STABILITY, BIFURCATION AND CHAOS IN DC-DC SWITCHING CONVERTERS

PhD Thesis – Summary

in order to get the scientific title of „Doctor of Philosophy" at
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in the PhD field of Electronic engineering, Telecommunications and Information Technologies

author eng. Mircea Gurbină
PhD Advisor Prof. dr. eng. Dan Lascu
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This thesis is motivated by the high impact that electronics has on industry, green energy which particularly imposes performant power supplies, of high reliability and efficiency, miniaturization, programmed voltage and currents, user protection, reduced harmonic pollution, and electromagnetic compatibility. The dc-dc switching converters are indispensable blocks in any equipment, either power factor correction circuits or switching regulators, chargers in automotive, photovoltaic energy processing, electrolysis or welding equipment.

The great drawback of dc-dc switching converters is that they are nonlinear systems employing at least a feedback loop and exhibiting typical instability, bifurcation and chaos phenomena. Therefore it is of great interest the deep knowledge of the causes that can trigger such an undesired behavior.

The importance and the actuality of the subject is justified by the electronic equipment prices that are traded on the electronic market. According to a study published by Worldwide Market for Power Supplies this amount of money was 1125 million Euros in 2013, with a spectacular forecast of 1665 million Euros in 2025.

The nonlinear phenomena in electronics have been studied only at the end of the XXth century and these operating "abnormalities" were designated as uncomprehensive. Although many researchers considered that this field will rapidly vanish, the reality invalidated this opinion just by the dynamics and diversity of the dc-dc power supplies. Thus there emerged resonant dc-dc converters with higher efficiencies, other converters employing different control principles compared to the classical ones such as V^2 or I^2, COT or FOT and many others. On the other side, new combinations of topologies will surely lead to the converters of the future. After a decrease of the interest in bifurcation and chaos in power electronics, the last years showed a comeback in this field, finalized into many publications, workshops or lectures.

Framing the theme in the international research area is argued by the numerous publications that addresses the nonlinear, bifurcation and chaos phenomena: International Journal of Bifurcation and Chaos, Elsevier: Nonlinear Analysis, Physica D (Nonlinear Phenomena), IEEE Transactions on Power Electronics, IEEE Transactions on Industrial Electronics. In addition, a series of books have been published, some of them becoming reference works, such as: A. Aroudi, S. Banerjee, G. Verghese, "Chaos in Switching Converters for Power Management"; S. Banerjee, G. C. Verghese, "Nonlinear Phenomena in Power Electronics"; C.K. Tse, "Complex Behavior of Switching Power Converters" Z. T. Zhusubaliyev, E. Mosekilde "Dynamical Systems". Also papers exploring chaos and bifurcation in power electronics are published in all prestigious conferences and the interest of famous researchers such as A. Aroudi, S. Banerjee, G. Verghese, W. C. Y. Chan, C. K. Tse, in bifurcation and chaos phenomena determines the thesis to stay in the same trend of the international research topics.

The scientific objectives to be solved focus on the study of nonlinear phenomena in constant frequency dc-dc converters, operating both in CCM and in DCM modes, employing different control techniques – one cycle control, current mode control, charge control, different modulation techniques - leading-edge (LE), trailing-edge (TE) or triangular and natural or uniform sampling as well. For each topic the goal was to develop exact techniques for the analysis, without truncating the Taylor series and in the same time with a high degree of generality in the sense that they can be applied to any topology. These techniques allow the high accuracy determination of the critical value of a parameter for which the bifurcation phenomenon occurs.

The research methods adopted are in the traditional approaches in power electronics. They comprise of problem identification, mathematical modelling of the theoretical concept, system simulation as a first validation, optimization, design and finally conducting the experiment as a final validation. Throughout the thesis the abbreviations and the notations are in perfect agreement to those accepted by the international community, the Anglo-Saxon notations been largely adopted.

Chapter 1 is dedicated to a presentation of the current state in the field and to the typical mathematical tools used. Starting from the classical equations of the Lorenz system and Feigenbaum equation, the dynamical systems are analyzed regarding their stability by defining the operating conditions and the methods used. This touches both analytical methods – linearization, Lyapunov exponents – and graphical methods – Poincaré section, in order to better understand the phenomena exhibited by different dc-dc converters in the next chapters. A classification of bifurcations is presented, also mentioning the scenarios and the routes that lead to bifurcation and chaos.

Chapter 2 performs an analysis of the nonideal one-cycle control (OCC), proving that in the real case of a buck converter in which the integration capacitor is discharged through a nonzero resistor the system is governed by Lambert equations and can become unstable, exhibiting a period doubling bifurcation. It is demonstrated that stability does not depend on the absolute values of the parameters but on their normalized values and also stability is load independent. All theoretical considerations have been validated by simulation and experiments.

Chapter 3 has the goal to extend OCC analysis to 4^{th} order ideal converters: Ćuk, Sepic şi Zeta. The analysis uses a technique based on geometrical considerations, similar to current mode control analysis. The detailed analysis is performed on the Zeta converter, then showing how it can be extended to the Ćuk and Sepic topologies. It is proved that when these converters employ OCC they are unconditionally unstable.

Chapter 4 starts by developing a new general and exact method for analyzing dc-dc converters operating with two topological states. The relationships are given in vector form, namely a recurrence equation and one constraint represented by the control. Linearization of these relationships allows local stability investigation. The Jacobian and the transcendent system that has to be solved in order to find the steady-state state vector and duty cycle are given. The technique can be used not only with any topology, but also with any control method, modulation or sampling technique. The examples start by applying the method to dc-dc converters with proportional control, leading-edge and trailing-edge modulation, ramp carrier and natural sampling. Both in the situation when the bifurcation parameter is the reference voltage and in the case when this parameter is the supply voltage it is shown that instability occurs by Neimark-Sacker bifurcation. The buck converter with OCC and nonideal integrator reset is reinvestigated now in a pure analytical manner, revealing period doubling when the reference voltage changes. This is confirmed by simulation and experiment. In the final part of the chapter the charge controlled converters are analyzed and the period doubling bifurcation is demonstrated and validated by simulation and experiment.

Chapter 5 is entirely theoretical and a new method for analyzing stability for three topological states converters is proposed. The method is exact and general because it can be applied to any topology. The general equations for the recurrence and the two constraints are provided, together with the equations used to find the static operation point, the Jacobian and the steps sequence for applying the method. It is shown that the method can be simplified by eliminating one constraint in the situation when the two duty cycles can be expressed in terms of one active switch duty cycle.

Chapter 6 deals with the topic of CCM operated dc-dc converters employing triangular leading-edge and trailing-edge modulation, natural and uniform sampling and proportional control. The technique proposed in Chapter 5 is applied. It is shown that there are qualitative differences in the sense that for uniform sampling the bifurcation is of Neimark-Sacker type, while for natural sampling the bifurcation is period doubling type. The most favorable cases regarding the carrier shape are analyzed. It is shown that for uniform sampling the optimum shape is an increasing sawtooth, while for natural sampling the symmetrical triangular shape assures maximum differential gain. It is also shown that for a buck converter with natural sampling and symmetrical carrier unconditioned stability is achieved and this is present even for an asymmetry range of the carrier.

Chapter 7 is dedicated to exact stability study for dc-dc converters using type 2 and type 3 error amplifiers in their controllers. The chosen bifurcation parameter is the value of the resistor that is arbitrarily chosen in the *K* factor method. The presence of the Neimark-Sacker bifurcation is proved, but the most important conclusion is the fact that designing the error amplifiers using the *K* factor or polea-zeros placement methods, that is based on averaged and linearized models is pessimistic, as there is a stability reserve that can be used to improve closed loop dynamics.

Chapter 8 has three study goals: a nonideal current controlled CCM Ćuk converter, the same converter employing OCC and a coupled inductors two phase boost converter. The strength of the chapter is the exact determination of the parameter values for which instability appears by bifurcation. This determination is more precise compared to the limiting approximations or range localization reported in the literature. For the two-phase boost converter a general analysis method for dc-dc converters operating with four topological states is proposed. This method correctly predicts the occurrence of the Neimark-Sacker bifurcation.

Chapter 9 proposes the analysis of DICM operated dc-dc converters employing uniform and natural sampling and current-mode control. It was succeeded to obtain the desired recurrence relationship by elegantly avoiding the problems induced by the singularity of a state matrix in the third topological state. It was shown that in DICM there are also major qualitative differences regarding stability for the two types of sampling. Thus, for a boost converter with natural and uniform sampling and proportional controller, with the gain as the bifurcation parameter, instability appears by Neimark-Sacker bifurcation. This behavior is also experimentally confirmed. Moreover, the literature statement that there are only minor differences between natural and uniform sampling is infirmed. An interesting aspect revealed in this chapter is that a DICM operated buck converter with proportional control and natural sampling is unconditionally stable. In the final part of the chapter a DICM current-mode controlled buck converter is investigated, revealing the instability by the border collision phenomenon.

Chapter 10 brings together the final conclusions and summarizes all the personal contributions that have resulted in the chapters of the thesis. In fact these contributions are present at the end of each chapter. Also some forecasts and suggestions for possible future research directions are presented.

For each topic under study the research strategy starts by elaborating the theoretical concepts, by providing all the necessary mathematical relationships, followed by simulation verification and finally the validation by experiment. In this spirit, the annexes of the thesis include all the Matlab programs developed for the verification and implementation of theoretical concepts. They do not include the simulation schematics because they have been inserted in the chapters in which the respective issues were investigated. Also in the annexes some photo details corresponding to the experiments performed are presented.

The results obtained within the thesis were disseminated and validated by publication in international journals and conferences as follows:

18 papers, of which at 8 the PhD student is the first author, distributed as follows:

- 13 WoS indexed papers of which:
  - 2 papers in WoS indexed journals, of which 1 paper in a Q2 journal
  - 11 papers in WoS indexed international conferences
- 5 papers indexed in international databases (IDB), of which:
  - 4 papers in IDB journals
  - 1 paper in a IDB indexed conference

The published papers received in total 15 independent citations, excluding self-citations and citations of all authors. According to Journal Citation Report published by Clarivate Analytics in 2019, the cumulative impact factor of independent citations is ???. The citations are grouped according to the databases in which they are indexed as follows:

- o 3 Clarivate Analytics Web of Science citations, h-index 2
- o 15International databases citations, h-index 2
- o 11Google Scholar citations, h-index 2

The doctoral thesis includes:

- o 298 pages
- o 187 figures
- o 26 tables
- o 122 bibliographic references
- o 62 -annexes

Selective references

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PhD Advisor
Prof. dr. eng. Dan Lascu

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PhD student
Eng. Mircea Gurbină

PhD Advisor
Prof. dr. eng. Dan Lascu

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