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ENERGY CABLE MODELING UNDER POWER ELECTRONIC CONVERTER CONSTRAINTS

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ABSTRACT

The rapid commutation of the modern power semi-conductor devices used in the static converters is the source of the conducted and radiated emissions. These devices produce high voltage variations (dv/dt) which excite leakage elements of the power circuit and induce high frequency parasitical currents. These currents used the energy cables to be propagated from the converter to the load and the power grid.

This paper proposes a high frequency modelling method of energy cable that takes into account phenomena that appear when the switching frequency increase as: skin and proximity effects and dielectric losses. The proposed method is applied to the three-wire unshielded cable and extended to the four-wire shielded cable. The obtained models are validated in both frequency and time domain in Adjustable Speed Drives system.

KEYWORDS

Power cables, skin effect, dielectric losses, modeling, transmission line circuits, frequency-domain analysis, time-domain analysis.

INTRODUCTION

In the power electronic converters, energy cables are the spreading paths of the conducted disturbances in the whole system. In order to use a circuit simulation tool as SPICE software to study the conducted emissions, it is necessary to use the high frequency models of each part of the system [1] [2].

Because most simulation software's doesn't have high frequency power cable models, one proposes in this study, a modelling method of shielded and unshielded cable. The proposed models are taking into account skin and proximity effects, dielectric losses in a distributed parameters model [3].

In the first section of this paper, the power cable model method is described and applied to model a 3-wire unshielded cable, and a 4-wire shielded. The second section presents the validation of the obtained models in both frequency and time domain.

UNSHIELDED 3-WIRE CABLE MODEL

The unshielded cable under study is composed of three conductors, the cross sectional area of each conductor is 2,5mm². Each conductor is coated with PVC and the unit is placed in a rubber sheath.

To model this cable, a distributed parameter circuit composed from cascaded basic cells is used whose the elementary cell is represented in Figure 1. However, a preliminary study has shown that 32 cells per meter length give a good compromise between simulation duration and model accuracy.

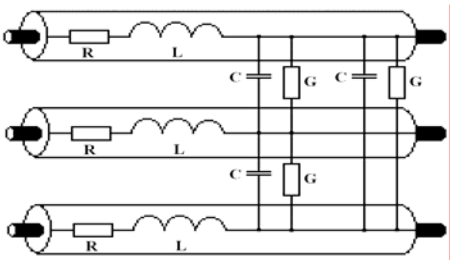


Figure 1: Unshielded 3-wire Cable model

The cable parameters per unit length (R, L, C and G) are obtained by three methods: analytic calculation, Finite-Element Method and measurement using impedance bridge (HP4294A).

To measure the cable parameters, two test configurations are necessary: the cable in short-circuit configuration to obtain R and L and in open circuit for C and G parameters as shown in Figure 2. All the cable parameters are measured with one-meter cable length.

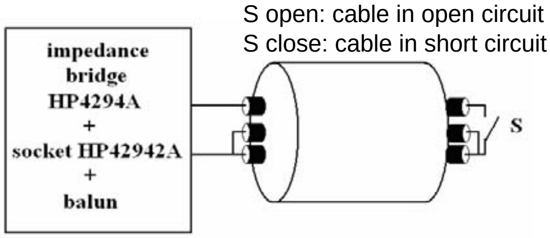
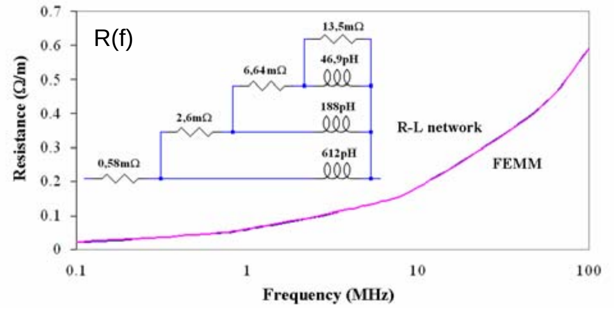


Figure 2: Cable parameters measurement

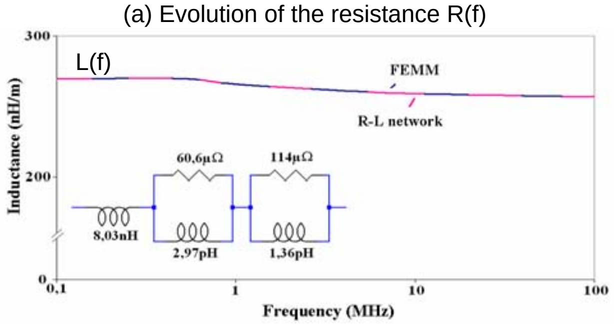
The previous study has shown that the simulation of the cable using the constant parameters measured at 500 kHz do not give satisfactory results. However, it is necessary to take into account the conductor resistance variation caused by the skin and proximity effects, and the conductance variation that which is due to the dielectric losses between wires. Measurements data have also shown that the wire inductance varies according to the frequency. On the other hand the capacitance between each pair of conductors is constant.

There are various methods making it possible to model the evolution of the cable parameters per unit length according to the frequency [4] [5]. In this study, to model the evolution of the conductor resistance and inductance when the frequency increases, two R-L networks shown in Figure 3a-b are used [6]. A comparison of the simulation results of these ladder circuits with those obtained with Finite-Element code “FEMM software” shows a good agreement.

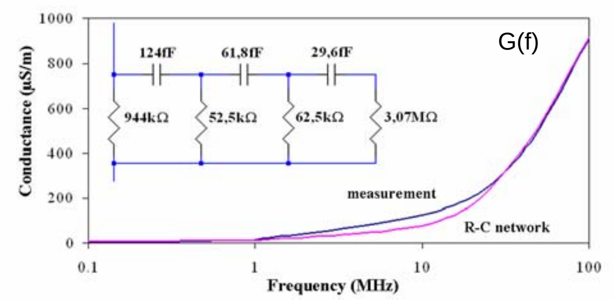
As presented previously, the evolution of the conductance between each pair of conductors is modeled using an R-C ladder network. This conductance is measured with Impedance Bridge in the configuration presented on Figure 2. The comparison of the simulation results of R-C ladder network with those measured (Figure 3c) shows a good agreement. The model of elementary cell (32cells/meter) of unshielded cable model, taking into account the skin and proximity effects and the dielectric losses is shown in Figure 3d.



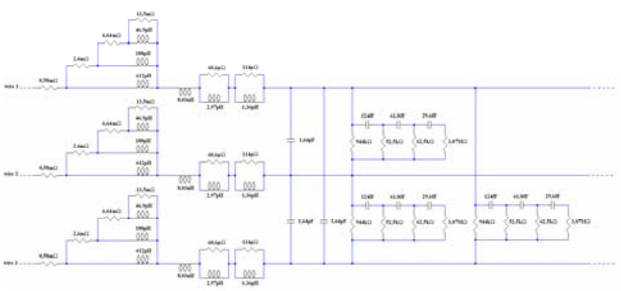
(a) Evolution of the resistance R(f)



(b) Evolution of the inductance L(f)



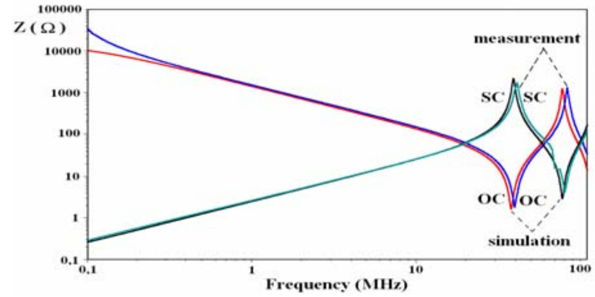
(c) Evolution of the conductance G(f)



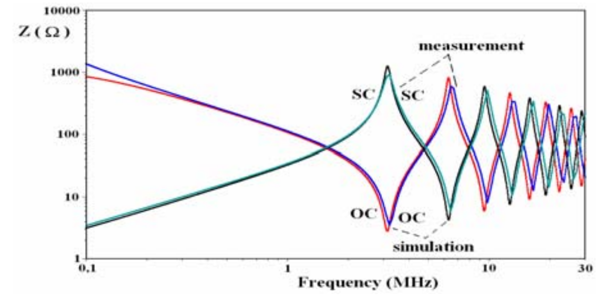
(d) Elementary cell of the cable model

Figure 3 Basic cell of the unshielded cable model

To validate the proposed model in frequency domain, the cable simulation results of 1 and 12 meters cable length are compared with experimental data, in open and short circuit configurations as shown in Figure 4. These results show good agreement between simulation and measurement.



(a) 1 meter cable length



(b) 12 meters cable length

Figure 4 : Evolution of the cable impedance in short and open circuit configurations

SHIELDED 4-WIRE CABLE MODEL

In the following section, the unshielded cable modelling method is applied to the shielded power cable that is composed from 4-wire. The cross sectional area of each conductor is equal to 1.5mm². These conductors are coated with PVC and a shield made from the same material as the conductors is placed around the wires. The unit is placed a PVC sheath.

The proposed elementary cell of shielded 4-wire cable model, represented in Figure 5, is formed by:

- Serial impedances Z_s that represent the resistance R and the inductance L of each conductor,
- Parallel impedances Z_p that represent the capacitance C_p and conductance G_p between each pair of conductor,
- Conductor-shield impedances Z_b that represent the capacitance C_b and the conductance G_b between each conductor and the shield.

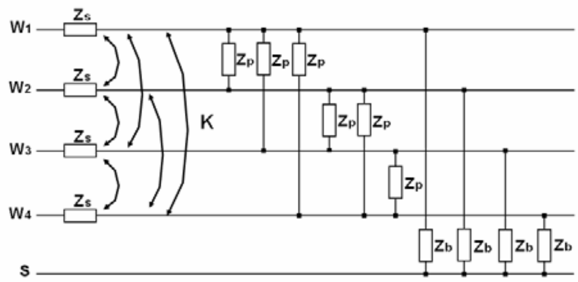
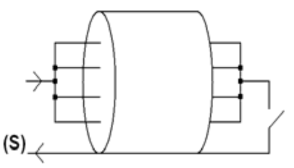
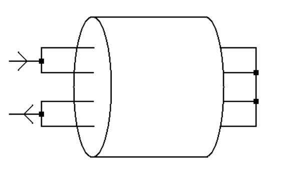


Figure 5 : Basic cell of the 4-wire shielded cable model

The study of the shielded cable model has shown that it is necessary to add a coupling coefficient K between each pair of conductor [3]. The various parameters values of the shielded cable model (R, L, K, C_i, G_i, C_b, G_b) are measured in frequency band varying from 100KHz to 40MHz.

In the case of the shielded cables, it is necessary to carry out two tests: the first in common mode and the second in differential mode configuration as shown in Figure 6. For each configuration the cable is tested in a short circuit and an open circuit.



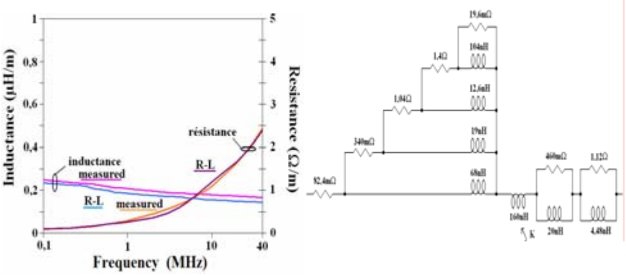


(a) : common mode test (b) : differential mode test

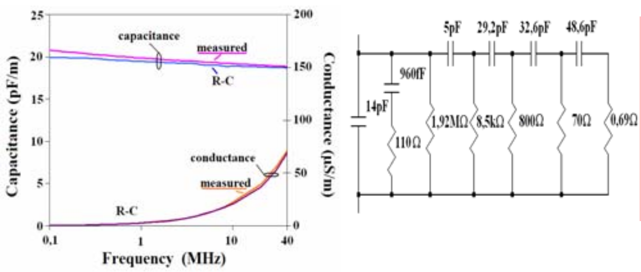
Figure 6 : Cable test configurations

As for the unshielded cable, the simulation of the shielded cable using the constant parameters measured at 500 kHz do not give satisfactory results. However, it is necessary to take into account the variation of the cable parameters according to the frequency.

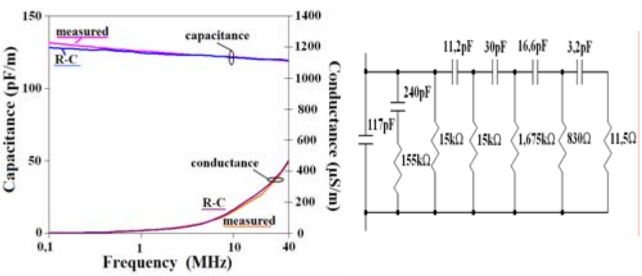
As the unshielded cable model method, the shielded cable parameters evolutions are modeled by the R-L and R-C ladder networks as shown in Figure 7.



(a) Evolution of impedance Zs (or R and L)



(b) Evolution of impedance Zp (or Rp and Cp)

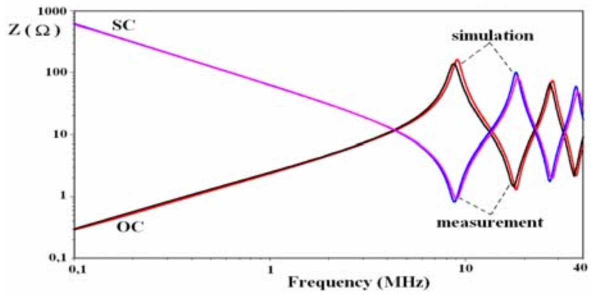


(c) Evolution of impedance Zb (or Rb and Gb)

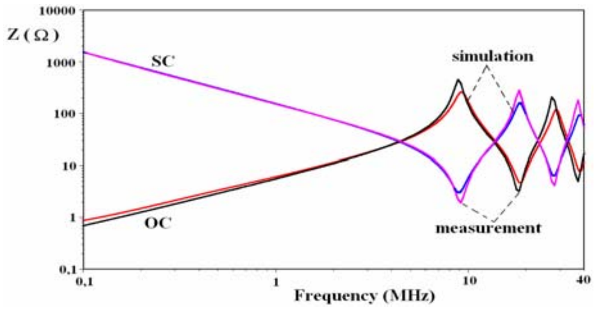
Figure 7 : Evolution of the shielded cable model parameters

Preliminary study has shown that 32 cells for 5 meters cable length give a satisfactory compromise between simulation duration and model accuracy.

The simulation results of the 5-meters length shielded cable in open and short circuit configurations compared to the experimental measurement for the two-test configurations are shown in Figure 8. One note a good agreement between measurement and simulation results of the cable impedance in the frequency domain.



(a) Common Mode configuration



(b) Differential Mode configuration

Figure 8 : Shielded cable impedance in short and open circuit tests

VALIDATION OF THE CABLE MODELS IN TIME DOMAIN

Unshielded 3-wire cable

To validate the obtained unshielded cable model in the time domain, a buck converter supplied an 3-phase AC motor between 2 phases through a unshielded 3-wire power cable as shown in Figure 9.

The aim is to observe the voltage and current waveforms at the input and output side of the power cable when transistor switchings occur, and to compare them with the simulation results obtained by cascading the models of converter, cable, and ac-motor. The high frequency models of the power converter (SPICE power MOSFET and SiC diode models are used) and the AC motor has been proposed in a previous study [7].

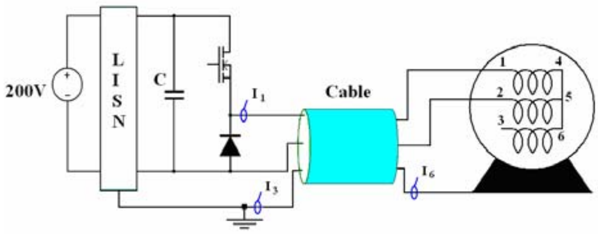


Figure 9 : Experimental set up use to validate the unshielded 3-wire power cable

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In the following section, a diode to MOSFET transition is only presented. The comparison of the measured and simulated current waveform at the input side of the cable (Figure 10) shows a good agreement. The current waveforms in the third wire (Figure 11 a-b) are similar.

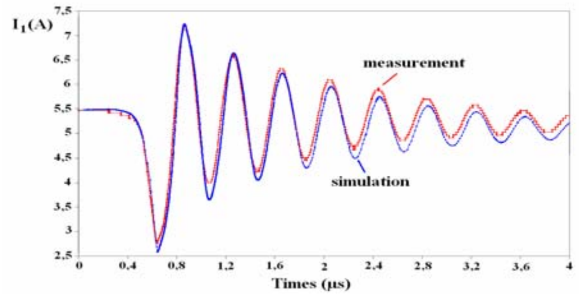
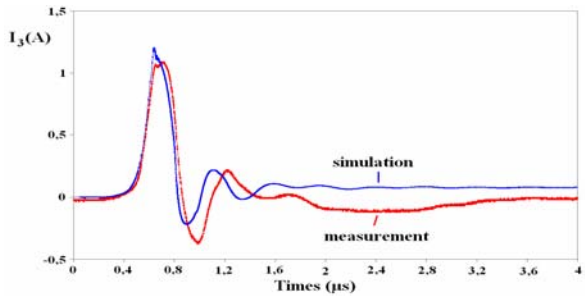
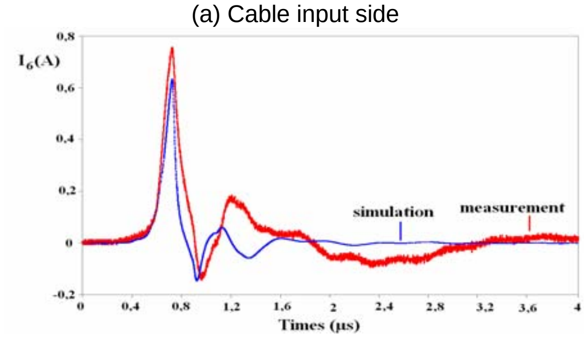


Figure 10 : Current I_1 at the input side of the cable



(a) Cable input side



(b) Cable output side

Figure 11 : Common mode current in the cable at the input side (a) and at the output side (b)

Shielded 4-wire cable

The experimental setup is an Adjustable Speed Drive that is built from a 3-phase IGBT inverter, operating at 20 KHz switching frequency where a 2 kW asynchrone motor is fed trough 5 meters shielded 4-wire cable. The inverter is supplied trough a LISN (Line Impedance Stabilization Network) and 1-meter of the unshielded 3-wire cable (previously study) as shown on Figure 12.

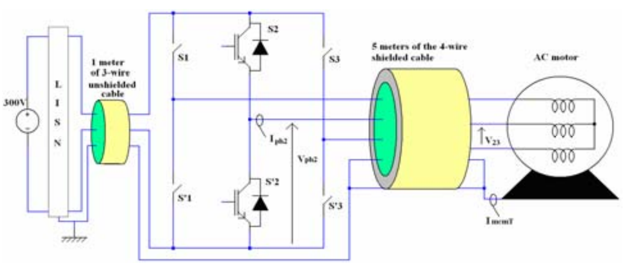
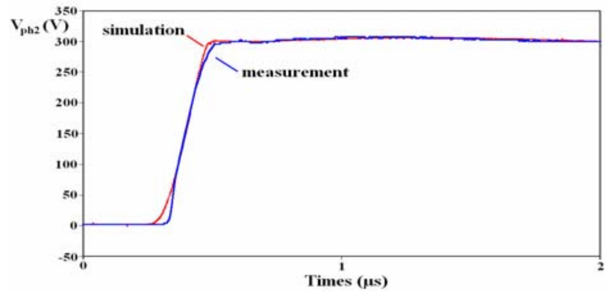
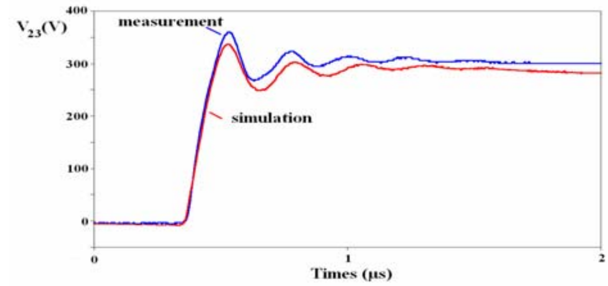


Figure 12 : Experimental set up use to validate the 4-wire shielded cable model

To simulate the ASD, high frequency models are used that proposed in the previously study [2]. Figure 13 shows voltages waveform at the shielded cable input and the output side. On Figure 13b, One can note the apparition of over-voltage on the motor terminals [8].



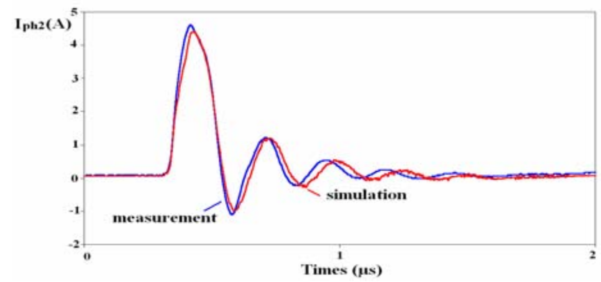
(a) The voltage at cable input side



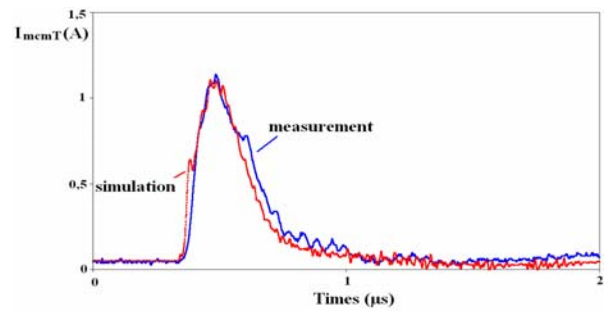
(b) The voltage at cable output side

Figure 13 : Phase-to-phase cable voltage

The current in phase 2 shown in Figure 14a corresponds to the differential mode and common mode. The motor ground current (common mode) is shown in Figure 14b. The comparison with experimental data shows a good agreement.



(a) Current in phase 2 of the inverter



(b) Current in motor ground

Figure 14 : Current waveforms in (a) in the cable, (b) common mode current

CONCLUSION

In order to analyze the spreading paths of the conducted emissions (EMI) produced by the power static converters connected to the power network, it is necessary to use a satisfactory model of the power cable.

In this paper, the energy cable modelling method using a distributed constants circuit is proposed. The obtained models take into account the evolution of the cable parameters according to frequency. This method is applied to model the unshielded and shielded cables.

To validate these models in time domain, an buck converter and ASD were used. The comparison of the simulation and measurement data shows that the proposed model allows to reproduce, with a lower difference, the amplitude and the frequency of the most important oscillations of voltage and current in the study systems.

These models can thus be used to test various solutions making it possible to reduce output overvoltage under the motor terminals. They can also be used to study the EMI propagation in the power electronic systems connected to the power network.

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