IOSUD – Politehnica University Timişoara
Doctoral School for Engineering Studies

ARCHITECTURES, MODELING TECHNIQUES AND CONTROL METHODS FOR DC-DC SWITCHING CONVERTERS

PhD Thesis – Summary

for obtaining the scientific PhD title from
Politehnica University Timișoara
in the field of Electronics, Telecommunications and Informational Technologies Engineering
by

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luna mai anul 2025

The relevance of the research topic is motivated by the major role that switching dc-dc converters play in power electronics, with the aim of efficient energy conversion and voltage regulation. These converters find applications in a wide range of fields, including automotive industry, lighting systems, electrolysis, and renewable energies.

The goal in power electronics is to miniaturize and reduce converter costs while maintaining high efficiency and high-quality dynamic response. These objectives can be achieved through increasing power density, raising switching frequency, introducing new high-efficiency topologies (soft-switching, resonant, quasi-squarewave, quasi-resonant, etc.), expanding the use of new types of power transistors and diodes (silicon carbide - SiC, gallium nitride - GaN), and, last but not least, adopting intelligent control techniques (digital control, nonlinear control methods, evolutionary algorithms, fuzzy logic, neural networks).

The objectives of this PhD thesis are the investigation of new families of hybrid switching dc-dc converters, along with the analysis and modeling of power converters under analog, digital, and nonlinear control methods.

The research methods employed involve identifying the challenges of existing technologies, systematically generating and mathematically modeling new proposed topologies, as well as designing, validating through simulation, and experimentally testing these topologies.

Chapter 1 is dedicated to the synthesis of new hybrid switching converters from the Ćuk 2 family. Additionally, it contains the static analysis, design equations and the small-signal model. The theoretical considerations are validated through simulation and then experimentally, both in open-loop and closed-loop configurations.

The author of the thesis brings the following **contributions**:

- The synthesis of all 72 Ćuk 2-type converters using the base cell rotation method;

- Out of these 72 topologies, 42 are new functional converter topologies proposed by the author;
- Classification of converters into families and unitary static analysis of these;
- Providing general design equations for converters;
- Expanding these families by introducing coupled inductors, thereby introducing an additional degree of freedom;
- Identifying all converters proposed by D. Zhou in her doctoral thesis by short-circuiting the resonant inductor and revealing a one-to-one correspondence between Zhou converters and Ćuk 2 converters;
- Conducting an analysis based on conversion nature—buck, boost, and buck-boost—highlighting four buck families, four boost families, and one buck-boost family;
- Within each of the above categories, there are converters with a static conversion ratio equal to the classical one, as well as topologies with negative output voltage and converters with a more pronounced buck or boost characteristic compared to their classical counterparts;
- Validation of the theoretical considerations both through simulation and experimentally for a representative Buck-type converter with a negative output voltage and validation of theoretical considerations regarding component stress and semiconductor switching nature.

Chapter 2 is dedicated to the small-signal modeling of hybrid switching converters. The author proposes, for the first time, a small-signal model for this type of converter. Two methods for obtaining the control to output transfer function, essential for feedback loop design, are presented. Closed-loop operation is validated both through simulation and experimental testing.

The author of the thesis brings the following **contributions**:

- A method for obtaining the state-space model for Ćuk 2-type converters;
- The fourth-order small-signal transfer function is obtained in two ways, both analytically and through simulation using impulse response analysis in the PLECS simulation program;
- To design a regulator using classical methods, the way to approximate the converter's transfer function with a second-order function is presented;
- Theoretical considerations are validated through both simulation and an experimental prototype of the converter;

Chapter 3 presents a unitary control approach for frequency-controlled converters. In this sense, a universal controller is proposed that can be easily modified depending on the chosen topology. The operation of this controller is demonstrated for both a quasi-resonant converter and a resonant converter, both in closed-loop operation. Additionally, a generalized method for obtaining the small-signal model for resonant converters based on the extended describing function (EDF) method is proposed.

The author of the thesis brings the following **contributions**:

- Systematization of the EDF method for easy application to resonant converters for obtaining the small-signal model;

- Validation of amplitude and phase characteristics of the control to output transfer function obtained using the EDF method through comparison with published results in literature;
- Approximation of the control to output transfer function for a LLC converter with a second-order transfer function that simplifies controller design;
- A universal controller for frequency-controlled converters;
- Demonstration of the controller for two types of converters: a quasi-resonant Buck QRC ZCS FW converter and an LLC-type resonant converter.

Chapter 4 presents the derivation of the small-signal model for PWM CCM converters with two topological states using the extended describing function. It is demonstrated that applying this method provides an alternative to the classical averaged state-space model for PWM CCM converters, while also enabling the determination of the fundamental amplitude of classical state variables and their transfer functions with respect to control and power supply.

The author of the thesis makes the following **contributions**:

- A large-signal averaged model in the state-space that allows the determination of the steady-state continuous components of classical state variables and, in addition to the classical method, the fundamental amplitudes of these variables;
- A small-signal state-space model from which small-signal transfer functions—such as audiosusceptibility and control to output transfer function—can be calculated. It is shown how this model applies to second- and fourth-order PWM converters, with its applicability extending to any PWM converter by following the same steps;
- This small-signal model demonstrates that, in addition to classical audiosusceptibilities and control to output transfer functions—which match those found in literature—it is possible to determine the audiosusceptibilities and control to output transfer functions relative to the fundamental amplitudes of classical state variables in any PWM converter;
- It is noteworthy that, although the order of large- and small-signal models is 3n (where n is the converter's order), the small-signal transfer functions remain of order n, as in the classical case.

Chapter 5 presents a general method that simplifies and unifies sliding mode control (SMC) design for second-order converters in CCM. The demonstration is done for a buck converter with coupled inductors.

The author of the thesis makes the following **contributions**:

- A procedure that derives from the state-space description a general formulation suitable for applying sliding mode control to PWM CCM converters with two topological states;
- The design of sliding mode control (SMC) for a second-order buck converter with coupled inductors.

Chapter 6 contains the final **conclusions** and **future directions**.

Future research directions suggested by the author include:

- Experimental investigation of Ćuk 2-type converters with coupled inductors and comparative studies on current and voltage stresses for identical input, output, and power conditions;
- Exploration of alternative control methods, including nonlinear ones, for Ćuk 2 converters;
- Application of the extended describing function method to quasi-resonant, square-wave, and dual active bridge (DAB) converters;
- Application of the extended describing function method to PWM DCM converters;
- Investigation of sliding mode control for higher-order PWM converters.

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