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A preliminary approach to the ALFRED reactor control strategy

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ABSTRACT

In this paper, a preliminary approach to the definition of a suitable control strategy for the Advanced Lead Fast Reactor European Demonstrator (ALFRED), developed within the European 7th Framework Program, has been undertaken. The Generation IV reactors offer new challenges for what concerns the nuclear power plant control since several constraints both on primary and secondary loops have to be faced, differently from the conventional Light Water Reactors. A simulator of the ALFRED plant has been developed in a previous work (Ponciroli et al., 2014) with the main purpose of studying the system free dynamics and stability features in a control-oriented perspective. Based on the outcomes of these investigations, in the present work, the possibility of adopting decentralized control schemes has been investigated. Accordingly, *Single Input Single Output* control laws have been applied directly to the selected couples of input–output variables, which have been identified first on the basis of the preliminary plant dynamics analyses, and then confirmed by the indications of the *Relative Gain Array* method. Afterwards, two different control schemes have been studied depending on the number of available inputs, and then implemented and compared in order to evaluate the effect of each control action on the associated potential control strategy effectiveness. As a last step, the ALFRED control system has been finalized. The regulator design has been set up based on a simultaneous feedforward-feedback scheme incorporating four closed feedback loops. A controlled power reduction and a controlled overpower transient have been simulated in order to assess the performance of the two proposed control schemes. Results show that both the adopted control strategies can assure an efficient control of the thermal power while guaranteeing an effective control of lead and steam temperatures as well. In addition, some non-negligible differences between the two schemes have been observed and discussed in the simulation results of control and controlled variables.

1. Introduction

The main purpose of the control system in Nuclear Power Plants (NPPs) is adjusting the reactor power in accordance with the system demands in a consistent and constrained way. The control system development represents a crucial issue in the design process since the nuclear reactor is a part of an integrated plant including ultimately the load in the form of electrical grid. “Consistent and constrained way” means that the control system has to ensure the optimum working conditions for the system, avoiding the need for the protection system to shutdown the plant during operational transients (Lewins, 1978; Bernard, 1999).

A particular attention to these aspects should be paid whether an innovative NPP is considered because of the safety concerns which may be different from the ones of water-cooled reactors. In particular, for the Lead-cooled Fast Reactor (LFR), selected by the Generation IV International Forum as one of the candidates for the next generation of nuclear power plants (GIF, 2002), the need of developing an effective control strategy has been recognized. Actually, the control scheme requirements due to the technological issues brought by the use of lead as coolant (Tucek et al., 2006) have not been investigated yet. In this perspective, the main focus of this paper consists in developing a preliminary attempt to the control strategy definition of LFRs, adopting as a reference plant the Advanced Lead Fast Reactor European Demonstrator (ALFRED) (Alemberti et al., 2013), developed within the European FP7 LEADER Project (http://www.leader-fp7.eu, 2012).

The design of a NPP control system is a multi-step process whose final result is the development of dedicated controllers. First of all, it is necessary to prove the intrinsic system stability and to assess the control system robustness at different operational conditions. In particular, it is important that no problems arise in certain crucial transients, e.g., during the start-up sequence or following any change of load in full power conditions. Secondly, the

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reactor dynamics should be deeply investigated since these aspects are fundamental for the study of the overall plant performance. Moreover, this analysis allows investigating the interactions among input and output variables providing fundamental insights on stability and useful guidelines for the conception of an appropriate control system.

In order to perform such analyses, two flexible, straightforward, and fast-running simulators have been sought expressly meant for this early phase of the ALFRED design, during which all the system specifications are still considered as open design parameters and thus may be subject to frequent modifications. Such tools have been conceived for: (i) evaluating the robustness and stability of the dynamic system itself on its entire power range thanks to the possibility of linearizing the constitutive equations around different working conditions; (ii) predicting the reactor response to typical transient initiators and thus obtaining more detailed information about its dynamic behaviour; and (iii) helping the control system implementation for both its realization and its validation.

As far as the first item (i) is concerned, an analytical zero-dimensional model allowing for all the main reactivity feedbacks has been developed (Bortot et al., 2013). The resulting nonlinear model has been linearized and then implemented in MATLAB® (MATLAB® and SIMULINK® software, 2005) so as to verify the reactor stability through the calculation of the system eigenvalues. As a major result of this study, considering both a stand-alone core and a primary loop configuration, the system has been tested to be inherently stable on the entire power range. Moreover, the governing dynamics of the system has been identified, underlining the fundamental impact of the coolant density reactivity coefficient on the system stability and control strategy.

Concerning items (ii) and (iii), a one-dimensional, nonlinear *object-oriented* simulator has been developed (Ponciroli et al., 2014) by employing the reliable, tested, and well-documented Modelica language (Fritzson, 2004). Such tool has been specifically addressed to transient analyses as its detailed geometry description allows getting more accurate simulation results. As far as the core is concerned, point reactor kinetics and heat transfer models have been implemented coherently with the ALFRED specifications by incorporating geometry, material properties and correlations, reactivity feedback coefficients, and kinetic parameters (Grasso et al., 2013). An effort has been spent to build a specific model for the Steam Generators (SGs) due to their non-conventional bayonet-tube design, in order to reproduce their characteristic configuration (Alemberti et al., 2013), whereas specific models have been selected to describe the fluid flows (i.e., two-phases for water and single phase for lead). Several design-basis transient scenarios have been simulated to characterize the system dynamic behaviour and to evaluate the most effective inputs and their influence on the output variables to be properly controlled.

As far as LFRs are concerned, the control approach adopted in acknowledged reactor concepts, such as Light Water Reactors (LWRs) and Sodium-cooled Fast Reactors (SFRs), cannot be immediately applied due to the different features related to the use of lead as coolant and resulting in several constraints on control and controlled variables. The most challenging issue regards the lead temperature in the cold pool, which has to be kept in a narrow range, in addition to the lower limit fixed by the coolant solidification (327 °C). In particular, the vessel temperature should not exceed 420 °C (thermal creep threshold), whereas the minimum temperature is fixed at 380 °C due to the embrittlement of the structural materials in aggressive environment enhanced by the fast neutron irradiation. Consequently, the currently adopted approach cannot be immediately applied, but it is necessary to define a proper control strategy based on the system dynamics and taking into account the technological constraints of the plant.

In this perspective, a first approach to the control strategy of an innovative LFR concept has been developed. Given that for the considered system neither prior experience nor operational data are available, it has been considered necessary to adopt a quantitative well proven investigation tool. Therefore, the indications provided by the simulation of the system governing dynamics have been supported by a dedicated quantitative technique such as the *Relative Gain Array* (RGA) method (Bristol, 1966). This tool allows developing the most efficient control strategy starting from the constitutive equations that describe the physical system taken into account. In particular, this method has been widely used in several industrial fields including chemical processes and power production (Papadourakis et al., 1987), and recently adopted in nuclear applications as well (Guerrieri et al., 2014).

This work constitutes a preliminary stage of the control system design, adopting an existing and reliable technique (such as the RGA) for the pairing selection of a Generation IV LFR, whose control strategy has never been deeply studied (no dedicated papers have been found in the literature). In this way, through the RGA approach, it has been possible to evaluate the impact and the effectiveness of two different control strategies, based on different control variables, and to compare the performance of the proposed control solutions.

The paper is organized as follows. In Section 2, a brief introduction to the ALFRED reactor is provided. In Section 3, the main features of the object-oriented model of the overall plant, which has been employed both to develop and to assess the proposed control strategies, are summarised. In Section 4, the RGA technique has been adopted to select the most effective pairings between the control and the controlled variables. In Sections 5 and 6, the regulators implemented in the adopted control schemes are described and the importance of the lead mass flow rate in the primary circuit as a system input is investigated. Finally, in Section 7, two controlled operational transients have been simulated and the outcomes are discussed.

2. Reference reactor description

ALFRED is a small-size (300 MW_{th}) pool-type LFR and its primary system current configuration is depicted in Fig. 1. All the primary components (e.g., core, primary pumps and SGs) are contained in the main reactor vessel, being located in a large pool within the reactor tank. The coolant flow coming from the cold pool enters the core and, once passed through the latter, is collected in a volume (hot collector) to be distributed to eight parallel pipes and delivered to as many SGs. After leaving the SGs the coolant enters the cold pool through the cold leg and returns to the core.

The ALFRED core is composed by wrapped hexagonal Fuel Assemblies (FAs) with pins arranged on a triangular lattice. The 171 FAs are subdivided into two radial zones with different plutonium fractions guaranteeing an effective power flattening, and surrounded by two rows of dummy elements serving as a reflector. Two different and independent control rod systems have been foreseen, namely, Control Rods (CRs) and Safety Rods (SRs), which are assigned regulation/compensation and scram functions assuring the required reliability for cycle reactivity swing control and safe shut-down (Grasso et al., 2013).

Each of the eight SGs incorporated in ALFRED (Fig. 2) consists of bundles of bayonet vertical tubes with external safety tube and internal insulating layer (delimited by a slave tube), which is aimed at ensuring the production of superheated dry steam since, without a proper insulation, the high temperature difference between the rising steam and the descending feedwater promotes steam condensation in the upper part of the SG. The gap between the outermost and the outer bayonet tube is filled with pressurized