OVERVIEW OF SIMULATION AND CONTROL TOOLS FOR EXTENDED OPERABILITY OF NUCLEAR REACTORS

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ABSTRACT

The increasing penetration of Renewable Energy Sources (RES) requires the current power grid to be suitably improved. Because of the unsteady nature of RES, as long as energy storage facilities are not deployed and commercialized, an increased effort for the frequency regulation in order to ensure high reliability and performance is necessary. In such a scenario, nuclear units (traditionally deployed as baseload generating units) will be required to cooperate with intermittent RES-based power plants. Therefore, new reactors will need larger operational flexibility with respect to the capabilities of the currently operated units. Over the last few years, a comprehensive research program oriented at developing a suite of simulation tools and control system development capabilities was pursued at Argonne National Laboratory. In addition to the study of advanced reactor concepts (e.g. metal-fueled Sodium-cooled Fast Reactors) and technological innovations (such as S-CO_2 Energy Conversion Cycles), new control approaches were developed to improve the operability of nuclear power plants. In particular, Model-based Predictive Control algorithm for Multiple Input Multiple Output control strategies and set-point definition algorithm based on Reference Governor were studied and applied to specific scenarios, providing with a range of novel capabilities able to meet the expected greater sets of requirements mentioned above. In this work, an overview of such tools and case studies is presented with particular focus on their impact on operability and economic competitiveness of nuclear energy.

Key Words: Extended Operability, Model-based Predictive Control, Supervisory Control System, Passive Safety Features.

1. INTRODUCTION

Historically, nuclear power plants (NPPs) have been conceived, designed and operated as base-load generators in the US. Though this paradigm worked for decades, the new features of today's energy market make it not suitable any more, and the competitiveness of nuclear systems is being put into question. From this premise, to ensure the nuclear unit profitability, the possibility of expanding their operating conditions beyond the traditional use needs to be evaluated. Several worldwide research programs are today focused on improving the economics of existing NPPs and on proving the potential of advanced reactor concepts. A commonly accepted statement among the assessment of the present and future of nuclear energy as a low-carbon energy source is that its economics and sustainability in the near and far future will necessarily rely on the ability of NPPs to operate beyond base-load power generation. This consideration is based on one hand on the RES intermittency that constitutes a serious challenge to the stability and the continuity of service of complex electric grid systems, and on the other hand on the need to be able to compete in deregulated energy markets. In these latter markets, large energy price fluctuations (caused by market structure itself and by the existence of technology-selective subsidies) create an economic penalty for the technologies that cannot follow the price curve and maximize, on a daily basis, the earnings of the single units.

Argonne National Laboratory (ANL) has been a pioneer research institution for the study and design of advanced reactor concepts, and in particular sodium fast reactors (SFRs) [1]. Over the last few years, considerable efforts have also been invested in characterizing the potential and challenges for extended operability of NPPs (existing and advanced) through the development of simulation, analysis and control tools. In this paper an overview of such tools and related applications is presented.

2. ECONOMICS DRIVEN ANALYSIS OF NUCLEAR UNIT OPERABILITY

Historically, in the US electricity regulated market, nuclear units were operated as base-load generators as a way to address the financial burden of such a capital intensive technology. To reduce as much as possible the payback time, the nuclear units were operated at full nameplate capacity. With the deregulation process, started in the 1970s, such an approach to nuclear unit operation began to lose validity. In addition, the increasing penetration of renewable energy sources is changing the priorities of the grid operators. In order to compensate for the renewable power fluctuations, even the thermal units characterized by low marginal costs are requested to ensure a more significant contribution to the grid operating reserve. By ensuring a higher level of flexibility, NPPs can increase their revenue by providing additional services to the grid. In this perspective, the characterization of the operation capabilities needs to be improved. Unfortunately, in the US fleet, there is no operational experience with regard to NPP flexible operation. It is then necessary to improve the available modeling tools to design a reliable technology-independent model-based approach to identify and test the opportunities for extended operability [2].

3. APPLICATIONS OF EXTENDED OPERABILITY CONCEPTS AND TOOLS

3.1 Reactor Fast Runback

One way of improving the nuclear unit economic competitiveness is pursuing the reduction of operational costs. Plant operation and maintenance costs are significantly driven by plant availability, which can be enhanced by means of innovative control strategies by avoiding unnecessary reactor trips. In this context, an effective strategy for achieving the fast runback of a SFR was developed. The runback transient involves the prompt disconnection of the power plant from the grid following a generator trip, and the subsequent rapid reduction of the electrical power output. After the grid disconnect, the reactor remains neutronically critical at low power level, while the residual electric power produced is used to meet the house loads. When it becomes possible to reestablish grid load-frequency regulation, the power plant is promptly brought back to nominal conditions. Generally, the occurrence of such transients is not known in advance to the plant operators. In particular, if a fault on the grid either requires or results in disconnect, it is advantageous to regard this as an operational occurrence and initiate a fast runback transient. Avoiding a reactor shutdown in favor of a power runback eliminates all the complex and time-consuming operations needed for the eventual reactor startup. Such flexibility would therefore lead to significant savings in the operational costs of the reactor while also improving the power plant availability.

When the NPP electrical power output is dropped, the balance of plant (BOP) heat disposal capabilities are greatly reduced. Therefore, the objective of the control system is to drop as promptly as possible the power level, without scramming the reactor. During this operational transient, the sodium temperature in the hot plenum needs to be effectively controlled as well. The reactor outlet temperature represents the higher fluid temperature in the plant and is directly related to the achievable thermal efficiency, which ultimately affects the cost of electricity. However, materials and thermodynamic considerations (such as the boiling point of the coolant or the mechanical response of the internals at high temperatures) set an upper limit for such a temperature (550°C). From this standpoint, the adoption of feedback single-input/single-output (SISO) control loops based on proportional-integral-derivative (PID) regulators would hardly allow achieving a prompt reactor power drop while ensuring limited temperature variations in the primary circuit. These limitations can be addressed through the use of a multiple-input/multiple-output (MIMO) control strategy that provides the capability to coordinate the control variables.

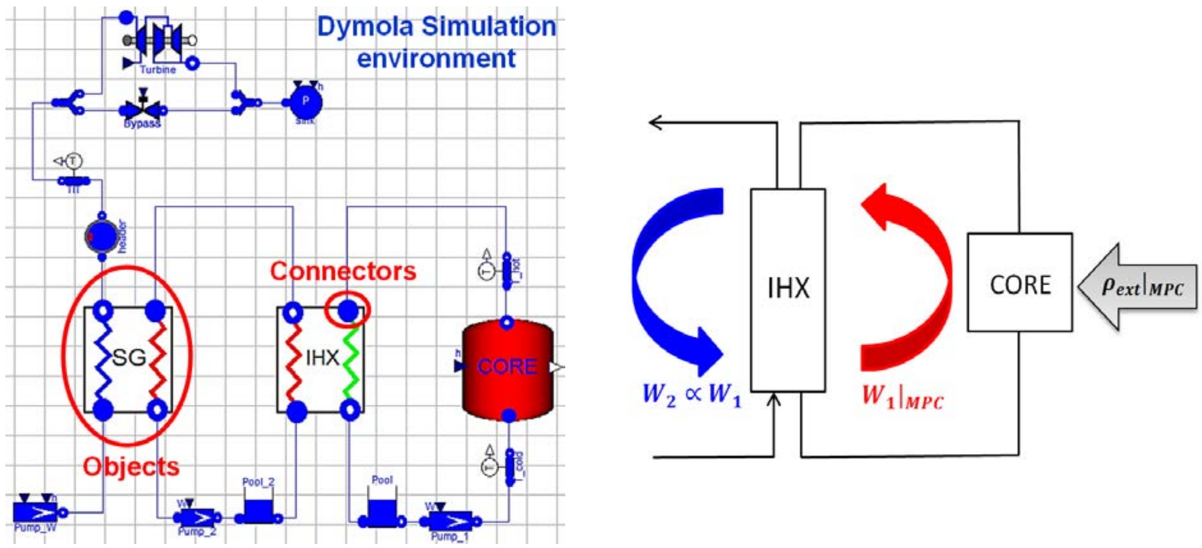


Figure 1. On the left, graphical interface of the Dymola object-oriented model; on the right, coordinated control actions performed by the MPC algorithm.

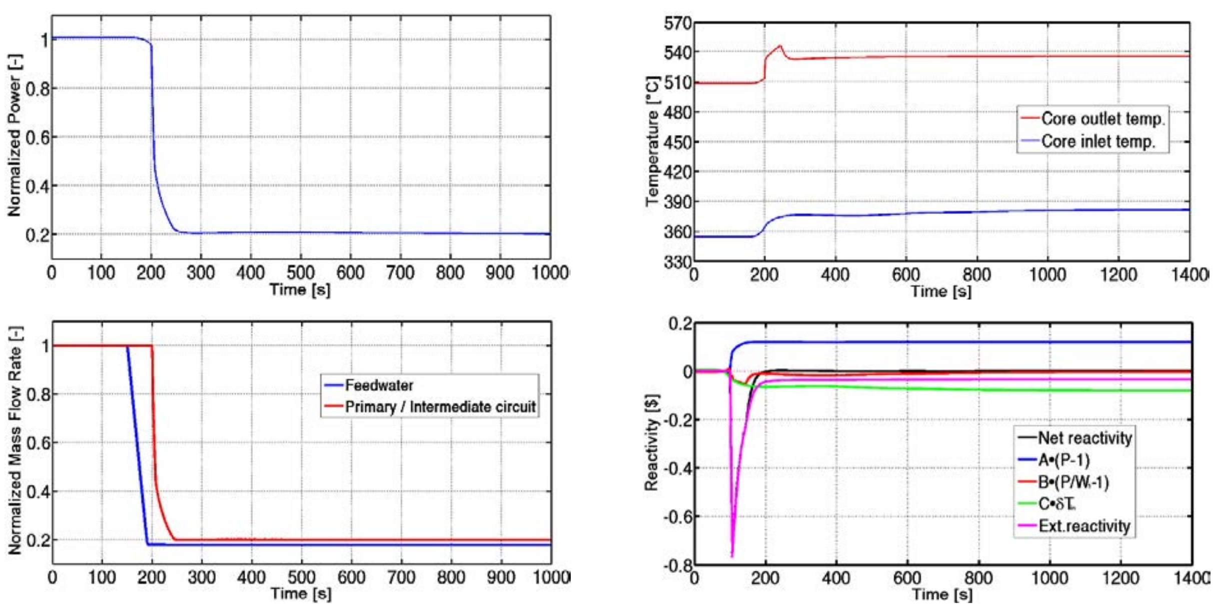


Figure 2. Simulation outcomes of the Fast-Runback operational transient performed by adopting the designed MPC-based control scheme [3].

The problem of defining a suitable control strategy to achieve the system fast runback can be studied as a constrained optimization problem. In this perspective, the model-based predictive control (MPC) methodology is an effective means to deal with large multivariable constrained control problems. The control algorithm seeks to optimize an objective or "cost" function, which is a user-specified mathematical indicator of the desired performance of the feedback regulator. In this work, the nonlinear system dynamics is represented by adopting an object-oriented model in Dymola simulation environment (Figure 1), and the designed controller is implemented in the MATLAB MPC control toolbox [3]. As for the developed control strategy, the control rod reactivity (ρ_{ext}) and the primary circuit flow rate (W_1) are adjusted to regulate the thermal power produced in the core (P) and the sodium temperature in the upper plenum (T_{out}). At the same time, the intermediate circuit flow rate (W_2) is changed in proportion to W_1 to maintain constant temperatures across the IHX.

Some of the obtained simulation outcomes are reported in Figure 2 for a metal-fueled core configuration. Because of the favorable behavior of the inherent reactivity feedbacks and the optimized coordination of the actuators, a prototypical fast runback from 100% to 20% thermal power (5% electric power) can be achieved in about 60s with an overall modest temperature increase in the primary circuit (25K in the hot leg). It should also be noted that for this core configuration the asymptotic value of the control rod reactivity contribution to be provided is equal to just 12 pcm. A full discussion of the results for an oxide core configuration as well can be found in [3].

3.2 Advanced Energy Conversion Cycles

Supercritical carbon dioxide (S-CO_2) Brayton cycle represents a promising solution as energy converter for advanced high temperature reactors (Figure 3). It offers the benefits of high cycle efficiency, very compact turbomachinery, and the elimination of sodium-water reactions. The efficiency gains calculated for the S-CO_2 cycle are particularly significant if advantage can be taken of the sharp changes in the carbon dioxide thermo-physical properties near the critical point. On the other hand, these property variations give rise to challenges in the cycle design, analysis, and control. The S-CO_2 energy conversion cycle is characterized by nonlinear governing dynamics which might limit the performance of linear controllers. Large variations in fluid properties with respect to temperature and pressure degrade the performance of conventional resistance temperature detectors (RTDs). Since density and specific heat capacity cannot be determined within a few percent, a feedback controller which can effectively deal with the uncertainties affecting the system parameters would be suitable. In addition, RTD age-related degradation mechanisms might cause calibration drift and response time increase, which should be accounted for. To address these issues, a MPC control scheme for the S-CO_2 temperature regulation at the pre-cooler outlet coupled with a Kalman filter for the state estimation is designed (Figure 4). Thanks to this approach, the uncertainties affecting the system dynamics and the measured output variables can be suitably accounted for, and the potential presence of sensor time delays can be dealt with.

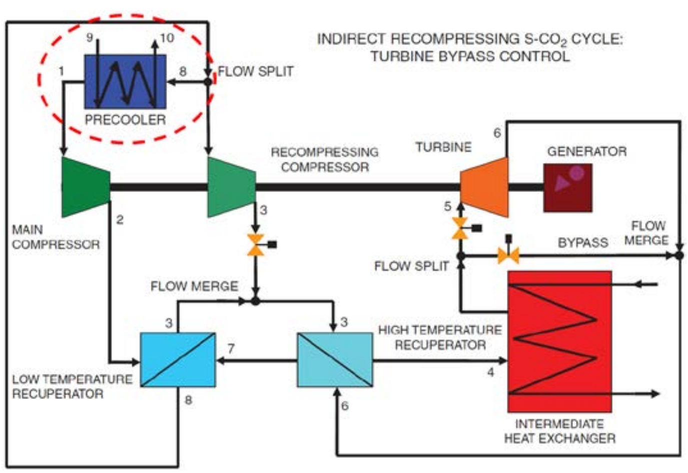


Figure 3. Overall Balance of Plant layout. The pre-cooler is outlined [4].

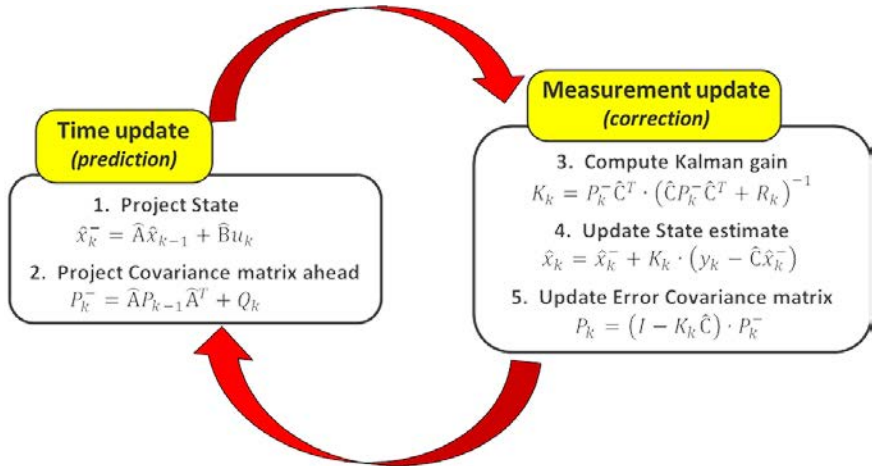
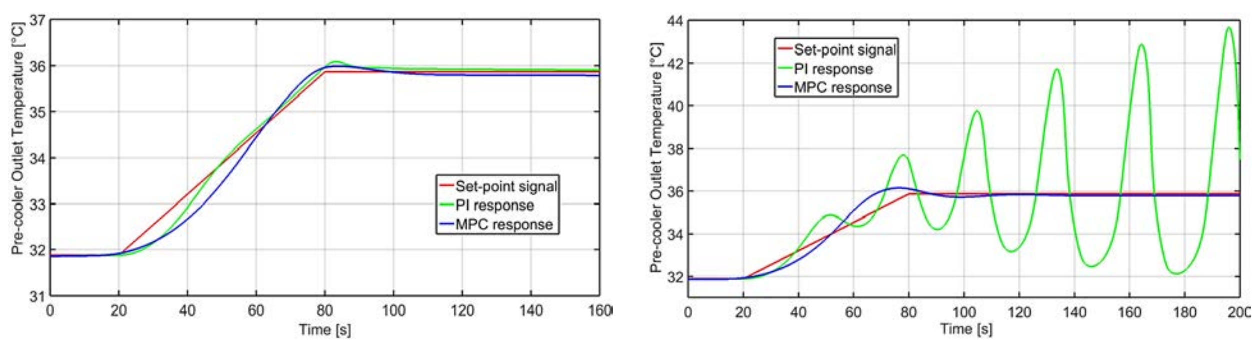


Figure 4. Graphical representation of the Kalman filter concept [4].

In Figure 5, the simulation outcomes of the same transient performed by adopting the PI controller and the MPC are presented. In Figure 5a, the RTD delay is set equal to 2.0 seconds (nominal conditions). PI controller parameters are such that good tracking capabilities are obtained without causing oscillations. Though the satisfactory performance, the PI regulator cannot compensate for the presence of the sensor time delay (a lead-lag compensator would be necessary), whereas the MPC allows dealing with that. In Figure 5b, the simulation outcomes referring to the same transient were reported, though in this case a longer time delay representing the sensor response degradation was set (6 seconds). In order to compare the performance of the considered regulators, the tuning was maintained the same adopted for the transient performed at nominal conditions. At this perturbed conditions, the PI controller tuning is not effective anymore since concerning oscillations occur. On the other hand, MPC algorithm demonstrates a superior robustness to sensor time delay uncertainties since the ensuing oscillations are effectively damped and the tracking capabilities are preserved. In [4] additional outcomes about the application of this control scheme to S-CO_2 energy conversion cycle can be found.



(a) (b)

Figure 5. Controlled responses of the S-CO_2 temperature at the pre-cooler outlet obtained by adopting the PI controller and the MPC regulator. On the left, the RTD delay was set equal to 2.0 seconds (RTD nominal response); on the right, the RTD delay was set equal to 6.0 seconds (RTD degraded response) [4].

3.3 Conceptual Design of Supervisory Control System Architecture

Sections 3.1 and 3.2 explore the possibility to apply modern control tools to improve the performance of advanced nuclear systems. However, it is well known that the state of the art for nuclear technology is not yet ready for a direct implementation of such tools and therefore one may ask if incremental performance improvements are possible by better managing existing control schemes based on

SISO controllers. In this perspective, it is of interest the implementation of a multi-level control system architecture characterized by the presence of a *supervisory control system* (Figure 6).

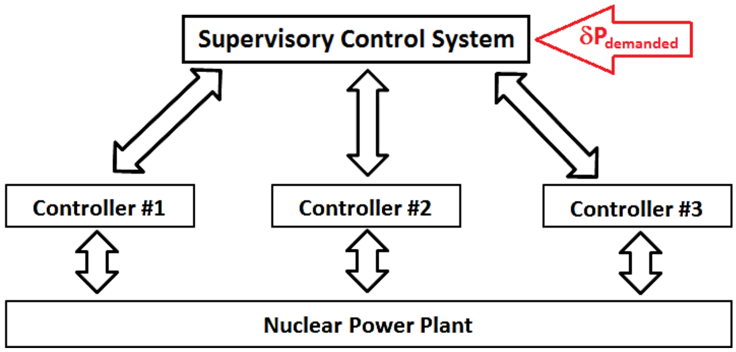


Figure 6. Control System Architecture.

Thanks to this structure, the set of decision-making responsibilities are divided into different levels. Each level has its own objective and its own function, and it is associated with a certain level in the control system hierarchy. Distributed throughout the plant, different actuators (primary circuit pumps, control rods, intermediate circuit pumps, turbine admission, etc.) execute the commands received from the higher levels. The supervisory control system is meant primarily to synchronize the operation of the local controllers and to supply them with the corresponding set-points, according to the grid demanded power level. From this standpoint, a set of *lookup tables* is traditionally adopted. According to this approach, the set-points are evaluated through a mono-directional data flow, i.e. once defined the power demand and the operational mode, the set-points for the different controlled variables are evaluated by means of a tabulated sets of values referring to the design reactor performance (Figure 6).

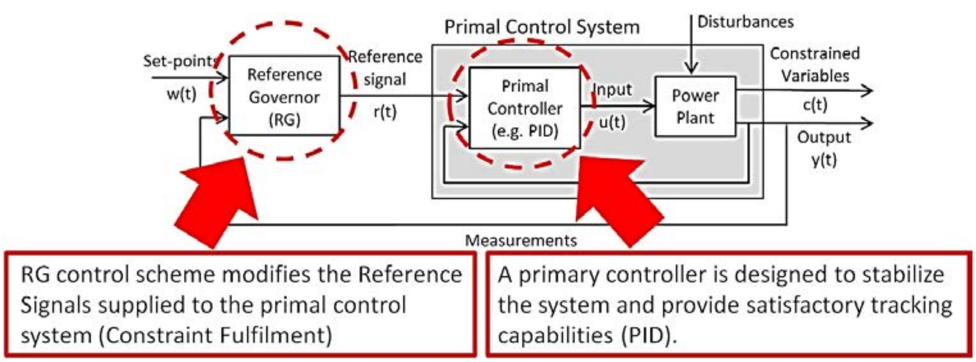


Figure 7. Reference Governor based feedback control scheme [5].

On the other hand, in the perspective of extending the SFR operability, the classic lookup table approach does not ensure a sufficient level of robustness in case of actuator failures. Let us consider the scenario in which a SISO control loop fails and the other feedback loops keep on regulating the corresponding process variables, without the intervention of the plant protection system. In such a scenario, though the system is experiencing off-normal operating conditions, the implemented PID regulators would try to maintain the control variables close to the tabulated values, i.e. the set-points supplied to the feedback regulators would not be adjusted in response to the dynamic evolution of the process variables. In these cases, it would be useful if the selection of the set-points was also a function of the instantaneous plant operating conditions. Thanks to this additional feedback, the consequence of this kind of accidents would be somehow damped, even without relying on diagnostics systems. To this aim, the adoption of the Reference Governor (RG) approach allows adjusting the reference signals supplied to the feedback controllers without affecting the system safety features during off-normal scenarios (Figure 7).

In the perspective of adopting the RG approach for the NPP control system design, the set-points supplied to the PID controllers are suitably modified according to the system operating conditions through the iterative optimization of a cost function, which represents the objectives of the control system. It is important to stress that this approach does not constitute a MIMO control scheme. By means of the RG approach, only the reference signals are adjusted, and then the scheme can be implemented without modifying the configuration of the existing inner control loops. By so doing, the main advantage of SISO controllers is preserved, i.e. there would be no additional common cause failure, while the operation of the system could be greatly improved. Potential for application of such methodology is discussed in greater detail in [5], where also the additional possibilities and challenges of implementation of novel control strategies for advanced reactors are mentioned and preliminarily explored.

4. PASSIVE SAFETY AND EXTENDED OPERABILITY

A claim often made regarding advanced reactors is that they are passively safe against unprotected upset events. In common practice, these events are analyzed through the use of dedicated safety analysis codes without accounting for the normally programmed response of the control system (*open loop* approach). The conventional approach to safety is typically derived from three general design criteria [6]:

- *The protection system must be independent of the plant control system and no credit is to be taken for control system action in accomplishing protection system function.*
- *The protection system must protect the plant from control system failures and operator errors.*
- *The protection system must be able to perform its function in the presence of a single failure in a safety system.*

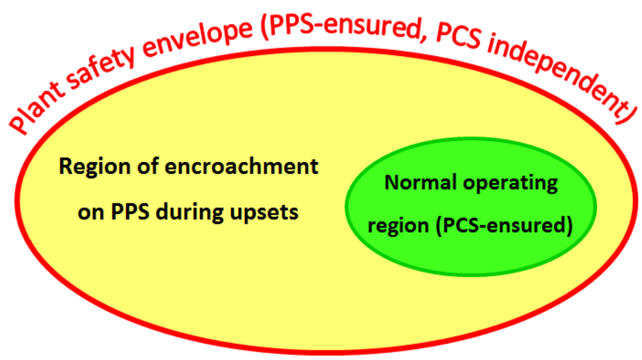


Figure 8. Scheme representing independence of the Plant Protection System [7].

However, depending on the upset affecting the control system (operator error, active control system failure, or inadvertent control system override), an actuator does not necessarily influence the system in the same direction as needed for safety. Therefore, neglecting to account for control system response during an unprotected upset is non-conservative from the safety standpoint. In order to provide a methodology to eliminate such non-conservatism in reactor safety analysis, the potential for the control system to work against the inherent and safe regulating effects of purposefully engineered temperature feedbacks is investigated. In particular, the Plant Protection System (PPS) is traditionally conceived to be functionally independent of the Plant Control System (PCS), tripping or energizing actuators when monitored process variables are no longer within the safe limits. This is represented in Figure 8, where the region of normal operation is represented in green while the region shown in red contains those plant states that trigger the PPS intervention. According to the classic approach, when an internal or external disturbance causes the plant to unexpectedly deviate from a safe equilibrium operating point (*initiating event*), the PPS overrides PCS actions and takes the plant to a safe state. Typically, when controlled process variables move outside limits, rotating machinery (pumps and turbomachinery) are tripped by the PPS in a coordinated action with the reactor scram.

When the PPS successfully scrams the reactor, the ensuing system evolution is referred to as *protected transient*. In Figure 9a, this system response is represented by the green trajectory with the green spot representing the moment at which the PPS overrides the PCS. However, it may happen that PPS fails to scram the reactor. In this scenario (blue trajectory, Figure 9a), the PPS overrides the PCS following the initiating event so that the rotating machinery are tripped. In the time between the initiating event and the PPS override, the PCS still operates its actuators and possibly not in the direction of the ultimate safety goal of a passive shutdown. Ultimately, inherent feedback mechanisms provide the reactivity needed to safely regulate the reactor, and the system evolves within the safety envelope. Although the PPS failed to scram the reactor, the system was purposefully designed to limit the consequences of the unprotected initiating event. Let us refer to this as the *classic unprotected transient*. Now let us consider the case where the PPS fails to perform any of its active functions in response to the initiator so that the PCS control loops continue to influence the system. The PCS has no real "decision making capability", i.e. the control system algorithms simply respond without adaptation to the current plant conditions. After the initiating event has occurred, the PCS does not recognize that an upset event is underway (Figure 9b). Let us refer to this as the *unprotected transient with active control* (red trajectory, Figure 9a). Since the control system has no diagnostic capabilities, there is the possibility that the performed control actions might exacerbate the overall plant conditions, i.e. the plant response along this specific trajectory might be worse than for the case of the classic unprotected transient.

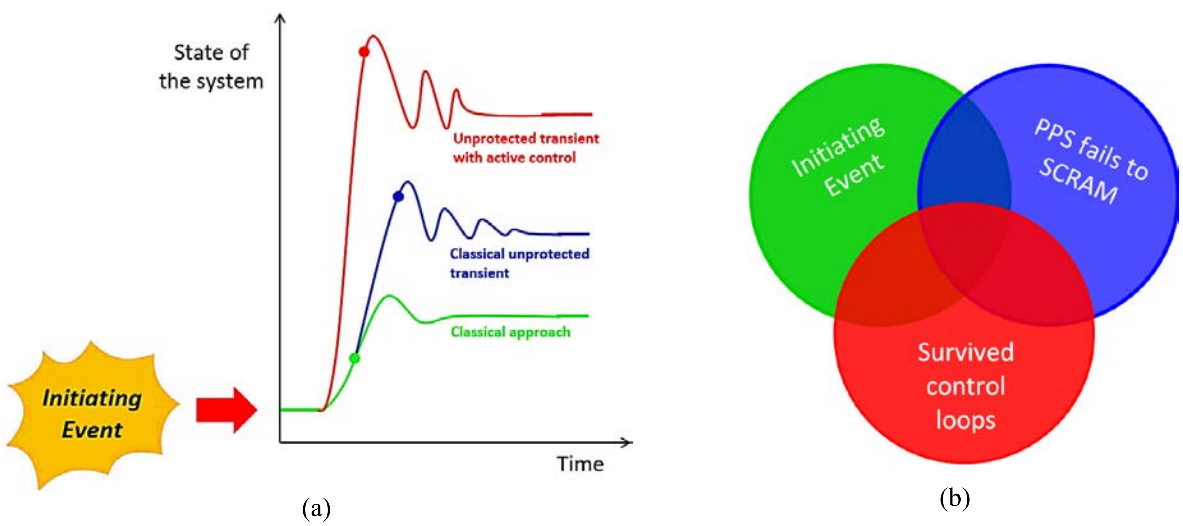


Figure 9. Graphical representation of the three different system evolutions (left), graphical representation of the *unprotected transient with active control* (right) [7].

To determine if the control actions performed by active regulators might limit the effectiveness of passive safety features of an advanced reactor concept, a dedicated model-based methodology was developed (Figure 10). The first step is the development of a dynamic model able to describe the overall plant and its governing dynamics so that it can be used to verify that the desired performances are met in the time domain. Such model is then to be used to iteratively define the plant operability region and identify all the reasonable and suitable control strategies. Once the PCS envelope (see also Figure 8), the PPS envelope is to be defined, modeled and implemented (note that this is the only technology-specific step of the methodology) so that then active system failures can be injected in the model and scenarios testing the interaction of PCS and PPS features (including passive safety features) can be iteratively run and analyzed. Following this final iteration where single failures or combination of failures at different operating conditions can be tested for all the identified control strategies, the strategies can be ranked according to the performance, and the margin for interaction between active controllers and passive safety features can be assessed. A first-of-a-kind application of this methodology was applied to SFR technology. Details about implementation and results can be found in [7] and [8].

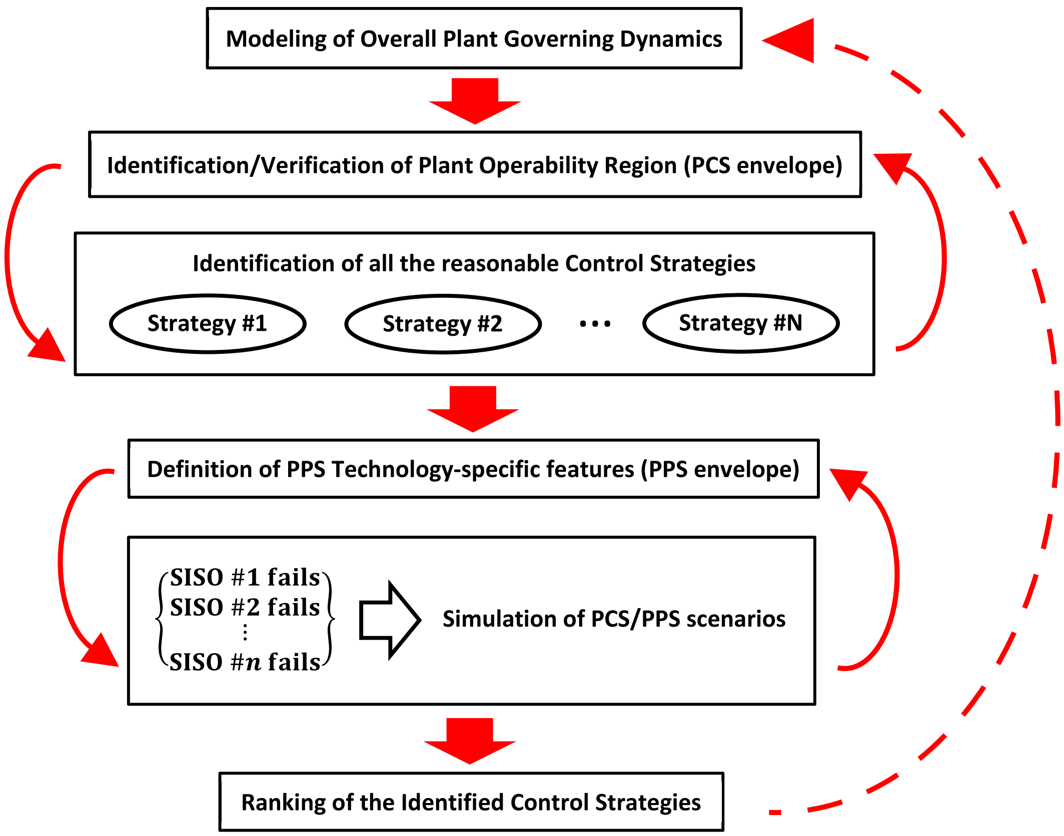


Figure 10. Developed model-based methodology to evaluate the impact of active controllers on passive safety.

5. CONCLUSIONS

In this paper an overview of the simulation tools and control system development capabilities developed at Argonne National Laboratory over the last few years is presented, focused on the need for improving the operability (and therefore the economic sustainability) of current and advanced nuclear power plants. In particular, novel uses of techniques such as Model-based Predictive Control for Multiple Input Multiple Output control strategies, and set-points definition algorithm based on Reference Governor are shown with reference to specific scenarios by giving proof of the potential to meet the expected greater sets of requirements needed to improve the economic and technological sustainability of nuclear energy in the future.

6. ACKNOWLEDGMENTS

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