Radiated emission from DC bus loop of AC induction motor inverter FEM based and experimental evaluation

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ABSTRACT

The paper describes practical method how to analyze locally radiated magnetic field to improve the geometry of printed circuit board (PCB) or busbar structure, select better control method and design electromagnetic interference (EMI) filter. Experimental prototype of three-phase induction motor variable frequency drive has been created and controlled by microcontroller with sinusoidal, namely pulse with modulation (PWM) method. Three-dimensional finite element model simulation of DC bus structure has been created and results has been obtained. Electromagnetic field was measured, practically and results compared with simulation-based ones. Simulation based and experimental results matches thus allowing to conclude method usefulness for cost effective way to test different geometries of DC bus, different modulation methods, EMI filters for variable frequency drive, and other power electronics converters.

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1. INTRODUCTION

In the last years, demand for high power density, efficient and low-cost applications in the motor drives is leading to growth of inverter-based electrical drives controlled digitally. Inverter operates at high switching frequency and therefore electromagnetic interference (EMI) with other devices should be analyzed. To bring inverter to market, electromagnetic compatibility (EMC) is evaluated to be compatible with other electronic products. The emissions that the inverter transmits is measured and must not exceed a limit set by international standards.

Emissions can be divided into conducted and radiated. Conducted emissions flow through wires, the printed circuit board (PCB) tracks and connectors. Radiated emissions travel from the source to a receiver via air as electromagnetic waves and can be measured by antennas. Maximum level of radiated emissions is set by several standards depending of region and application, most commonly used ones are: CISPR 11, CISPR 32, or FCC Part 15. Practical description of requirements is given in [1]. To get a certificate the test should be done in EMC laboratories with an expensive antenna, spectrum analyzer in the shielded room. Therefore, the cost for failure in such a test is expensive and pre-compliance simpler tests or/and EMI reduction actions are usually done before final certification test.

In these tests electric (E) field or magnetic (H) filed antennas are used as receiving antennas. In electric field test physical quantity of interest is the E-field [dBμV/m], and the measured physical quantity is the voltage Vmeasure [dBµA] at the measurement equipment-spectrum analyzer. The field strength of the E-field at the antenna can be calculated as (1) [2]:

$$E = AFE + losses + V_{measure} \tag{1}$$

where: E - RMS field strength of the E-field at the antenna in [dBµV/m], AFE - antenna factor of an E-field antenna in [dB/m].

To provide such tests there is need to build physical prototype of the converter. This process can be expensive and time consuming. The conducted emissions can be simulated more precise–such analysis has been shown in [3]–[7]. The simulation of the electric and magnetic radiated fields could be helpful to identify main EMI sources and optimize layout of the inverter. Mainly in the scientific papers are analyzed radiated emissions from the wires that connects inverter and motor [8]–[11] by applying different modulation methods and shielding of cables. Other important source of EMI is inverter itself and especially connection between DC bus capacitors and transistors. The parasitic inductance of this path should be as minimal as possible. Simulation based optimization with goal to minimize this inductance has been carried out in many research papers [12]–[17], even motors with integrated inverter are proposed in the literature [18]–[20]. In several papers it is proposed simulation based determination parasitic inductances and capacitances [21]–[23]. This paper will focus on the application of magnetic field simulation to analyze radiated emission sources and potential improvements of DC bus of the inverter as an example. Results obtained by simulations will be compared to measurement results as the prediction of the electric drive inverter's level of electromagnetic interference is becoming increasingly necessary to reduce EMI at the design stage. The benefits of application of finite element method (FEM) to make first guess about radiated EMI are possibility to analyze different geometric configurations of the system components and such method eliminates costly and complicated testing procedures [22].

2. THREE PHASE INVERTER PROTOTYPE DESIGN

The printed circuit board (PCB) was developed using Altium software, the PCB can be seen in Figure 1. Inverter includes the EasyPIM 3B insulated-gate bipolar transistor (IGBT) module FP100R12W3T7_B11 from Infineon, which is located on the bottom side of the PCB. The heatsink is fastened to this IGBT module to reduce the temperature. EiceDRIVER compact 1ED3131MC12H for low-power losses has been used. Isolated power supplies were used to supply power to IGBT drivers. The inverter can be powered via DC or AC power, therefore free space for more capacitors is available. It is possible to change the location of capacitors when powered from DC source, as in this case. In this case, capacitors are placed away from transistors to increase radiated emissions, and it would be possible to measure them.

For the control of the inverter, STM32G474 microcontroller board was used. Software for sinusoidal pulse with modulation (PWM) generation and open loop control maintaining voltage versus frequency constants was implemented. 1 µs dead time was inserted between the high side and the low side transistors to prevent shoot-through current. The switching frequency was selected equal to 17 kHz to generate almost sinusoidal current since the radiation of cables in this case is not in focus. The motor and DC bus currents can be seen in Figure 2 and Figure 3. Motor current was measured with a Hall sensor-based probe with ratio 100 mV/A, but DC bus current was measured with Rogowski coil-based current sensor.

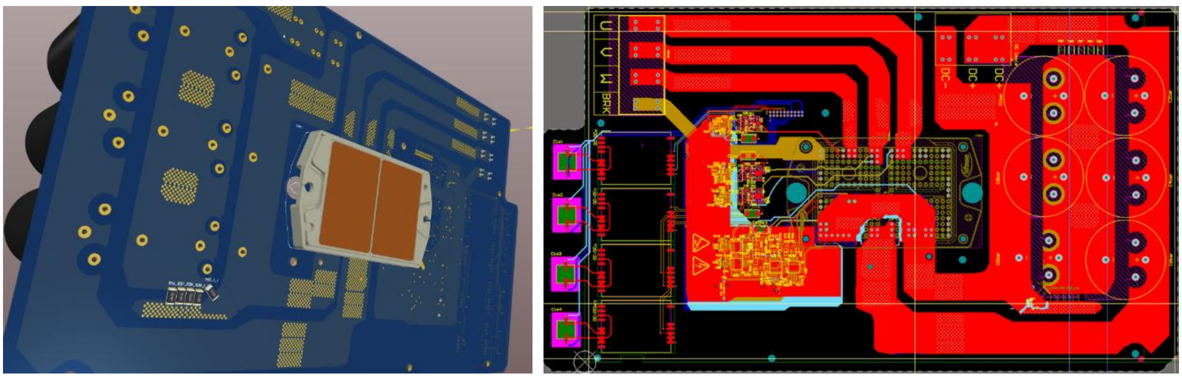

Figure 1. PCB of three phase inverter for induction motor application

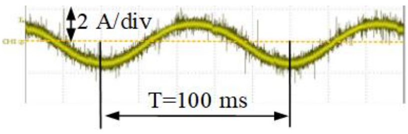

Figure 2. Motor current and DC bus current measured with an oscilloscope

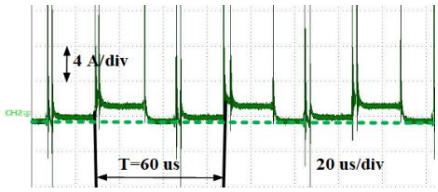

Figure 3. DC bus current measured with Rogowski coil and oscilloscope

3. DEVELOPMENT OF THE SIMULATION MODEL

The simulation model has been created to find out what is the difference between simulation-based results and experimental ones. RF module of COMSOL simulation software was used to obtain electrical and magnetic field of the inverter DC bus. The geometrical model of the DC bus of PCB copper layer has been created. The IGBT transistors are replace with short circuit and in place of DC bus capacitors current source has been connected to obtain radiated magnetic field. The model can be seen in Figure 4.

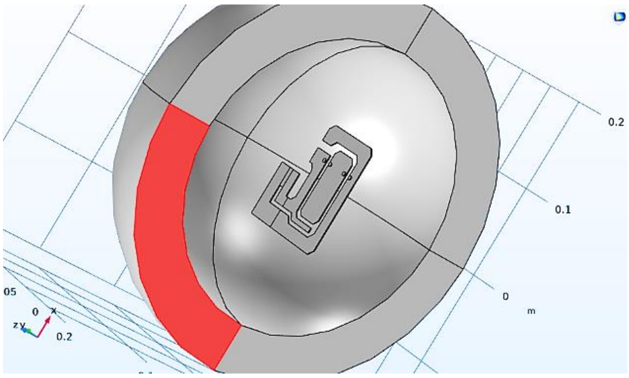

Figure 4. Simulation geometrical model of inverter's DC bus

FEM model of geometry of the DC bus of the inverter can also be used to obtain an electrical field. Electrical field should be measured at a distance of at least 1 meter so the boundaries should be extended. It is difficult to separate electrical field radiated only from the DC bus as other parts and wires create significant electric field. Therefore, in this paper mostly magnetic field will be investigated.

The magnetic field is created with a current flowing into PCB. In case of DC bus current is flowing from the capacitors to IGBT transistors. This current can be obtained weather by simulation as shown in Figure 5 or experimentally as it is shown in Figure 3. Figure 5 shows the DC bus current from the PSIM simulation model of three-phase inverter controlled by sinusoidal pulse with modulation. Waveforms obtained by simulation model or experimental ones can be used to further express them as a sum of higher harmonics which can be supplied into COMSOL geometric model to obtain electrical and magnetic fields. Each periodical signal can be expressed as a sum of harmonics and described by (2).

$$f_x = \frac{a_0}{2} + \sum_{n=1}^{\infty}[a_n \cos(nx) + b_n \sin(nx)] \tag{2}$$

There exist equations that can be found in the literature [24] to calculate coefficients from the data points. One period of the current can be described with data points with higher or lower precision. An example where a period is split into 50 points is shown in Figure 6. Modern oscilloscopes have high resolution and simulation software also allow to extract quite precise signals. The challenge with a current measurement is to remove noise and measure a high-frequency signal since the current is growing with a fast rate. The current signal was described with data points and harmonics calculated, amplitude of some harmonics is shown in Figure 7.

To calculate magnetic and electric field mesh has been created into COMSOL of geometrical DC bus model and surrounding of device. The mesh can be created with a different diameter. In a case of magnetic field small diameter has been selected to improve the precision of the model. The model can be seen in Figure 8.

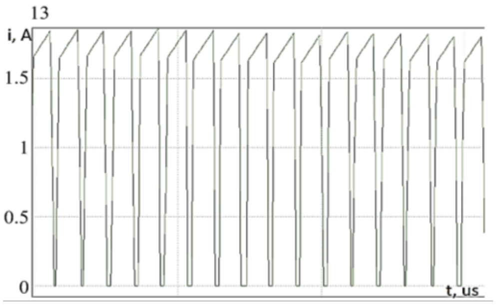

Figure 5. DC bus current obtained from PSIM simulation model

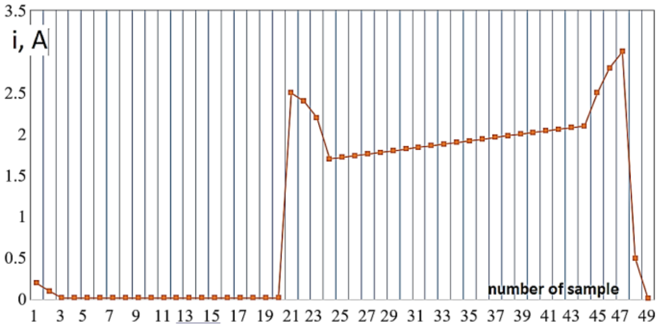

Figure 6. DC bus current reconstructed from discrete data points

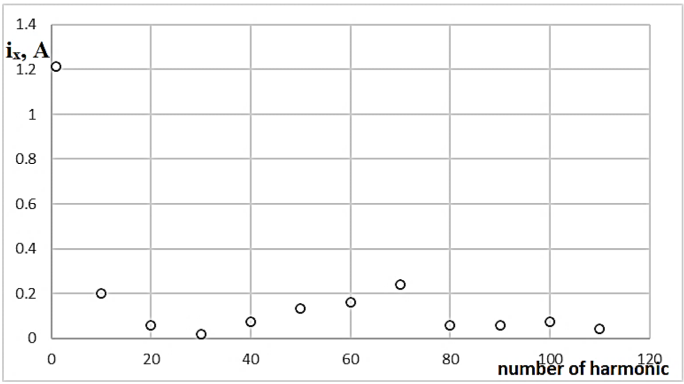

Figure 7. Some of the harmonics of DC bus current calculated from discrete data points

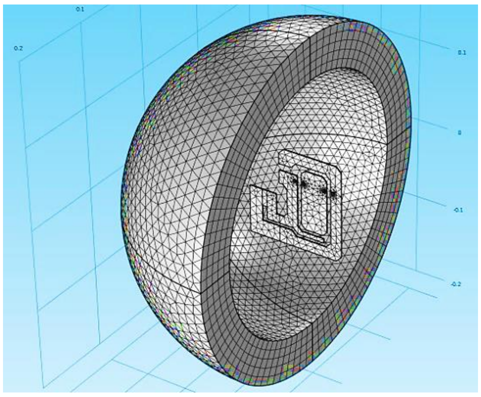

Figure 8. Simulation geometrical model of inverter's DC bus with a mesh

4. THE EXPERIMENTAL RESULTS AND DISCUSSION

To measure magnetic and electric field, an experimental setup has been created. As can be seen in Figure 9, the induction motor (see number 3) is controlled by the inverter (see number 4). Control signals to inverter drivers are generated with the STM32G474 development board (see number 7), driver is supplied from 15 power supply (see number 1). DC bus capacitors (see number 5) are placed not in an optimal place to create more radiated field. Antenna (see number 6) is connected to spectrum analyzer Rigol DSA 815 (see number 2). To measure magnetic field H field antenna EM-6994 from company electro-metrics 6) is connected to spectrum analyzer Rigol DSA 815 2) in Figure 9.

The FEM based model with DC bus geometry was connected to current source with corresponding harmonic. The magnetic field in 10 cm distance is shown in Figure 10. To obtain full spectrum of magnetic field emissions in distance of 10 cm the current source frequency has been changed to the corresponding harmonic and amplitude to value obtained from the Fourier transform calculate by (2) and some examples shown in Figure 7.

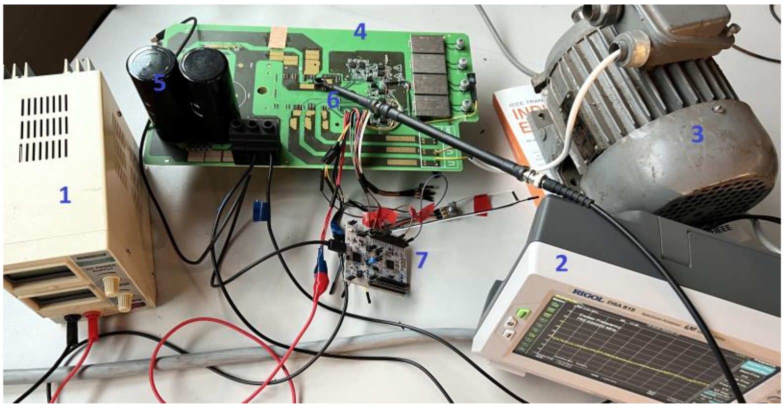

Figure 9. Experimental setup to test radiated emissions

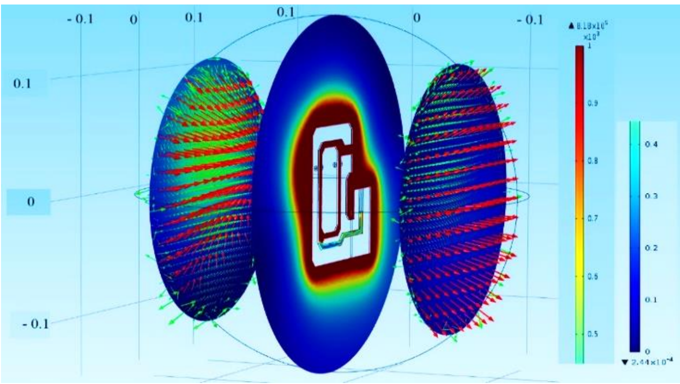

Figure 10. Electric and magnetic field of DC bus in 10 cm distance

In the spectrum analyzer it is set certain attenuation and reference magnetic field value to measurements will be able to see in monitor. The obtained magnetic field can be seen in Figure 11. This value is not an absolute value – attenuation, reference level, and antenna gain should be considered. The antenna probe factor can be seen in Figure 12. For selected antenna it is quite constant below 100 MHz. The transition between magnetic field in μA/m and dBμA/m can be used as (3).

$$H_{dB\mu A/m} = 20lg\frac{H_{\mu A/m}}{1\mu A} \quad (3)$$

Considering antenna probe factor, attenuation, reference level, and antenna gain the measured magnetic field level was recalculated. At the same time the simulated magnetic field was obtained at the several frequencies at approximately the same distance of DC bus PCB traces. The comparison of results is shown in Figure 13, the difference between cases does not exceed 5 dB which is enough to evaluate radiated EMI level. Especially useful such results can be to compare different modulation techniques, different DC bus geometrical designs, and to test different passive EMI filters. In EMI filter design a new waveform of current should be measured or simulated and then fed into FEM model. The busbar DC bus of high-power inverter also can be analyzed in a similar way just the copper of the PCB should be replaced by geometry of DC bus. Also, other parts of power electronics converters can be analyzed similarly. Such analysis also can be extremely useful to pass EMI test and find part of the converter that creates the main part of radiated emissions. When the source is detected then the model helps implement methods how to reduce EMI.

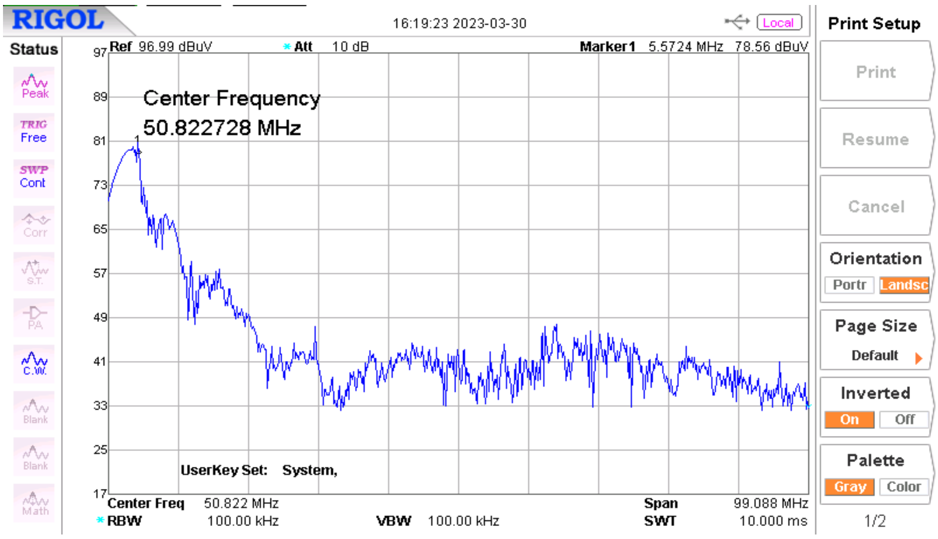

Figure 11. Measured H field

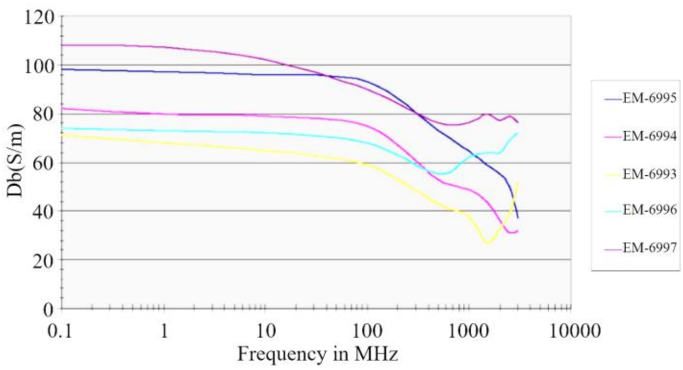

Figure 12. Typical probe factor of near field probe set EM-6992 antennas [25]

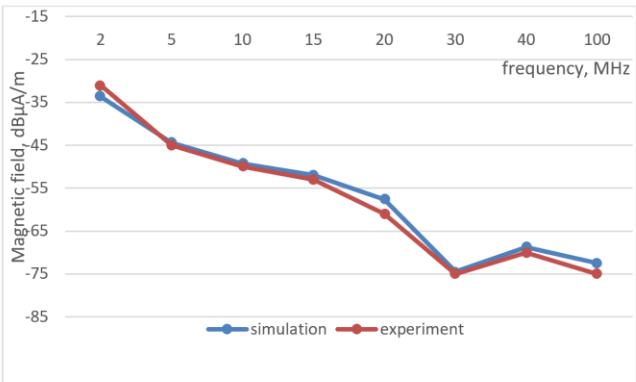

Figure 13. Comparison of experimentally and simulation-based H field data at different frequencies

5. CONCLUSION

The paper describes methodology how to use FEM based simulation model of variable frequency drive's DC bus inverter PCB to obtain magnetic field that can be used to improve DC bus design or select additional EMI filters. The paper shows example-based steps that verifies usefulness of FEM based simulation model for EMI analysis. DC bus geometry of the printed circuit board of the inverter has been transferred to FEM model that has been created in COMSOL software. To simulate electromagnetic field the mesh has been created and parameters of the material has been introduced into simulation model.

Experimental prototype of three-phase induction motor has been created and controlled by microcontroller. The sinusoidal PWM method has been selected as example. The DC bus current has been obtained from simulation model and has been measured practically. The spectrum of the current was obtained by mathematical operations and the sources with frequencies with corresponding amplitudes from current spectral analysis was introduced into FEM simulation model. The electromagnetic field was obtained in the simulation model and that can be used for radiated EMI evaluation.

Magnetic field was practically measured by H-field antenna and spectrum analyzer. Simulation based and experimental results are quite similar thus allowing to conclude that simulation-based results are accurate. Such simulation-based analysis could be a cheaper way to test different geometries of DC bus, to test different modulation methods and EMI filters. Presented work could be useful to scientists and engineers for EMI reduction of their electronic converter designs.

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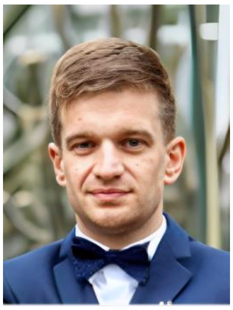

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