NATIONAL PH.D. PROGRAM IN AUTONOMOUS SYSTEMS

Optimization and control techniques for Energy management systems

Ph.D. candidate

Abdelilah Benrekia

Cycle

XL

Tutors

Prof. Filippo D'Ippolito

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1. Description of the research program

The research program focuses on developing advanced control methodologies for power electronics in the context of hybrid and electric vehicle powertrains, with the primary goal of improving energy efficiency and promoting sustainable mobility. Leveraging recent advancements in silicon carbide (SiC) and gallium nitride (GaN) devices, this program addresses the challenges associated with high-speed switching and system stability in modern automotive power converters. Traditional control approaches, which rely on fixed switching frequencies, are insufficient for systems that incorporate both continuous and discrete dynamics, like those in automotive applications. Therefore, this program utilizes hybrid dynamical systems to provide a more comprehensive model that captures the complex dual dynamics of automotive powertrain converters, facilitating optimized energy distribution.

The initial phase of the program involves the design and development of two key converter prototypes: a full-bridge DC/DC isolated converter and a three-phase inverter, both of which utilize SiC and GaN technology. These converters play critical roles in automotive powertrains by connecting energy sources, such as batteries and supercapacitors, to the high-voltage bus and electric motors. Developing these prototypes enables experimental testing of control strategies under realistic conditions, forming the foundation for further model refinement and control optimization.

The program then progresses to creating hybrid mathematical models for these converters, representing them as switched affine systems. These models delineate between continuous "flow maps" and discrete "jump maps" to accurately capture the converters' dual-mode behavior, essential for achieving control precision. Additionally, these hybrid models account for nonlinearities and parasitic effects, providing a high-fidelity representation of real-world operating conditions.

With validated models, the program advances to optimizing the control strategies for individual converters. Lyapunov-based techniques are applied to establish control algorithms that ensure stability while minimizing switching events, a critical factor in reducing energy losses and thermal stress on components. This approach enhances the lifespan and efficiency of powertrain components by carefully balancing switching frequency with system performance.

For energy management across the entire vehicle powertrain, a supervisory control framework is developed using model-predictive control. This upper-level controller coordinates the flow of energy between various power sources (e.g., batteries, supercapacitors, and fuel cells) and loads (e.g., motors, lighting, and climate control) to maximize global efficiency across the powertrain. The supervisory controller sets reference signals for the lower-level controllers that manage individual components, ensuring cohesive and optimized energy distribution throughout the vehicle's systems.

In addition, hybrid observers are developed to estimate current using voltage transducers rather than physical current sensors, making the system more cost-effective and robust. For operational modes that are unobservable, persistent jumping and minimum dwell-time methods are incorporated to maintain observability across all system states, ensuring effective control without added hardware complexity.

The final phase of the program is dedicated to experimental validation, employing a scaled powertrain test setup to evaluate the control techniques' real-world effectiveness. This testing phase is essential for assessing the practical efficiency gains and validating the theoretical and simulation-based advancements achieved throughout the program.

Overall, this research program combines hybrid dynamical modeling, innovative control design, and practical experimentation to improve energy efficiency in automotive power electronics. By optimizing energy flow and minimizing switching losses, this program aims to make significant contributions to sustainable automotive technologies, enhancing the efficiency, durability, and adaptability of hybrid and electric vehicle powertrains.

2. Schedule of the research activities

First academic year (planned)

	Description	Period	Activity abroad
Background study	Study of dynamic hybrid systems, GaN and SiC power converters	11-2024/ 2-2025	NO
Problem Statement	Preliminary problem formulation and introduction to the proposed solutions.	3-2025/11-2025	NO

Second academic year (planned)

	Description	Period	Activity abroad
Proposed solutions	Development of Lyapunov-based control techniques to optimize the efficiency of each converter individually. Control laws based on Lyapunov matrix-based min-projection will ensure uniform asymptotic stability and minimize switching events, increasing system efficiency.	11-2025/12-2025 (UNIPA) 1-2026/7-2026 (abroad)	YES
Proposed solutions	Developing a power management controller using model-predictive control. This supervisory controller will manage the energy flow between power sources and power users in the vehicle	8-2026/11-2026	NO

Third academic year (planned)

	Description	Period	Activity abroad
Simulations and analysis	Development of a simulation setup, analysis, and validation of the results.	11-2026/5-2027	NO
Thesis writing	Thesis writing, editing and submission.	6-2027/11-2027	NO

3. Training and research activities plan

First academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses				
B. Master's degree courses	Estimation, Filtering and System Identification	March 2025 - June 2025	Yes	9
C. Soft skill courses	Linear and nonlinear Kalman filtering: theory and applications	Feb 2025	Yes	2
	Introduction to autonomous systems	June 2025	Yes	1

	Machine learning	Jan-Feb 2025	Yes	2
	Introduction to autonomous systems	June 2025	Yes	1
	Simulation, optimization, and management of smart energy systems	Sep 2025	Yes	1
D. Participation to seminars	Innovations in Sustainable Energy Conversion Technologies	Nov 2024		0.5
	Introduction to dynamic control allocation	2025		3
	Predictive Controllers within a Digital Transformation framework	2025		0.5
E. Participation to international congresses or workshops	Mediterranean Conference on Control and Automation	June 2025		2
	CDC: Conference on Decision and Control	Dec 2025		2
F. Presentation of research products at international congresses or workshops	Automatica.it 2025	Sep 2025		2
	SIDRA 2025 Summer School	July 2025		6
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			32
G. Individual research activity	Research activity.	500h		20
H. Supervision of students	Tutor of students during the master thesis development	25h		1
I. Integrative teaching activities	Assistant professor during teaching activities	25h		1
J. Preparation of manuscripts for conferences or journals	Preparation of manuscripts for journals, as research products of individual research activity	150h		6
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			28
	TOTAL OF ECTS			**60**

Second academic year (planned)

	Description	**Period**	**Final Exam**	**ECTS**
A. Ph.D. courses	Human autonomous system interaction		Yes	2
B. Master's degree courses	Digital control		Yes	6
C. Soft skill courses	Non-linear control	June 2026	Yes	2
D. Participation to seminars				
E. Participation to international congresses or workshops	SIDRA 2026 Summer School	July 2026		6

F. Presentation of research products at international congresses or workshops				
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			16
G. Individual research activity	Research activity.	950h		38
H. Supervision of students	Tutor of students during the master thesis development	25h		1
I. Integrative teaching activities				
J. Preparation of manuscripts for conferences or journals	Articles concerning the research activity carried out for publication in scientific journals.	125h		5
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			44
	TOTAL OF ECTS			**60**

Third academic year (planned)

	Description	Period	Final Exam	ECTS
A. Ph.D. courses				
B. Master's degree courses				
C. Soft skill courses				
D. Participation to seminars				
E. Participation to international congresses or workshops				
F. Presentation of research products at international congresses or workshops	European Control Conference (ECC) 2027	June 2027		2
	TOTAL OF ECTS FOR TRAINING ACTIVITIES			2
G. Individual research activity	Research activity and writing of the PhD thesis	1200h		48
H. Supervision of students	Tutor of students during the master thesis development	25h		1
I. Integrative teaching activities	Assistant professor during teaching activities	25h		1
J. Preparation of manuscripts for conferences or journals	Articles concerning the research activity carried out for publication in scientific journals	200h		8
	TOTAL OF ECTS FOR RESEARCH ACTIVITIES			58
	TOTAL OF ECTS			**60**

4. List of the publications written by the candidate in the triennium

Not yet

Ph.D. candidate name

Abdelilah Benrekia

Tutor 1 name

Prof. Filippo D’Ippolito

Tutor 2 name

Prof. Antonino Sferlazza
