Titre Thèse **Title**	**EMR-based Control of POwer systems for Proton Synchotron (POPS) accelerator**	
(Co)-Directeur	Alain BOUSCAYROL	E-mail : Alain.Bouscayrol@univ-lille.fr
(Co)-Encadrant	Fulvio BOATINI	E-mail : Fulvio.Boattini@cern.ch
(Co)-Encadrant	Philippe DELARUE	E-mail : Philippe.Delarue@univ-lille.fr
Laboratoire(s)	L2EP	Web : http://l2ep.univ-lille.fr/
Groupe(s)		Web :
Financement demandé	Contrat Doctoral Etablissement	ULille ☒ Centrale Lille ☐ Yncrea ☐
	Région – Autre ☒ Préciser : CERN	Co-financement acquis Oui / non ☐ Préciser : en cours de validation
Financement acquis ? ☐ **Financement partiellement acquis ?** ☐	Contrats de Recherche ☐ Préciser :	Autre ☐ Préciser :

Abstract

CERN is developing new power converter to increase the performance of the most important particle collider in the world. L2EP is developing the EMR (Energetic Macroscopic Representation) to define controls of energy conversion systems. After a first collaboration on the control of particle injector systems, CERN and L2EP propose a PhD thesis focused on the control of power supply of a particle accelerator. Ultra-high accuracy and high dynamics are requested before implementation of the control on the real system.

General context

CERN is the well-known international research centre on physics of particles with the most important particle collider in the world (27 km). Active researchers are preparing the next generation of accelerators for the discovery of new particles and matter. In particular, new power electronics converters are developed with higher modularity, high current, fast dynamics and very high accuracy. In that perspective advanced control methods should be used to ensure the required performances (ultra-high precision for high current of several kA).

L2EP of University of Lille has developed the EMR-based control method which consists of a systematic deduction of a control schemes of complex system from the Energetic Macroscopic Representation (EMR). Since 2000, the EMR-based control method has been successfully applied to various systems, from low power (piezoelectric actuators) to high power (supply system of subway lines), including renewable energy systems, electric and hybrid vehicles, paper band processing, etc.

A first collaboration has been achieved between L2EP and CERN for the control of a specific converter family (SIRIUS FP2P2S for pulse beam injector) leading to accurate results (error 0.1%) of fast pulsed current in magnets (pulses of 1 ms duration and with peak amplitude up to 3 kA). This control is now implemented inin operational converters at CERN.

New POPS

The CERN PS (Proton Synchrotron) accelerator is part of the LHC (Large Hadron Collider) injectors chain. It is constituted by 101 series connected magnets through which particle beams flow in circular pattern. This pulsating machine accelerates proton or ion beams from 1.2GeV to different energy levels according to the final user of the beam (26GeV for the LHC). In 2011 a new 60MW peak power system named POPS (Power for PS) has been installed to replace an old fly-wheel system [Boattini 2015]. The system has been designed for current and voltage peak values of respectively 6 kA and 10 kV (hence 60 MW peak power).

The POPS is composed of two Active Front End (AFE) AC/DC converters connected to the AC grid and six DC/DC converters connected in series to provide the voltage and current levels required

by the magnets. Each DC/DC unit is coupled with a big energy storage capacitor bank, dimensioned to provide the energy requested by the magnets at peak current in an energy exchange scheme. Two out of the six capacitor banks are named chargers because they are connected with an AC/DC converters (the AFE) whereas the remaining four are named floaters .

In order to guarantee the high accuracy required by the application (≈ 50 ppm on the current/field), a polynomial multi-coefficients control structure (aka RST) is used for both the outer Bfield controller and the internal voltage one. An important part of the control philosophy is the way that the energy balance among the six storage capacitors, the magnets and the AC network, is dealt with in the different phases along a typical accelerator pulse.

The POPS system is modular, and the above-described functionalities must be assured even in case of faults and removal of one DCDC or one AFE.

After 10 years of operation, CERN is planning a renovation project for POPS, called POPS+, that aims at improving the number of reconfiguration modes following a fault of one DCDC or one AFE, ultimately increasing the availability of the system. This will be achieved by increasing the number of AFEs to 3 (from 2) and of DCDCs to 7 (from 6).

Also a complete control approach (and control platform) will be implemented with, in particular, the goal of finding a more efficient strategy for the energy management mentioned above.

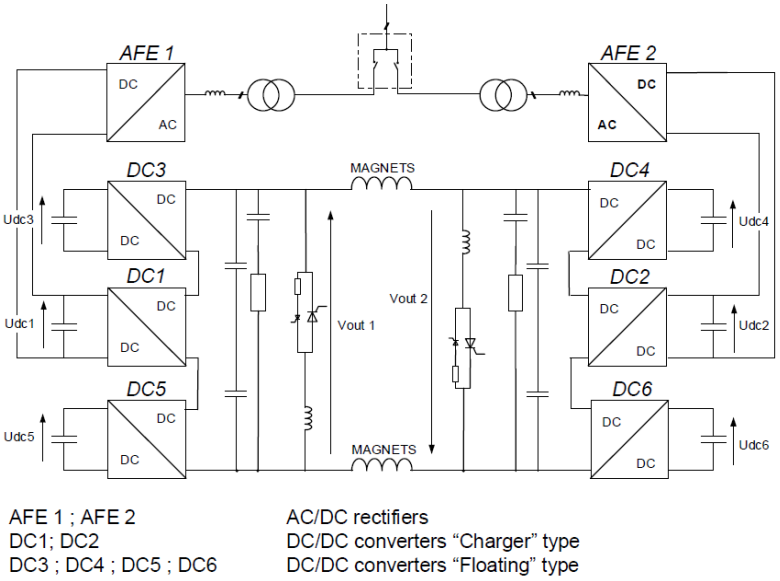

Figure 1 Single line schematics of the POPS power converter

Previous collaborative works

Since 2015, a collaboration between CERN and L2EP has studied the inversion-based control of the new SIRIUS FP2P2S using the EMR, graphical formalism developed by L2EP for control organization of complex energy conversion systems.

The SIRIUS FP2P2S is a new family of fast pulsed power converters that delivers current pulses of 1 ms duration, up to 3 kA peak amplitude, with an accuracy of +/- 3A. Such performances can be achieved only with a very high-precision control system. In that aim, the collaboration has developed an inversion-based control based on EMR. Based on this positive experience, the control organization would be extended to other power converter types.

In 2019 a new collaboration between L2EP and CERN has compared the performance of this EMR-based control of the SIRIUS FP2P2S power converter with an RST-based control, a more classical control approach used by other converter families at CERN. In 2022, another Master thesis is plan to compare the EMR-based control with a state feedback control used by other teams of CERN.

The on-going convention between CERN and University of Lille on Inversion-based Control of Advanced power converter for REsearch in particles physics (ICARE) will be extended to include the EMR-based control of POPS.

Objective

This PhD aims to develop an inversion-based control of the new POPS to achieve the required performances. The control of the actual POPS will be achieved using simulation, and the EMR-based control will be compared to the actual control in simulation. In a second step the EMR-based control will be extended to the new POPS including the management of the supplementary degrees of freedom for both normal and fault operation. A specific focus will be paid in the Energy Management Strategy (EMS) to exploit all the degrees of freedom to increase the performances while reducing the energy consumption and ensuring safe operations.

An experimental validation is expected on a reduced-power system using the Hardware-In-the-Loop testing method before an implementation on the full-power system.

The first 18-month period will be focused on theoretical and simulation development at University of Lille (fellowship about 1400 €/month) with regular visits of CERN. The last 18-month period will be focused on experimental developments at CERN (fellowship about 3500 CHF/month) with regular visits at University of Lille.

Challenges

The technological challenges are in the implementation of the control logic in the final control hardware using C++ functions. To achieve this goal several steps will be progressively achieved before the real-time implementation on the full-power set-up: digital twin (pure simulation), signal HIL (Hardware-In-the-Loop) testing (testing the ECU), and reduced-power HIL testing (testing operation between the ECU and low power equivalent system). The development of these different tests in a unified and flexible way whatever the platform (simulation, real-time simulator, ECU, power…) is also a technical challenge.

The scientific challenges are on the development of innovative and flexible control with ultra-high accuracy for high-power system with an important number of degrees of freedom. If the power converter flexibility is a real advantage in terms of fault operation, it leads to an increase of the complexity of the control. The EMR-based control method aims to face this complexity by a systematic decomposition of the control scheme and the development of multi-strategy energy management layer. It can be note that the development of multi-strategy controls is one of the two priority of the control team of L2EP for actual research program (2020-2025). This CERN application is particularly relevant in that objective.

Application

Deadline: March 10th for the CERN application

Required documents: CV, marks of the last 3 years, motivation letter.

Only for applicants with nationality of the states' members or associated members of CERN.

https://home.cern/about/who-we-are/our-governance/member-states

To be sent to: Alain.Bouscayrol@univ-lille.fr and Fulvio.Boattini@cern.ch

An interview will be organized for the most relevant applications.

References

{Boattini 2015] F. Boattini, J. P. Burnet, G. Skawinski, "POPS: the 60MW power converter for the PS accelerator: Control strategy and performances", *EPE'15 ECCE Europe*, Geneva (Switzerland), September 2015.

{Bouscayrol 2012] A. Bouscayrol, J. P. Hautier, B. Lemaire-Semail, "Graphic Formalisms for the Control of Multi-Physical Energetic Systems", Systemic Design Methodologies for Electrical Energy, tome 1, Analysis, Synthesis and Management, Chapter 3, ISTE Willey editions, October 2012, ISBN: 9781848213883.

[Horrein 2017] L. Horrein, J. M. Cravero, "Hybrid Capacitor Discharge/Switch-Mode Converter for Pulsed Applications: Topology and Control design", *EPE'17 ECCE Europe*, Warsaw (Poland), Sep. 2017.

[Horrein 2020] J L. Horrein, J. M. Cravero, P. Delarue, A. Bouscayrol, D. Aguglia, C. Ortega-Perez, "Dead-Time influence on fast switching pulsed power converters design – A high current application for accelerator's magnets", *EPE'20 ECCE Europe*, Lyon (France), September 2020 (common paper of L2EP Univ Lille and CERN).