ELEKTROTEHNIŠKI VESTNIK 85(3): 103-108, 2018
ORIGINAL SCIENTIFIC PAPER

A Conducted EMI Noise Prediction in DC/DC Converter Using a Frequency-Domain Approach

Nassireddine Benhadda, Abdelber Bendaoud, Nawel Chikhi

Laboratory of Applications of Plasma, Electrostatics and Electromagnetic Compatibility (APELEC), Djillali Liabes University of Sidi Bel-Abbès, Sidi Bel-Abbès, Algeria
E-mail: benhadda_nasreddine@hotmail.com, abdelber.bendaoud@univ-sba.dz

Abstract. In this paper, a simplified approach to predict conducted EMI generated by a DC/DC buck converter in a frequency domain is proposed. This approach will improve the conventional model by adding electromagnetic interference (EMI) generated during the diode and MOSFET turn-off. Two high-frequency equivalent circuits are presented for modeling EMI during these switching phases. In the LTspice software, the CM and DM noise spectra are obtained rapidly and directly in the frequency domain. The precision of the proposed approach is checked by comparing it to a time-domain simulation.

Keywords: DC/DC Buck Converter, Parasitic Components, Time and Frequency domain, Differential Mode, Common Mode.

Napovedovanje prevodne elektromagnetne interference pri pretvorniku DC/DC v frekvenčnem prostoru

V prispevku je predstavljen poenostavljen pristop za napovedovanje prevodne elektromagnetne interference (EMI) v frekvenčnem prostoru, povzročene pri delovanju pretvornika DC/DC. Predstavljen pristop izboljša običajen model z upoštevanjem elektromagnetne interference povzročene pri zapiranju diode in tranzistorja MOSFET. Za modeliranje EMI v fazah preklopa smo zasnovali dve visokofrekvenčni ekvivalentni vezji. S programskim orodjem LTspice smo izvedli spektralno analizo. Pravilnost dobljenih rezultatov smo preverili s simulacijo v časovnem prostoru.

1 INTRODUCTION

Nowadays, the use of static converters is widespread, because there are significant benefits from their reduced size and increased efficiency [1]. However, the static converters are sources of a conducted electromagnetic interference (EMI) [1, 2]. Conducted EMI is generated by a fast variation in the voltage and current values during switching transitions of semi-conductor devices. Prediction of conducted EMI has become a major issue [3]. To predict the emitted disturbance level, converters need to be modeled in order to allow easy testing of EMI in the design stage [1, 4].

Previous research has recommended two basic ways of the conducted EMI prediction, the time - and frequency-domain approach. The time-domain approach uses a circuit-simulation software and the noise spectrum is then obtained by a fast Fourier transform (FFT) [1, 2]. The frequency-domain approach is preferable because it requires a shorter simulation time and has no convergence problem [1]. It consists of a representation of the propagation paths by means of localized impedance and disturbance sources by equivalent (voltage or current) generators. These equivalent generators represent the semiconductor behavior during switching [3].

The frequency-domain approach based on the noise source and noise path, including parasitic components of interconnect and semiconductor devices, is applied in [5] and [6] to model the DM and CM noise for a single-phase leg inverter, where the high-frequency equivalent circuit during the bottom active-switch turn-off and the high-frequency equivalent circuit during the top active-switch turn-off are the same and can be synthesized to a common circuit.

However, in a DC/DC buck converter, the high-frequency equivalent circuits during the diode turn-off is different than the high-frequency equivalent circuits during the MOSFET turn-off, so they should be modeled separately. In this paper, the method of frequency domain is used to predict the DM and CM noise generated by a DC/DC buck converter. The conventional frequency model with a simple noise path and trapezoidal noise source is improved by adding two high-frequency equivalent circuits for the DM and CM models during switching transients, one for the diode turn-off and the other for the MOSFET turn-off.

The validity of the proposed approach is verified with the time-domain simulation results. The rest of this paper is organized as follows. In Section 2, the studied converter with its circuit in the time-domain simulation,

Received 25 December 2017
Accepted 28 March 2018

including all parasitic components, is presented. Section 3 presents the conventional frequency-domain method and its limit to predict the DM and CM noise in a high-frequency range. Section 4 presents the DM and CM high-frequency equivalent circuits during turn-off of the semiconductor devices. In Section 5, a complete model for the EMI noise prediction and simulation results are presented. Conclusions of our work are given in Section 6.

2 Time-Domain Modeling of the DC/DC Buck Converter

The circuit of the DC/DC buck converter is shown in Fig. 1. The converter is composed of MOSFET IRFP250N, MUR460 diode, filtering capacitance with its parasitic elements and RLC load. The switching frequency is 20 kHz. The parasitic components of the interconnect and semiconductor devices are taken into account. C_p represents the CM propagation path. The DC voltage source is 42 V and I_{load} = 3 A. The converter is connected to a line-impedance stabilized network (LISN).

This circuit is implanted in the LTspice software to simulate the converter in the time domain. For MOSFET and diode, the Spice software proposes models of these switches to be relatively precise based on semi-conductor physical equations [7]. The DM and CM noises are obtained in the time domain and the frequency representation is given using a Fourier transform (FFT). The objective of the time-domain simulation is to verify the precision of our approach.

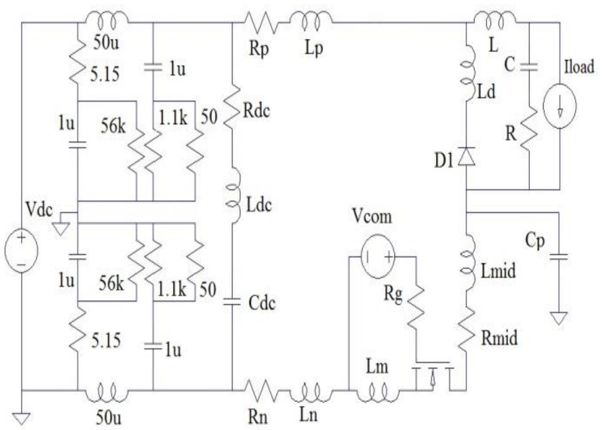

Figure 1. Time-domain simulation circuit of a buck converter connected to LISN [4, 5].

3 EMI Frequency-Domain Modeling

3.1 Conventional Differential-Mode Noise

The conventional DM EMI model is composed of trapezoidal current source I_{mos}, which represents the current seen by the DC link, and of the DC link capacitor with its parasitic elements, which represent the propagation path [4, 8].

Trapezoidal DM current source I_{mos} in the Laplace form is expressed as follows [9]:

$$I_{mos} = \frac{2}{s^2} \cdot f_d \cdot I \cdot \left(\frac{1-e^{-st_r}}{t_r} - \frac{e^{-s\left(\frac{d}{f_d}+\frac{t_r}{2}-\frac{t_f}{2}\right)} - e^{-s\left(\frac{d}{f_d}+\frac{t_r}{2}+\frac{t_f}{2}\right)}}{t_f} \right) \quad (1)$$

Where I is the DC current, f_d is the switching frequency, d is the duty cycle, t_r is the rise time, t_f is the full time and s is the Laplace operator.

The conventional DM EMI model and implementation of current source I_{mos} in the LTspice software are shown in Fig. 2.

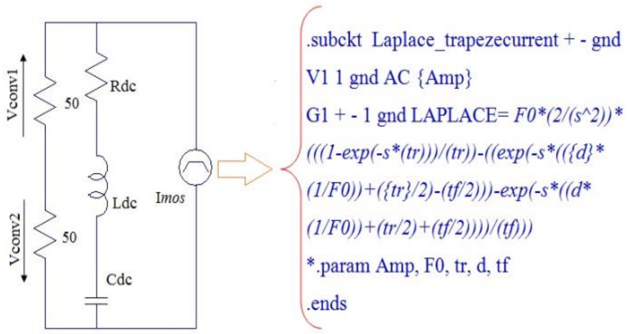

Figure 2. Conventional DM EMI Model [4, 5, 10].

For the Spice implementation, the Spice software allows to define the current and voltage sources directly by their Laplace transform using either arbitrary or controlled sources [10]. The equivalent noise source is represented by a voltage-controlled current source (GLaplace) in the Laplace form, following Eq. (1). GLaplace is excited by an AC voltage source (1Vac). The AC analysis in SPICE (a sweeping frequency from 150 kHz to 30 MHz) is applied [1].

The DM voltage noise is expressed in Eq. 2 in which V_{conv1} and V_{conv2} are the LISN voltages as shown in Fig. 2 [2, 4, 5].

$$V_{conv\ DM} = \frac{(V_{conv1} - V_{conv2})}{2} \quad (2)$$

3.2 Conventional Common-Mode Noise

The conventional common-mode EMI model is composed by a trapezoidal voltage source, which represents diode voltage V_d, equivalent HF representation of the DC link capacitor and parasitic capacitance *Cp* which represents the CM propagation path [4, 11].

Trapezoidal CM voltage source V_d in the Laplace form is expressed as follows [9]:

$$V_d = \frac{2}{s^2} \cdot f_d \cdot V \cdot \left(\frac{1-e^{-st_r}}{t_r} - \frac{e^{-s\left(\frac{d}{f_d}+\frac{t_r}{2}-\frac{t_f}{2}\right)} - e^{-s\left(\frac{d}{f_d}+\frac{t_r}{2}+\frac{t_f}{2}\right)}}{t_f} \right) \cdot e^{-s \cdot \frac{d}{f_d}} \quad (3)$$

Where *V*, is the DC bus voltage.

The conventional CM EMI model and implementation of voltage source V_d in the LTspice software are shown in Fig. 3.

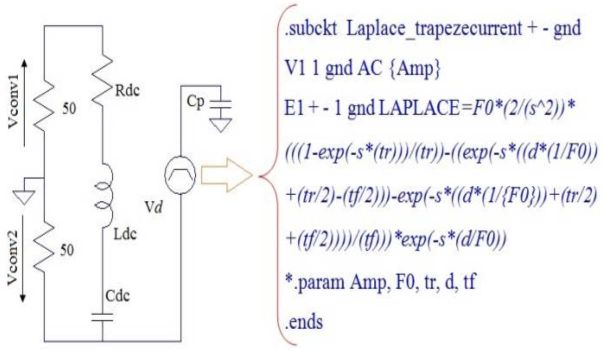

Figure 3. Conventional CM model [4, 5, 10].

The equivalent-noise source is represented by a voltage-controlled voltage source (ELaplace) in the Laplace form following Eq. (3). ELaplace is excited by an AC voltage source (1Vac) [1].

The CM voltage noise is expressed in Eq. 4 in which V_{conv1} and V_{conv2} are the LISN voltages as shown in Fig. 3 [2, 4, 5].

$$V_{conv\ CM} = \frac{(V_{conv1}+V_{conv2})}{2} \quad (4)$$

The parameters of the DC/DC buck converter used to determine the DM and CM noise are listed in Table 1.

Figs. 4 and 5 show results of a simulation of the DM and CM conducted EMI noise for a conventional-frequency model. We can see the difference between the spectra of the conventional-frequency model and the time-domain simulation results at a high-frequency range.

In the time-domain simulation, the spectra of both the CM and DM noise have a resonant peak at the frequency of 19.10 MHz. However, the conventional-frequency model spectra have no resonant peak, because the parasitic components of the interconnect and semiconductor devices are not included in the models.

Table 1. Simulation parameters

Parameters	Values	Parameters	Values
V_{dc} [V]	42	Duty cycle	0.5
I_{load} [A]	3	C_{dc} [mF]	1
L_p [nH]	67	R_{dc} [mΩ]	30
R_p [mΩ]	12	L_{dc} [nH]	2
L_n [nH]	72	C_p [pF]	95
R_n [mΩ]	13	C_{oss} [pF]	350
L_{mid} [nH]	60	C_d [pF]	20.73
R_{mid} [mΩ]	12	L [uH]	1
R_{on} (MOSFET, diode) [Ω]	0.4	C [pF]	5
L_d [nH]	0.4	R [Ω]	10
R_g [Ω]	10	f_d [kHz]	20
L_m [nH]	0.4	$t_r = t_f$ [ns]	30

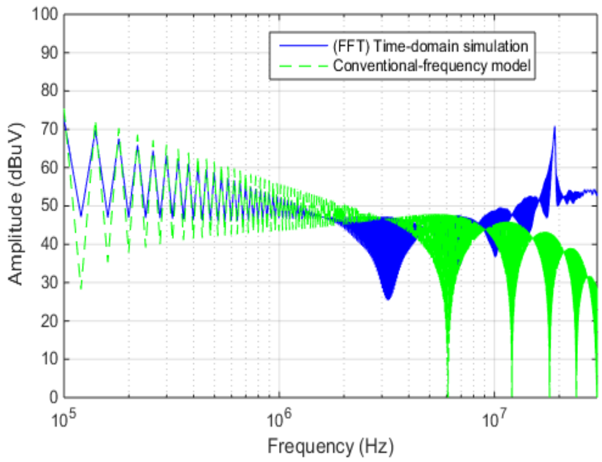

Figure 4. Conventional DM EMI noise spectrum.

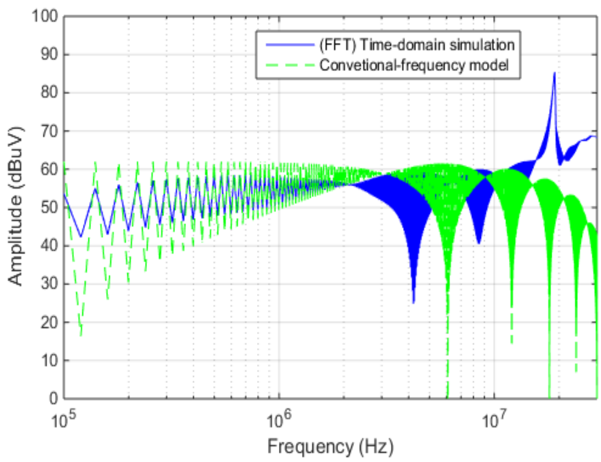

Figure 5. Conventional CM EMI noise spectrum.

4 DM and CM Model During a Switching Transient

For the DC/DC buck converter circuit, there are two switching transients, one for the MOSFET turn-off and the other for the MOSFET turn-on, which is equivalent to the diode turn-off [5].

Fig. 6 shows a decomposition of the noise-source waveform of the current and voltage, which is a sum of the trapezoid and parasitic ringing [4, 5]. The parasitic ringing occurs at a switching transient [5]. The trapezoid noise source is already discussed above in the past on conventional EMI models. In this part, the ringing-noise source and their propagation path will be described.

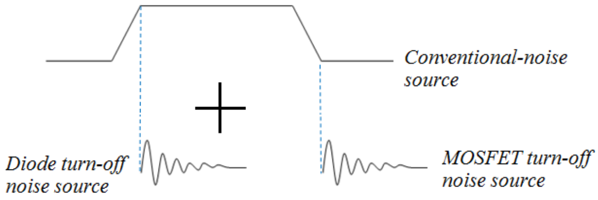

Figure 6. Decomposition of the waveform noise source in a DC/DC buck converter.

4.1 DM High-Frequency Equivalent Circuits

During a switching transient, two high-frequency equivalent circuits for the DM model can be derived; one for the diode turn-off and the other for the MOSFET turn-off. Fig. 7 shows these circuits [5].

In regard to the pulse nature of the power-electronic converters, the step function is often used in simplified analyses as an excitation source during a switching transient [12]. In the EMI DM equivalent circuits, the excitation source is a step current with a finite rising time as shown in Fig. 8 [5].

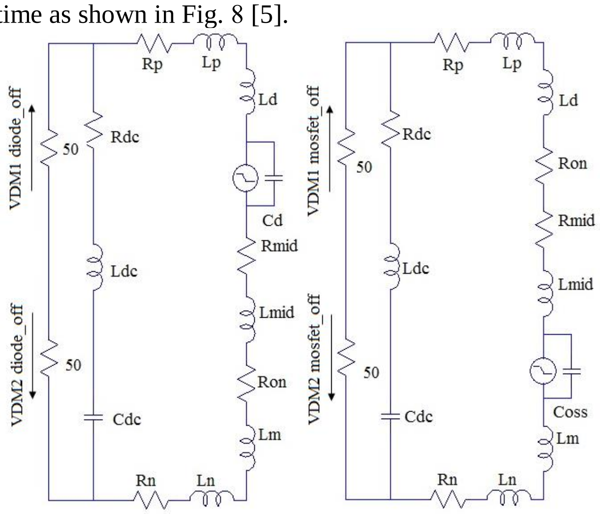

Figure 7. DM high-frequency equivalent circuits during a switching transient (a) diode turn-off (b) MOSFET turn-off [5].

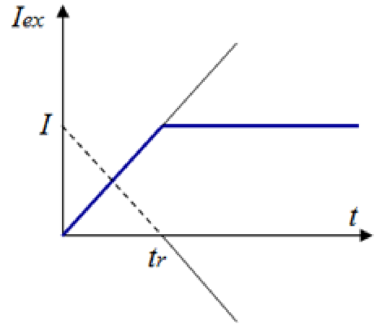

Figure 8. Excitation source during a switching transient [5, 12].

The excitation current for the diode turn-off in the Laplace form is expressed as [13]:

$$I_{ex} = \frac{I}{t_r}\cdot\frac{1}{s^2}\cdot\left(1-e^{-s\cdot t_r}\right) \tag{5}$$

For the MOSFET turn-off, the excitation current takes into account the time delay between two transients:

$$I_{ex} = \frac{I}{t_r}\cdot\frac{1}{s^2}\cdot\left(1-e^{-s\cdot t_r}\right).\, e^{-s\cdot\frac{d}{f_d}} \tag{6}$$

The expressions of the DM noise during the diode and MOSFET turn-off are given in Eqs. (7) and (8):

$$V_{DMmosfet\_off} = \frac{(V_{DM1mosfet\_off}-V_{DM2mosfet\_off})}{2} \tag{7}$$

$$V_{DMdiode\_off} = \frac{(V_{DM1diode\_off}-V_{DM2diode\_off})}{2} \tag{8}$$

Where $V_{DM1mosfet\_off}$ and $V_{DM2mosfet\_off}$ are the voltages across LISN 50 Ω during the MOSFET turn-off in the DM high-frequency equivalent circuits.

$V_{DM1diode\_off}$ and $V_{DM2diode\_off}$ are the voltages across LISN 50 Ω during the diode turn-off in the DM high-frequency equivalent circuits.

4.2 CM High-Frequency Equivalent Circuits

Similarly to the DM case, two high-frequency equivalent circuits for the CM model can be derived, one for the diode turn-off and the other for the MOSFET turn-off. Fig. 9 shows these circuits.

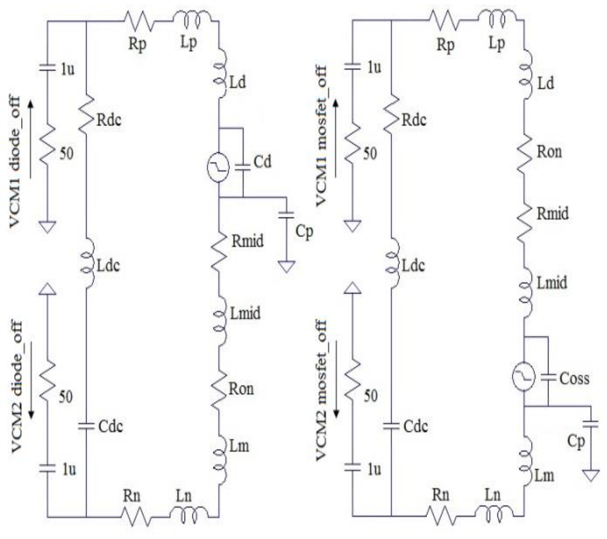

Figure 9. CM high-frequency equivalent circuits during a switching transient (a) diode turn-off (b) MOSFET turn-off [5].

The excitation source is a step-current source during the MOSFET and diode turn-off similarly to the DM model. C_p represents the CM propagation path.

The expressions for the CM noise during the diode and MOSFET turn-off are given in Eqs. (9) and (10):

$$V_{CMmosfet\_off} = \frac{(V_{CM1mosfet\_off} + V_{CM2mosfet\_off})}{2} \quad (9)$$

$$V_{CMdiode\_off} = \frac{(V_{CM1diode\_off} + V_{CM2diode\_off})}{2} \quad (10)$$

Where $V_{CM1mosfet\_off}$ and $V_{CM2mosfet\_off}$ are the voltages across LISN 50 Ω during the MOSFET turn-off in the CM high-frequency equivalent circuits.

$V_{CM1diode\_off}$ and $V_{CM2diode\_off}$ are the voltages across LISN 50 Ω during the diode turn-off in the CM high-frequency equivalent circuits.

5 A Complete Model for the EMI Noise Prediction

The new expression for the proposed DM model is given in Eq. (11):

$$V_{DM} = V_{conv\ DM} + V_{DMmosfet\_off} + V_{DMdiode\_off} \quad (11)$$

Where $V_{conv\ DM}$ is the DM noise obtained from the conventional EMI Model.
$V_{DMmosfet\_off}$ is the DM noise during the MOSFET turn-off.
$V_{DMdiode\_off}$ is the DM noise during the diode turn-off.

The new expression for the proposed CM model is given in Eq. (12):

$$V_{CM} = V_{conv\ CM} + V_{CMmosfet\_off} + V_{CMdiode\_off} \quad (12)$$

Where $V_{conv\ CM}$ is the CM noise obtained from the conventional EMI Model.
$V_{CMmosfet\_off}$ is the CM noise during the MOSFET turn-off.
$V_{CMdiode\_off}$ is the CM noise during the diode turn-off.

The parameters of the DC/DC buck converter used to determine the DM and CM noise are listed in Table 1 and the simulation results of the conducted CM and DM EMl noises are shown in Figs.10 and 11.

The results of the time-domain simulations and our approach for the CM and DM noise EMI spectra shown in Figs.10 and 11 have the same envelop in the low-, middle- and high-frequency range.

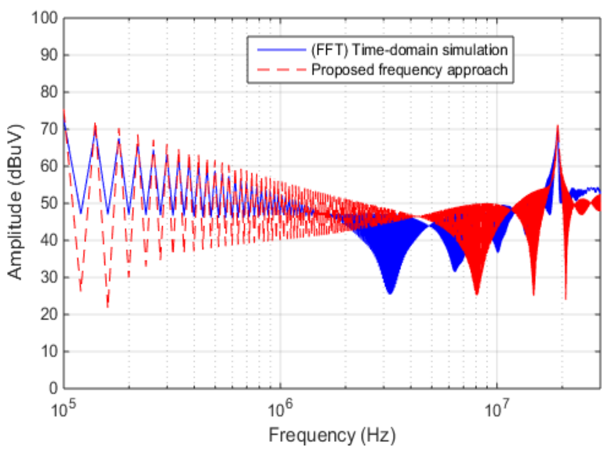

Figure 10. DM EMI noise-voltage spectrum.

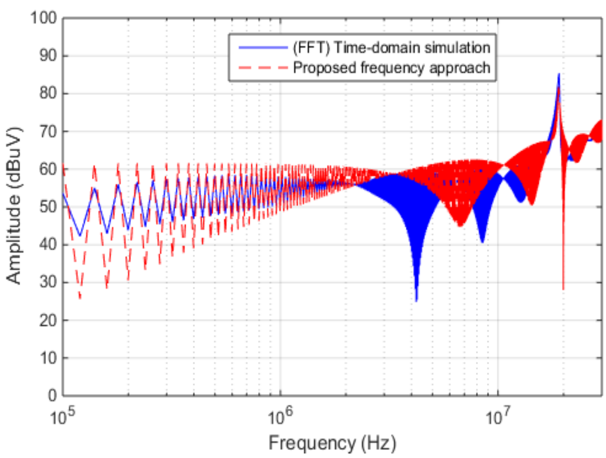

Figure 11. CM EMI noise-voltage spectrum.

6 CONCLUSION

The paper presents a simplified frequency-domain approach to calculate the EMI noise generated by a DC/DC buck converter. The limit of the conventional method to predict the DM and CM noise in a high-frequency range is presented. As the equivalent noise source and propagation path in the conventional model are rather simple, the parasitic ringing is not included.

In the proposed approach, this problem is resolved by adding two high-frequency equivalent circuits during a switching transient to model the DM and CM noises during diode and MOSFET turn-off. The excitation source is the step current that creates another high-frequency voltage-noise source responsible for the EMI noise of up to tens of the MHz range. A comparison of the results to the time-domain simulations indicates the efficiency of the proposed approach for the conducted EMI prediction in a DC/DC buck converter.

REFERENCES

[1] V. Tarateeraseth, I.A. Maio, F.G. Canavero, “Assessment of Equivalent Noise Source Approach for EMI Simulations of Boost Converter”, *Proceedings, 20th Int. Zurich Symposium on EMC*, Zurich 2009.

[2] L. Fakhfakh, A. Amous, “New simplified model for predicting conducted EMI in DC/DC converters”, *Springer*-Verlag Berlin Heidelberg 2016.

[3] D. Labrousse, B. Revol, F. Costa, “Switching Cell EMC Behavioral Modeling by Transfer Function”, *Proc. of the 10th Int. Symposium on Electromagnetic Compatibility (EMC Europe 2011)*, Yourk, UK, Septempber 26-30, 2011.

[4] L. Fakhfakh, A. Alahal, A. Amous, “Fast Modeling of Conducted EMI Phenomena Using Improved Classical Models”, *Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC)*, 2016.

[5] X. Huang, “Frequency Domain Conductive Electromagnetic Interference Modeling and Prediction with Parasitics Extraction for Inverters”, doctoral thesis, Blacksburg, Virginia, 2004.

[6] J.S. Lai, X. Huang, E. Pepa, S. Chen, W.N. Thomas, “Inverter EMI Modeling and Simulation Methodologies”, *IEEE Transactions on Industrial Electronics, vol. 53, no. 3, June 2006*.

[7] M. Moreau, “Modélisation haute fréquence des convertisseurs d’énergie. Application à l’étude des émissions conduites vers le réseau”, Ecole Centrale de Lille, These de doctorat, 2009.

[8] M. Nave, “The Effect of Duty Cycle on SMPS Common Mode Emission: Theory and Experiment”, *IEEE EMC Symposium Proceeding, 23-25 May 1989*, pp. 211-216.

[9] B. Revol, “Modélisation et optimisation des performances CEM d'une association variateur de vitesse – machine asynchrone”, Thèse de doctorat de l’UJF, novembre 2003.

[10] D. Chariag, D. Guezgouz, J.C. Le Bunetel, Y. Raingeaud , “Modélisation et simulation fréquentielle d’un convertisseur statique sous SPICE”, *https://www.researchgate.net/publication/267202550.*

[11] M. Nave, “Prediction of conducted emissions in switched mode power supplies”, *IEEE Int. Symp. On EMC'86*, pp 167-173.

[12] Z. FEDYCZAK, A. KEMPSKI, R.SMOLEŃSKI, “Conducted high frequency disturbances observed in electrical power systems with switch mode converters”, *PRZEGLĄD ELEKTROTECHNICZNY*, R. 89 NR 6/2013.

[13] W. Teulings, “Prise en compte du câblage dans la conception et la simulation des convertisseurs de puissance: performances CEM”, Thèse de doctorat de l’INPG, avril 1997.

Nassireddine Benhadda received his M.S. and magister (Dr. Eng.) degrees in electrical engineering from the University of Sidi Bel Abbes, Sidi Bel Abbes, Algeria, in 2006 and 2011, respectively. Currently, he is employed with the Algerian Electricity and Gas Distribution Company (SDC). His current research interests include design and EMC study of the static converter.

Abdelber Bendaoud is an Assistant Professor at the Institute of Electrical Engineering at the University of Sidi Bel-Abbès, Algeria. His research interests include electrostatic separation technologies, high-voltage insulation, gas discharges, electric and magnetic fields, and electromagnetic compatibility. He received his PhD degree from the University of Djilali Liabes of Sidi Bel-Abbès.

Nawel Chikhi is a graduate student at at the Institute of Electrical Engineering at the University of Sidi Bel-Abbès, Algeria. She is pursuing her PhD studies in Electrical Engineering. Her research interests include electromagnetic compatibility, system identification, and electronic power converters.