieżność prognozowanych poziomów z pomiarami lepszą niż ± 6 dB, co stanowi potwierdzenie tezy niniejszej pracy. Przenalizowano również trzy pytania badawcze, z których każde znalazło właściwe umocowanie w wykonanych badaniach i uzyskało potwierdzającą odpowiedź.

1 Motivation and aims

An increasing number of electronic modules integrated within a modern vehicle aims to improve energy efficiency, car security, and driving safety. These new features target fulfilling customers' expectations and increasing overall traveling comfort. On the other hand, however, they introduce complexity in their development, as the equipment coexisting in a confined car space can increase the risk of electromagnetic interference (EMI).

The development of electronic modules typically requires many verification steps during a design process and not only the final validation at the end-stage. With limited time and access to the laboratory resources ensuring EMC compliance is challenging. Having an alternate method capable of predicting radiated disturbances at the early development phase reliably and at a reasonable cost is thus necessary.

The thesis proposes a simplified yet still accurate approach oriented especially to fulfill the strict needs of the automotive industry targeting narrowband (NB) devices operating in the low-frequency (LF) band.

2 Proposed methodology

The methodology considers inductively-coupled coils freely positioned in space, for which their mutual inductance is determined analytically. To support that, an approximation of the coil winding as a circular ring of a rectangular cross-section is proposed. To prove the applicability of such an approach, a structural simulation model using the filamentary method is applied.

The coil load is represented by the low-power component acting as an analog front end (AFE) circuit. The AFE's complex impedance (i.e., including the magnitude and phase) at the carrier frequency and the excited harmonic spurs (both magnitude and phase) are obtained using the compensation method employing a spectrum analyzer as a null detector.

Identified nonlinearities allow determining distorted currents using the equivalent AFE model. The measurement-based modeling implementing gray-box or black-box approach is introduced. The required nodal quantities (i.e., system currents and voltages) are determined using the harmonic balance method.

Prediction of radiated disturbances is aligned with the practical methodologies used in the EMC laboratory, reflecting CISPR 25 compliant setup.

3 Research questions and the work thesis

The first question addressing the proposed prediction methodology is how accurate it is and does it fit the automotive industry demands.

Another important aspect is the consideration of magnetically coupled coils in the simplified form as circular rings. The second question is that, if those forms accurately describe the coupling mechanism for various positions and coil types in proximity.

The third research question put in this work is the possibility of determining circuit nonlinearities in a wide excitation range with the support of a spectrum analyzer and an external, dedicated test setup accurately in the considered band?

This work argues that the proposed methodology of predicting the radiated emission levels satisfies the ± 6 dB limit for the carrier signal and the dominant harmonic spurs within the LF band. This research claim states, that using such complete approach it is possible to estimate the radiated emission level in a reliable way.

4 Conclusions and the work achievements

In radiated emission compliance tests of automotive components according to standard CISPR 25, the semi-anechoic ALSE chamber is used. It supports a good correlation with disturbances observed in a vehicle; therefore, it is also used for verifications at the early designing phase. However, the associated development cost is high, and not all manufactures can afford it. In this context, a straightforward alternative method is required to provide a reliable assessment of radiated emission levels.

This thesis focuses on accurately determining radiated disturbances introduced by the nonlinear circuits through the inductively coupled coils. The proposed methodology is comprehensive and supports the necessary steps to establish an appropriate radiation model of a complete system.

The thesis put in this work is confirmed, together with a positive answer to each of the research question. The developed alternative methodology can be summarized in the following steps.

Firstly, the detailed model of the air and ferrite-core based coils was introduced. It supported the semi-layered winding structure observed in actual inductors. The causes of disordered turns placement were identified as the material and manufacturing capabilities. It was emphasized that the standard estimation formulae showed decreasing accuracy for the higher frequencies and non-ideal windings. To improve the comparability with measurements, the frequency-dependent coil impedance components were determined using structural simulations. That resulted in accurate representation (below 2 %) of the coils, which supported reliable estimation of the mutual inductance in the next step.

The inductive coupling was supposed to determine resulting distortion levels; therefore, it was studied in detail. The practical approaches were analyzed, starting from the analytical methods known from the literature. Initially, the Babic method was incorporated, which described mutual inductance for each considered position of the coupled coils. It was then referenced with the proposed compact coil model, which was used to determine accurately (better than 0.5 % in a case of a ferrite coil) the magnetic field in the proximity. The following measurements confirmed a satisfactory (4 % maximum difference) representation of the inductive coupling mechanism, including frequency dependence in the LF band. Many spatial positions of coils were investigated, including axial, radial, and angular displacement rarely available in the literature. Therefore, the completed evaluation of the mutual inductance can be regarded as the first important contribution of this work.

Capabilities and limitations of the nonlinear low-power characterization have been investigated and discussed within the next major step. First, the existing gap in the available instrumentation was identified in the low-frequency band. Then, the complete solution was proposed to overcome the limitation in the frequency offset measurements of the harmonic spurs (including their phase relations). It employed the two generator-based method of synchronous cancellation of a given harmonic spur. It was supported by the spectrum analyzer operating as a null detector, providing a high dynamic range. The matched four-stage bandpass filter supported the required pure harmonic excitation. The frequency and level-dependent nonlinear characteristics were obtained using the introduced methodology. The relative expanded uncertainty of the proposed solution was estimated as 3.2 % (with the option to improve it further) in the case of the angle measurement, which was found very satisfactory. Developing the complete characterization methodology is regarded then as the second significant contribution of this work. The resulting accurate distortion characteristics of the considered nonlinear AFE circuit maintained the construction of the equivalent model in the next step.

Prediction of harmonic spurs required knowledge of system currents and voltages as the sources of radiated disturbances. Obtaining them utilized the complete model of the magnetic link, thus coil equivalents and the appropriate representation of the circuit nonlinearities. It was managed twofold. The nonlinear AFE model was formulated using the complex impedance form described by differential circuit equations. It contained voltage-dependent capacitive and resistive components, accurately representing operating modes of the considered AFE circuit. This so-called gray-box model supported frequency characteristics (i.e., magnitude and phase) within the whole operating range of the nonlinear component. That modeling approach allowed restoration of the harmonic spurs from the measurements, not only describing circuit operation compared to previous works. Supplementary, the AFE modeling has also been represented by the polyharmonic distortion approach, reflecting the nonlinear part as the one-port device. On its basis, the efficient representation of the low-frequency operation was proposed using the X-parameters. This unique approach helped to describe accurately (limited in practice only by the accuracy of the measurement equipment used) the harmonic spectrum of the nonlinear part. Therefore, it was possible to employ the common RF simulation tools to analyze also the LF parts.

The important topic of uncertainty propagation was considered regarding complex impedance. The long-term measurements referenced to the Monte Carlo simulations showed the comparable (0.9 dBm and - 2°, respectively) spurs magnitude and phase data. That was simultaneously confirmation of the high quality of the proposed model, supporting the reliable determination of the planar map of disturbances.

Three aspects of the real validation in the ALSE chamber have been considered during the last step of analyzing the CISPR 25 environment. Firstly, the appropriate near-field quasi-static methodology was used to simplify the setup parts and reduce them to the forms containing only the harness and coils as radiating components. Secondly, the low-frequency model of the monitoring rod antenna was introduced. On its basis, the individual couplings with the remaining setup parts were determined. That supported estimation of the antenna voltage (hence radiated disturbances) by using the equivalent transmission factor concept. In addition, they were specified for both capacitive and inductive couplings, from which the latter was typically neglected in recent works. However, their presence was vital to determine introduced disturbances accurately. And thirdly, a detailed procedure allowing reliable measurements of the weak distortions was implemented. It was emphasized that the spectral purity of the excitation source plays a significant role during the disturbance measurement process.

There are at least two noticeable scientific findings obtained from this work. First, the assumption of the only dominant role of the automotive harness during the CISPR 25 compliant measurements shall be revised when the magnetic field sources are present. Their importance can increase with a frequency due to the existence of magnetic coupling with the rod antenna. Additionally, multiturn windings can intensify magnetic fields by the factor reflecting their number of turns, which is nonnegligible. The second finding is the possibility of analyzing even complicated nonlinear systems in a low-frequency with support of the relatively simple instrumentation. That observation simultaneously provides a positive answer to the last research question. It was confirmed that the accurate determination of harmonic nonlinearities is possible with the support of the elementary spectrum analyzer and the dedicated circuit embedding the bandpass filter and the low-power transformer.

Analyzing the second research topic addressing coil coupling can conclude that relatively simple forms represented by the circular rings of the rectangular cross-section correctly described the LF operation. Induced voltage determined on their basis accurately predicted the excitation level of the nonlinear part, thus the introduced level of radiated disturbances. Furthermore, the simulation time was significantly reduced due to their optimized forms, which helped perform the evaluations efficiently. Therefore, that research question is also acknowledged.

The last research question put in this work needs a bit more comments. During evaluations in the ALSE chamber, the exact placement of the setup parts played an essential role during the measurements. The small asymmetry of the harness placement, a slight tilt of the rod antenna, or the vertical orientation of the connections to the coils introduced measurable effects on the recorded spectrum. Only the precise parts placement, strictly following the CISPR 25 defined positions, allowed obtaining the data comparable with the simulations reflecting the nominal conditions. The measured disturbances were close to their predicted levels, with differences below 1 dB for carrier cases and the maximum + 5.8 dB for the dominant 3rd spur. The overall extended uncertainty was estimated below ± 6 dB level, which is a highly satisfying result. In that context, the introduced methodology allows the reliable prediction of radiated disturbances, which acknowledges the thesis put in this work. Additionally, it is possible to relatively fast estimate the level of introduced disturbances using the simplified model of the complete measurement setup. Therefore, it can be concluded that the proposed approach fits automotive industry demands.

5 List of relevant publications

[1] G. Oleszek, "2D Disturbance Map of Low-Power Front-End Circuits in Low Frequency Band," *Progress In Electromagnetics Research C,* vol. 92, pp. 87-100, 2019.

[2] G. Oleszek, "Estimation of the Operating Range of Automotive Key Fobs during a Radiated Emissions Test under a Low Frequency Band," *2019 MIXDES - 26th International Conference "Mixed Design of Integrated Circuits and Systems,* pp. 350-355, 2019.

[3] G. Oleszek, "RF disturbances from magnetically coupled nonlinear AFE circuit under LF band," in *EPNC 2020 Electromagnetic Phenomena in Nonlinear Circuits : XXVI symposium*, Torino, Italy, 2020.

[4] G. Oleszek, "Coexistence of the wireless charger and low-power circuit in a car interior," *2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC),* pp. 237-242, 2021.