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Nonlinear phenomena study in serial multicell chopper

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Abstract: In this paper, chaotic behavior study of a five-cells chopper when it is associated to a nonlinear load is reported. The model of such system is described by a piece-wise smooth six dimensional non-autonomous system. Then, some basic dynamical properties, such as Poincaré mapping, first return map and continuous spectrum are investigated to highlight the main characteristic of this particular chaotic behavior.

Keywords: Chaos, chaotic behavior, serial multicellular chopper, nonlinear phenomena, dynamical properties.

1. INTRODUCTION

Hybrid systems piecewise affine form is an important and simple class of hybrid dynamic systems Liberzon (2003), Liberzon and Morse (1999). This is a finite set of affine subsystems associated with one or more laws that define switching every moment the system refines assets. These systems are nonlinear and can have a variety of complex phenomena associated with bifurcations and chaos Branicky (1995). Switching circuits in power electronics are considered as a good application for hybrid analysis, because they are intrinsically hybrid in their structures. Under this hybrid model, the system has discrete inputs, continuous outputs, and disturbances that are either continuous, such as parametric variation in a load or source, or discrete, as in a fault state of a particular switch. Among these switching circuits, there are the multicellular converters that are based on the series connection of elementary switching cells. This structure has emerged in the early 90 Meynard and Foch (1992), it is possible to share the constraints in voltage when functioning in high-voltage installation by switching connected cells in series and also to improve the harmonic content of the waveforms. These converters have two major advantages: first, the distribution of voltage and current constraints under high powers and the second are the spectral qualities that present the output voltage. Besides, the modeling is a very important phase for the synthesis of control laws and observers Sadig et al. (2010). The accuracy of the model depends on the required objectives. For this reason, we can find several types of models for the same process and the choice among these models depends on its using and the purpose of control. For the synthesis of the control or observer, the chosen model must be simple enough to allow the realization of real-time control (or observer), but it must be precise enough to get the desired behavior Ghanes et al. (2009). To benefit from the

most enormous potential of the multicellular structure, the research is oriented in different directions. The modeling of multicellular converters is generally difficult. Indeed, it contains continuous variables (voltages and currents) and discrete variables (switches, or a discrete location). In the literature, there are three main types of models Stala et al. (2009):

- An average model whose principle is based on calculating average value of all the variables over one sampling period. This model cannot represent the natural balancing of the terminal voltages of the capacitors. Indeed, natural balancing is due to the harmonics of the charging current at the cutting frequency;
- The second model takes into account of the harmonics, and is called for this fact harmonic model. It is based on the determination of the phases and amplitudes of the voltages harmonics by considering the charging current in steady-state operation;
- The third model is the exact or instantaneous model which takes into account the evolution at every moment of all the variables including the state of the switch (discrete location). This model is difficult to use for the design of controllers and observers based on; because of the converter is not continuous system but a combination of continuous/discrete systems Hosseini et al. (2009), Stala et al. (2009), Hagar (2009). However hybrid modeling allows multicellular converter to use powerful tools of analysis and synthesis for better exploration of the controllers possibilities Hosseini et al. (2010).

In recent decades, it was discovered that most of static converters were the seat of unknown nonlinear phenomena in power electronics Di Bernardo and Chi (2002), Defay et al. (2008), Ghanes et al. (2012), Leon et al. (2008). It is for example the case of multicellular choppers that can exhibit unusual behaviors and sometimes chaotic be-

haviors. Obviously, this may generate dramatical consequences. However, the usually averaged models do not allow to predict nonlinear phenomena encountered. By nature, these models obscure the essential nonlinearities Tse (2003). To analyse these strange behaviors, it is necessary to use a nonlinear hybrid dynamical model Barbot et al. (2007), Ghanes et al. (2012). There have been many methods for detecting chaos from order Contopoulos (2002), Chen and Dong (1998). Among them, routes to chaos Contopoulos (2002), routes to chaos with phase portraits, first return map, Poincaré sections, Lyapunov exponents Benettin et al. (1976), fast Lyapunov indicators Froeschlé et al. (1997), SAI (Smaller Alignment Index) Skokos (2001) and its generalized alignment index Skokos et al. (2007), bifurcations, power spectra Binney and Spergel (1982), frequency analysis Laskar (1990), 0-1 test Gottwald and Melbourne (2004), geometrical criteria Horwitz et al. (2007), Wu (2009), and fractal basin boundaries Levin (2000), and so on, are developed in the literature. Each of these methods has its advantages and drawbacks in classifying the attractors. The main purpose of the present paper is to propose a framework of chaotic behavior study for five-cells chopper connected to a nonlinear load. Three chaotic indicators, considered in the above literature, will be studied by using numerical approaches such as Matlab / Simulink in the case of multicell chopper. The paper is structured as follows. Section 2 deals with the modeling process. The electronic structure of the serial multicell chopper is addressed and the appropriate mathematical model is derived to describe the dynamics of the chopper. Five cells chopper modeling is then considered. Chaotic behavior and simulation results are presented in Section 3. Finally, some conclusion and remarks are reported in section 4.

2. SERIAL MULTICELLULAR CHOPPER MODELING

2.1 Serial multicellular chopper

The multicellular chopper consists of cells. Each cell contains two complementary power electronics components and it can be controlled by a binary switch sc_k Davaucens and Meynard (1997), Meynard and Foch (1992), Gateau et al. (1997). This signal sc_k is equal to 1 or 0 when the upper or lower complementary switch of the cell is conducting. These cells are associated in series with R, L load and separated by capacities that can be considered as continuous sources to these cells. The converter has $p - 1$ floating voltage sources. In order to ensure a normal functioning, it is necessary to guaranty a regulated distribution of the voltages V_{C_k} to their equilibrium values that equal to $k \frac{E}{p}$ Bethoux et al. (2008). The output voltage V_s possesses p voltage levels $(0, \frac{E}{p}, \dots, \frac{(p-1)E}{p}, E)$. The model of this system can be obtained and represented by p differential equations giving its state space representation with floating voltages v_{C_k} and load current i_L as state variables.

$$\left\{ \begin{array}{l} \frac{dV_{C_1}}{dt} = \frac{sc_2 - sc_1}{C_1} i_L \\ \frac{dV_{C_2}}{dt} = \frac{sc_3 - sc_2}{C_2} i_L \\ \vdots \\ \frac{dV_{C_{p-1}}}{dt} = \frac{sc_p - sc_{p-1}}{C_{p-1}} i_L \\ \frac{di_L}{dt} = \frac{sc_1 - sc_2}{L} V_{C_1} + \frac{sc_2 - sc_3}{L} V_{C_2} + \dots \\ \quad + \frac{sc_{p-1} - sc_p}{L} V_{C_{p-1}} + \frac{sc_p}{L} E - \frac{R}{L} i_L \end{array} \right. \quad (1)$$

To simplify the study and the notations, we will study the overlapping operation of a converter with five cells (Fig. 1). Its function is to supply a passive load (RL) in series with another nonlinear load connected in parallel with a capacitor Tse (2003). Note that the chopper, which has a purely dissipative load, can not generate a chaotic behavior. Nevertheless, it is well known since from Meynard et al. (1997) that power converter when it is connected to nonlinear load may have a chaotic behavior.

2.2 Five cells chopper modeling

A five cells chopper connected to a nonlinear load (Fig. 1) can be represented by six differential equations giving its state space.

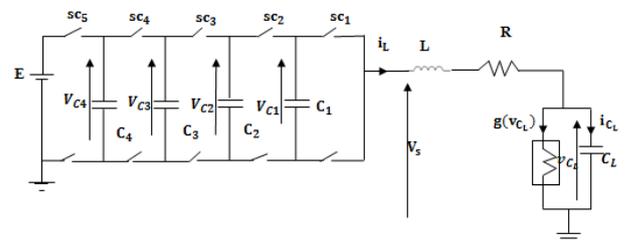


Fig. 1. Five-cells chopper connected to a nonlinear load

$$\left\{ \begin{array}{l} L \frac{di_L}{dt} = (sc_2 - sc_1)V_{C_1} + (sc_3 - sc_2)V_{C_2} + \\ \quad (sc_4 - sc_3)V_{C_3} + (sc_5 - sc_4)V_{C_4} \\ \quad -V_{C_L} - Ri_L + sc_5E \\ C_1 \frac{dV_{C_1}}{dt} = (sc_2 - sc_1)i_L \\ C_2 \frac{dV_{C_2}}{dt} = (sc_3 - sc_2)i_L \\ C_3 \frac{dV_{C_3}}{dt} = (sc_4 - sc_3)i_L \\ C_4 \frac{dV_{C_4}}{dt} = (sc_5 - sc_4)i_L \\ C_L \frac{dV_{C_L}}{dt} = i_L - g(v_{C_L}) \end{array} \right. \quad (2)$$

where
 $g(V_{C_L}) = G_b V_{C_L} + \frac{1}{2}(G_a - G_b)(|V_{C_L} + 1| - |V_{C_L} - 1|)$
 which is the mathematical representation of the characteristic curve of nonlinear load. The slopes of the inner and outer regions are G_a and G_b (Fig. 2). The parameters of the circuit elements are fixed as $C_1 = C_2 = C_3 = C_4 = 0.1\mu F$, $C_l = 40\mu F$, $L = 50mH$, $R = 10\Omega$, $E = 150V$.

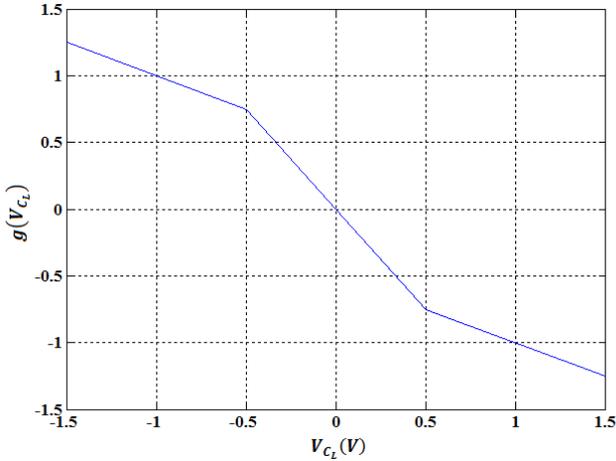


Fig. 2. Graph of nonlinear resistor

3. CHAOTIC BEHAVIOR STUDY

In this section, three indicators are used to illustrate the presence of chaos Wiggins (2003) in the system (2): Poincaré section, first return map and spectrum map. Chaotic behavior of system (2) can be obtained only by varying the switching frequency f_s of the chopper. To be able to enter the chaotic behavior, the parameters values given at the end of section 2 are considered and assigned constants in the three indicators. To show for example the chaotic nature of this system, the 3D phase portraits are shown in Fig. 3 and Fig. 4.

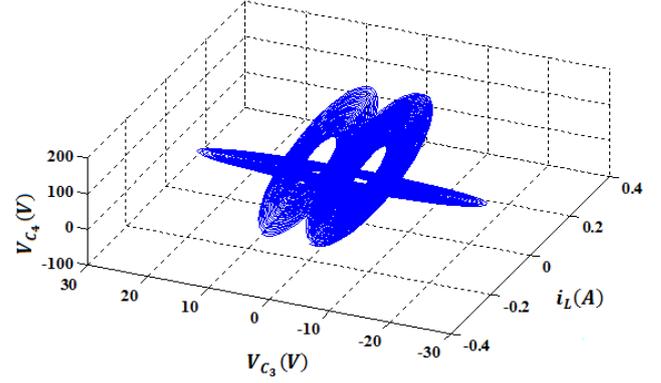


Fig. 3. Projection (i_L, V_{C_3}, V_{C_4})

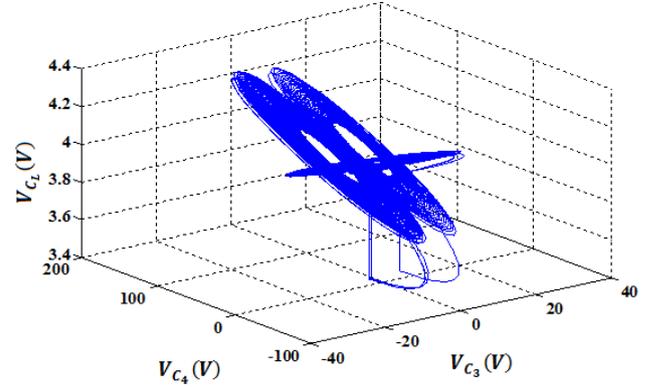


Fig. 4. Projection $(V_{C_3}, V_{C_4}, V_{C_L})$

3.1 First indicator: Poincaré section analysis

We performed a simulation at a calculation time $0.2s$ with an initial condition $x_0^T = (0.5 \ 5.5 \ 5.4)$. The classical Pulse Width Modulation (PWM) used, is intersective PWM which consists in comparing the modulating sinusoidal signal to a triangular carrier. Any Poincaré section performed on an attractor is defined by $|x_1| < 0.01$ when the switching frequency is $20Hz$ Djondiné et al. (2014). In this simulation, 12 264 points are obtained on the considered Poincaré section. Poincaré sections are shown in Fig. 5. To ensure that the behavior of the system does not stay on part of the strange attractor after a transient, we have divided our 12 264 iterations into four equal parts, and we find that we have the same topology for each quarter period of time. It is also noted that the number of ellipses to the Poincaré section, x_2 versus x_1 is five while those of Poincaré sections x_3 versus x_1 and x_4 versus x_1 are respectively three and two. This causes us to believe that the number of ellipses is function of the possible combinations between the floating capacitor and the voltage source. Looking carefully Poincaré section x_2 versus x_1 , we see that, at a scale factor, we find the same behavior. This is highlighted by the zoom performed in Fig. 5 (a). The same phenomenon of scale factor is observed in the other two sections (Fig. 5 (c), Fig. 5 (d), Fig. 5 (e) and Fig. 5 (f)).

This remark between the complexity of the Poincaré section and the place of flottant capacitor considered raises naturally the question of the relationship between the

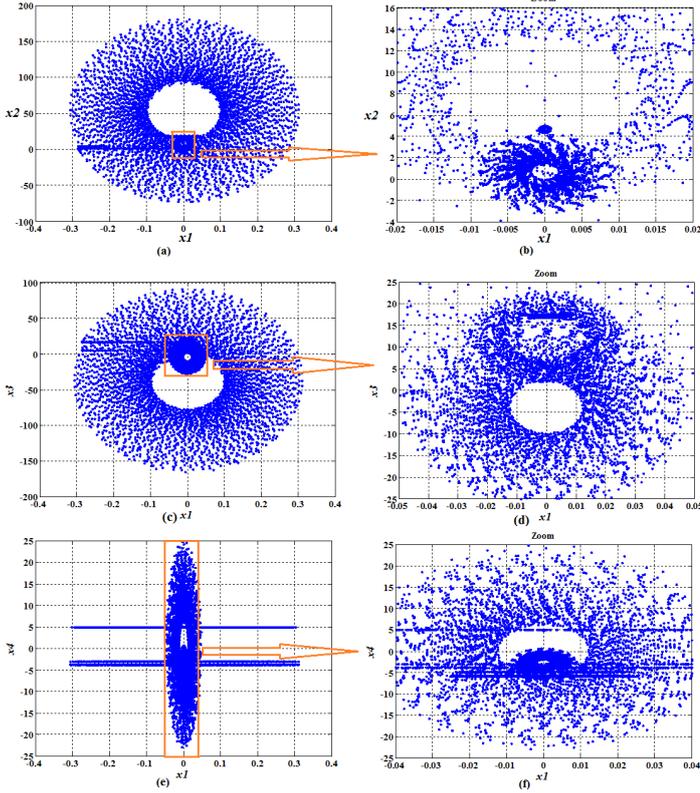


Fig. 5. Poincaré sections

configuration of switches and ellipses of the Poincaré section. We recall that in a circuit with k switches, there are 2^k possible discrete states. However, in practice, these discrete states can not all be executed. Some of these states are not feasible because of the physical characteristics of switches, while others are forbidden in the design because they are destructive, unnecessary or unsuitable for the application. In our case, for each Poincaré section, as we project from \mathbf{R}^6 to \mathbf{R}^3 , and from \mathbf{R}^3 to \mathbf{R}^2 , we find that the chopper five cells associated with a nonlinear load can take only five possible switch configurations on the considered Poincaré section. So we will consider only Poincaré sections from one of these different configurations. Consider the configuration $[-110-10]$. Poincaré sections of this configuration are shown in Fig. 6. We find that, the Poincaré section x_2 versus x_1 (Fig. 6 (a)) gives us two ellipses of small dimensions. As noted on the full Poincaré section, Poincaré sections x_3 versus x_1 (Fig. 6 (b)) and x_4 versus x_1 (Fig. 6 (c)) have less ellipses, which is verified for this configuration. When we make operate the converter with a switching configuration fixed, we find immediately that the chaotic behavior disappears (see Fig. 7). So the switchings are at the origin of chaotic behavior.

3.2 Second indicator: first return map

The application of the first return on the voltage across the load capacitor x_6 is shown in (Fig. 8 (a)). By zooming at the point $x_{6_k} = 4V$, and $x_{6_{k+1}} = 4V$, we find that there is an ellipse and around that ellipse leave the folds that are four in number. We find for example a folding near $x_{6_k} = 4.006V$ and $x_{6_{k+1}} = 3.995V$. Furthermore

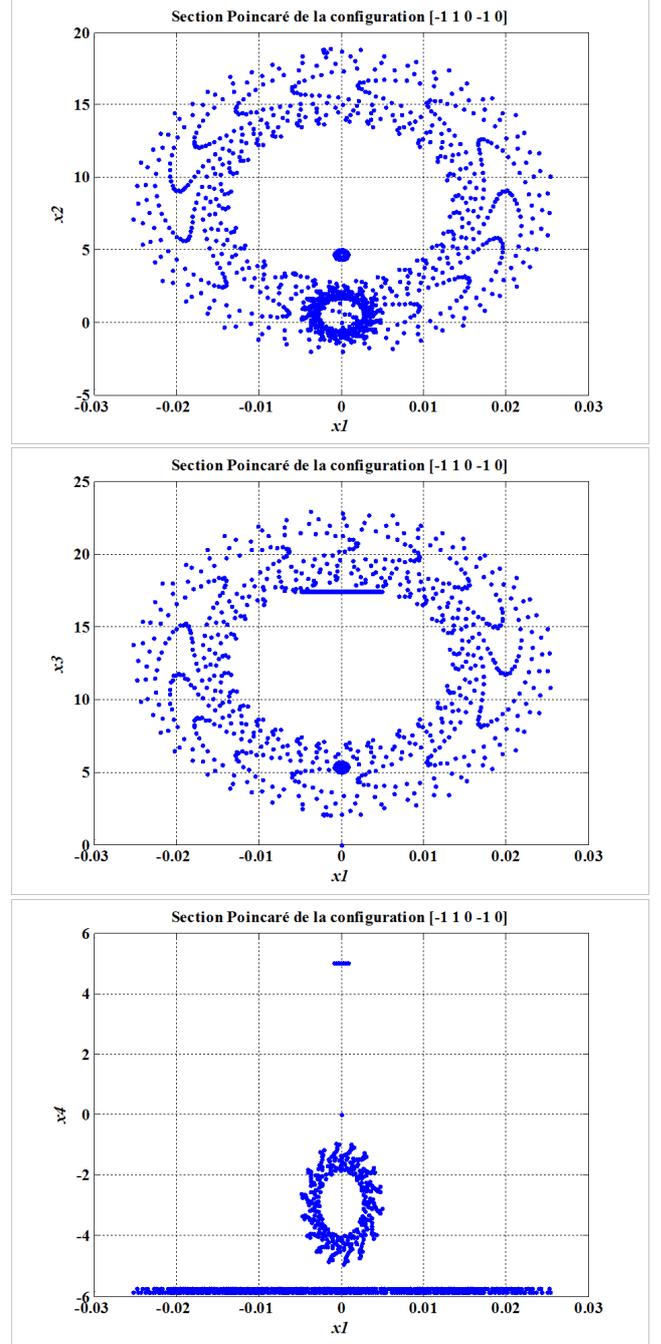


Fig. 6. Poincaré sections of Configuration $[-110-10]$

these foldings are symmetrical with respect to the point $x_{6_k} = 4V$, and $x_{6_{k+1}} = 4V$.

Furthermore the application of the first return on the current of x_1 load (Fig. 8 (b)) shows ellipses along the diagonal, leaving us think of a toroidal chaos Amroun-Aliane et al. (2011), Amroun-Aliane et al. (2010).

3.3 Third indicator: spectrum map

The spectral representation of current x_1 , or any other state variable (voltages across the capacitors) is continuous. This is an indicator of the chaotic nature of our system is - to - say a continuous spectrum. Below the spectrums of load current x_1 (Fig. 9 (a)) and voltage x_2 across the flottant capacitor C_1 (Fig. 9 (b)) for the

Configuration [-110 -10]

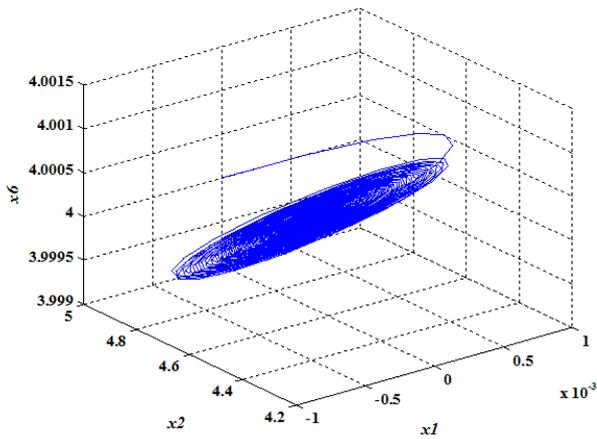


Fig. 7. Projection of Configuration [-110 -10]

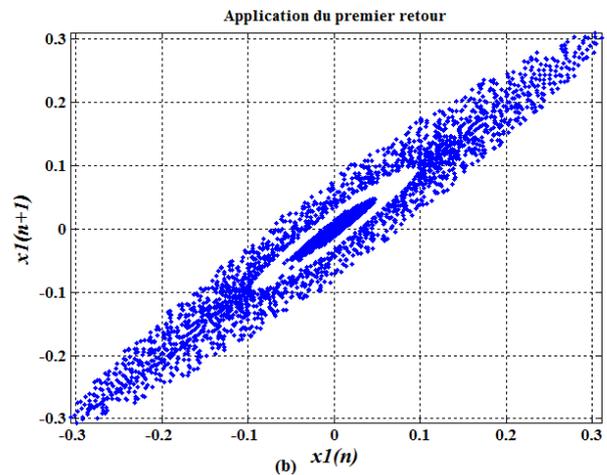
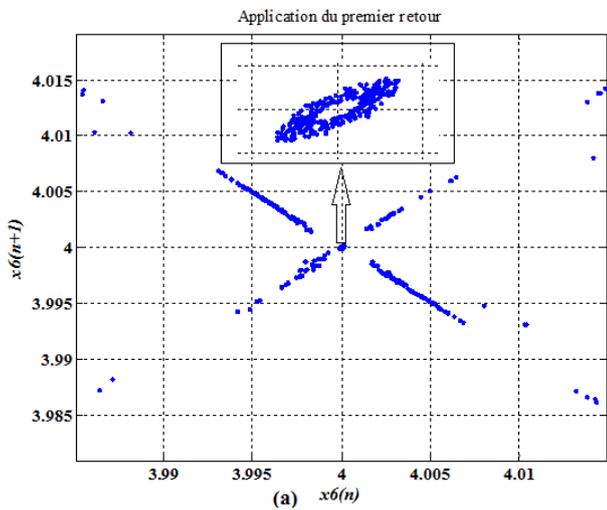


Fig. 8. First return maps

switching frequency of the switches $f_s = 20Hz$.

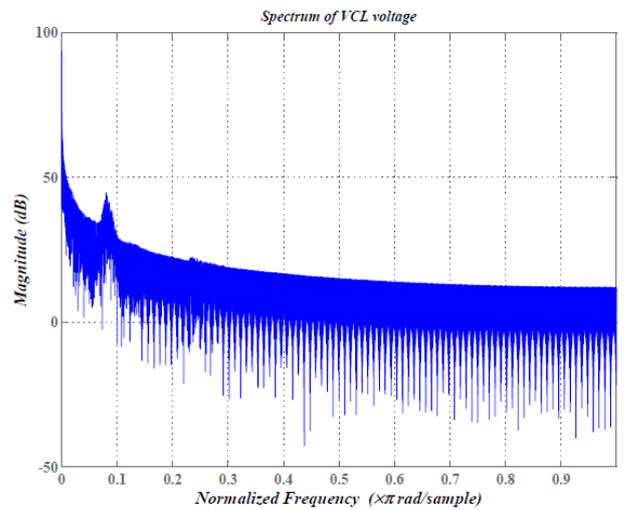
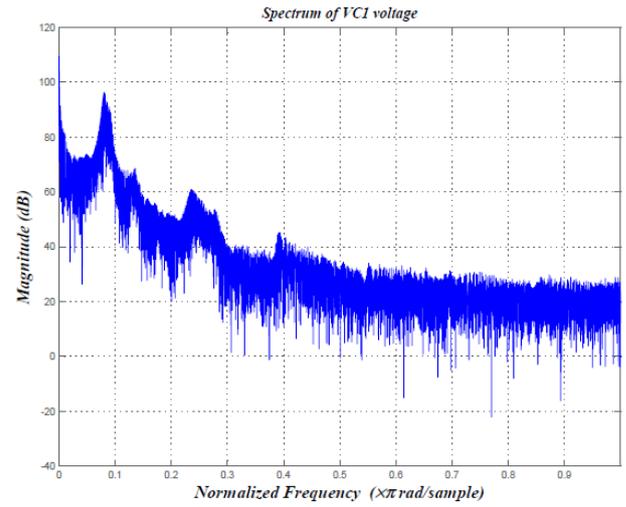


Fig. 9. Spectral representation

4. CONCLUSION

We studied the dynamic behavior of the five cells chopper associated with a nonlinear load. We made a digital study of this chopper based on Matlab / Simulink tool. We showed from the application of the first return, the Poincaré section and the power spectrum that this system can have a chaotic behavior. This study has shown the capital importance of the regulation of the internal variables of multicellular to avoid chaotic behavior. To speak pictorially, it must avoid pumping phenomena between capacitors due to different configurations. To better control the chaotic behavior, we will, in our future work, study the different controls that can rapidly bring the converter in nominal operation compared to the load, but also in relation to these internal variables (voltages across the floating capacitors).

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