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Evaluation of Radiated EMI in 42-V Vehicle Electrical Systems by FDTD Simulation

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Abstract—In this paper, a full 3-D numerical scheme based on the finite-difference time-domain method is used to predict the electromagnetic (EM) radiated interference generated by 42-V vehicle power electronic driven electrical loads. An experimental setup has been arranged in order to validate the proposed simulation tool. To this aim, the features of a semi-anechoic EM chamber have been exploited in order to operate in a shielded test site for the measurement of near-field radiated emissions. Two different 3-D geometrical configurations of realistic vehicle installations of the loads are studied. A comparative analysis among measured and computed results is performed. A good agreement between simulated and measured data is obtained. The proposed approach is suitable for the prediction of radiated EM interference generated by dc/dc converters and, particularly, by dual-voltage vehicle electric plants. In fact, due to the presence of complicated layout, the prediction of EM emissions can be a useful task in order to evaluate the EM compatibility (EMC) compliance from the design stage. Furthermore, with the growing market penetration of the “More Electric Vehicle” (MEV) concept in designing new vehicle electrical architectures, low-cost test methods for EMC assessments and suitable technical standard requirements have to be introduced. The proposed simulation tool can be usefully adopted to this aim. As an important advantage, it requires only a current measurement in the time domain. Such measurement does not need the use of a special test site or of a radiated field measurement setup.

Index Terms—Dual-voltage vehicle electrical system, electromagnetic compatibility (EMC), electromagnetic radiative interference, electromagnetic transient analysis, finite-difference time-domain (FDTD) method.

I. INTRODUCTION

IN THE automotive environment, the development of 42-V electrical architectures is currently considered to be the solution to the growing demand for onboard electrical power. In fact, the need for electrical power in a vehicle amounts to several thousands of watts; thus, the traditional 12-V systems are getting into the physical limit, especially with reference to the alternator [1].

The availability of low-cost power electronic components together with the new 42-V systems allows to devise new control strategies in order to manage the power load requirements [2].

This issue completely agrees with the More Electric Vehicle (MEV) concept that emphasizes the employment of electrical power systems in place of mechanical and hydraulic systems in the automotive field. The MEV concept simplifies the use of high power loads and enables the introduction of power electronics in order to optimize fuel economy, environmental emissions, performance, and reliability [3].

In order to improve the flexibility of load management and the overall vehicle energy saving, a massive use of switching power converters in such new 42-V electrical architectures is therefore expected. This leads to a strong increase in onboard electromagnetic (EM) emissions.

Some contributions that deal with onboard switching dc/dc converters and their EM compatibility (EMC) implications can be found in the scientific literature. In particular, different solutions in driving automotive conventional 12-V small motors at 42-V dc bus by using dc/dc converters are presented and compared in [4] in order to reduce conducted EM interference (EMI). A computer-aided design approach for the optimization of the design of automotive dc/dc converters, which also consider EMC aspects, is presented in [5].

In [6] and [7], experimental investigations on high frequency (HF) EM emissions from a vehicle fuel pump motor, which is supplied through a 42-V/14-V dc/dc step-down converter, are presented. These studies have shown that the drive generates HF disturbances due to the fast commutations of the dc/dc converter. These HF emissions exceed all classes of limits prescribed by the existing standards related to 14-V vehicle electrical systems.

Therefore, the impact of EMC has to be reconsidered for the new vehicle electrical architectures in order to obtain safe, reliable, and competitive products. Unfortunately, at this time, the standard experimental procedures to assess the EMC of electrical equipment are very expensive, and many industries are not equipped with suitable EMC test laboratories. In order to assess EMC compliance since the design step, it is important to set up cost-effective experimental EMC test procedures and to develop suitable tools that allow the prediction of onboard EMI. In particular, due to the mutual close proximity of the various electronic units of the vehicle, the evaluation of the near-field emissions generated by switching converters is a challenging problem of prior importance in the automotive environment. Such a problem has been studied in previous papers by the authors with respect to an electrical load in a...
42-V automotive system for simple geometrical configurations [8]–[10].

In this paper, a full 3-D numerical scheme based on the finite-difference time-domain (FDTD) method is proposed in order to predict the EMI generated by a 42-V vehicle electrical load in realistic configurations.

The FDTD approach has been successfully used in the automotive field, especially with hybrid techniques, to evaluate HF far-field radiated emissions at vehicle level [11], [12].

Hereafter, the FDTD method is used to predict the near-field radiated emissions, which are generated in a 42-V vehicle electrical system, at electrical/electronic subassembly (ESA) level.

The chosen emission source is a 42-V electrical drive dedicated to the fuel pumping. The near-field EM analysis is carried out by considering the cables where the supply current flows as radiating sources.

A test structure has been arranged in a laboratory in order to simulate the actual vehicle application with such a load. A semi-anechoic EM chamber has been used as a shielded test site for the validation of the proposed simulation tool: the computed results have been compared with the data measured in the chamber.

The experimental system allows the measurement of HF currents due to the dc/dc switching converter. Such currents generate the EM emissions and are used for the numerical evaluation of the radiated EM field. The computed radiated emissions give results that are in good agreement with the experimental measurements. The proposed approach can therefore be considered as a virtual laboratory facility for radiated EMI prediction in realistic MEV systems and also for the identification of EMC-oriented design and optimization criteria for 42-V electrical architectures. Moreover, it can give useful information for the development of cost-effective EMC test methods, and it can also aid to define dedicated EMC technical standards for the new vehicle electrical systems. In particular, by using the simulation tool, the contribution of each EM source to the vehicle EM environment can be identified without the need of costly EMC test facilities. As an important advantage, the proposed tool enables evaluation of the radiated EM emissions at only the cost of a measurement of the electric current generating the EMI that does not require any particular test site, as well as low computational resources.

II. PRELIMINARY ANALYSIS OF THE LOAD EM BEHAVIOR

The system under study is a dc fuel pump motor drive supplied at 42 V. It is formed by a 14-V dc electric motor excited by permanent magnets, which drive the fuel pump, and by a dc/dc step-down switching converter that reduces the 42-V voltage supply into 14 V [6], [7]. The converter is realized by the power switching regulator ST L4970A that operates at a switching frequency of 100 kHz. The fuel pump has been chosen for the presented analysis since it represents a typical auxiliary power electronic driven load in a 42-V automotive electrical architecture.

A preliminary analysis of the load behavior is presented hereafter in order to find out the main characteristics of the related EM emission phenomena. Such an analysis is also useful in order to choose the more suitable measurement instrumentation.

Due to the commutation of the brushes, when the pump motor is supplied through a dc generator, the current is affected by a sinusoidal ripple whose frequency is equal to 200 kHz and the maximum amplitude is equal to about 0.1 A peak to peak. By driving the pump through the dc/dc converter and assuming the reference current sign from the converter to the fuel pump motor, the current exhibits negative spikes superimposed to the sinusoidal ripple, as shown in Fig. 1(a). Each spike is a trapezoidal-like pulse with a fall time \( t_f \) equal to about 40 ns, a rise time \( t_r \) equal to about 60 ns, an average amplitude equal to about 100 mA peak to peak, and a duration \( \tau \) (measured between the points at 50% amplitude) equal to about 0.5 \( \mu \)s.

The repetition rate of negative spikes is 100 kHz. The detail of a spike is reported in Fig. 1(b), where the measured current waveform [Fig. 1(a)] has been obtained by filtering the dc component.

It is of great interest to analyze the frequency spectrum of the current disturbance, as reported in Fig. 2. In the same figure, the theoretical asymptotic envelope of such an amplitude spectrum is also reported. The theoretical asymptotic envelope has been obtained by assuming \( t_r = t_f = 50 \text{ ns} \); it has the first cutoff frequency \( f_1 = 1/(\pi \tau) = 636 \text{ kHz} \), then it falls with slope \(-20 \text{ dB/dec up to } f_2 = 1/(\pi t_r) = 6.366 \text{ MHz} \), and finally it falls with slope \(-40 \text{ dB/dec} \) [13]. The frequency spectrum of the current disturbance has significant frequency content up to \( f_2 \).

III. EXPERIMENTAL ARRANGEMENT

The measurement of the EM near field is performed by using the experimental setup described in the following. Then, the results are used to validate the FDTD numerical code implemented by the authors in order to obtain a useful tool to predict the radiated EMI generated by the selected automotive
electrical load in realistic configurations. The device under test (DUT) is connected via a line impedance stabilization network (LISN) to a 42-V dc power supply formed by three 12-V storage batteries that are series connected and by an electronic de power supply parallel connected to the batteries in order to reproduce the onboard 42-V generator. The LISN is used to standardize the line impedance and to decouple, at high frequencies, the supply line and the load in order to make the measurements independent from the disturbances on the supply line. The DUT is locally grounded in order to reproduce its actual installation on vehicle. The length of the line between the LISN and the converter is 1 m, and the length of the line between the converter and the motor is 0.4 m.

The measurement system is assembled by using the following: a digital oscilloscope (Tektronix TDS 680C) with a bandwidth of 1 GHz and a maximum sampling frequency of 5 Gs/s; a current measurement system, including an amplifier (Tektronix AM 503B) and a current probe (Tektronix A6303) with a bandwidth of 50 MHz; and a near-field loop probe AFJ RF for magnetic field measurement, which is constituted by a coil with 0.025 m of diameter, which is indicated hereafter as the loop sensor.

As already underlined, the experimental investigations have been carried out in a semi-anechoic chamber in order to operate in a shielded test site.

Fig. 3 shows a schematic representation of the experimental setup with the details of the DUT parts and of the measurement system. The current disturbance flowing through the cable connection between the converter and the fuel pump motor is considered as the source of the radiated EM field, whose distribution in the near-field region is predicted through the FDTD method, as will be explained in the following sections.

In order to simulate the realistic presence of structures surrounding the radiating cable, metallic bars have been included in the experimental arrangement. In particular, an angle iron (L-bar) and a C-bar, which have the dimensions specified in Section V, have been set up and placed around the emitting cable. Other particulars of the measurement system, in the case of considering the L-bar and the C-bar as surrounding metallic structure, are reported in Figs. 4 and 5, respectively.

IV. FDTD Numerical Model

The EM field in the near-field region is predicted by the FDTD method [14]–[16]. This scheme employs Yee’s basic lattice to describe the problem domain in which the electric and magnetic fields are computed; this feature allows to model complex 3-D structures, but as a consequence, the spatial region has to be simulated, which therefore requires significant computational resources.

In the following, a brief summary of the FDTD method is reported for reader convenience. More details can be found in [14] and [15]. By using Maxwell’s curl equations together
with the constitutive relations of the medium, the following relations hold:

\[
\text{curl} \vec{E}(\vec{r}, t) = -\mu(\vec{r}, t) \frac{\partial \vec{H}(\vec{r}, t)}{\partial t} \tag{1}
\]

\[
\text{curl} \vec{H}(\vec{r}, t) = \varepsilon(\vec{r}, t) \frac{\partial \vec{E}(\vec{r}, t)}{\partial t} + \sigma(\vec{r}, t) \vec{E}(\vec{r}, t) \tag{2}
\]

where \( \vec{E} \) is the electric field vector, \( \vec{H} \) is the magnetic field vector, \( \varepsilon \) is the dielectric permittivity, \( \mu \) is the magnetic permeability, and \( \sigma \) is the conductivity of the medium. In this paper, these parameters are referred to the air (\( \mu = \mu_0 \), \( \varepsilon = \varepsilon_0 \), \( \sigma = 0 \)). Generally, all these quantities can be considered as functions of space \( \vec{r} \) and time \( t \). In the following, these parameters are considered to be time invariant. In a Cartesian coordinate system \( x, y, z \), the previous vector field equations can be split into six scalar ones:

\[
\begin{align*}
\frac{\partial H_x}{\partial t} & = \frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right) \\
\frac{\partial H_y}{\partial t} & = \frac{1}{\mu} \left( \frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right) \\
\frac{\partial H_z}{\partial t} & = \frac{1}{\mu} \left( \frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right) \\
\frac{\partial E_x}{\partial t} & = \frac{1}{\varepsilon} \left( \frac{\partial H_y}{\partial y} - \frac{\partial H_z}{\partial z} - \sigma E_x \right) \\
\frac{\partial E_y}{\partial t} & = \frac{1}{\varepsilon} \left( \frac{\partial H_z}{\partial z} - \frac{\partial H_x}{\partial x} - \sigma E_y \right) \\
\frac{\partial E_z}{\partial t} & = \frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial x} - \frac{\partial H_y}{\partial y} - \sigma E_z \right) .
\end{align*}
\tag{3}
\]

The region of interest has to be divided into a grid of nodes, and the given differential equations have to be approximated by finite-difference equations. These equations are then solved under the prescribed boundary and initial conditions. By using a central finite-difference approximation for space and time derivatives, and by considering the identities \( x = i \Delta x, y = j \Delta y, z = k \Delta z, \) and \( t = n \Delta t \), the discretization of (3) and (4) can be carried out. As an example, the third line of (4) becomes that in (5), shown at the bottom of the page.

\[
E^{n+1}_z(i, j, k + 1/2) = \left\{ 1 - \frac{\sigma(i, j, k + 1/2) \Delta t}{2 \varepsilon(i, j, k + 1/2)} \right\} E^n_z(i, j, k + 1/2) + \left\{ \frac{\Delta t}{2 \varepsilon(i, j, k + 1/2)} \right\} \left\{ 1 + \frac{\sigma(i, j, k + 1/2) \Delta t}{2 \varepsilon(i, j, k + 1/2)} \right\} E^n_x(i, j, k + 1/2) \\
\times \left\{ \frac{H^{n+1/2}_z(i, j - 1/2, k + 1/2) - H^{n+1/2}_z(i, j + 1/2, k + 1/2)}{\Delta y} \right\} + \left\{ \frac{H^{n+1/2}_y(i + 1/2, j, k + 1/2) - H^{n+1/2}_y(i - 1/2, j, k + 1/2)}{\Delta x} \right\}
\tag{5}
\]
Fig. 7. Geometrical placement and dimensions of L-bar around the radiating current line wire.

Fig. 8. Geometrical placement and dimensions of C-bar around the radiating current line wire.

around the wire. In this way, the measured current can be related with the local magnetic field components and then via the FDTD scheme with the electric field components too.

After the numerical solution of the two linked curls (1) and (2), the open circuit voltage \( V_i \) induced by the time variable magnetic flux at the terminals of the loop sensor can be calculated by Maxwell–Faraday relation

\[
V_i = \mu_0 \frac{\partial}{\partial t} \int_S \vec{H} \cdot d\vec{S} \tag{6}
\]

where \( S \) is the loop sensor surface.

The computation of \( V_i \) is carried out by considering the magnetic field to be constant over the entire \( S \). This approximation does not substantially influence the precision of the computed \( V_i \) due to the very limited extension of the loop sensor surface in comparison with the maximum wavelength in the Fourier spectrum of the radiating current.

V. Model Validation

In order to validate the proposed numerical tool, the experimental setup has been simulated by considering the following geometrical layout. In Fig. 7, the geometrical layout of the configuration with the L-bar around the line conductor carrying the radiating current is sketched, as shown in Fig. 4. The auxiliary lead wires are placed far from the loop sensor position in order to simulate the circuit of the radiating current.

In Fig. 8, the geometrical layout of the configuration with the C-bar around the line conductor carrying the radiating current of Fig. 5 is shown. Both metallic structures allow the simulation of realistic configurations similar to those expected in the vehicle installation of the DUT. The metallic bars are supposed to be thin.

The current disturbances and the magnetic field in the near-field zone have been measured by setting up the experimental arrangement described in Section III.

The current disturbances have been measured by using the current probe with its amplifier and the oscilloscope.

Particular care has been taken in the choice of suitable measurement sampling frequency to acquire current disturbance time profiles. In fact, it is necessary to find an optimal tradeoff between the need of picking up the interesting HF phenomena and the need of cutting off the noise floor. This is necessary in order to avoid undesirable amplification of such noise. To this aim, the frequency \( f_{\text{max}} \) over which the frequency spectrum content of the current becomes negligible compared with the fundamental component has been determined, as described in the preliminary analysis. As already underlined, the value of \( f_{\text{max}} \) is about 6.3 MHz; then, a sampling frequency of 50 MHz has been chosen [8].

The magnetic field has been measured by setting the loop sensor near the radiating element at 0.03 m with the probe axis parallel to the \( z \) axis (Figs. 7 and 8) and connecting the probe to the oscilloscope in order to acquire the time-domain waveform of the open circuit voltage \( V_{lp} \), which is induced by the time-varying magnetic induction.

The measured current time profile, as reported in Fig. 9, only shows the disturbance due to the fast commutation of the switching power converter measured in the line between the converter and the fuel pump motor without the dc current component, which has been filtered.

In order to validate the effectiveness of the numerical model, two different quantities have been compared.

The measured open circuit voltage \( V_{lp} \) is compared with \( V_i \), which was obtained by FDTD simulation.

By using (6) again, replacing \( V_i \) with \( V_{lp} \), it is possible to achieve the time profile of the magnetic field in the middle point of the loop sensor. This quantity is compared with the magnetic field obtained by FDTD simulation.

In Figs. 10 and 11, the measured and computed voltages and the \( z \)-component of the magnetic field time profiles in the configuration with the L-bar are reported.
In Figs. 12 and 13, the measured and computed voltages and the z-component of the magnetic field time profiles in the configuration with the C-bar are reported. In both cases, the loop sensor is placed at the midpoint of the radiating line cable.

As shown, a satisfactory agreement is achieved among the measured and computed time profiles. It should be underlined that the used model has required only a measurement of the current in time domain.

As a further comparison among measured and computed data, the maximum deviation between $V_{lp}$ and $V_i$ is reported in Table I. These quantities are those that can be usefully compared, since the loop-sensor-acquired data are voltages. A satisfactory agreement is clearly shown in Table I.

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<th>Evaluated quantity</th>
<th>Maximum deviation between measured and computed results</th>
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<td>L-bar</td>
<td>$V_{lp}$</td>
<td>1.66%</td>
</tr>
<tr>
<td>C-bar</td>
<td>$V_{lp}$</td>
<td>1.90%</td>
</tr>
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VI. CONCLUSION

In this paper, a full 3-D approach, which is based on the FDTD method, for predicting near-field EM-radiated emissions in an automotive environment generated by a 42-V dc motor drive is presented.

The numerical model has been validated by means of experimental investigations carried out by setting-up experimental layouts corresponding to realistic configuration and by exploiting the features of a semi-anechoic EM chamber. In particular, the open circuit voltage induced at the terminal of a near-field loop sensor has been compared with the voltage calculated through the proposed numerical tool. A comparison between measured and computed magnetic field is also presented.
This comparison has pointed out that the model allows a satisfactory prediction of the behavior of the system under study in realistic configurations similar to those expected in onboard installations. Indeed, the presented numerical approach allows the study of geometrically complicated structures, therefore reproducing realistic EM environments. As an important feature, the presented method requires only a current measurement in the time domain. Such measurement does not need the use of a special test site nor of a radiated field measurement set up. Moreover, since the standard experimental procedures for the evaluation of EMC compliance require the use of very expensive measurement sites and instrumentation, the proposed method can be a useful tool to carry out cost-effective EMC-oriented design criteria for automotive ESAs and low-cost EMC test procedures in MEV, such as a vehicle equipped with a 42-V electrical system. In other words, the proposed approach can be considered as an EMC virtual laboratory facility.

Furthermore, the proposed approach allows to trace the phenomena (EM emissions) to their origins (HF currents), which suggest new possibilities to devise suitable EMC standard requirements for the new vehicle electrical systems.

REFERENCES

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