Ph.D. in Information Technology
Thesis Defense

July 4th, 2025
At 10:30 a.m.
Aula Beta – Building 24

Matteo Luigi De PASCALI– XXXVII Cycle

MODELLING AND CONTROL OF INNOVATIVE OXY-TURBINE POWER GENERATION SYSTEMS

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Abstract:

The European energy scenario evolution in the following years is guided by ambitious goals that aim at limiting the global average temperature increase and reach net-zero carbon emissions by the year 2050. To this end, an increasing penetration of renewable energy sources is changing the energy mixes of countries involved in this transition as more and more intermittent power generation units are installed (e.g. solar photovoltaic, wind turbines...). Until renewables will not be able to cover the entire energy demand while supported by an infrastructure capable of storing excess energy production and supply power when requested, balancing electrical power system in the upcoming scenarios will be challenging.

To fill in the gaps left by renewable sources, innovative, low- or zero-emissions thermal power generation units can be employed in the next decades to replace outdated and pollutant power plants.Among these new solutions, the ones resorting to carbon capture utilization and storage (CCUS) technologies are thoroughly studied by researchers and have attracted industry interest for their high efficiency and decreasing investment costs.

The objective of this work is the study of innovative oxy-turbine power generation systems and in particular of the Solid-Oxide Semi-Closed CO2 (SOS-CO2) cycle and the assessment of its flexibility to operate in the energy scenarios described above.This concept unit resorts to the oxy-combustion CCUS technology, a technique to easily obtain a pure stream of CO2 to be stored after the fuel combustion.By operating the combustion with pure O2 instead of air, which contains N2, the only products of the combustion process are CO2 and H2O, that can be easily separated through water condensation.The SOS-CO2 cycle, thus, features an oxy-combustion Brayton cycle connected to a Solid-Oxide Fuel Cell (SOFC) module, which efficiently oxidizes about 70% of the fuel before it is sent to the oxy-combustor.

As its name suggests, the SOS-CO2 cycle operates with peculiar working fluids, i.e., a pure CO2 stream recycled from the turbine exhaust and a CO2 and O2 mixture, which replaces air in the cathode channels of the SOFC. The efficiency and the flexibility of such an innovative system should thus be assessed before the power plant commissioning.

To perform such analysis, the object-oriented and equation-based Modelica language is used to code a library of components to assemble the SOS-CO2 cycle model. The models of the components, which are employed to perform plant-wide studies, are described, with particular attention on the strategies employed to complete the plant steady-state initialization successfully.

Since the phenomena occurring in the power plant are described by highly nonlinear equations, the initialization of the model simulation is a difficult and critical task, prone to convergence failures if not properly addressed. The modeling techniques employed aim at simplifying and decoupling the solution of the huge original nonlinear system of equations of the initialization problem and provide ways to consistently perform the initialization of this class of power plants. Moreover, specific utility blocks for object-oriented and equation-based models are presented to directly initialize the plant in off-design conditions and employ the model for linearization, open-loop and closed-loop simulations.
Once the power plant model is ready for simulation, the characterization of off-design policies to control efficiently the SOS-CO2 cycle during partial load operations is addressed. Taking as inspiration the conventional off-design strategies for thermal power generation systems, four strategies were defined, each one with the aim of maximizing the efficiency of the power plant while respecting the technological limitations of its components. The first two strategies limit the fuel cell usage, while the last ones shift remarkably the power production towards this component.
The partial load trajectories formulated are employed as reference signals for a suitably tuned control system. First, a novel algorithm to support the formulation of reduced-order models for thermal power generation systems is presented, together with the procedure adopted for the synthesis of a model-based controller. Second, a preliminary analysis on the coupling between the input and output variables of the plant reveals that the power block of the SOS-CO2 cycle should be controlled with a centralized control system to handle the input-output coupling, while quantities related to the technological limitations of the plant (e.g. maximum SOFC inlet temperatures, minimum pressure of the cycle...) can be controlled with decentralized PI controllers. Finally, following the indications provided by the developed algorithm, a reduced-order model of the power block is built to capture the main dynamic characterization of the considered plant portion. The reduced-order model is employed to build the control architecture and simulations are performed to track fast load variation ramps and simulate a rapid intervention of the plant to balance the electrical grid.
As final topic of the dissertation, optimization tasks are considered. Since Modelica tools do not offer open-source solutions to code optimization problems involving Modelica models, a compiler from Modelica to Pyomo language is coded to automatically translate simulation problems into optimization ones. The compiler takes care of scaling properly the generated models and performs code manipulations to substitute difficult to handle expressions like logarithms. As test case, the fuel cell model included in the SOS-CO2 cycle is converted into a Pyomo model and static and dynamic optimization routines are performed. First, parameter identification problems are addressed and finally open-loop dynamic optimal control problems are solved while enforcing constraints on the variation of critical quantities like the temperatures of the fuel cell solid layers.

PhD Committee

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