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Abstract – *In this work, an innovative control approach for metal-fueled Sodium-cooled Fast Reactors is proposed. With respect to the classical approach adopted for base-load Nuclear Power Plants, an alternative control strategy for operating the reactor at different power levels by respecting the system physical constraints is presented. In order to achieve a higher operational flexibility along with ensuring that the implemented control loops do not influence the system inherent passive safety features, a dedicated supervisory control scheme for the dynamic definition of the corresponding set-points to be supplied to the PID controllers is designed. In particular, the traditional approach based on the adoption of tabulated lookup tables for the set-point definition is found not to be robust enough when failures of the implemented SISO (Single Input Single Output) actuators occur. Therefore, a feedback algorithm based on the Reference Governor approach, which allows for the optimization of reference signals according to the system operating conditions, is proposed.*

I. INTRODUCTION

In the past, Nuclear Power Plants (NPPs) were designed and operated almost exclusively to cover base load demand to maximize availability and load factor. This approach, while sound for the early generations of NPPs and for large units, is not optimal for future units which are expected to operate cooperatively with Renewable Energy Sources (RES), whose unsteady nature can lead to fluctuations in voltage and frequency on the grid. In this perspective, the need to provide NPPs with the flexibility to adjust the electrical power output in accordance to the grid request is a pressing issue. The presence of intermittent RES-based power plants, along with the limited presence of energy storage facilities, requires an increased effort for the frequency regulation in order to ensure high reliability and performance. To maintain the grid stability, new reactors will need larger operational flexibility with respect to the capabilities of the currently operated Light Water Reactors[1]. To this end, in this work, the development of a control approach for the flexible operation of a metal-fueled Sodium-cooled Fast Reactors (SFRs) is considered. In particular, along with the definitions of a suitable control strategy, the possibility of coordinating the reference signals supplied to the feedback regulators is studied to ensure operational flexibility without affecting the plant safety features[2].

The paper is organized as follows. In Section II, the main features of a reference reactor are reported, and the object-oriented model of the overall plant is briefly described. In Section III, the main concepts of the control system design of SFRs are presented. Then, in Section IV, the influence that active controllers might have on the passive safety features during accidents initiated by an actuator failure is evaluated. Subsequently, in Section V, an innovative approach to the control system architecture is proposed. Finally, the main conclusions are drawn in Section VI.

II. REFERENCE REACTOR CONFIGURATION

The reference design reflects conventional fast reactor technology in terms of plant configuration and materials, use of active control systems and standard operation. The reference plant is a SFR of the pool type with a metal-fueled core. The simplified plant layout is shown in Figure 1 and consists of a primary system and an intermediate system, both using sodium coolant, and a Rankine cycle as the Balance of Plant (BoP) power conversion technology. A previously developed object-oriented model of the reference design[3] deployed in Dymola[4] simulation environment was adopted. The model consists of a primary loop, an intermediate loop with an intermediate heat exchanger (IHX) and a once-through steam generator (SG). As for the primary circuit, the dynamics of the coolant flowing through the core channels is represented by mass, momentum and energy conservation equations, whereas the thermal behavior of the fuel elements is described by means of the time-dependent Fourier equation. As for the neutronics model, the point kinetics with single energy group and one group of precursors is adopted. The system reactivity is defined by adopting the integral reactivity coefficients[5]. This quasi-static approach provides a clear and easily understood model for understanding the interplay between control and safety. The time constants of the temperature feedback processes are such that the temperatures that are responsible for feedbacks are essentially in equilibrium with the instantaneous power, flow rate and inlet temperature[6]. A reactivity balance on the reactor then gives, relative to some equilibrium zero reactivity reference state,

$$\rho_{net} = A(P-1) + B\left(\frac{P}{W} - 1\right) + C\delta T_{in} + \rho_{ext} \tag{1}$$

where

$$P = p/p_0 \qquad W = w_p/w_0$$
$$\delta T_{in} = T_{CORE,in} - T_{CORE,in,0} \tag{2}$$

$$A = \alpha_d \Delta T_{f,0} \tag{3}$$

$$B = \left(\frac{\alpha_r}{2} + \alpha_{cr} + \frac{\alpha_{Na}}{2} + \frac{\alpha_d}{2} + \frac{\alpha_e}{2} + \alpha_b\right)\Delta T_{c,0} \tag{4}$$

$$C = \alpha_r + \alpha_{cr} + \alpha_v + \alpha_{Na} + \alpha_d + \alpha_e \tag{5}$$

and where p is power, w_p is primary flow rate, $T_{CORE,in}$ is the reactor inlet temperature, and a reference state is identified by the subscript *0*. The subscript *ext* denotes external reactivity; α is a temperature reactivity feedback coefficient with *d*, *r*, *cr*, *v*, *Na*, *e*, and *b* denoting Doppler feedback, core radial expansion, control rod expansion, vessel expansion, coolant density, fuel axial expansion, and bowing, respectively. ΔT is the temperature rise, and subscripts *f* and *c* denote fuel and coolant respectively.

As for the intermediate loop and the BoP, the IHX as well as the SG was axially discretized in nodes (respectively, 10 and 30). For each node, six equations were used: a distributed-parameter mass, momentum and energy balance equation for both the hot fluid as well as for the secondary cold fluid. Three equations were also implemented for each pump (continuity, momentum and energy), plus an additional equation for the pump shaft and motor. In Table I, neutronics parameters and thermal features of interest are reported. In Table II significant quantities describing the steady-state values for the reference design at full operating power can be found.

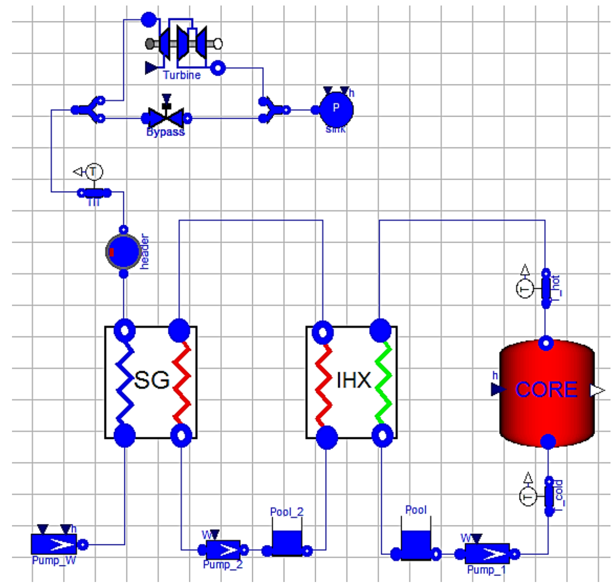

Fig. 1. Graphical interface of the object-oriented model of the overall plant.

TABLE I
Reactor core main data[5, 7].

Definition	Value
A, net reactivity decrement [$]	-0.15
B, power/flow coefficient of reactivity [$]	-0.45
C, inlet temperature coefficient of reactivity [$/K]	-0.0032
Fraction of delayed neutron [pcm]	330
Mean time generation [μs]	0.6
Decay constant of one group precursor [s^{-1}]	0.1
Thermal conductivity [W/mK]	20
Specific heat capacity [J/kgK]	180
Density [kg/m^3]	11625

TABLE II
Primary and intermediate circuit steady state conditions[6].

State variable	Value
Reactor Nominal Power [MW]	900.0
Primary Loop Flowrate [kg/s]	4623
Intermediate Loop Flowrate [kg/s]	4586
Average Fuel Temperature [°C]	669.3
Average Clad Temperature [°C]	456.9
Core outlet temperature [°C]	507.5
Core inlet temperature [°C]	353.8
IHX Intermediate Coolant Tout [°C]	479.2
IHX Intermediate Coolant Tin [°C]	324.4
Primary Tank Coolant Mass [kg]	379000
Intermediate Tank Coolant Mass [kg]	379000

III. SODIUM-COOLED FAST REACTORS CONTROL SYSTEM DESIGN

III.A. Objective

As for the operation of this reactor concept, the temperature range plays a fundamental role. One of the most important process variables is the sodium temperature at the core outlet ($T_{CORE,out}$), which represents the highest fluid temperature in the system, and is directly related to the maximum achievable thermal efficiency, which ultimately affects the cost of electricity. Materials and thermodynamic considerations (such as the boiling point of the coolant or the behavior of structural materials at high temperatures) set an upper limit for such a temperature under operational and accidental conditions[8]. During load power range operational transients, it would be beneficial to keep the core outlet temperature as close as possible to the nominal value to avoid thermal fatigue all across the primary system components.

III.B. Classical approach

Commercial SFRs must meet grid electric demands which impose their own response requirements on the plant. In addition, to limit thermal stresses of structural materials, system temperature variations shall be limited both in magnitude and rate of change. A control strategy based on a classical approach would typically rely on control rods ($\Delta\rho_{ext}$) to adjust the power (P), and on the primary circuit flow rate (W_1) to maintain the core outlet temperature ($T_{CORE,out}$) close to the nominal value to maintain flow temperatures as steady as possible over the expected load schedule range. As for the intermediate circuit flow rate (W_2), it could be used to regulate the steam temperature at the SG outlet (T_{steam}).

TABLE III
Selected pairings for a classical approach control strategy.

$\boldsymbol{u}$	$\boldsymbol{y}$
$\Delta\rho_{ext}$	P
W_1	$T_{CORE,out}$
W_2	T_{steam}

III.C. Extended operability approach

This classical approach can be shown not to be optimized with respect to an expected extended operability range[7]. In this case and for the considered reference reactor design, in fact, a dedicated controller for the reactor power control is not strictly needed. A metal-fueled, sodium-cooled fast reactor can be indeed designed to control power over an extended operability range without an extensive use of control rods. Instead, the coolant inlet temperature and the primary coolant flow rate can be engineered as communication channels so that the reactor adjusts inherently in open loop its power level to match the heat sink removal rate[9]. In addition, the use of control rod channel to control reactor power in closed loop might be inadvisable because it routinely subverts what in the open loop would be passive self-regulation of power to match the presented heat-sink[7].

Consequently, as for the selected pairings between input and output variables, control rods ($\Delta\rho_{ext}$) are available to maintain the core outlet temperature ($T_{CORE,out}$) close to the nominal value, while the power to flow ratio is adjusted to keep the flow temperature change across the core constant ($P/W_1 \rightarrow 1^*$). Thanks to this algebraic control loop, it is possible to globally control the temperature field in the primary circuit. The feasibility of this control strategy for metal-fueled SFR is based on the favorable values assumed by the properties of fuel and coolant combination, and in particular the large thermal conductivity which limits the operational temperature of the fuel allowing for taking advantage of elements of inherent control[9]. Finally, the intermediate circuit flow rate (W_2) is adjusted to regulate the sodium temperature at the core inlet ($T_{CORE,in}$).

TABLE IV
Pairings selected for an extended operability control strategy.

$\boldsymbol{u}$	$\boldsymbol{y}$
$\Delta\rho_{ext}$	$T_{CORE,out}$
W_1	$P/W_1 \rightarrow 1$
W_2	$T_{CORE,in}$

The effectiveness of the proposed pairings between input and output variables was also assessed through a quantitative technique such as the Relative Gain Array (RGA) method[10,11]. RGA is a heuristic technique which allows evaluating the relative influence of input variables on the process variables of interest. As reported in TABLE V, the pairing $\Delta\rho_{ext}$ -$T_{CORE,out}$ is characterized by a high-level interaction and by a limited disturbance provided by the other channels. In addition, because of the tight coupling level assessed by the RGA outcomes, the intermediate circuit flow rate is a good candidate for the control of the sodium temperature at the core inlet, and therefore the proposed pairing constitutes a good choice for implementing a feedback control loop

[*] The dedicated active controller adjusts the value of the primary circuit mass flow rate (W_1) to keep the power/flow ratio close to unity.

TABLE V
RGA approach outcomes.

OUTPUTS	INPUTS		
	$\Delta\rho_{ext}$	W_1	W_2
P	0.1498	0.1994	0.1912
$T_{CORE,out}$	**0.8131**	0.1269	0.0600
$T_{CORE,in}$	0.0292	**0.6632**	**0.3076**

III.D. Supervisory Control Scheme

In the perspective of interfacing SFRs to the grid to meet the load demand, it is of interest, and has been largely considered in previous works, the implementation of a multi-level control system architecture characterized by the presence of a *supervisory control system* (Fig. 1).

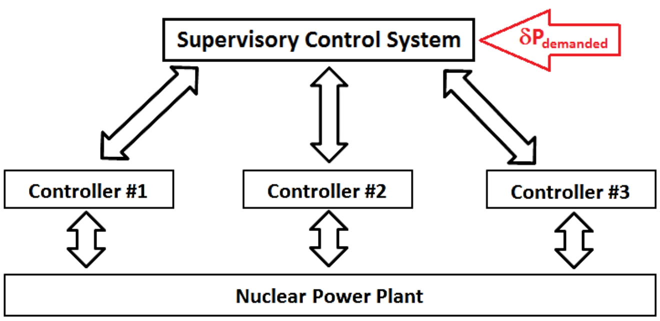

Fig. 1. Preliminary configuration of the control system architecture.

This implementation can be accomplished by subdividing the functionalities of the control system into simpler functions, obtaining in this way a hierarchy of features to be implemented by means of dedicated components. 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. All the activities of subordinate levels are prescribed by the immediate supervisory level. 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 controllers are used primarily for synchronizing the operation of the local controllers and for supplying them with the corresponding set-points, according to the grid demanded power level. To this aim, the classical approach is based on the adoption of a set of *lookup tables* as function of the combination of reactor power and power plant state. According to this approach, the set-points are evaluated through a mono-directional data flow, i.e., there without a feedback-determined continuous adjusting of the set-points according to the instantaneous value of the process variables. 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 derived from the operational experience and licensing.

IV. IMPACT OF CONTROL SYSTEM'S SINGLE FAILURE ON PASSIVE SAFETY CHARACTERISTICS

IV.A. Assumptions

The traditional approach for evaluating the inherent safety features of a NPP is somewhat simplified. The plant is assumed to be at full power and one of three unprotected upsets occurs: loss of flow, loss of heat sink, and rod withdrawal. It is assumed that plant control system does not respond during these upsets. The resulting worst case conditions are referred to as the *standard passive safety envelope*. Conversely, one needs to consider such upsets in a wider context than just full power operation and the open loop response of the plant to the initiator. In particular, a necessary condition for a plant to be inherently safe is that neither the plant's active control system nor the operator can act to confound or override the operation of inherent feedback processes to safely regulate power and temperatures[9]. That is, control system equipment failures and operator errors should not be capable of interfering with the ability of inherent safety features to perform as intended. As for the considered transient scenario, the system is assumed not to have diagnostics capabilities, i.e., after the initiating event has occurred, the control loops continue performing their tasks. Indeed, the system cannot verify whether an operation or an incidental scenario is occurring, and the set-points corresponding to normal operating conditions remain unchanged.

IV.B. Preliminary results for the extended operability control strategy

In the perspective of evaluating the plant robustness towards control loop failures, a partial coast-down of the BoP feedwater pumps is considered. As qualitatively shown in Fig. 2, the feed-water flow rate drop (down to 40% of its nominal value in 60 seconds) causes a degradation of the BoP heat removal capability. In response to this, the corresponding feedback control loop response gets the intermediate flow rate to drop ($W_2\downarrow$) trying to keep the inlet core temperature constant. However, by losing the BoP feedwater pumps, the primary circuit cannot properly dispose the thermal power produced, and the core inlet temperature rises ($\delta T_{CORE,in} > 0$). Because of the negative reactivity feedbacks contribution, the thermal power output drops ($P\downarrow$), and the core outlet temperature decreases ($T_{CORE,out}\downarrow$). The response of the still operating control loops causes the primary circuit mass flow rate to decrease ($W_1\downarrow$), and the control rods to be extracted ($\Delta\rho_{ext} > 0$).

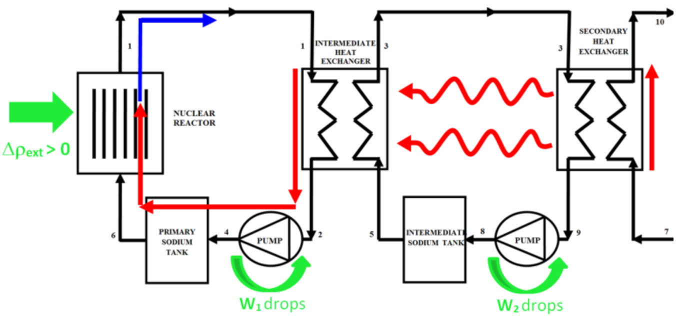

Fig. 2. Graphical representation of the dynamics involved in the studied scenario.

This scenario is simulated by adopting the object-oriented model of the overall plant presented in Sec. II. As for the adopted assumptions, after the initiating event has occurred (single actuator failure), the control actions performed by still operating feedback loops are simulated, without intervention of the Plant Protection System, i.e., the reactor scram is not performed (*unprotected transient in presence of active control*). In particular, the dedicated PI causes the control rods to be extracted until reaching the upper operating limit to maintain the core outlet temperature close to the nominal value.

As for the outcomes, weakly damped oscillations occur in the evolution of primary system process variables as shown in Fig. 3, Fig. 4 and Fig. 5. The system is not stable anymore, and reactor passive safety features are limited by the action of the still operating actuators. This behavior is traced to the use of the algebraic controller that maintains power-to-flow ratio equal to one. To assess that the stability loss is due to the implemented control loops, the simulations are repeated with a PI (Proportional-Integral) controller in place of the algebraic power-flow ratio controller. In the repeated simulations, these oscillations disappear, showing that such a concerning behavior is a consequence of the controller governing the primary circuit flow rate.

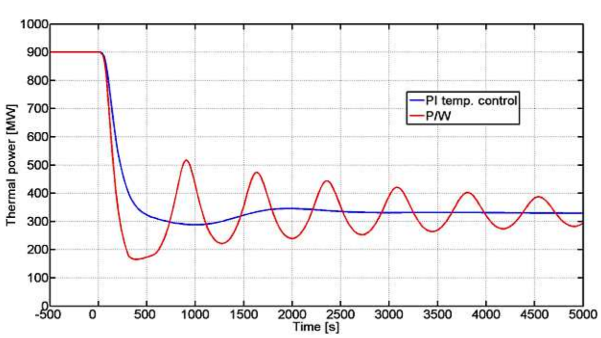

Fig. 3. Reactor power evolution.

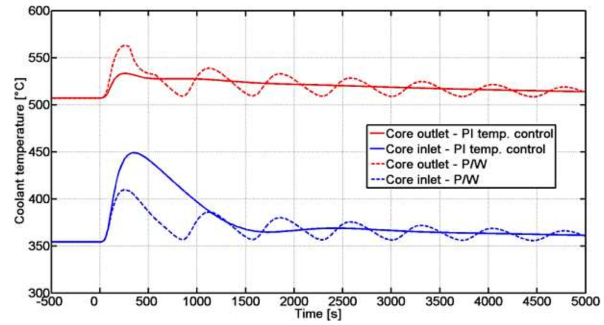

Fig. 4. Primary circuit coolant temperature.

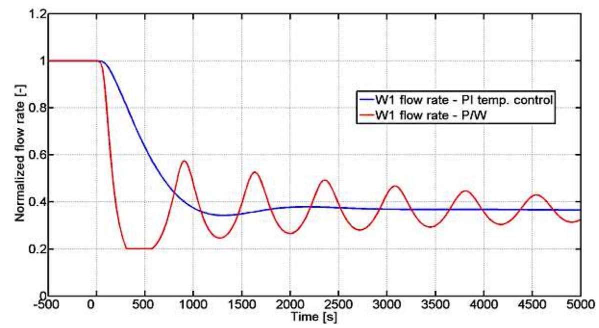

Fig. 5. Normalized primary circuit flowrate.

V. REFERENCE GOVERNOR SUPERVISORY CONTROL SCHEME

The system unfavorable dynamic transient initiated by the feedwater pumps coast-down is due to the pairings which characterize the extended operability control strategy. As for the set-points supplied to the feedback regulators, they are not adjusted in response to the dynamic evolution of the process variables. When the BoP heat disposal capability is reduced, the implemented PID regulators try to maintain the control variables close to the reference design values. Conversely, it would be useful if the selection of the set-points was also a function of the instantaneous operating conditions of the plant. By so doing, thanks to this additional feedback, the thermal power imbalances between the hydraulic loops would be limited, even without relying on diagnostics device. This can be better illustrated by adopting for the supervisory control system design the Reference Governor (RG) approach[12,13]. The corresponding control scheme is shown in Fig. 6.

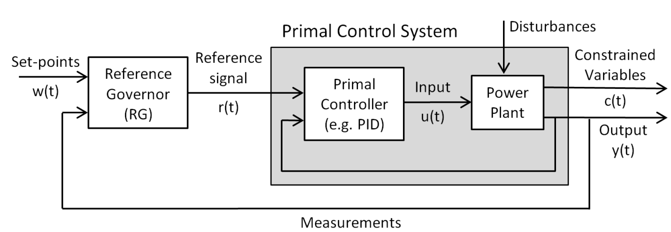

Fig. 6. RG-based feedback control scheme[13].

In the operation of a power plant, it is key to take into account the physical constraints affecting the components, in particular during transients. Generally, ad hoc solutions are adopted, i.e., dedicated saturation effects and/or ramp limiters filter the control actions to be performed by the actuators. Commonly adopted linear controllers (e.g., PID) manage to provide the system with asymptotic stability, dynamic performance, and robustness towards disturbances, but they cannot explicitly consider the presence of constraints. Unlike the common approaches which attempt to solve stabilization, tracking, and constraints fulfilment at the same time, the proposed procedure is based on a two-step approach. First, a primary compensated controller is designed to stabilize the system and provide satisfactory tracking capabilities in the absence of constraints. Then, the RG control scheme, which modifies the reference signals supplied to the primal control system, is added in order to enforce the constraint fulfilment[12].

With respect to Fig. 6, $c(t)$ is the vector of process variables whose evolution is subjected to constraints, $w(t)$ is the set-point trajectory to be tracked and $r(t)$ is the actual reference sequence applied to the feedback regulators. The procedure implemented by the RG aims at smoothing out transitions from the current value of the plant output to the desired set-point. Accordingly, the reference patters selected on-line by the RG ($r(t)$) at each time step is given as follows

$$r(t+i|t) = \lambda^{i+1}(t)y(t) + (1-\lambda^{i+1}(t))w(t) \tag{6}$$

where $\lambda(t) \in [0,1)$. Let $c(\cdot\,|t) = \{c(t+1|t)\}_{i=0}^{\infty}$ be the predicted evolution of the constrained vector corresponding to the use of the reference pattern $r(\cdot\,|t) = \{r(t+1|t)\}_{i=0}^{\infty}$. When a set-point variation occurs, the "time constant" $\lambda(t)$ is adjusted to keep $c(\cdot\,|t)$ admissible. The idea is to adopt at each t the time constant $\lambda(t)$ which gives the shortest settling time while keeping $c(\cdot\,|t)$ admissible[12].

In the perspective of adopting the RG approach for the NPP control system design, the reference signals 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 (Multiple Input Multiple Output) control scheme. The main concern of adopting a multivariable control strategy is the consequent additional complication of control system architecture. In particular, although the same algorithm allows the simultaneous operation of all the adopted actuators, the potential for common cause failure is introduced, i.e., a fault to the control algorithm might affect all the operating control loops. Conversely, 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 SISO (Single Input Single Output) controllers are preserved, i.e. there would be no additional common cause failure, while the operation of the system could be greatly improved.

When a variation of the electrical power output is needed, the NSSS (Nuclear Steam Supply System) is expected to adjust its operating conditions accordingly. The operation of the turbine admission valve determines a variation of the SG heat disposal capabilities, which causes a power imbalance between the BoP and the intermediate circuit. Such a thermal perturbation propagates towards the primary circuit by altering the value of the process variables. Since they are controlled through feedback PID regulators, when the corresponding constraints are violated, the RG approach-based supervisory control system supplies updated reference signals to the implemented PID controllers whenever necessary. In this way, the NPP is expected to promptly and safely align to the new power level conditions.

V.A. Set-points definition as a constrained optimization problem

The problem of adjusting the reference signals in accordance with the new demanded power level by minimizing a cost function can be formulated as a constrained optimization problem. Among the objectives of the optimization for the NPP regular operation, the most important is that the thermal power unbalances between the thermal circuits should be minimized as promptly as possible:

$$\min_{T_{CORE,in}{}^{ref},\ T_{CORE,out}{}^{ref}} \mathrm{J} = \|P_{th} - P_{neu}\|^2 + \|P_{IHX} - P_{th}\|^2 + \|P_{SG} - P_{IHX}\|^2 + \|P_{BoP} - P_{SG}\|^2 \tag{7}$$

$$\begin{aligned} P_{BoP}(t) - P_{SG}(t) &\equiv 0 \\ P_{SG}(t) - P_{IHX}(t) &\equiv 0 \\ P_{IHX}(t) - P_{th}(t) &\equiv 0 \\ P_{th}(t) - P_{neu}(t) &\equiv 0 \end{aligned} \tag{8}$$

where $P_{BoP}(\mathrm{t})$ is the thermal power processed by the BoP to meet the load demand, $P_{SG}(\mathrm{t})$ is the thermal power exchanged by the SG, $P_{IHX}(\mathrm{t})$ is the thermal power exchanged in the IHX, $P_{th}(\mathrm{t})$ is the thermal power extracted from the reactor core, $P_{neu}(\mathrm{t})$ is the thermal power generated during fission events, estimated through the point-kinetic model. The aforementioned thermal powers can be evaluated from the enthalpy rise across the reactor core, the IHX, the SG and the BoP.

$$P_{th}(t) = W_1(t) \cdot W_{1,nom} \cdot c_p(t) \cdot \left(T_{CORE,out}(t) - T_{CORE,in}(t)\right) \tag{9}$$

$$P_{IHX}(t) = W_2(t) \cdot W_{2,nom} \cdot c_p(t) \cdot \left(T_{IHX,out}(t) - T_{IHX,in}(t)\right) \quad (10)$$

$$P_{SG}(t) = W_{feed}(t) \cdot W_{feed,nom} \cdot \left(h_{SG,out}(t) - h_{SG,in}(t)\right) \quad (11)$$

$$P_{BoP}(t) = W_{steam}(t) \cdot W_{steam,nom} \cdot \Delta h_{turbine} \cdot \frac{\eta_{is}}{\eta_{cycle}} \quad (12)$$

where W_{feed} is the feedwater flow rate, W_{steam} is the normalized steam flow rate, $\Delta h_{turbine}$ is the enthalpy drop across the turbine, η_{is} is the turbine isentropic efficiency, and η_{cycle} is the energy conversion cycle efficiency.

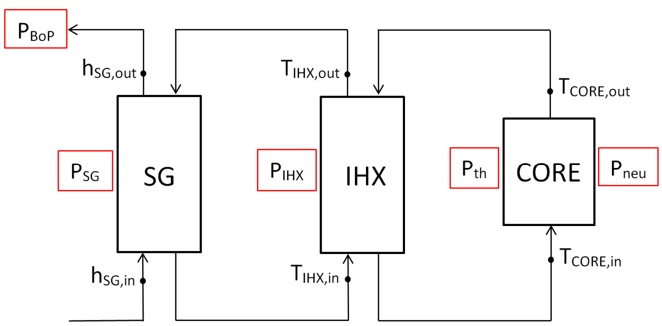

Fig. 7. Schematic view of the system thermal circuits. The process variables involved in the control algorithm are represented.

It is important to point out that the optimal definition of the controlled variable reference signals is not to be intended as a proper control problem. The goal is to evaluate the new values of the regulator reference signals according to the new operational conditions taking into account the system dynamic evolution. In this perspective, the minimization of the instantaneous thermal power unbalances between thermal circuits represents a convenient criterion.

The constrained optimization problem can be studied by adopting the optimal control techniques. In particular, the algorithms used for the Model-based Predictive Control (MPC)[14], which is an effective mean to deal with large multi-variable constrained control problems, were considered. The control algorithm seeks to optimize a quadratic cost function, which is a user-specified mathematical indicator of the desired performance of the feedback regulator.

$$J(k) = \sum_{i=1}^{N} \|\hat{y}(k+i|k) - r(k+i)\|^2 \cdot Q(i) + \sum_{i=1}^{M} \|\Delta\hat{u}(k+i)\|^2 \cdot R(i) \quad (13)$$

where $\hat{y}(k+i|k)$ is the estimated future value of the output variable, $r(k+i)$ is the reference signal, $\Delta\hat{u}$ is the control action to be taken, $Q(i)$ and $R(i)$ are the matrices weighting these contributions.

In the MPC approach, the control actions are oriented at minimizing a performance criterion over a prediction horizon, whose length is kept constant in time (*receding-horizon algorithm*). According to this scheme, a sequence of future control actions is chosen according to a prediction of the future evolution of the system and applied to the plant until new measurements are available. Then, a new sequence is evaluated and replaces the previous one [12]. The optimization problem might be subjected to constraints on the manipulated input and output variables, whose future behavior is estimated according to the model of the plant. In this way, the controller can predict whether or not the proposed control maneuver will cause future violations of system constraints, while still ensuring that the early control actions do lead to a long term control strategy that minimizes the cost function.

The outcomes of the optimization procedure are the reference signals which define the desired sodium temperature at the core inlet and at the core outlet. These operating conditions must remain within the safety envelope, which corresponds to the system safe operation. For example a suitable set for the problem under investigation could be:

$$\begin{cases} 480°C \le T_{CORE,out}{}^{ref} \le 520°C \\ 310°C \le T_{CORE,in}{}^{ref} \le 380°C \end{cases} \quad (14)$$

V.B. Implementation of the Reference Governor scheme to the Extended Operability approach

The developed algorithm is applied to the reference reactor operating in full power mode. In particular, the controlled variables are governed by means of the SISO feedback as in the extended operability control strategy. This strategy is of particular interested for the adoption of a supervisory control scheme since a dedicated control loop for the reactor power is not foreseen. In particular, the operation of the primary circuit of the reference reactor is considered. In Fig. 8, the closed-loop system is represented. In particular, $R_1(s)$ and $R_2(s)$ represent PI regulators (the former controls the sodium temperature at the core outlet ($T_{CORE,out}$) by adjusting the control rods reactivity contribution ($\Delta\rho_{ext}$), the latter governs the sodium temperature evolution at the core inlet ($T_{CORE,in}$) by adjusting the intermediate circuit flow rate (W_2)), $G_1(s)$ and $G_2(s)$ represent the corresponding transfer functions which describe the dynamics of the processes to be controlled, $R_3(s)$ is the controller that defines the primary circuit flow rate as function of the reactor power ($P/W_1 \rightarrow 1$). Finally, the block "PK model" contains the point kinetics model, and $K_1(s)$ evaluates the value of the thermal power produced in the core from the measurement of the monitored temperatures.

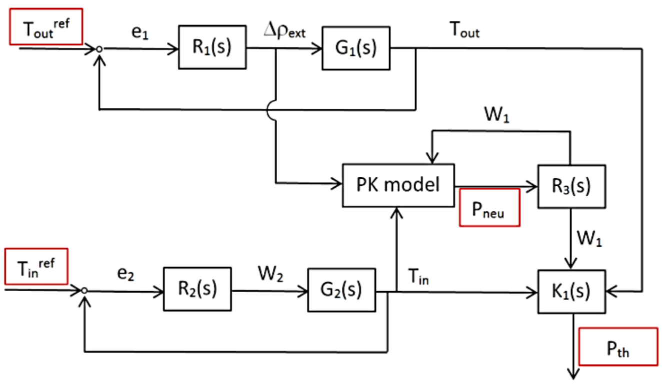

Fig. 8. Schematic representation of the transfer functions influencing the system closed-loop dynamics.

The unknowns of the optimization problem are the reference signals (r) to be supplied to the feedback regulators. The values of the input variables (u) is derived from the error between the instantaneous values of the output variables and the corresponding desired values (e) through the PI transfer functions.

$$u(t) = K_P e(t) + K_I \int_0^t e(t)dt \tag{15}$$

where K_P is the gain of the proportional controller, and K_I is the integrator gain.

As for the output variables (y), the adopted criterion is based on the minimization of the thermal power unbalances between the different circuits. According to the demanded power variation, the thermal power exchanged by the SG (P_{SG}) will change. Such an imposed thermal power variation will need to be met by the intermediate and primary circuits. In this perspective, the value of ${T_{CORE,in}}^{ref}$ and ${T_{CORE,out}}^{ref}$ will be dynamically adjusted so as to balance the thermal power production with the thermal power disposal. As for the implementation of the adopted criterion, P_{neu}, P_{th} and P_{IHX} are expressed as function of ${T_{CORE,in}}^{ref}$ and ${T_{CORE,out}}^{ref}$. With respect to Fig. 8,

$$\begin{aligned} P_{neu} &= P_{neu}(\Delta\rho_{ext}, W_1, \delta T_{CORE,in}) \\ &= P_{neu}(R_1, R_3, {T_{CORE,in}}^{ref}, {T_{CORE,out}}^{ref}) \end{aligned} \tag{16}$$

$$\begin{aligned} P_{th} &= P_{th}(W_1, T_{CORE,out}, T_{CORE,in}) \\ &= P_{th}(R_1, R_2, R_3, {T_{CORE,in}}^{ref}, {T_{CORE,out}}^{ref}, G_1, G_2) \end{aligned} \tag{17}$$

$$\begin{aligned} P_{IHX} &= P_{IHX}(W_2) \\ &= P_{IHX}({T_{CORE,in}}^{ref}, R_2, G_2) \end{aligned} \tag{18}$$

In this way, the thermal power balance expressed in Eq. 7 can be optimized and solved with respect to the unknowns ${T_{CORE,in}}^{ref}$ and ${T_{CORE,out}}^{ref}$. As for the primary and the intermediate circuit, the input and output variable vectors are, respectively,

$$u = \begin{Bmatrix} \Delta\rho_{ext} \\ W_1 \\ W_2 \end{Bmatrix} \tag{19}$$

$$y = \begin{Bmatrix} T_{CORE,in} \\ T_{CORE,out} \end{Bmatrix} \tag{20}$$

$$r = \begin{Bmatrix} {T_{CORE,in}}^{ref} \\ {T_{CORE,out}}^{ref} \end{Bmatrix} \tag{21}$$

The detailed implementation of this approach is currently in progress and first preliminary results will be presented when available to prove the conceptual and analytical structure of the problem here presented. Even without fresh results, a few additional considerations can be made to better illustrate the context in which this methodology and approach are being developed. Considering the design of a supervisory control system, the RG approach and the classical lookup tables approach represent two implementations sitting at the two extremes of a wide range of possibilities. They are meant to be representative of the whole spectrum and as such they can be useful in illustrating pros and cons of the two conceptual approaches. Performance-wise it is clear that a higher degree of signal integration and data processing can provide a higher ceiling in adapting the control strategy to the specific plant conditions and therefore in extending the operational capabilities way beyond the current state-of-the-art. On the other hand, this comes at the price of new sets of potential failures, wrong diagnosis and erroneous evaluations that, being buried deep in a digital representation of the plant, are not easily addressed in the current regulatory environment. Lookup table approach, on the contrary, is a well-known, robust and solid methodology which however operates blindfolded with respect to the specific plant conditions and as such cannot extend the operability much further and is always heavily relying on the plant protection system in managing consequences of unforeseen events. While the former may represent a natural evolution of the technology, the latter is the likely currently achievable compromise considering regulatory needs and the natural reluctance of industry in adopting radical technological changes. Notwithstanding, in order to meet the needs of the actual power grids, the deployment of more efficient approaches for the synchronization of the performed control actions may very well turn out to become necessary.

VI. CONCLUSIONS

In this work, an alternative approach for the operation of a metal-fueled SFR is proposed. Because of the rising penetration of RES-based power plants in the actual power grids, NPPs should be able to adjust the power output according to the load demands and the grid needs. In this perspective, a control strategy which allows operating the system at different power levels while preserving the primary circuit temperature field was conceived. The simulation outcomes show the onset of concerning oscillation for transient scenario initiated by control loop failures. These results assess that the proposed control strategy, along with the classical lookup tables approach for the set-points definition, may limit the system inherent safety features. To overcome this issue, the RG-based approach for the supervisory control system design is proposed. By adopting the criterion of minimizing the thermal power unbalances between the thermal circuits, the reference signals supplied to the controllers are evaluated via a feedback optimization algorithm. The implementation of the conceived control system architecture and the assessment of the performance ensured by this innovative approach are currently under investigation.

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