Determination of the Frequency Behavior of Passive Power Electronics Components

Abdelhakim ZEGHOUDI [1], Abdelber BENDAOUD [1], Helima SLIMANI[2]

[1] APELEC Laboratory, Djilali Liabes University, Sidi Bel Abbes, Algeria
[2] APELEC Laboratory, Univerity Ibn Khaldoun of Tiaret, Tiaret, Algeria

E-mail: hakooumzeghoudi@gmail.com

Abstract - Energy conversion in power electronics comprises two complementary phases: switching, performed by semiconductors. There are two types of switch: controlled components (MOSFET, IGBT, thyristor, etc.) and uncontrolled components (diodes). Energy storage takes place via passive components such as capacitors and inductors, as well as resistors, which transform electrical energy from one form to another. The use of semiconductor components (MOSFETs, IGBTs, thyristors, etc.) during switching leads to rapid variations in voltage (dv/dt) and current (di/dt). This generates high-frequency electromagnetic disturbances and interference on passive components. The aim of this study is to determine the equivalent models and frequency behaviors of passive components (resistor, inductor, capacitor) at high frequency, using LT-spice software.

Keywords - frequency behavior, passive components, LT-spice software, resistors, inductors, capacitors.

I. INTRODUCTION

In the field of power electronics, Electromagnetic Compatibility (EMC) aspects encompass the following essential characteristics: converters act both as sources, due to the phenomena associated with power switch switching, and as victims, because their "control-command" board is generally digital or hybrid in nature. What's more, they can be self-disturbed by the power section. There is also the possibility of external interference from natural and industrial environments [1-4].

In general, power converters incorporate switching cells that produce rapid variations in voltage (dV/dt) and current (dI/dt), as well as filter inductances, disconnecting capacitors and extraneous components such as inter-component parasitic inductances and common-mode capacitors. These elements create circuits with second-order resonances, leading to the emergence of an oscillatory phenomenon [4-7].

All passive components, i.e. resistors, capacitors, and coils, have parasitic elements that have a strong impact on impedance behavior as a function of frequency and can give rise to resonances. Parasitic elements can be classified into three effects (resistive effects, inductive effects and capacitive effects) [8]:

- Resistive effects arise from the resistance to current flow in the materials used. These effects depend on the geometric and physical characteristics of the materials. They can be considered invariant within a certain frequency range or, on the contrary, frequency-dependent, notably due to skin and proximity effects.
- Inductive effects occur when a current flows through a circuit, creating a magnetic field and flux in the loop formed by the circuit. The very concept and value of an inductance depend on the magnetic flux generated and its environment..
- Capacitive effects occur when two conductive surfaces are not at the same potential. The apparent capacitance depends on the geometry of the surfaces, their relative position and the type of material (electrical permittivity of the dielectric) separating them. [9].

The document is structured as follows: Section II presents and defines passive components. Section III describes the modeling of passive components, and their frequency behavior through simulation using LTspice software. The conclusion is presented in section V.

II. PASSIVE COMPONENTS

✓ *Resistors*

The resistor is a common passive component in power electronics, but one that is "shunned" because of its energy losses [10]. It is mainly used in electrical circuits, filters, and converter control electronics. They generally come in three different forms: carbon resistors, wire-wound resistors, and film resistors. [9].

✓ *Capacitors*

Capacitors are an essential part of any converter. They are found in input and output filters, and sometimes in the converter core. They are also indispensable in resonant and soft-switching converters. A capacitor is a passive component that stores energy in the form of an electric field [11]. In its simplest form, a capacitor consists of two conductive plates separated by an insulating material called a dielectric. The capacitance is directly proportional to the surface areas of the plates, and inversely proportional to the distance between them. Capacitance also depends on the dielectric constant of the material separating the plates.

✓ *Coils*

Coils, like capacitors, are essential to power electronics. They are found in filters and in the heart of all converters. They are also indispensable in resonant and soft-switching converters. A coil is a passive component that stores energy in the form of a magnetic field [12]. At the very least, it consists of a simple conductive loop. Most often, this is a multi-turn winding. This is usually wound around a magnetic material or a set of materials forming the magnetic circuit, in order to channel the magnetic field, reduce losses and increase the value of the inductance.

III. MODELING PASSIVE COMPONENTS

The steps involved in modeling passive components are as follows:

1. Modeling begins with the selection of an equivalent electrical model of the component (resistor, capacitor, and inductor).
2. The models developed in this work are of two types:

- Analytical models, based on the component's geometric and physical properties.

- Experimental tests based on measurements of the component's behavior in terms of time and frequency, enabling us to obtain satisfactory results on a regular basis and then compare them with the results obtained from references. [13-15].

A) Resistance model

The equivalent resistance model we are considering is common to the different types mentioned. This model is illustrated in Figure 1.

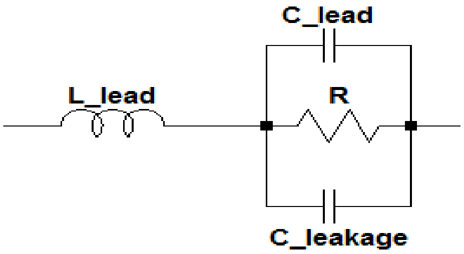

Fig. 1. Equivalent resistor model [9].

The model is built around a resistor R, which must be close to the nominal resistance. The equivalent series inductance L_{lead} and the capacitances C_{lead} (connector-related) and $C_{leakage}$ (leakage capacitance) complete the model. Since the two capacitances in question are in parallel, we can simplify the equivalent model by replacing them with an equivalent capacitance: [9]

$$C_{eq} = C_{lead} + C_{leakage} \quad (1)$$

➢ *Modeling Example*

We have taken a high-frequency model, for a resistor R = 820 Ω as shown in figure 2, which presents the modulus and phase of the impedance.

The frequency response for an ideal resistor is zero phase over the entire frequency range. However, the actual behavior of a resistor involves the following three elements :

R_{pr} : self-resistance
L_s : parasitic inductance
C_p : caparallel parasitic capacitance

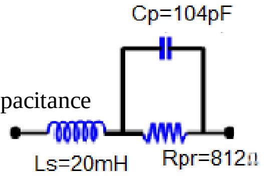

Fig. 2. Equivalent diagram of a resistor in the real case.

We simulated the frequency behavior of a resistor in order to demonstrate the effect of frequency on resistor impedance. Figure 3 shows the frequency variation of the impedance of a resistor R = 820 Ω.

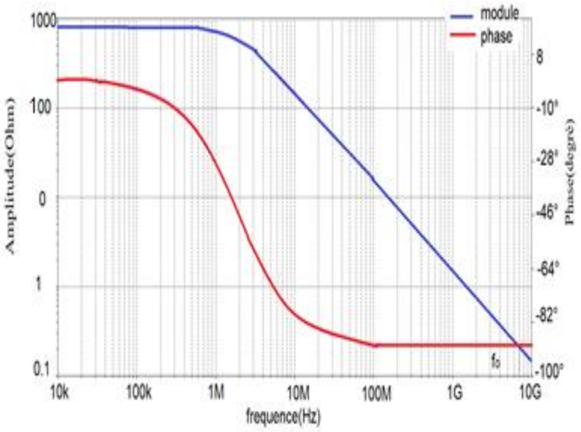

Fig. 3. Frequency behavior of a resistor

Analysis of these results shows that at low frequencies, the resistor's behavior is close to that of an ideal resistor. With increasing frequency, the impedance of the parasitic capacitor C_p decreases (C_P = 1/jcω) and consequently, the impedance of the resistor decreases up to frequency f_0, because the resistor and parasitic capacitor are in parallel, as shown in the resistance model. Where the parasitic inductance L_s and the parasitic capacitor C_p resonate. At this frequency f_0, the impedance of the resistor is minimal.

B) Capacitor Model

A generalized equivalent circuit for capacitors can be constructed (Fig. 4), but the values of the elements in this model differ according to the type of capacitor. The conductive parts of the component introduce an inductance L_{lead} and a capacitance C_{lead}.

On the other hand, the capacitor plates themselves introduce a resistance R_{plate}. The dielectric between the capacitor plates is modeled by a large $R_{\mathrm{dielectric}}$ resistor placed in parallel with the component's nominal capacitance C [9].

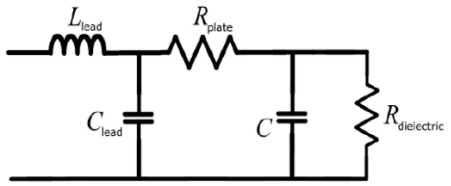

Fig. 4. Equivalent capacitor model [13].

The capacitance of the C_{lead} conductive parts is generally lower than the rated capacitance and can be neglected. Similarly, the resistance of the dielectric is very high and can be considered as an open circuit. By eliminating these two parameters, the equivalent model can be reduced to the nominal capacitance, in series with the plate resistance and the inductance of the conducting parts. The model is shown in figure 5.

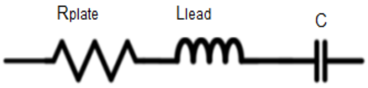

Fig. 5. Simplified equivalent capacitor model [13].

The plate resistance R_{plate} is often called ESR (Equivalent Serial Resistance) and the inductance of the conducting parts L_{lead} is often called ESL (Equivalent Serial Inductance).

This capacitor model reflects a frequency-dependent behavior:

- At low frequencies, ESL behaves like a short-circuit and capacitor C like an open circuit. The model as a whole behaves like an open circuit as Z_{eq} tends towards infinity, more exactly like a capacitor..

- As frequency increases, capacitor impedance decreases, and so does total impedance, until a minimum is reached

For this particular pulsation ω, the circuit reaches resonance and the imaginary part and phase of the impedance cancel out; beyond the resonance frequency, the impedance of the inductor increases linearly; the total impedance increases.

ESR does not have a constant value for all capacitors. This factor constitutes a difference between the various technologies. In all cases, the model remains the same.

➢ *Modeling Exemple*

As shown in Figure 6, in reality, the behavior of the *C* capacitor involves the following three elements [13, 15]:

C_{PR}: own capacitor.
R_S: parasitic series resistance of the connection wires and internal resistors.
L_S: series parasitic inductance due to connecting wires.

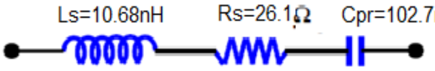

Fig. 6. Equivalent diagram of a real-rate capacitor [9].

Figure 7 shows frequency variations in the impedance of a polypropylene film with a capacitance *C* of 100 nF.

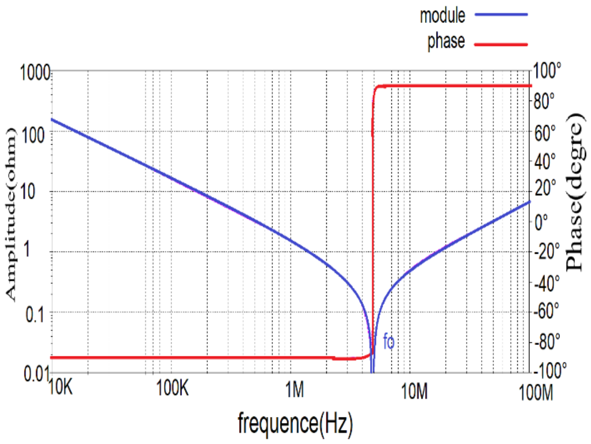

Fig. 7. Frequency behavior of a Capacitor

Analysis of these results shows that at low frequencies, the influence of parasitic series inductance is negligible. With increasing frequency, the capacitor impedance decreases linearly with a phase approaching -90°. Up to resonance frequency f_0, capacitor impedance is equal to internal resistance R_s. Above frequency f_0. Inductance impedance Ls increases linearly with phase approaching +90°, so capacitor impedance C also increases.

C) Model of a Coil

As with other passive components, a generalized equivalent model for coils can be constructed as shown in Figure 8.

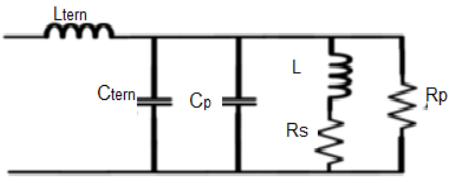

Fig. 8. Coil equivalent model [9].

✓ The conductive part of the terminations introduces an inductance L_{term} and a capacitance C_{term} ;

✓ An equivalent series resistance R_s which takes into account the resistive part of the copper of the turns;

✓ A parallel equivalent capacitance C_p representing the capacitances between the different turns of the coil;

✓ An equivalent parallel resistance representing the coil's iron losses R_p.

✓ The nominal inductance *L*.

This model can be simplified by neglecting the termination inductance L_{term} and replacing the capacitances by an equivalent capacitance C_{tot}.

✓ As in the previous cases, the impedance behavior of the equivalent model is studied as a function of frequency:

- at low frequencies, series resistance dominates and impedance is very close to the value of R_s, as R_p is very high;
- as frequency increases, the nominal inductance *L* begins to dominate up to a certain resonance frequency close to that of ω_r ;
- at the resonance frequency, the phase will be zero and the impedance will have a value very close to that of R_p

- after the resonance frequency, parasitic capacitance begins to dominate the equivalent circuit. In this frequency range, impedance decreases with frequency, since the behavior is capacitive [9].

➢ ***Modeling Example***

In contrast to the behavior of the capacitor, the modulus of the inductor increases linearly with frequency, with a phase that tends toward + 90° over the entire frequency range.

In reality, the behavior of the inductance involves three elements, as shown in Figure 9.

Where L_{pr}: self-inductance,
R_s: series wire resistance,
C_p: parasitic capacitance.

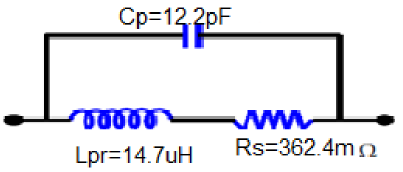

Fig. 9. Equivalent diagram of an inductor in the real case.

In Figure 10, we show the frequency variations of the impedance of an inductor whose value L is 15 µH.

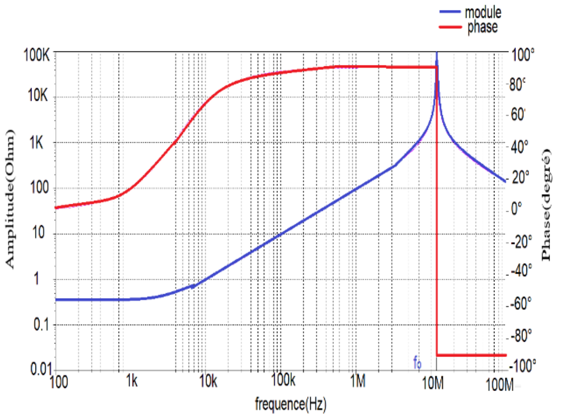

Fig. 10. Frequency behavior of a Coil.

For reasons strictly symmetrical to those of the capacitor, we can see that at low frequencies, the impedance of the inductance L is equal to R_s. With increasing frequency, the inductance begins to increase linearly until the frequency f_0 is equal to 10 MHz. This is where the inductance L_{pr} and the parasitic capacitor C_{pr} resonate, with a phase angle close to + 90°. As the frequency increases further f_0, the impedance of the parasitic capacitor decreases, and consequently, the impedance of the L increases also.

IV. CONCLUSION

The physical behavior of passive power components in static converters is changed because of the rapid variation of voltage and current as function of time due to the switching frequency of electronic switches. In this work, we have modeled the passive components (inductor, capacitor), and the resistor under LT-spice software, then determines the frequency behavior at high frequency, or concluded that the impedance values (the phase, and the modulus) changes as a function of frequency). So, it must be well chosen the control frequency of a converter. Future work will be based on experimental determination of frequency behavior using impedance analyzers.

V. REFERENCES

[1] Hrigua, S., Costa, F., Revol, B., Gautier, C. (2012).Nouvelle méthode d'analyse des interférences électromagnétiques (IEM) dans les convertisseurs statiques. 14ème édition de la Conférence Electronique de Puissance du Futur Bordeaux: 5-7 juillet 2012, Bordeaux, France.

[2] Idir, N. (2016), CEM en Électronique de Puissance : Convertisseurs Statiques Propres. Quatrièmes Journées d'Etude. Réseaux Electriques, Haute Tension et Compatibilité Electromagnétique. REHTCE'2016, 7-9 novembre 2016, Sidi Bel-Abbès.

[3] Slimani, H., Zeghoudi, A., Bendaoud, A., Reguig, A., Benazza, B., Benhadda, N. (2021), Experimental measurement of conducted emissions generated by static converters in common and differential modes. European Journal of Electrical Engineering, Vol. 23, No. 3, pp. 273-279. https://doi.org/10.18280/ejee.230312

[4] A. Zeghoudi, A. Bendaoud, H. Slimani, B. Benazza, and Bennouna 2022 Determination of electromagnetic disturbances in a buck chopper, Australian Journal of Electrical and Electronics Engineering,

DOI: 10.1080/1448837X.2021.2023073.

[5] Zeghoudi, A., Slimani, H., Bendaoud, A., Benazza, B., Bechekir, S., & Miloudi, H. (2022). Measurement and analysis of common and differential modes conducted emissions generated by an AC/DC converter. *Electrical*

Engineering & Electromechanics, (4), 63–67. https://doi.org/10.20998/2074-272X.2022.4.09

[6] Bechekir, S., Zeghoudi, A., Ould-Abdeslam, D., Brahami, M., Slimani, H., & Bendaoud, A. (2023). Development of a boost-inverter converter under electromagnetic compatibility stress equipping a photovoltaic generator. *Electrical Engineering & Electromechanics*, (5), 14–19. https://doi.org/10.20998/2074-272X.2023.5.02

[7] Benazza, B., Bendaoud, A., Slimani, H., Benaissa, M., Flitti, M., & Zeghoudi, A. (2023). Experimental study of electromagnetic disturbances in common and differential modes in a circuit based on two DC/DC boost static converter in parallel, *Electrical Engineering & Electromechanics*, (4), 35–39. https://doi.org/10.20998/2074-272X.2023.4.05.

[8] Slimani, H., Zeghoudi, A., Bendaoud, A., & Bechekir, S. (2023). Experimental evaluation of conducted disturbances induced during high frequency switching of active components, *Electrical Engineering & Electromechanics*, (5), 26–30. https://doi.org/10.20998/2074-272X.2023.5.04

[9] Jad Taki, Contribution aux modèles des perturbations électromagnétiques émis par les convertisseurs de l'électronique de puissance, Thèse de doctorat, en physique et ingénierie : électron, photon, sciences du vivant, spécialité Génie Electrique, Gif-Sur-Yvette, Octobre 2017.

[10] L. W. Turner, Electronics Engineer's, Reference Book", 4th Edition, Butterworth, 1976.

[11] Kemet, Introduction to capacitor technologies, kemet Corporation, 2013.

[12] W. K. chen, The Electrical Engineering Handbook, Elsevier Inc, 2005.

[13] Randall W. Rhea, HF Filter Design and Computer Simulation, Founder and President Eagleware Corporation, Noble Publishing Atlanta.1994.

[14] Marlin O. Thurston, SPICE for Power Electronics and Electric Power, Université de Columbus, Ohio, 2ème Edition, 11 Août 2006.

[15] Peter Mantovanelli Barbosa, Three-Phase Power Factor Correction Circuits for Low-Cost Distributed Power Systems, Thesis PHD, Faculté de Polytechnique, Blacksburg, Virginia 31 Juillet 2002.