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Passive device degradation models for a electromagnetic emission robustness study of a buck DC-DC converter

Abstract—Past works showed that the degradation of the passive devices caused by aging could induce failures of electronic system, including a harmful evolution of electromagnetic compatibility. This paper presents the impact of accelerated aging conditions on several typical passive components (capacitor, inductor). The preliminary degradation models of electrolytic capacitor and powder iron inductor are proposed based on experimental results and physical analysis. The overall objective of this study is to predict the evolution of electromagnetic emission level produced by a buck DC-DC converter under a thermal aging, by using these passive device degradation models.

Keywords—*passive device; electromagnetic emission; accelerated aging; degradation modeling*

I. INTRODUCTION

The consideration of the electromagnetic robustness (EMR) of integrated circuits (IC) appeared in these last years, i.e. the evolution of parasitic emission and susceptibility to electromagnetic interferences with time for electronic devices operating in harsh environments. Publications such as [1] have shown the electromagnetic emission (EME) of digital circuits and I/O buffers changes with time because of the activation of intrinsic degradation mechanisms. As presented in only few works, the simulation can be used to predict the long-term EMC behavior. For example, in [2], the simulation results confirm the evolution of the electromagnetic susceptibility (EMS) of a phase-locked loop before and after aging.

A switch-power mode supply is chosen as the device under test (DUT) in this study. Because of their high power efficiency, switch-power mode supplies (SMPS) are widely used in electronic applications [3]. However, one of their main drawbacks is the noise produced by the switching activity, responsible of conducted and radiated electromagnetic emission. Consequently, the management of the parasitic emission of SMPS is a frequent topic in literature specialized in electromagnetic compatibility (EMC). Numerous papers deal with the analysis of the origin and the modeling of electromagnetic emission and the development of design guidelines to overcome these issues [4] [5].

Several recent studies present the long-term behavior of SMPS. With the degradation of the electrolytic capacitor which is used to filter the output voltage of SMPS, an increase of ripple of the output voltage of SMPS was illustrated [6] [7]. Another consequence is the increase of electromagnetic emission, as shown in [8]. The increase of the EME of a DC-DC converter after thermal stress is associated to the degradation of filtering passive devices, not only the capacitor but also the inductor in the output side. Electrical modeling of

the converter confirmed the effect of aging of passive devices on the conducted emission.

This paper focuses on the construction of degradation models of passive components, and the application of these models in the robustness study of EME of a buck DC-DC converter. The paper is organized as follows: the section II presents some former works on the degradation of passive devices. The section III describes the studied converter and passive components, the experimental set-up and the accelerated aging condition are also presented in this section. The experimental results of aging impact on different passive components and the evolution of EME are presented in section IV. In section V, the degradation of passive devices is analyzed and modeled, and the model of the EME evolution of the converter is constructed. Finally, the conclusion and perspectives are proposed.

II. DEGRADATION MECHANISMS OF PASSIVE DEVICES - STATE OF THE ART

There are already several works which focused on the aging impact on various passive components, especially about capacitors. It is well-known that aluminum electrolytic capacitors wear out in electrical or thermal overstress condition [9] [10]. Thermal aging affects two electrical parameters: Equivalent Series Resistance (ESR) and capacitance (C). The similar aging impact could be found in the study of Metallized Film Capacitors [11]. In [12], the teflon film capacitors and the C0G ceramic capacitors experienced little change in capacitance as a function of thermal aging time. As resumed in [13], the aging process has a negligible impact on Class 1 (C0G) ceramic capacitor but should be taken into account when measuring Class 2 (X7R, Y5V & Z5U) ceramic capacitor. Besides, another technical report of industry [14] revealed the aging process is reversible at high temperature for ceramic capacitors. Furthermore, Leakage current (LC) and capacitance are two sensitive characteristics of tantalum capacitors with time [15].

Otherwise, an increase of resistance value of carbon resistors is revealed in [16], and the aging impact of the powder iron inductors are discussed in [17], which is related with the increase of core loss.

For electrolytic aluminum capacitors, there are already some degradation models based on the physical degradation analysis and experimental data. Because of the difference of devices under test and modeling method, the proposed models are not always the same. For example, the capacitance of the aluminum capacitor has a linear relation with aging time in the model of [18], but an exponential relation in the model of [19].

III. DEVICE UNDER TEST AND EXPERIMENTAL SET-UP

A. Description of the buck DC-DC converter

The studied SMPS is based on the NCP3163 monolithic DC-DC converter from On Semiconductor. It is configured in step-down operation, in order to convert the 12 V voltage provided by a battery into a 3.3 V regulated voltage for a constant load equal to 3.4 Ω . The switching frequency is set to 237 KHz. A simplified schematic of the converter is presented in Fig. 1. The output voltage is adjusted by resistors R_1 and R_2 through the Feedback pin.

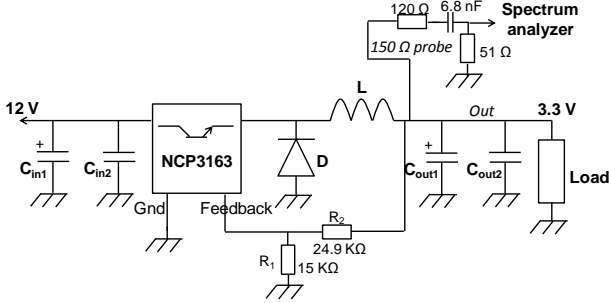


Fig. 1. Schematic of the studied buck DC-DC converter

The board has been designed to characterize both conducted and radiated emissions from the converter. The conducted emission at the output of the converter is measured through a 150 Ω probe [20].

B. Passive components under aging test

The characteristics of the tested passive devices are given in Table. I. Several types of components or references from different manufacturers are tested and compared. Besides, the different combinations of these two output filtering devices are employed in 8 test cards, as listed in Table. II.

TABLE I. PASSIVE DEVICE CHARACTERISTICS

Name	ID	Reference	Type	Value
C_{out1}	C1	EEHBA101UAP	Aluminum capacitor	100 μ F
	C2	T491D107K010AT	Tantalum capacitor	
C_{in1}	C3	EEFP1E470AP	Aluminum capacitor	47 μ F
C_{in2}	C4	GCM21BR71H104	X7R ceramic capacitor	100 nF
C_{out2}	C5	KA37L	X7R ceramic capacitor	
L	L1	IHLP4040DZ11	Shield powder iron inductor	22 μ H
	L2	HCM1103220R		

TABLE II. DIFFERENT COMBINATIONS OF OUTPUT FILTERING DEVICES

No. Card	No. C_{out1}	Description	No. L	Description
Card_1	C1_1	Aluminum capacitor	L1_1	Powder iron inductor, Vishay
Card_2	C1_2	Tantalum capacitor	L1_2	
Card_3	C2_1	Tantalum capacitor	L1_3	
Card_4	C2_2	Aluminum capacitor	L1_4	
Card_5	C1_3	Aluminum capacitor	L2_1	Powder iron inductor, Coiltronics
Card_6	C1_4	Tantalum capacitor	L2_2	
Card_7	C2_3	Tantalum capacitor	L2_3	
Card_8	C2_4	Aluminum capacitor	L2_4	

C. Accelerated aging

Accelerated aging test are always applied to obtain reliability data of electronic components in a short period.

Former experiments have confirmed that significant changes of EME of converter can be observed after several days, and the different devices of the converter are sensitive to electrical or thermal overstress conditions, which accelerate the degradation [8]. In order to accelerate the converter aging, the converter PCBs are placed in a high temperature environment in nominal operation mode. Eight test boards with the passive devices embedded above (Table. II) are placed 200 hours in a thermal oven, which regulates the ambient temperature at 150 $^{\circ}$ C. The stress conditions are interrupted each 20 hours in order to measure the evolution of the passive impedance and the output emission level while the converter operates under a nominal environment temperature of about 25 $^{\circ}$ C.

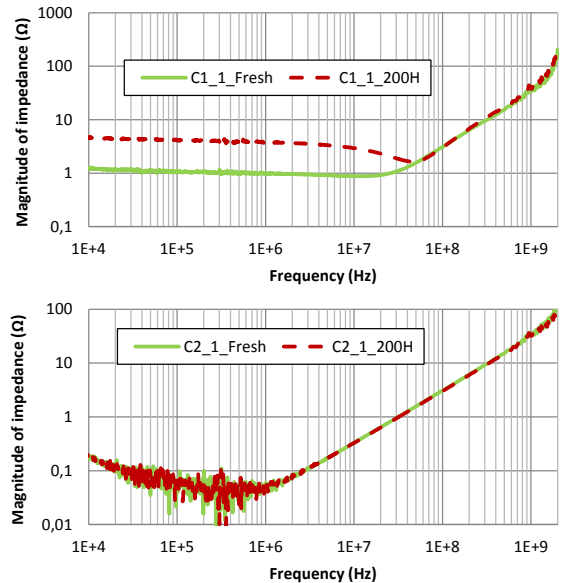
D. Passive impedance measurement

Impedance is an important parameter to characterize passive devices. In this test, S-parameter measurements are performed with a network analyzer to extract the impedance profile of passive devices between 9 kHz and 2 GHz. As explained in [21], to obtain a better accuracy, the measurement configuration (one port or two port measurements, serial or parallel configuration) is chosen according to the impedance value to be measured.

IV. EXPERIMENTAL RESULT AND ANALYSIS

A. Aging impact on different capacitors

Three different types of capacitors: aluminum capacitor, tantalum capacitor and ceramic capacitor suffered the thermal overstress of 150 $^{\circ}$ C for 200 hours. The comparison of impedance profiles before and after aging shows that a significant degradation is only observed with aluminum electrolytic capacitors, as illustrated in Fig. 2. Besides, a graduate increase of ESR of electrolytic capacitors is illustrated in Fig. 3. The results present only one capacitor of each type, but the plotted data are representative of all the tested samples of the same type.



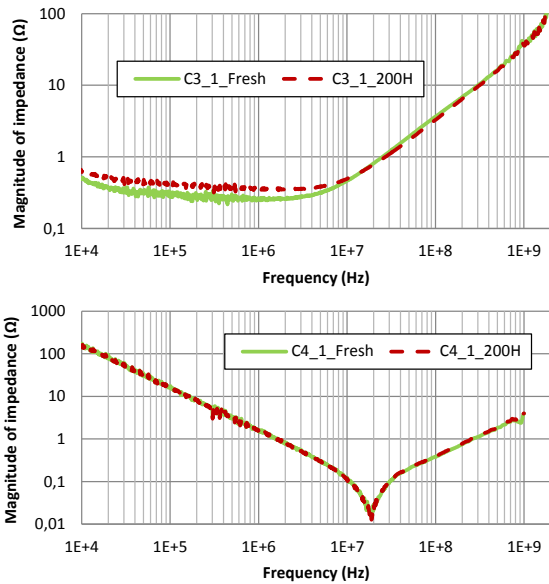


Fig. 2. Impedance evolution of capacitors before and after thermal aging: C1: Aluminum electrolytic capacitor 100 μ F; C2: Tantalum capacitor 100 μ F; C3: Aluminum electrolytic capacitor 47 μ F; C4: X7R ceramic capacitor 100 nF

The capacitance value is measured by a multimeter, the results show a similar aging impact on the three different types of capacitors. Little change in capacitance is measured for ceramic capacitors. The aluminum and tantalum capacitors go through a gradual decrease in capacitance over time. The average variation level is illustrated in Fig. 4. The variation is more important for the aluminum capacitors.

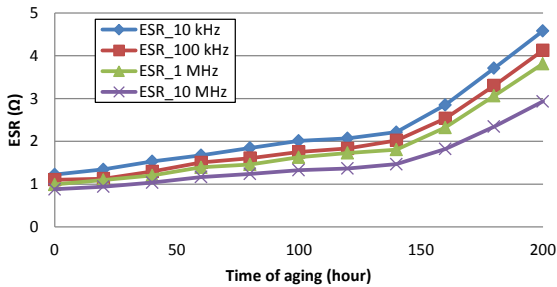


Fig. 3. ESR evolution of C1_1 with time at different frequencies

According to the former analysis of aluminum electrolytic capacitors, the degradation of this capacitor is due to the vaporization of the electrolyte accelerated by heat and the degradation of electrolyte caused by ion exchange during charging/discharging [9] [10] [18]. The consequence of the degradation of aluminum capacitor is the drift of two important electrical parameters: the ESR of capacitor increases after aging while the terminal capacitance decreases. However, few studies discussed the aging impact on tantalum capacitors, which are known to have good reliability. It is commonly accepted that tantalum capacitors have no wear-out mechanisms [22]. The slight degradation of capacitance illustrated in Fig.4 confirms the results presented in [15]. Finally, as the crystalline structure of the ceramic capacitor is returned to its original state at temperature over the Curie point [14], no aging impact could be observed.

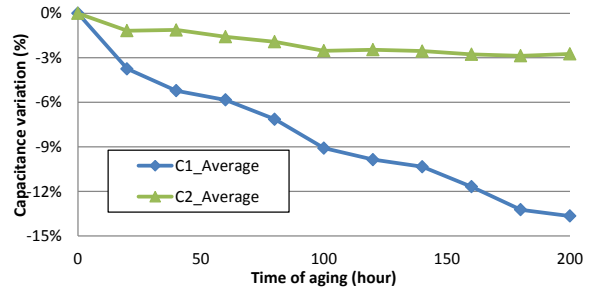


Fig. 4. Variation of capacitance with aging time

B. Aging impact on powder iron inductor

The tested powder iron inductors are produced by two different manufacturers, and they have similar characteristics. As illustrated in Fig. 5, both inductor references have the similar degradation trend after aging. The self-resonant frequency of inductor declines and the impedance reduces between the resonant frequency and 150 MHz. Moreover, the quality factor of the inductor decreases in this frequency range. A gradual degradation are measured over the aging time, as shown in Fig. 6, the impedance peak values at the resonant frequency decrease with time.

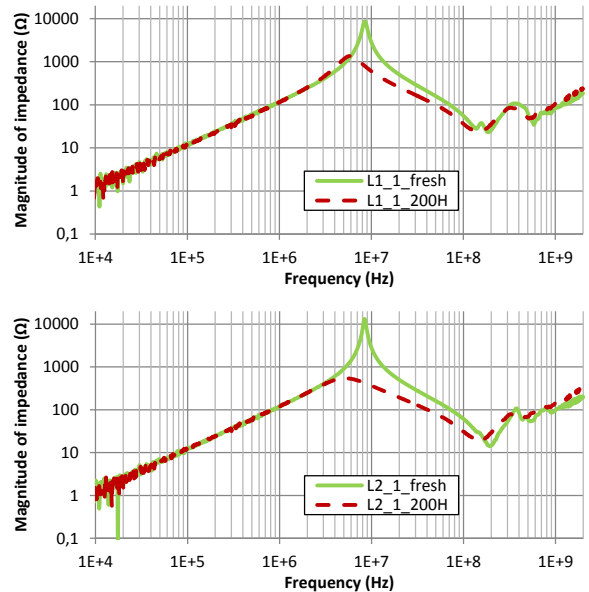


Fig. 5. Impedance evolution of inductors before and after thermal aging: L1, manufacture Vishay; L2, manufacture Coiltronics

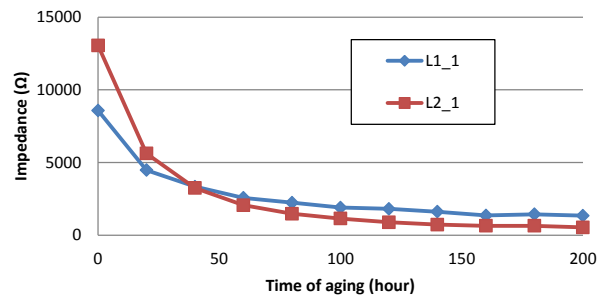


Fig. 6. Evolution of impedance at the resonant frequency with time

The degradation of powder iron inductor can be explained by an increase of core loss after the thermal stress [17]. The source of the aging is the organic binding material of the powder, such as epoxy. Due to the organic material's low resistance to high temperature, the thermal environment can accelerate the core loss.

C. Evolution of the conducted emission

As revealed in [8], except an increase amplitude of ripple in the output after aging, the conducted emission level increases over a large frequency range. The average increase ranges between 6 and 20 dB between 200 KHz and 150 MHz. The identification test shows that the degradation of the electrolytic capacitor C_{out1} and the powder iron inductor L affects the emission level in different frequency ranges: C_{out1} degradation has an impact on the low frequency range while the inductor degradation increases the emission level above 2 MHz. The degradation of all the other devices has a minor impact.

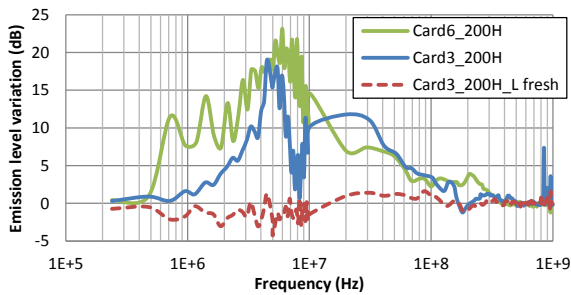


Fig. 7. Variation of conducted emission after aging

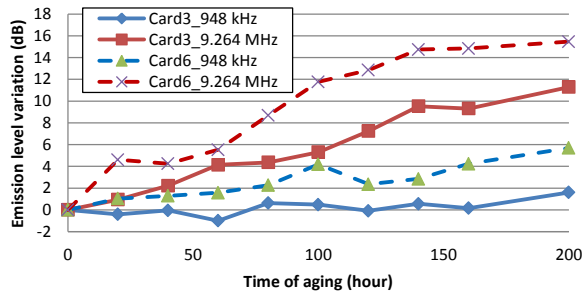


Fig. 8. Conducted emission variation at 948 kHz and 2.37 MHz with time

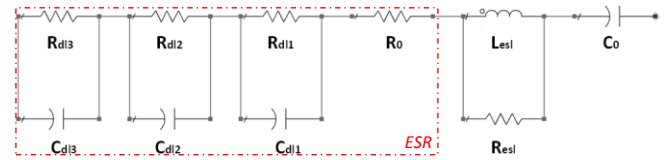
The relative variations of conducted emissions after aging measured on card 3 and 6 compared to the initial emission level at the harmonic frequencies are illustrated in Fig. 7. The difference between both cards is the type of output filtering capacitor: unlike an aluminum capacitor chosen by card 6, card 3 embeds a tantalum capacitor. As the tantalum capacitors do not have great degradation after aging, for the converters which use these capacitors, the conducted emission level does not demonstrate a significant rise in the low frequency range until 1.4 MHz. If the aged inductor L on card 3 is replaced by a fresh one, the emission comes back to the initial level (red line in Fig. 7). The results verify that the major influence of the output filtering passive devices on the change of emission level in [8]. Like the degradation of the passive devices, the evolution of conducted emission at two harmonic frequencies is gradual over the aging time, except in

low frequency for card 3 which embeds tantalum capacitor, as depicted in Fig. 8.

V. DEGRADATION MODELS OF PASSIVE DEVICES

The electrical models of the aluminum capacitor and the powder iron inductor are already constructed and explained in [8]. In this study, the modeling of passive devices focuses on the degradation evolution over aging time. As the aging process is assumed to be “random” [23], the degradation model cannot fit perfectly with the measurement, but it can illustrate an important evolution trend of impedance caused by aging. All the simulations are performed with Agilent’s Advanced Design System (ADS).

A. Modeling of aluminum capacitor



C_0 : Terminal Capacitance (F)
 $Lesl$: Inductance of ESL (H) $Resl$: Resistance of ESL (Ω)
 R_0 : Resistance of foil, tabs and terminals & Resistance of electrolyte(Ω)
 $Rdl1, Rdl2, Rdl3$: Dielectric loss resistance(Ω)
 $Cdl1, Cdl2, Cdl3$: Dielectric loss capacitance(F)

Fig. 9. Electrical model of the electrolytic capacitor C_{out1} [8]

The electrical model of the aluminum capacitor is presented in Fig. 9. In this model, ESR (up to 3 MHz) and C_0 are the two parameters affected by thermal aging. According to several degradation predictive models of aluminum capacitor [13] [14] [15] and the experimental results, the degradation model is given by:

$$ESR(t) = ESR(0) / (1 - k_1 \cdot t) \quad (1)$$

$$C_0(t) = C_0(0) / (1 + k_2 \cdot t) \quad (2)$$

$ESR(0), C_0(0)$ is the ESR and C_0 initial value;

$ESR(t), C_0(t)$ is the ESR and C_0 value at aging time t ;

k_1, k_2 are two constants which depend on the design, the construction of the capacitor and the aging condition. The values are extracted from measurements and listed in Table. IV. Though the aging condition is the same, a small dispersion of degradation coefficient could be observed. However, the proportion between k_1 and k_2 is nearly constant.

TABLE III. PARAMETER VALUE OF DEGRADATION MODEL OF C1

ID	k_1	k_2	k_1/k_2
C1_1	3.68e-3	9.16e-4	4.01e3
C1_2	3.61ae-3	9.05e-4	3.99e3
C1_3	3.36e-3	8.09e-4	4.15e3
C1_4	3.32e-3	8.11e-4	4.09e3

The comparison between the degradation model and experimental result is shown in Fig. 10.

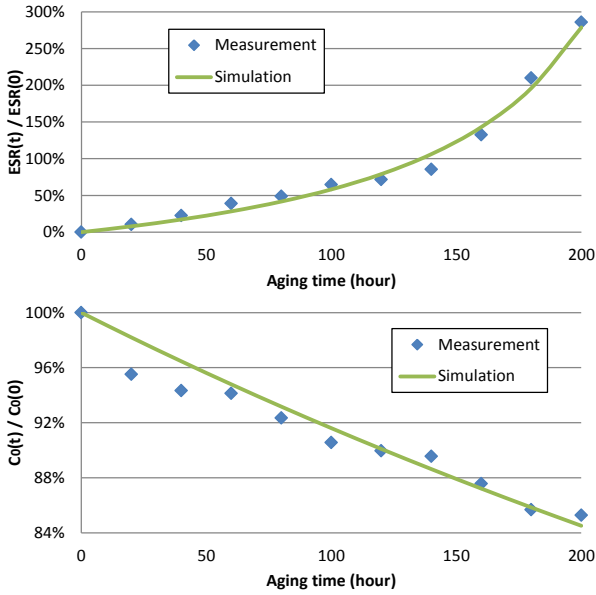


Fig. 10. Degradation parameters of aluminum capacitor C1_1 with time: $ESR(t)/ESR(0)$; $C_o(t)/C_o(0)$

B. Modeling of powder iron inductor

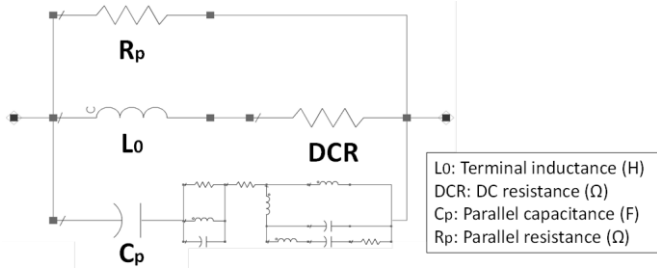


Fig. 11. Electrical model of the inductor L [8]

The model of the powder iron inductor is illustrated in Fig. 11. As presented in [8], the thermal aging affects two parameters: R_p and C_p . We have not found former studies about the degradation modeling of powder iron inductor, so the predictive degradation models with time are constructed according to the experimental results. A preliminary model of degradation parameters is given by:

$$R_p(t) = R_p(0) / (1 + k_3 t) \quad (3)$$

$$C_p(t) = C_p(0) \cdot (1 + k_4 t) \quad (4)$$

$R_p(0)$, $C_p(0)$ is the R_p and C_p initial value;

$R_p(t)$, $C_p(t)$ is the R_p and C_p value at aging time t ;

k_3 , k_4 are two constants which depend on the design, the construction of the inductor and the aging condition. Unlike the aging degradation of aluminum capacitors, the degradation of inductor demonstrates a great dispersion, as resumed in Table. V. Otherwise, it seems that there is no constant relation between k_3 and k_4 .

TABLE IV. PARAMETER VALUE OF DEGRADATION MODEL OF INDUCTORS

ID	k_3	k_4	k_3/k_4
L1_1	0.03	3.6e-3	8.33
L1_2	0.064	4.4e-3	14.55
L1_3	0.142	7.53e-3	18.86
L1_4	0.056	5.54e-3	10.11
L2_1	0.112	5.86e-3	19.11
L2_2	0.371	21.02e-3	17.65
L2_3	0.095	5.85e-3	16.24
L2_4	0.33	26.95e-3	12.24

The proposed empirical degradation model of inductors fits well with the experimental measurement results, as illustrated in Fig.12.

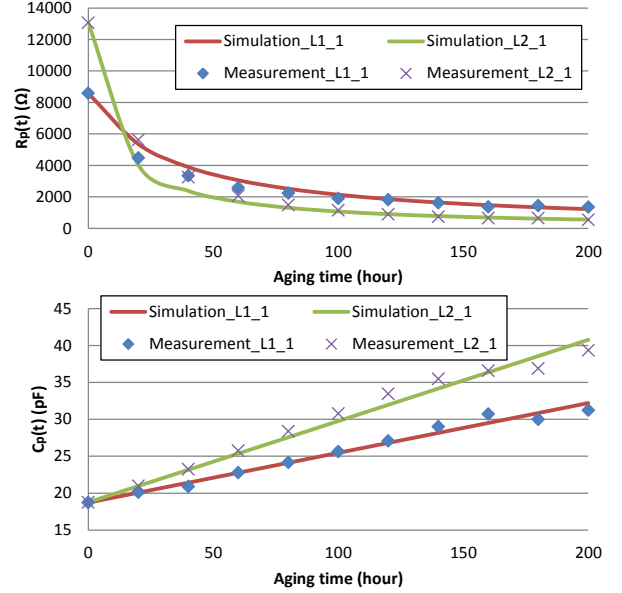


Fig. 12. Degradation parameters of inductors with time: $R_p(t)$; $C_p(t)$

VI. MODELING OF THE EVOLUTION OF CONDUCTED EMISSION

Fig. 13 details the output side of converter model. The converter is modeled by an ideal switch which is controlled by a rectangular voltage source. Besides, the models of passive devices are added in the output side of the switch. To model the long term behavior of converter, the degradation models over time of filtering capacitor and inductor presented in section. IV are injected in the simulation.

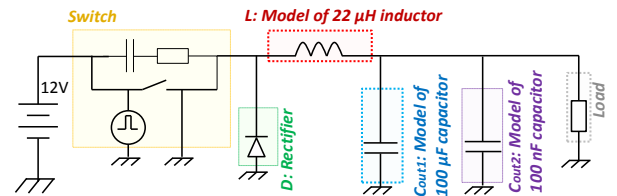


Fig. 13. Modeling of the DC-DC buck converter before stress[8]

The simulation results mentioned in [8] confirmed the increase of ripple amplitude and the conducted emission level. The simulations of emission variation of card 3 and card 6 are presented in Fig. 14, the gradual evolution of the conducted emission level with time is well modeled. The differences

between the simulation and measurement can be explained by the accuracy of degradation models of passive components as the aging impacts are considered to be random [23]. Besides, the temperature increase of components during the operation of system is not taken into account in the simulation.

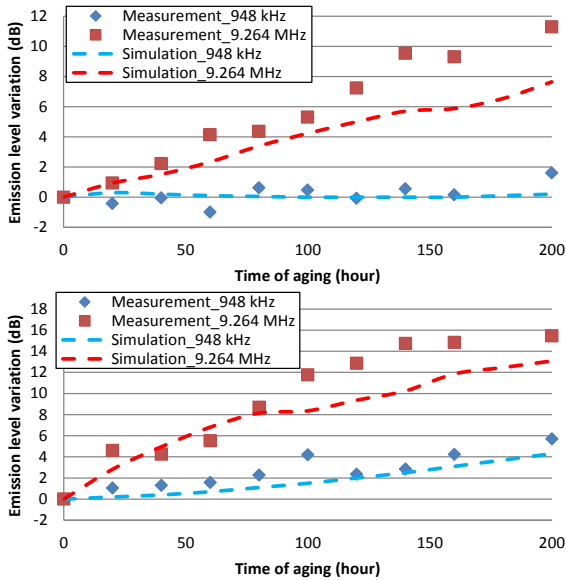


Fig. 14. Simulation results of output conducted emission variation with time: Card3 (top) and Card6 (bottom)

VII. CONCLUSION

This paper aims at studying the modeling of thermal accelerated aging impact on the emission of a buck DC-DC converter with time. The measurements are applied to observe the gradual evolution of conducted emission level over aging time, which is explained by the degradation of filtering capacitors and inductors. Different references of passive devices are chosen, tested and compared. The experimental results demonstrate the aluminum capacitor and the powder iron inductor have a gradual evolution over the aging time. According to the former studies and experimental measurements, a degradation model of aluminum electrolytic capacitor is proposed where ESR and capacitance vary during the thermal aging process. Besides, the evolution of both parameters seems to have a proportional relation. A preliminary degradation model of the powder iron inductor is constructed by the experimental data, where the loss resistance and parallel capacitor are impacted by aging. Finally, an electrical model of the converter output has been built, where the degradation models of passive components are injected. The simulation is able to predict the evolution of the output conducted emission of converter over aging time. In this study, the dispersions of aging impact are observed, so the statistical analysis should be led in the future study to consider the evolution of EMC safety margins.

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