Cyber-Physical Research Challenges and Opportunities in Next-Generation Power Plants

Eugenio Schuster, PhD
Lehigh University, Mechanical Engineering and Mechanics
19 Memorial Drive West, Bethlehem, PA 18015-3085

The increasing demand for clean, safe, reliable, highly-efficient power generation plants requires the development of advanced control system architectures that exploit recent advances in sensing, communication and computation methodologies for process control and real-time optimization. Future power plants may need a level of system integration not found in present power generation systems in order to maximize overall performance and secure environmental compliance. While the development of a smart and reliable electricity network has recently attracted much attention, it is critical not to overlook the technological challenges that must be overcome not only by renewable power plants but also, and more importantly, by more conventional fossil and nuclear power plants in order to be able to operate efficiently in this smarter electricity network.

The most common and dominant approach to control of present power plants is an uncoordinated arrangement of single-input-single-output (SISO) feedback loops based on non-model-based proportional-integral-derivative (PID) controllers. The PID controller owns its popularity to the fact that it does not require a dynamic model of the plant for its design, since that the structure of the controller is fixed. However, the reason of its popularity is also the reason of its performance limitation. By not exploiting the knowledge of the system represented by the dynamic nature of the plant model during the control synthesis procedure, the PID controller puts itself in an unfavorable position in terms of performance, when compared to model-based controllers. In addition, tuning of the PID gains, which represent the only connection with the plant dynamics, is usually empirically carried out by the plant operators, who in general do not have the necessary control background. This often results in fixed-structure, poorly-tuned controllers. Another limitation of this control system architecture resides on the selection of set-points. The selection of control set-points is also usually left to the plant operators, which results in values that are far from being optimal in terms of overall power plant efficiency and do not incorporate at all the dynamic business models that the unit is supposed to operate on. Recent work on static optimization of power plants has played a crucial role in improving overall efficiency. However, static optimization falls short in dealing with real-time scenario changes (i.e., cycling unit load, fuel quality, system maintenance conditions, subsystem failures, plant aging, etc.). Taking into account all possible scenarios during an offline static optimization is simply unfeasible. When the plant conditions change in real-time and departs from the conditions considered during the offline static optimization, the optimal set-points are not longer optimal and need to be recomputed online.

In order to efficiently operate within a smart electricity network characterized by a vivid dynamics and a high level of producer-consumer interaction, the control system architecture in next-generation power plants must undergo drastic changes. The present *uncoordinated, non-model-based, SISO* control architecture must be replaced by an *integrated, model-based, MIMO* (multiple-input-multiple-output) control architecture in order to take into account the interdependence of the different subsystems. The current *offline static optimization* approach must be replaced by an *online dynamic optimization* approach in order to guarantee that the control system architecture adapts in real-time to changes in the controlled system. The present *set-point-control* paradigm must be changed to an o*verall-economics-control* paradigm, where the control goal is to achieve an overall objective that is directly related to the economics of the controlled system.

As a consequence, several cyber-physical research needs arise in power generation, which include:

1. Methods for modeling of large-scale systems: Next-generation power plants will be extremely-complex, large-scale, energy systems, allowing only control solutions that can guarantee performance, reliability, compliance and safety. The strong coupling between the different subsystems calls for an integrated model-based approach to obtain improvements in closed-loop performance. The approach requires the development of modeling methods that make large-scale system modeling tractable and efficient.

2. Hardware and software solutions to support heavy computational requirements of complex real-time calculations: The intrinsic nonlinearities, the extreme range of both time and spatial scales, and the high dimensionality of these large-scale power generation systems make their optimal control a unique challenge whose solution will require massive real-time computation. Some combination of faster hardware and more intelligent methods of computation on existing hardware is required to support these needs. The latter are likely to include methods for fast optimization that involve a trade-off between computational time and accuracy.

3. Software methods for state detection and logical decision-making based on high volume of sensor information with the ultimate goal of providing intelligent transitions between different nominal control regimes in response to changing time-dependent power plant conditions and priorities: The need for power plant optimization has raised awareness of the need for integrating different and sometimes competing controllers. Control efforts in present power plants focus on individual and isolated objectives. However, this approach is sometimes unrealistic since different control objectives may be heavily coupled. Development of a single controller that performs well under all power plant conditions is not feasible due to the complexity of the system and the variety of control problems. Therefore, a large-scale intelligent supervisory system must be developed to integrate the different control subsystems and to prioritize control objectives and actuator usage in order to optimize in real time the overall plant economics subject to safety and environmental constraints. Software methods for state detection and logical decision-making based on high volume of sensor information are required to provide intelligent transitions between different nominal control regimes in response to changing time-dependent power plant conditions and priorities.

4. Software methods for prediction and detection of faults followed by state-dependent logical decision-making to facilitate timely transition to fault response control methods: During operation, hundreds of subsystems must operate correctly for successful power generation. Verifying proper operation of the subsystems most prone to failure is often done manually in present power plants by human operators during and after operation. Efforts are needed toward developing automated fault detection and response systems. The handling of faults includes detection and identification of the fault, determination and execution of corrective actions, and execution of a mitigating response when correction or recovery is not possible. Fault detection and isolation (FDI) techniques developed during the last several decades based both on hardware and analytical redundancy must be extended to large-scale systems and later integrated in the intelligent supervisory systems.

5. Development methods to provide guarantees of software performance in order to support guarantees of safety, device protection, and performance in power plants: The impact of faults in a power plant can be summarized according to the severity of their consequences: (1) Risk of personnel safety; (2) Risk of equipment safety; (3) Performance degradation. Methods are required to guarantee that none of these faults are triggered by the software as its complexity increases.