Microelectronic design of controllers
for switching power converters

Eduardo Alarcón Cot

Departamento de Ingeniería Electrónica (DEE)
Escuela Técnica Superior de Ingenieros de Telecomunicación de Barcelona (ETSETB)
Universidad Politécnica de Cataluña (UPC)

PhD Thesis Advisor : Dr. Alberto Poveda López

Jury
Prof. Jean Claude Marpinard (CNRS-LAAS Francia)
Prof. Luis Martínez-Salamero (ETSE-URV-Tarragona)
Prof. Francisco Duque-Carrillo (DEIE-Univ. Extremadura)
Dr. Alfonso Carlosena Cabeza (UPNA-Pamplona)
Dr. Jordi Madrenas Boadas (DEE-UPC-Barcelona)

Mark : Sobresaliente *cum laude* by jury unanimity

SUMMARY

Introduction

Switching power converter circuits are characterized as nonlinear dynamic systems. This aspect justifies the lack of standard methods for modeling and controlling those systems. In this sense, their conventional control methods are based on the application of classical techniques (or modern techniques) of linear feedback (or state feedback), after a previous linearization around an equilibrium point of the nonlinear dynamic equations which model the converters' behavior. This approximation notably restricts the dynamic capabilities of those switching power conversion systems.

In front of that situation, there exist several control methods which exhibit remarkable dynamic features due to the use of fast-dynamics state variables of the converter, being possible to point out, among others, current-mode control, one-cycle control and sliding-mode control. In addition, the control method based on fuzzy logic inference, as well as being capable of operating with fast-dynamics state variables, allows the approximation of complex nonlinear control laws, although it has the additional difficulty of requiring high processing complexity.

In spite of the apparent heterogeneity in their description and their various historic origin, those control methods share the technological problem of their implementation, since their share the characteristic of considering fast dynamics state variables of the converter. An added difficulty for the implementation is imposed by the continuous rise of the switching frequency in those power processing circuits, which pursues a reduction in both the weight and volume of the energy-storing reactive elements, and which constitutes a key factor in converter design for high-power aerospace applications and low-power portable applications. This technological tendency increases the dynamic processing requirements of the analog or digital electronic circuits implementing the nonlinear control strategies under consideration, thus precluding the use of the discussed methods.

With the advent of current-mode analog signal processing, which constitutes a new tendency that is being successfully applied in several areas of electronic design, the possibilities of implementing advanced control methods for switching converters which are difficult to implement in terms of dynamic requirements or processing complexity are extended.

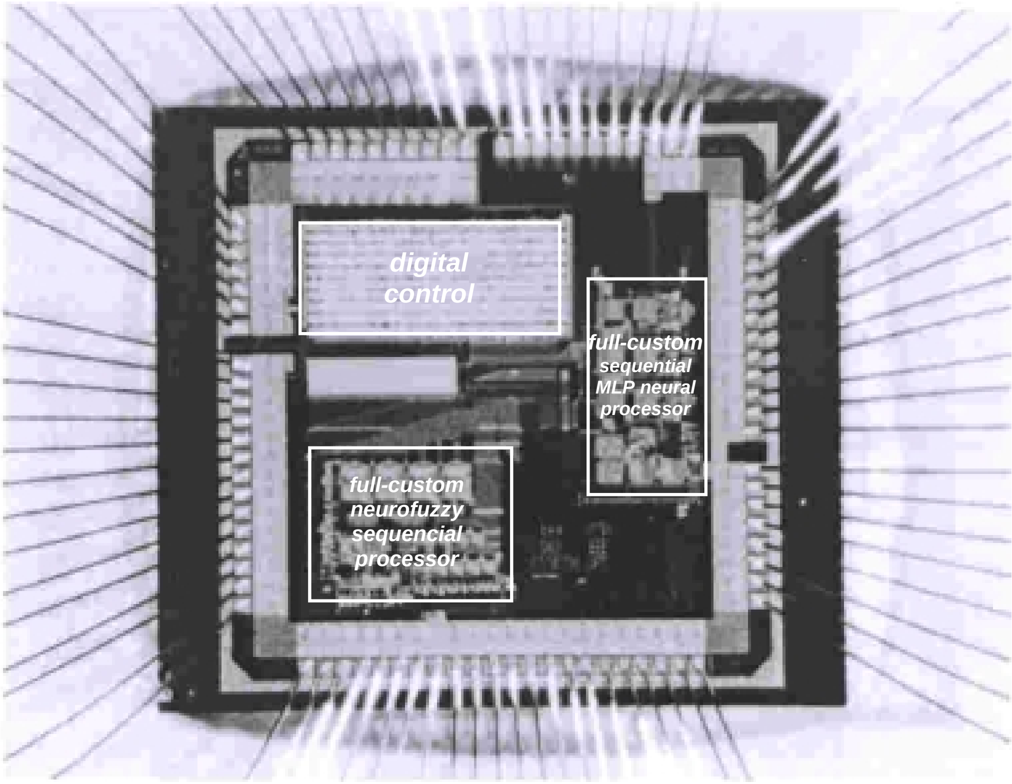
Contents

In front of the previous arguments, this doctoral thesis is circumscribed within the joint approximation between the areas of switching power conversion, control theory and analog microelectronic design. In particular, several microelectronic controllers are proposed as a synergetic combination of several high-performance control methods for switching power converters and current-mode analog signal processing methodology, a conjunction from which several circuital structures of high dynamic performance are derived.

As a self-contained work associated to this thesis, a thorough study of the analytical characteristics of fuzzy systems is presented. After presenting the foundations of fuzzy sets and fuzzy logic theory, and by drawing a comparative typology between different inference methods, implication definitions and defuzzyfication methods, an analytical model is established which describes the operation of a complete fuzzy inference system, and which allows to establish both functional and structural equivalencies with several function approximation paradigms and parallel processing networks. Subsequently, and after formulating a unified model -named as local aggregation system-, three mathematical justifications with demonstrative purpose, though constructive, are presented (based on an orthogonal description in Hilbert spaces, based on the concept of generalized delta, and after a description of the reconstruction of a sampled signal in a multidimensional space). They permit to infer both qualitative and quantitative results and criteria about the approximation properties of multidimensional nonlinear functions that local aggregation systems hold. In front of the previous homogeneous perspective, the study of the Takagi-Sugeno fuzzy systems, interpreted as the conjunction of, by one hand, a subdivision of local-in-space zones, and by the other hand, the allocation of local models (in particular affine models, which allows to establish a parallelism with piecewise linear PWL models), which are interpolated, reveals the virtues of that type of fuzzy model, which confer it a clear advantage in front of other approximation methods. A synthesis method based on the previous description is presented, which allows to recover part of the known results regarding the analysis, modeling and synthesis of linear systems. Afterwards, and with the inclusion of a dynamic description of the system, it is demonstrated the property of the fuzzy local-model systems as universal approximators of arbitrary nonlinear dynamic systems. Particularly, it is formalized their study as nonlinear PID controllers, arbitrary dynamic nonlinear compensators and nonlinear arbitrary state feedback systems.

As an extension of the study of the optimum modeling and approximation of nonlinear dynamic systems by fuzzy systems, analogies are established with the system descriptions based on Volterra series and Wiener models.

The previous study crystallizes, after comparing the different alternatives regarding the microelectronic implementation of fuzzy controllers, in the conception, design and implementation of a mixed-signal CMOS integrated circuit for fuzzy processing (shown in the figure) of the first-order Takagi-Sugeno model type, whose architecture is founded in a sequential operation, and whose signal processing is mostly performed in current-mode.



Microphotography of the Neurofuzzy ASIC

In addition, current-mode analog processing techniques are applied to the design of both one-cycle controllers and current-loop controllers. After analyzing the processing requirements of those control methods, their suitability to current-mode synthesis is discussed, and two CMOS circuital structures are described and verified through transistor-level complete simulations. Also, the implementation requirements for sliding-mode controllers are presented, considering in general nonlinear sliding laws, and in particular an extension of fuzzy control is presented that includes zone-wise sliding mode control. At circuit level, the suitability of sliding-mode control techniques to analog implementations, and in particular to current-mode analog implementations is discussed. As an specific application, the chapter ends with the complete description of a sliding-mode control BiCMOS microelectronic circuit for the generation of sinusoidal signals in buck switching converters.