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A model predictive control approach for the Italian LBE–XADS

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Abstract

In this paper, model predictive control (MPC) is applied to the Italian 80 $\mathrm{MW_{th}}$ experimental accelerator driven system (XADS), referring to a simple, non-linear model for the dynamic simulation of the plant, which has been developed and described in a previous work [A. Cammi, L. Luzzi, A.A. Porta, M.E. Ricotti, Prog. Nucl. Energ. 48 (2006) 578], in order to describe the interactions among the different subsystems: i.e., the accelerator-core coupling, the lead bismuth eutectic (LBE) primary system, the secondary system with diathermic oil and air coolers batteries, which reject the thermal power to the environment. Hereinafter, a model predictive controller is proposed, with the objective to minimize the difference between the average temperature of the diathermic oil and its reference value, while also minimizing the variations of the control input, which is the air coolers mass flow rate. The dynamic response of the LBE–XADS has been evaluated with reference to a reduction of 20% in the reactor power from nominal load conditions: this transient is very demanding for the overall plant, nevertheless the obtained results indicate the effectiveness of the proposed controller.

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1. Introduction

Nuclear power plants (NPP) are highly complex, nonlinear, time-varying, and constrained systems, whose control represents one of the most relevant issues to be solved during the design process. The control strategy usually adopted in the current NPPs is based on classical combined feedforward and feedback schemes (typically with a Proportional-Integral configuration).

Among the most promising control techniques [2], model predictive control (MPC) methodology [3–5] is an effective mean to deal with large multi-variable constrained control problems: MPC has so far received attention as a powerful tool for the control of industrial process systems [6], and it has been recently applied for the first time to a NPP with very good results [7].

In this paper, a model predictive controller is proposed for the Italian LBE–XADS [8], and the corresponding control scheme is briefly discussed.

2. Plant description and modelling

A complete description of the Italian LBE-cooled XADS is reported by Ansaldo [9]. Here, the main design data are summarized in Table 1 and the reactor layout is shown in Fig. 1. The configuration of the primary system is pool-type, similar to that adopted in sodium-cooled reactors: the core and all the primary LBE coolant are housed within the reactor vessel, which is surrounded by a safety vessel in order to ensure the containment of LBE and core cooling also in case of a reactor vessel leakage. The primary coolant, leaving the core at 400 °C, enters the riser channels at the periphery of inner vessel. Natural circulation of LBE is enhanced by argon gas injection, fed by a compressor, into the bottom part of the riser.

The secondary coolant system is made up of two independent loops: each loop consists of two intermediate heat exchangers (IHX) immersed into the primary coolant flowing down through the downcomer and entering the core at 300 °C. The secondary coolant is a low vapour pressure, organic diathermic fluid (referred from now on as 'diathermic oil') with cold leg and hot leg temperatures of 280 °C

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Table 1
Main design data of the Italian LBE–XADS

Core power MW_{th}	80
Primary coolant –	Lead bismuth eutectic
Core inlet temperature °C	300
Core outlet temperature °C	400
Coolant flow rate in the core kg/s	5471
Coolant velocity in the core m/s	~0.4
Secondary coolant –	Organic diathermic fluid
IHX secondary coolant inlet temperature °C	280
IHX secondary coolant outlet temperature °C	320
IHX secondary coolant flow rate kg/s	796.8
Effective core sub-criticality (BOL) –	0.97
Effective core sub-criticality (EOL) –	0.94
Fuel –	UO_2–PuO_2 mixed oxides
Target material –	Lead bismuth eutectic
Proton energy MeV	600
Maximum beam current mA	6

and 320 °C, respectively, at full power conditions. Diathermic oil cooling is provided by a battery of three air coolers connected in series in each loop, each loop being capable of removing the decay heat in natural circulation with only one air cooler in operation.

A dedicated, dynamic simulation model of the plant was discussed in Ref. [1]: it allows a simple, lumped and zero-dimensional description of the neutronic and thermo-hydraulic behaviours of the system (i.e., all variables are considered only as functions of time). The present work adopts this (non-linear) model and entirely refers to [1] for its description.

3. Control scheme and results

The XADS brings the secondary fluid up to 320 °C at the primary heat exchanger outlet, which is the same temperature at the inlet of the first air cooler in each battery. The outlet temperature of each air coolers battery is 280 °C, thus leading to an average temperature of 300 °C for the diathermic oil. This temperature range represents the optimum working condition of the secondary coolant: as a matter of fact, a temperature beyond 340 °C would cause the degradation of its physical–chemical properties, while a temperature below 260 °C could result in thermal shocks for the primary fluid and, eventually, for the structural components. Therefore, the aim of a correct control strategy is to keep the average temperature of the diathermic oil as close as possible to 300 °C, in response to reactor power variations (related to the external proton beam accelerator); it is also important to take into account the different time constants of the primary and secondary loops, which are the consequence of the different thermal inertia of the two fluids, because they affect the dynamic behaviour of the overall plant.

Choosing the average temperature of the diathermic oil as the controlled variable, and the air mass flow rate as the control variable, different approaches can be adopted for the system control. With a classical approach [10], a combined feedforward–feedback scheme can be applied, as described in Ref. [1], where the feedback controller is a Proportional-Integral (PI) based configuration, while the

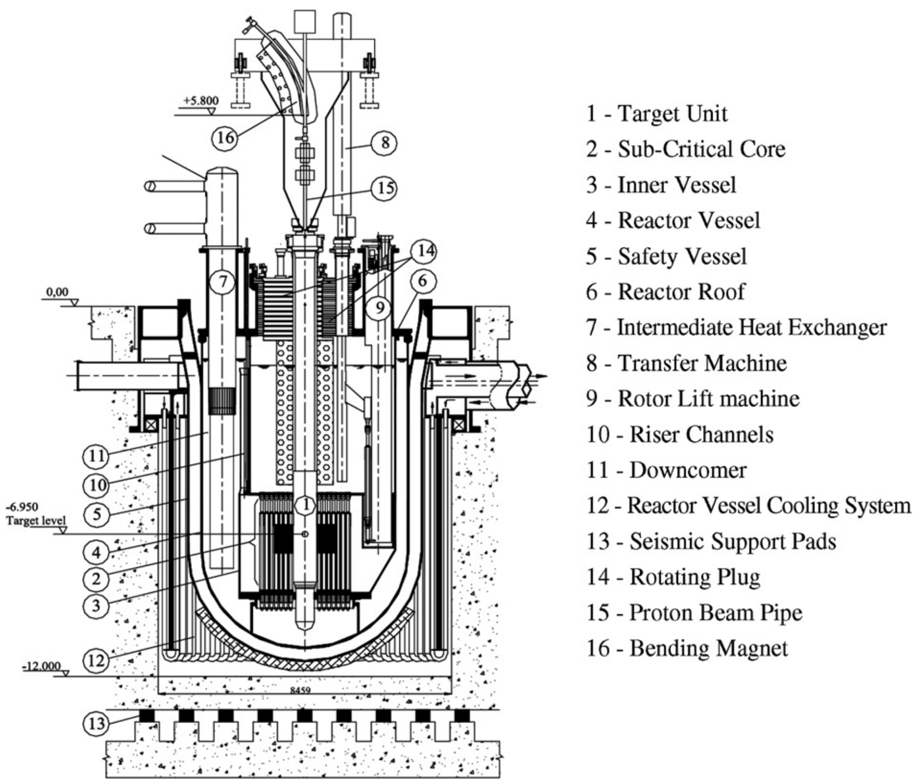

Fig. 1. LBE–XADS reactor layout [8].

feedforward action compensates for the main disturbance, and consists of a monotonically increasing function relating the required air mass flow rate to the reactor power. With a model predictive control approach, the main idea is to choose the control action by repeatedly solving on line an optimal control problem: this aims at minimizing a performance criterion over a future prediction horizon, possibly subject to constraints on the manipulated inputs and outputs, where the future behaviour is computed according to the model of the plant. The length of the prediction horizon is kept constant in time (receding horizon algorithm) [3].

The control algorithm of the model predictive controller proposed in this work can be summarized as follows:

(a) Past measured outputs of the controlled variable (i.e., the diathermic oil average temperature) and past control inputs are collected until the present time step k; future outputs along the prediction horizon N can then be estimated using a linearized dynamic model of the plant, initialized with past input and output data.

(b) A control sequence $\Delta\hat{u}(k+i), \quad i = 1, \ldots, M$ for the next M time steps is obtained by minimizing a cost function $V(k)$, which takes into account two terms: the first one is the squared tracking error (i.e., the squared difference between the reference output and the estimated output), while the second one is represented by the square of the change of control action between two adjacent time steps (Δu); both terms are multiplied by different weights. The cost function V can be expressed in the following way:

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

where i is the generic time step, k is the current time step, $Q(i)$ is the weight of the tracking error, $R(i)$ is the weight of the control input variations, and r is the set point (desired diathermic oil average temperature); $\hat{y}(k+i|k)$ is the ith step prediction of the system output (diathermic oil average temperature), based on measured data up to step k, and on future control variables computed along the prediction horizon, obtained with the linearized model.

(c) At next time step, only the first value of the control sequence is taken into account and applied to the plant, and the other terms of the sequence are discarded. The past measured outputs and control inputs are updated, then the whole procedure is repeated, for the following time step, from (a) to (c).

The model predictive control strategy blends a feedback action, which stems from the use of past measurements to set up the predictive model state at each time step, and a model-based feedforward action, which is implicit in the use of the system model in the tracking error formulation. In this paper, the feedforward action only depends on the set point, which is not that important, since the set point is kept constant; it is however straightforward to include the effect of the measured disturbance in the output prediction term $\hat{y}(k+i|k)$, thus effectively implementing feedforward disturbance compensation. Increasing the weight R will increase the penalty on the control variations, and thus lead to a smoother control action; conversely, increasing the weight Q will lead to a tighter tracking of the set point. The control scheme is summarized in Fig. 2.

In order to test the performance of the proposed controller, a demanding transient for the plant has been selected: it consists in the 20% reduction of the reactor power from nominal load conditions (80 $\mathrm{MW_{th}}$), as shown in Fig. 3, and it is due to a stepwise reduction of the proton beam current in the accelerator. The simulation has been performed adopting the non-linear model for the XADS plant [1], and using the MATLAB MPC control toolbox [11] to implement the controller. The following parameters have been selected:

- Time step equal to 1 s.
- Prediction horizon, $N = 60$ s.
- Control horizon, $M = 30$ s.
- Weight of the tracking error, $Q(i) = 0.8$.
- Weight of the control input variations, $R(i) = 0.2$.
- Simulation time of 5000 s.
- Starting time of the reactor power change equal to 200 s.
- Desired diathermic oil average temperature, $r = 300$ °C.

The time step and the length of the prediction and control horizons have been selected in order to obtain satisfactory performance without too much computational effort. The weights have been selected to strike a balance between control accuracy and control effort.

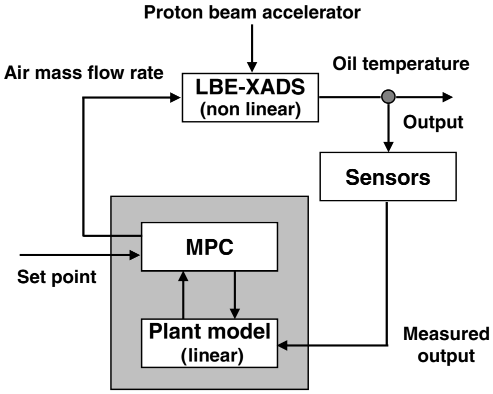

Fig. 2. Scheme of the XADS control.

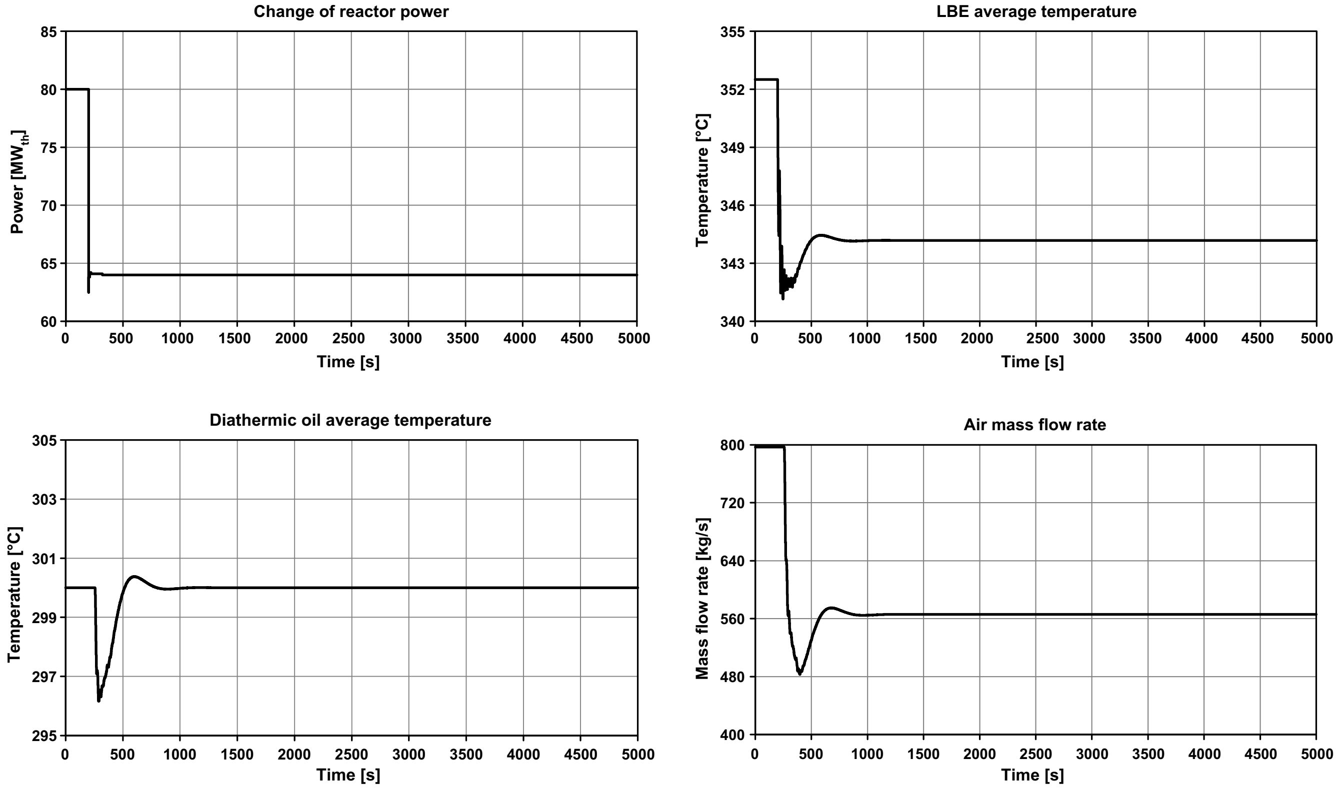

Fig. 3. Selected transient and corresponding response of the system.

In Fig. 3 the system response to the selected transient is shown in terms of the most relevant variables: in particular, it can be noticed that the maximum deviation of the diathermic oil average temperature (controlled variable) from the set point *r* is about 3.5 °C, and after 1200 s the diathermic oil reaches the desired value of temperature (300 °C). Moreover, the evolution of the air mass flow rate (control variable) indicates the effective action of the controller, due to the limited variation of the mass flow rate with respect to its asymptotic value (the maximum deviation is about 15%).

4. Conclusions

In this paper, the model predictive control approach has been briefly presented: its basic concept is to solve an optimization problem over a finite future horizon at each time step, and to implement the first control input as the current control input; the procedure is then repeated at each subsequent instant. The adoption of this control scheme has been proposed for the Italian LBE–XADS, with the aim (i) to keep the average temperature of the diathermic oil as close as possible to 300 °C, and (ii) to minimize the variation of the air coolers mass flow rate. The system response to a reduction of 20% in the reactor power has been simulated: in spite of this demanding transient for the overall plant, which exhibits strong interactions among the different subsystems, the obtained results indicate the effectiveness of the proposed controller in order to satisfy the above (two) requirements.

It is worth noting that the adoption of the MPC strategy could become even more useful if several constraints on the physical variables of the various plant components/subsystems have to be fulfilled during the transients. For instance, these variables could be the temperature and/or the velocity of the LBE coolant in the core, in addition to the average temperature of the diathermic oil and the air mass flow rate. In such cases, the MPC scheme would allow to handle these constraints in a systematic and straightforward manner, together with feedforward disturbance compensation, by just incorporating the corresponding terms within the optimization problem; classical control strategies would instead require to devise complex ad hoc schemes, with less-than-optimal performance.

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