Control approach to the load frequency regulation of a Generation IV Lead-cooled Fast Reactor

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1. Introduction

In the past, Nuclear Power Plants (NPPs) were operated almost exclusively to cover base load demand [1] so as to maximize the efficiency and the load factor. In addition, it is often stipulated that performing load frequency regulation (i.e., adjusting the power output in response to instantaneous frequency deviations) could accelerate the NPP wear and tear [2]. This approach may be feasible if the share of nuclear in energy production is small compared to the other energy resources as in the US case [3]. On the other hand, this strategy cannot be adopted if the nuclear production share is high as in France where the NPPs are requested to implement manoeuvrability capabilities to regulate the frequency in the electric grid [2].

In the light of the present energy scenario characterized by a strong penetration of Renewable Energy Sources (RES), the need to provide the NPPs with the flexibility to modulate the power production in accordance to the grid request is a preeminent issue whatever the nuclear share is. RES systems, in particular photovoltaic plants and wind farms, are characterized by a high level

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Nomenclature

Latin symbols

A_u	turbine admission area, m^2
dP	normalized power output, (–)
E_t	net energy, J
f	grid frequency, Hz
h	enthalpy, kJ kg^{-1}
J	normalized moment of inertia of the rotor, (–)
k_v	turbine admission valve coefficient, (–)
K_p	proportional gain of the PID regulator, (–)
$HP_{fraction}$	fraction of the enthalpy drop disposed by the HP stages, (–)
p	SG pressure, bar
P	power output, MW$_{el}$
Q_c	thermal power exchanged, MW$_{th}$
$R(s)$	controller transfer function, (–)
s	laplace variable, s^{-1}
T	temperature, K
T_a	characteristic time constant of the actuator, s
w	mass flow rate, kg s^{-1}

Greek symbols

σ_i	droop, (–)
Π_m	mechanical power, MW$_{el}$
τ_i	integral time, s
τ_{HP}	characteristic time constant of the HP stages, s
τ_{LP}	characteristic time constant of the LP stages, s
$d\omega$	normalized grid pulsation, (–)

Subscripts

0	nominal value
f	feedwater inlet conditions
v	steam conditions

of variability and uncertainty in their energy production [3]. The presence of these intermittent renewable resources, along with the limited presence of energy accumulators, requires an increased effort for the frequency regulation in order to ensure high reliability performances [4]. In this perspective, the NPPs should be operated in a flexible way so as to comply with the sudden variations in the grid frequency. To this end, it is necessary to develop suitable control strategies and to test the different alternatives [5] in order to guarantee manoeuvrability capabilities without affecting the plant safety features.

In the development of Generation IV nuclear reactors [6], the possibility of promptly adjusting the mechanical power produced is crucial considering the economic goals of advanced nuclear systems to be competitive with alternative energy options. In the present work, this possibility has been investigated for the Lead-cooled Fast Reactors (LFRs), adopting the Advanced Lead Fast Reactor European Demonstrator (ALFRED) [7] as a case study. ALFRED, developed within the European FP7 LEADER (Lead-cooled European Advanced Demonstration Reactor) Project (http://www.leader-fp7.eu), is aimed at being representative of the LFR technology [8]. Notwithstanding, the control approach proposed in this paper can be applied to any small LFR concept [9]. Though the impact on the power grid of this NPP has not been evaluated yet, the main aim of this work is to develop and test a proper control strategy so as to investigate the load following capabilities of the ALFRED reactor. In literature, this issue has not been deeply studied, especially for the new reactor concepts of Generation-IV, which require the problem to be tackled from scratch because of their different features with respect to the conventional reactor concepts. A classic approach to the frequency control can be found in Refs. [5,10] for CANDU and Pressurized Water Reactors (PWRs), respectively. The control strategy adopted for the load following in both these references is the *reactor-follows-turbine* approach. At first, this approach has been also considered for the ALFRED reactor in virtue of the outcomes of the reactor free dynamics analysis [11]. Indeed, the ALFRED response to the opening of the turbine admission valve is similar to that of PWRs. Such a favorable behavior is due to the value assumed by the thermal reactivity coefficients [8], thanks to which the reactor autonomously reaches an operating point compatible to the turbine demands. However, LFRs have some specific features with respect to the conventional reactor concepts that make this approach ineffective. First, the time constants ruling the primary circuit dynamics of ALFRED are such that the power transients can last even tens of minutes [11], and the time requirements demanded by the grid can hardly be met. Second, the approach traditionally adopted in the PWRs for adjusting the thermal power level through the operation of the gray control rods[2] cannot be employed, given that this kind of control rods are not foreseen in the present reactor configuration. Finally, the system has turned out to be *underactuated*, i.e., the manageable inputs (control variables) are fewer than the variables to be controlled. The pairings between these variables are strictly imposed by the technological constraints as in the case of the lead temperature in the cold leg [13]. In the perspective of governing this variable, the only available input is the feedwater mass flow rate, which in turn cannot be adjusted for complying with the secondary circuit demands. The major outcome of this work consists in the definition of a dedicated control strategy for performing the frequency regulation according to the time constants of the conventional part of the NPP, compatibly with the limitations imposed by the aggressive lead environment in the primary circuit.

The paper is organized as follows. In Section 2, the main aspects concerning the frequency regulation are briefly reported. In Section 3, a brief introduction to ALFRED and to its operational range is provided. Afterwards, once having demonstrated how the PWR approach is not feasible for ALFRED, a dedicated strategy is set up for adjusting the value of the mechanical power produced (Section 4). In Section 5, in order to assess the proposed scheme, the simulation outcomes of the system controlled response are presented. Finally, the main conclusions and the further steps of research are outlined.

2. Load–frequency regulation concept

Before presenting the developed strategies for the operation of ALFRED, it is important to point out the requirements that power plants must meet in performing the load–frequency regulation. In particular, the requirements of the Union for the Coordination of Transport of Electricity (UCTE), i.e., the organization responsible

[2] The difference between gray and black control rods (CRs) is their absorbing properties. A black CR absorbs all the incident neutrons, whereas the gray one absorbs only a part of them. If a slight power or reactivity compensation is needed, the gray CRs are preferred since they cause smaller depressions in the neutron flux close to the rod leading to a flatter neutron flux profile and more even power distribution in the core [12].

for the coordination of operations and development of the electricity transmission grid in continental Europe, have been referred to [14].

2.1. Primary frequency regulation

The aim of the primary frequency regulation is to restore the power balance in order to stabilize the grid frequency. Thanks to this kind of regulation, it is possible to limit frequency deviations, which are affected by the entity of the loads connected, by the total inertia of the system, and by the effectiveness of the primary frequency regulation itself. For the Continental Europe grid, all the power plants connected to the grid having an effective power greater than 10 MW should perform the *primary frequency regulation*, increasing or decreasing the active power generated in a proportional way [15]. The primary regulation of a power plant control system is characterized by:

- *Droop*: it represents the gain of the primary frequency regulator and it constitutes a kind of sensibility of the power plants in response to the frequency deviations. In particular, at equal frequency reduction, the lower the droop, the greater the active power increase.

$$\sigma_i = -100 \frac{\Delta f / f_0}{\Delta P / P_0} \tag{1}$$

For NPPs, this parameter assumes a typical value between 4% and 5.7% [16].
The controller usually adopted for the primary regulations is tuned according to the desired droop value. In particular, the regulators characterized by lower droops mostly contribute to the primary frequency regulation. The general form of the controller is

$$R(s) = \left[\frac{1}{\sigma_i}(1 + s\tau_i)\right]\left(\frac{1}{1 + sT_a}\right) \tag{2}$$

In Eq. (2), the dynamics of the actuator is taken into account via the second term, while the first one defines the kind of the used controller. Generally, a proportional and a derivative ones are sufficient to stabilize the system to a new steady state condition.

- *Insensitivity region.* In order to avoid excessive stresses to the controlled system, a dead band is introduced, so that the frequency variations, below a certain threshold, are not taken into consideration.

In Fig. 1, a typical frequency transient following a power imbalance is shown. It is worthy to notice that the final steady state frequency value is different from the nominal one after the primary regulation. The other relevant parameter to be considered during the transient is the maximum frequency variation. The primary frequency regulation must ensure that the latter remains limited within appropriate boundaries. In case of non-compliance of these limits, other burdensome measures are necessary, such as the disconnection of some loads or power plants.

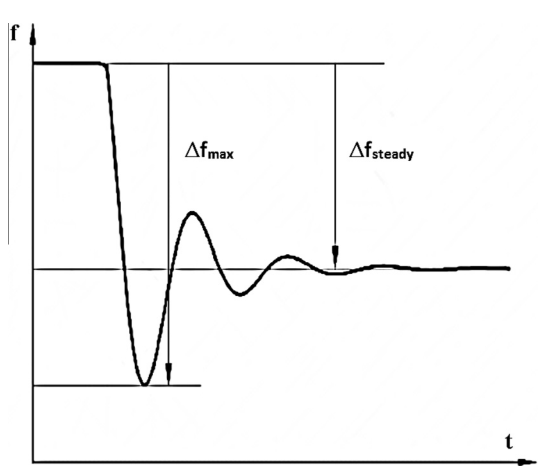


Fig. 1. Typical trend of frequency during primary frequency regulation.

2.2. Secondary frequency regulation

Following the primary frequency regulation, the secondary frequency regulation is performed. The main aims of the secondary regulation are:

- resetting the value of the frequency to the nominal one. In this way, it is also possible to disengage the primary regulation, thus allowing the primary reserve to be restored and to handle any further incoming disturbances;
- restoring the equilibrium among the different control areas (Fig. 2) at level of power exchange, in accordance with the contractual values [15].

The secondary frequency regulation is ensured by a system of automatic control and centralized power generated. It is important to note that, while the primary frequency regulation takes place everywhere in a distributed way, the control action of secondary frequency regulation must be undertaken only by the control zone within which the imbalance of power occurs, and it is in charge of only some power plants. However, the benefits deriving from the disengagement of the primary regulation reserve are extended to the overall grid, since the frequency value is approximately the same in all its nodes.

2.3. UCTE requirements

After having outlined the fundamental aspects of primary and secondary frequency regulations, the performance required to the adopted regulators are presented. In particular, the UCTE requirements are hereinafter briefly reported. Whether there would be a deficit of generation up to 3000 MW, primary frequency regulation must ensure that the minimum value of frequency, registered during the transient, is greater than 49 Hz. However, in order to get a good margin, it is preferred to set this threshold to 49.2 Hz. This means that, during this demanding transient, the frequency deviation must be kept below 800 mHz. Similarly, the highest permissible frequency, after a loss of load less than or equal to the so-called *Reference Incident*, is 50.8 Hz. The insensitivity range should be set as low as possible, and it should not exceed ±10 mHz. As far as the constraints concerning the times constants are regarded, the UCTE establishes that the system must be stabilized to a new steady state conditions via the control action performed by the primary frequency regulation within 30 s. Furthermore, the UCTE sets characteristic times for the return of the frequency and exchanged power to their nominal values, due to the secondary regulation as well. Whether an important group of production would be lost, the secondary frequency regulation must intervene at the latest 30 s after the occurrence of the disturbance and completing its control action within 15 min. The UCTE suggests to adopt a time constant for the controller which performs the secondary regulation between 50 and 200 s [14].

2.4. Islanding operational transient

In the last years, the development of the DER (Distributed Energy Resources) systems, within the HV (High Voltage) and the MV (Medium Voltage) grid, has been accompanied by a growing

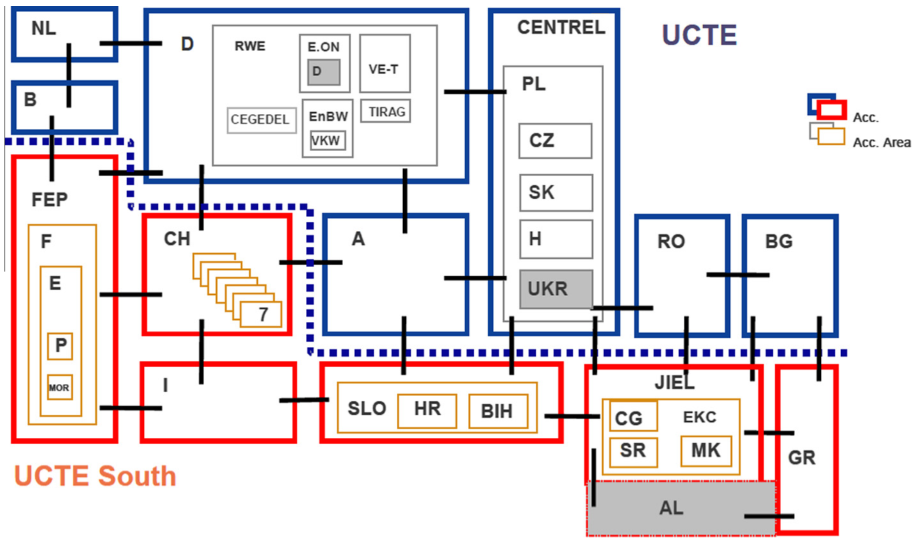


Fig. 2. Structure and organization of the Control Areas of the UCTE by countries/companies [14].

interest in the possibility of allowing the self-sustenance of portions of the grid. Indeed, operating a power plant when the alimentation of the remaining part of the grid is no longer available (i.e, islanding mode) allows keeping voltage in a portion of the distribution line. The islanding operational mode is an increasingly valuable perspective to ensure the service continuity, benefiting the utilities which are not equipped with UPS (Uninterruptible Power Supply). In particular, with the formation of intentional islands, it is possible to activate the appropriate control actions such as the detachment of interruptible loads or the activation of further generation units.

The possible reasons for the formation of intentional island are the following:

- loss of power transmission line due to a fault on the HV–MV transformer;
- failure within the distribution line, which can follow a grid partitioning into autonomous portions and non-functional portions;
- maintenance at the primary substation.

Since the present MV distribution lines have been designed, realized and operated as passive, so far the possibility of realizing self-sustaining islands of distribution has been often precluded. The infrastructures have been designed with reference to the old unidirectional model, according to which the electrical power, produced by few large power plants, and transported through the HV transmission line, reaches households and industries via the distribution line. Nowadays, the connection diagram of the transmission and distribution lines is still present. The innovative aspect, compared to the previous configuration, consists in the increase of generative capacity within the MV grid because of the development of distributed generators connected to the distribution lines. Consequently, in certain operating conditions, it may happen that the power flow between the MV and the HV lines could be inverted with respect to the traditional one (Fig. 3).

As mentioned in the Introduction, since ALFRED is meant to be a demonstrator, it is not expected to play a prominent role in the power production. Notwithstanding, the possibility of operating ALFRED in a flexible way, e.g., the capability of operating it in islanding mode, should be studied so as to provide initial insights to assess the feasibility of LFR technology, and the contribution that this reactor concept may ensure to the grid service continuity.

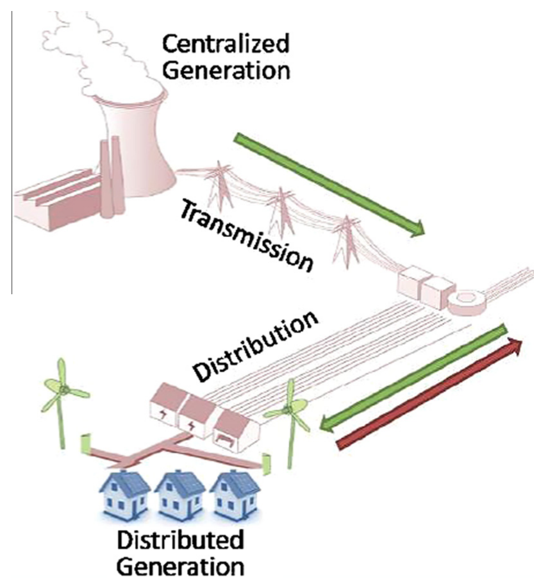


Fig. 3. Development of distributed generation and the consequent possibility of reversal of the traditional power flow, from the HV to the MV line.

3. The Advanced Lead Fast Reactor European Demonstrator

3.1. Reference reactor description

ALFRED is a small-size (300 MW_{th}) pool-type LFR whose primary system current configuration is depicted in Fig. 4. All the primary components (e.g., core, primary pumps and Steam Generators (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 reactivity

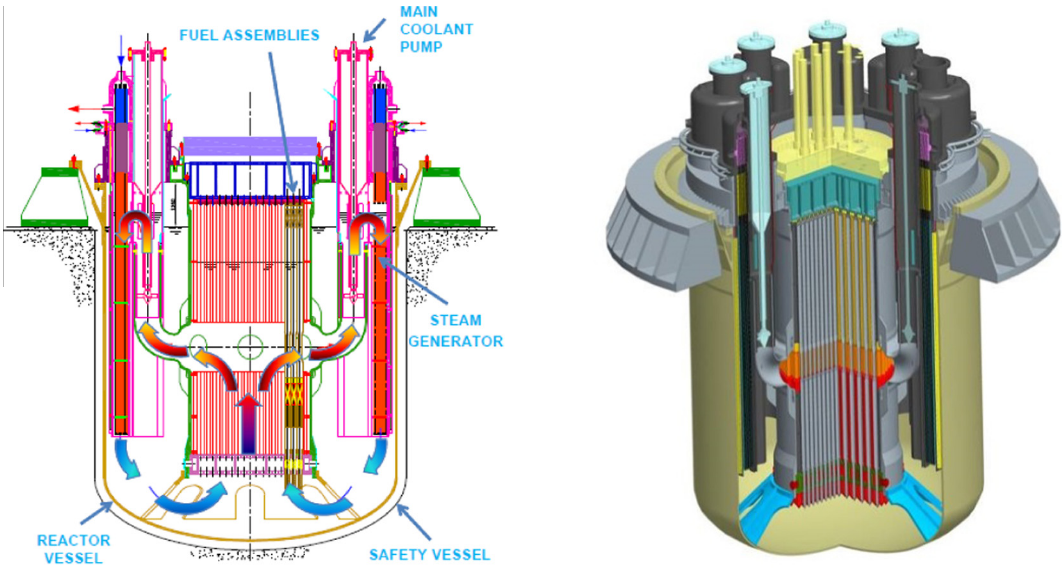


Fig. 4. ALFRED primary system and core layouts [7].

control systems, i.e., Control Rods (CRs) and Safety Rods (SRs), are assigned both regulation/compensation and scram functions assuring the required reliability for cycle reactivity swing control and safe shutdown [8].

Each of the eight SGs incorporated in ALFRED (Fig. 5) 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 helium and high thermal conductivity particles to enhance the heat exchange capability and provide mechanical decoupling between the components. The feedwater from the headers flows in the slave tube and, after reversing the motion at the bottom, rises along the annulus between inner and outer tubes. On the primary side, lead flows downwards axially along the outermost tube. In Table 1, the major parameters employed as input data to implement the core and SG models are reported.

3.2. Object-oriented simulator of ALFRED

In order to simulate the system controlled response so as to assess the feasibility of the proposed approach, the object-oriented model of ALFRED, whose graphical interface is represented in Fig. 6, has been adopted. The inputs (blue triangles)[3] and the outputs (white triangles) variables are pointed out, respectively, on the left and on the right of the figure. Based on the Modelica language and implemented in the Dymola environment [18], the system simulator has been built by connecting several dedicated models (for details, see [11]):

- *Core model*: it is composed by three subsystems. The model *Kinetics* describes the dynamics of the neutron generation processes in the core implementing a point reactor kinetic approach, with one neutron energy group and six delayed precursor groups. The model *FuelRods* is adopted to represent the thermal behavior of the fuel pins, which are discretized in five radial regions (i.e., the cladding, the gap and three concentric zones within the pellet). The model *LeadTube* represents the coolant flowing through the core channels adopting momentum and energy conservation equations in one-dimensional fashion.
- *SG Model:* as for the water side, a two-phase homogeneous model (i.e., same velocity for the liquid and vapor phases) has been adopted. On the lead side, the core component *LeadTube* is reused, describing the behavior of a single-phase fluid.
- *Primary circuit model:* the dynamics effects of the cold pool have been represented by employing a free-surface cylindrical tank component on which mass and energy balances are taken into account, assuming that no heat transfer occurs except through the inlet and outlet flows. In order to consider the time delays due to the transport phenomena between the core and the SG, two dedicated models have been implemented. As for the integrated primary pumps, an ideal mass flow rate regulator has been employed.
- *Secondary circuit model:* the model selected for the turbine describes a simplified steam turbine unit, in which a fraction of the available enthalpy drop is assumed to be converted by the High Pressure (HP) stage, whereas the remaining part to be converted by the Low Pressure (LP) one, with different time constants. In the developed model, in order to correctly describe the dynamics of the coupled turbine/turbo-alternator system, these time constants have been suitably chosen. To this aim, the following values which indicate the fraction of the enthalpy disposed by HP stages and the time constants characteristic of the HP and LP stages have been employed [19]:

$$\begin{aligned} HP_{fraction} &= 0.3 \\ \tau_{HP} &= 0.3s \\ \tau_{LP} &= 5.2s \end{aligned} \tag{3}$$

The steam mass flow rate is considered proportional to the inlet pressure and governed by acting on the turbine valve admission, not by throttling. Downstream of the steam temperature sensor, the steam mass flow rate can follow two ways. The former is a pipe that leads to the turbine, whereas the latter constitutes a bypass, which leads directly to the condenser.

[3] For interpretation of color in Fig. 6, the reader is referred to the web version of this article.

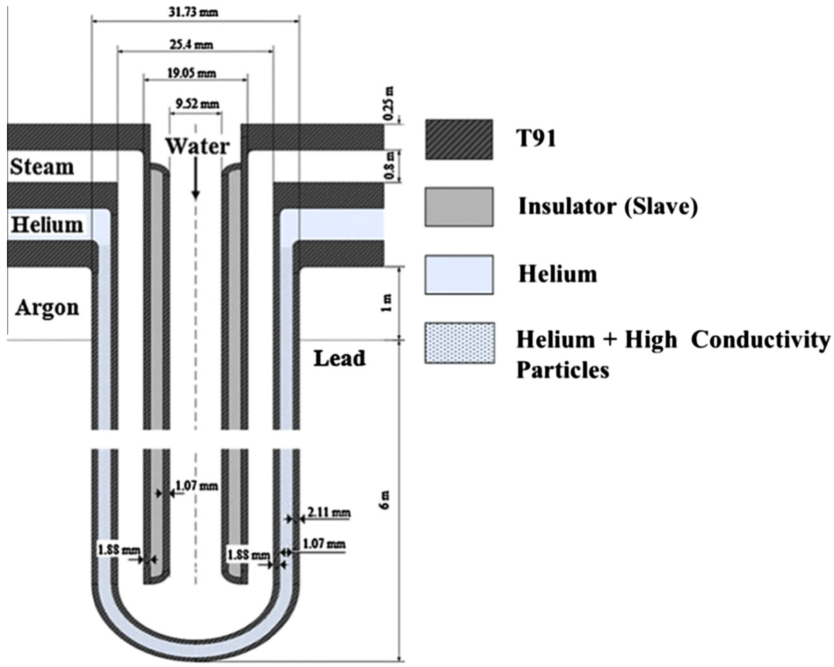


Fig. 5. ALFRED bayonet tube configuration [17].

Table 1
ALFRED system parameters.

Parameter	Value	Units
Thermal power	300	MW_{th}
Coolant mass flow rate	25,984	kg s^{-1}
Coolant SG outlet temperature	400	°C
Coolant core outlet temperature	480	°C
Feedwater mass flow rate	192	kg s^{-1}
Water inlet temperature	335	°C
Steam outlet temperature	450	°C
SG pressure	180	bar

3.3. Operational range of ALFRED

Since the primary frequency regulation has the most severe time requirements (the grid frequency has to be stabilized within 30 s), the simulation of this controlled transient for ALFRED turns out to be the most significant. As a first step, it is necessary to define the operational power range of ALFRED. Each Transmission System Operator (TSO) is entitled to define a minimum primary control range for generating units in terms of the nominal active power (P_{eff}), i.e., the maximum power that the generating unit can continuously provide. In particular, the operational range of a generating unit can vary between the P_{min} and P_{max} values, which are defined as follows:

$$P_{min} = P_{mt} + 1.5\% P_{eff} \tag{4}$$

$$P_{max} = P_{th} - 1.5\% P_{eff} \tag{5}$$

In particular, P_{mt} is the minimum power level at which the plant can operate and P_{th} is the highest power that the generating unit can produce in certain operational conditions [15]. For ALFRED, given that the maximum achievable thermal efficiency is equal to 44.75% [20], the value of P_{th} has been easily derived. As far as the definition of the primary reserve is concerned, the P_{eff} has been set equal to P_{th}, obtaining

$$P_{th} = P_{eff} = 134.25\ \mathrm{MW_{el}} \tag{6}$$

On the other hand, the minimum power level has been set equal to the lower threshold of the full power mode (40%), i.e., the power level at which the automatic reactor control starts to be performed. Therefore, the ALFRED operational range has been set equal to:

$$[54.81\ \mathrm{MW_{el}};\ 132.27\ \mathrm{MW_{el}}] \tag{7}$$

4. Primary frequency regulation performed by ALFRED

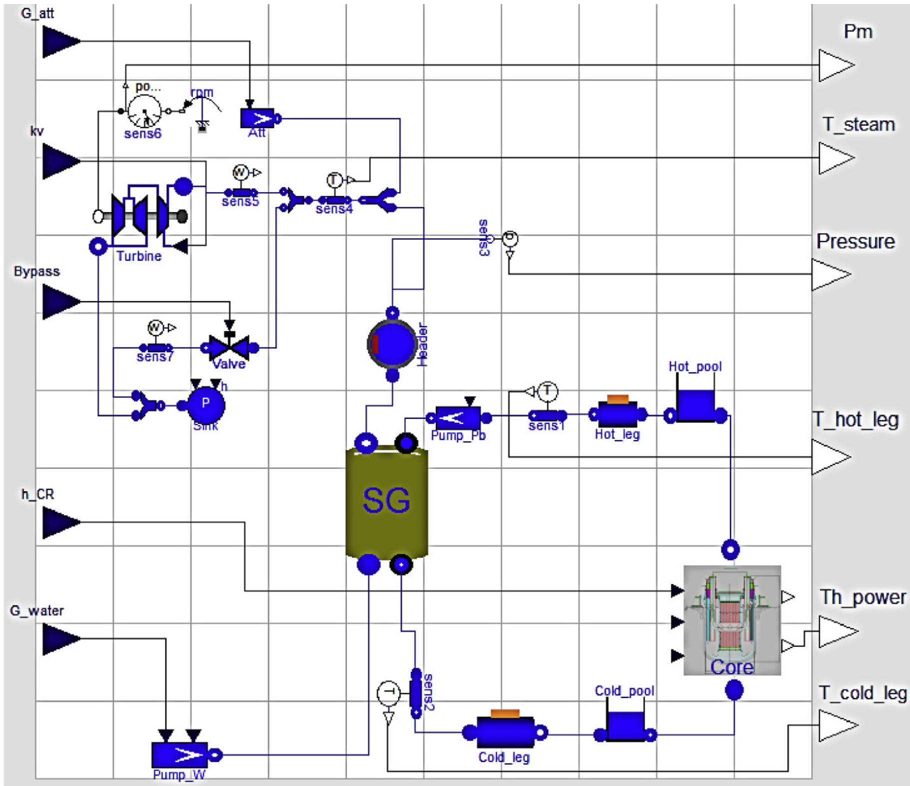
4.1. Definition of the mechanical power control loop

As for the load–frequency regulation, generally, the mechanical power produced is adjusted according to an opening signal sent to a regulating device (e.g., turbine admission valves). In particular, the produced electric power is adjusted in response to the value of the grid frequency, which is regarded as the controlled variable. If the synchronous generator is connected to a grid with a much higher installed power, it can be assumed that the frequency is imposed by the grid. Therefore, the nominal value is the fixed set-point close to which the controlled variable has to be maintained. In Fig. 7, the primary frequency regulation control scheme is shown. In particular, the control loops of the different generating units connected to the grid (represented by the blocks labelled by $G_{pi}(s)$) are represented. If the electrical dynamics is neglected, it can be assumed, as first approximation, that the synchronous generating units rotate at the same speed as they constitute a unique rotor having an effective moment of inertia.

In the perspective of performing the primary frequency regulation by means of a suitable control loop that allows regulating the mechanical power in response to grid frequency variations, a feedback proportional regulator has been adopted (represented in Fig. 7 by the blocks labelled by $R_i(s)$). The corresponding gain has been tuned so as to achieve the desired value for the generating unit droop (4%).

$$\sigma_i = -\frac{\Delta f/f_0}{\Delta P/P_n} = -\frac{d\omega}{dP} = -\frac{d\omega}{dk_v}\cdot\frac{dk_v}{dP} = K_p\cdot\frac{dk_v}{dP} \Rightarrow K_p = \frac{\sigma_i}{(dk_v/dP)} \tag{8}$$

In Fig. 8, the detailed view of the employed feedback control scheme is shown. As mentioned in Section 2.3, the presence of the insensitivity region has been foreseen in order to filter the



Input variables	Definition
G_att	Attemperator mass flow rate
kv	Turbine admission valve coefficient
Bypass	Bypass valve coefficient
h_CR	Control rod height
G_water	Feedwater mass flow rate

Output variables	Definition
Pm	Mechanical power produced
T_steam	Turbine inlet steam temperature
Pressure	SG pressure
T_hot_leg	Temperature of lead flowing out the core
Th_power	Thermal power produced within the core
T_cold_leg	Temperature of lead flowing into the core

Fig. 6. Graphical interface of the object-oriented model [11].

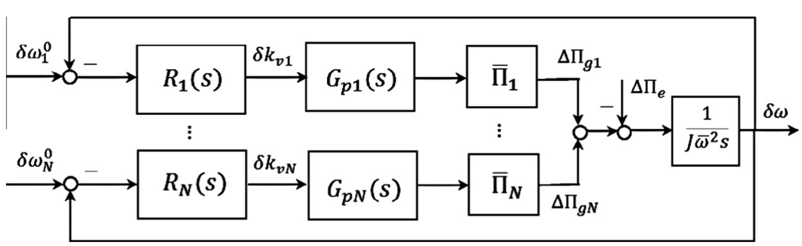


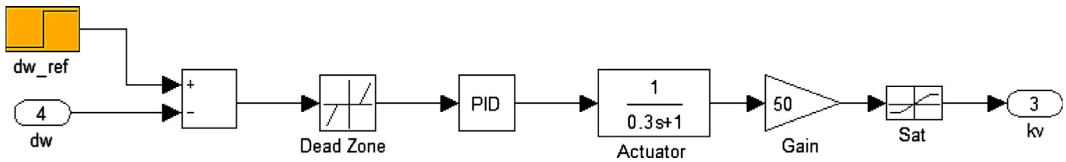
Fig. 7. Primary frequency regulation control scheme.

small-amplitude frequency fluctuations. Therefore, a suitable dead band (10 mHz) is envisaged so as to limit the stresses on the dedicated controller. Finally, the presence of the actuator of the turbine valve has been allowed for. For small variations, the actuator response can be approximated through a first-order transfer function with a characteristic time constant equal to T_a = 0.2–0.4 s.

$$\delta A_u = \delta A_{u,0}\frac{1}{1+sT_a} \tag{9}$$

4.2. Balance of Plant operation

The choice of the operational mode adopted for the SG operation is crucial since the criteria for the steam pressure control are often related to the effects of load changes on the plant life consumption. Two different approaches have been considered. The former is the *constant pressure mode*, in which the pressure is kept closed to its rated value and the power variation is obtained by acting on the water mass flow rate and on the thermal power exchanged. The latter is the *sliding pressure control mode*, in which the control valve of the steam turbine is fully open and the power variation is a consequence of the pressure variation. Though the sliding pressure control mode ensures a lower consumption of the steam turbine and it does not entail the consumption of pumps at reduced loads conditions, the constant pressure mode is more suitable for the SG operation. Indeed, this mode is the commonly adopted procedure in the Rankine cycle-based power plants since it establishes the saturation temperature, allows promptly varying



Component	Description
dw_ref	Grid pulsation set-point
dw	Instantaneous value of the grid pulsation
Dead Zone	Dead zone
PID	PID controller
Actuator	Transfer function representing the actuator dynamics
Gain	Gain on the PID regulator output
Sat	Saturation effect on the performed control action
kv	Turbine admission valve coefficient

Fig. 8. Control scheme implemented to perform the primary frequency regulation.

the power produced so as to rapidly meet the grid demands, and to avoid mechanical stresses when the load requests change.

In the perspective of connecting ALFRED to the grid, it has been decided to operate the SG in constant pressure mode. According to this approach, the thermal power exchanged and the cross-sectional area at the turbine inlet are respectively adjusted to regulate the load and to keep the pressure close to the nominal value. Furthermore, the correlation representing the choke flow conditions at the turbine inlet has been implemented so as to describe the evolution of the steam mass flow rate. Ultimately, the thermal power exchanged at steady state conditions is proportional to the feedwater mass flow rate, which is in turn proportional to the turbine admission valve coefficient, as follows:

$$Q_{c,0} = w_{f,0}\left(h_v(T_{v,0}, p_0) - h_{f,0}\right) \tag{10}$$

$$w_{v,0} = k_v p_0 \tag{11}$$

As for the SG dynamics, assuming that the pressure is approximately uniform, the system total net energy balance equation takes the following form:

$$\frac{dE_t}{dt} = -w_v(h_v - h_f) + Q_c \tag{12}$$

Since in the operational transients the influence of the pressure on the net energy is much more significant than the one of the steam temperature, the storage term is essentially function of the pressure:

$$\frac{dE_t}{dt} \cong \frac{\partial E_t}{\partial p}\frac{dp}{dt} = Q_c - \Pi_m \tag{13}$$

By considering the enthalpy drop $[h_v(p, T_v) - h_f]$ as a constant, the mechanical power available to the alternator has been derived

$$\Pi_m = w_v\left(h_v(p, T_v) - h_f\right) = k_v p(h_v(p, T_v) - h_f) \tag{14}$$

Therefore, in order to achieve a mechanical power step equal to $\Delta\Pi_m = \Delta\Pi_{m,0}$ by maintaining the SG pressure constant, the exchanged thermal power and the turbine admission valve coefficient have to be suitably adjusted:

$$\Delta Q_c = \Delta\Pi_{m,0} \quad \Delta k_v = \frac{1}{\mu_v}\Delta\Pi_{m,0} \tag{15}$$

where the parameter μ_v is defined as

$$\mu_v = \frac{\partial \Pi_m}{\partial k_v} = p_0(h_v - h_f) \tag{16}$$

According to the proposed control strategy, the employed control variables and their tasks in the SG operation have been defined as follows:

- The opening of the turbine admission valve is used to keep the pressure close to its nominal value.
- The thermal power supplied to the SG is necessary to regulate the mechanical power produced.
- The feedwater mass flow rate is adjusted according to the value of the thermal power produced. Thanks to the feed-forward scheme, it is possible to maintain a constant enthalpy drop.

4.3. Primary circuit operation

Traditionally, the load following in PWRs is performed according to the *reactor follows turbine* approach, i.e., when the connected loads demand a higher power output, the thermal power produced in the reactor core is adjusted to the required value together with the feedwater mass flow rate – Eqs. (10), (11). Ultimately, such a control strategy is favoured by the negative thermal reactivity feedback coefficients, which contribute to provide the most of the reactivity necessary to bring the NPP toward the requested power conditions. This dynamic behavior can be adapted to ALFRED, even though it is affected by a system governing dynamics particularly slow. Because of the large thermal inertia due to the cold pool and the reduced speed of the coolant in the primary circuit, the characteristic settling time for this kind of transient is about 1500 s.

However, the main concerns regard the frequency regulation, since the approach traditionally adopted in PWRs cannot be employed. As described in [13], the primary circuit configuration sets strict constraints on the feasible pairings between the input and the output variables. In addition, the secondary circuit configuration in the PWRs favors the prompt adjusting of the mechanical power output. Indeed, the U-tube SG design is characterized by a relevant thermal capacitance, which allows storing the excess thermal power that cannot be admitted to the turbine. In this way, a remarkable operational flexibility can be achieved in meeting the instantaneous fluctuations of the load demands. On the other hand, such an interim energy storage mechanism is not available in the reference bayonet tube SG design adopted in ALFRED.

In the present work, a dedicated control strategy that allows overcoming such limitations has been conceived. In the proposed scheme, a sensible role is assumed by the bypass valve, which is usually employed during the start-up procedure. Indeed, when the thermal power from the primary circuit is not sufficient to

Table 2
Selected pairings between input and output variables in the control strategy.

Control variable	Controlled variable	Loop
Control rods height (*h_CR*)	Thermal power (*Th_power*)	Feedback
Bypass valve (*Bypass*)	SG Pressure (*Pressure*)	Feedback
Turbine admission valve (*kv*)	Mechanical power (*Pm*)	Feedback
Attemperator mass flow rate (*G_att*)	Turbine inlet temperature (*T_steam*)	Feedback
Feedwater mass flow rate (*G_water*)	Cold leg temperature (*T_cold_leg*)	Feedback + Feedforward

ensure the steam nominal conditions, it allows venting the entire steam mass flow directly to the condenser. As the power level increases, the bypass valve is progressively closed, and when the reactor is operating at full power mode conditions, the bypass valve is usually kept completely closed [13].

Because of the severe technological constraints characterizing ALFRED, the lead temperature at the SG outlet has been designed to be controlled by adjusting the feedwater mass flow rate. Such a pairing may complicate the Balance of Plant (BoP) operation. Given that the variations of the feedwater inlet temperature are effectively damped and the steam conditions at the turbine inlet are meant to be kept constant, the SG operating points are fixed. Therefore, if the bypass valve is kept closed, the mechanical power is proportional to the produced steam mass flow rate, which is equal to the feedwater mass flow rate. However, as mentioned before, the value of this control variable cannot be adjusted to meet the grid demands. Therefore, an additional degree of freedom turns out to be necessary to regulate the electrical power in accordance with the load demands, to govern the cold leg temperature and, at the same time, to operate the SG at constant pressure.

A possible solution may be represented by the operation of the bypass valve, i.e., the turbine admission valve adjusts the mechanical power in response to the grid frequency variations, whereas the bypass valve governs the SG pressure. The reactor core is constantly operated at rated power level, and the heat produced in the primary circuit is effectively disposed to the BoP, thanks to the feedback control loop governing the feedwater mass flow rate. At the SG outlet, a fraction of the produced steam mass flow rate is disposed to the condenser without passing through the turbine, so as to adjust the mechanical power. In this way, it is possible to develop a control strategy in which the slow dynamics of the primary circuit is uncoupled from the operation of the BoP, and the frequency regulation can be performed in accordance with the UCTE time requirements. As a major outcome, these coordinated control actions would not affect the primary circuit, since the lead temperature in the cold leg is effectively controlled through the previously described control loop.

In Table 2, the control loops envisaged by the proposed control strategy are pointed out. In particular, the control scheme configuration described in [13] has been slightly modified so as to allow the *constant pressure* operation of the SG.

As final remark, it is necessary to mention the aspects concerning the steam mass flow rate that is not admitted to the turbine. As shown in Fig. 6, the steam line governed by the bypass valve directly leads to the condenser. This representation, however, cannot be definitive. Indeed, it would be an excessive stress if such superheated steam flow rate were directly and continuously vented to the condenser. Though designing the remaining part of the BoP is out of the scope of this work, different applications for the recovery of this steam flow can be foreseen (e.g., pre-heaters, storage).

In conclusion, two possible control approaches for adjusting the mechanical power output in ALFRED have been identified:

- *Reactor Follows:* the reactor thermal power is continuously adjusted according to the variations of the load demands.
- *Uncoupled Reactor:* once reached the rated thermal power, the reactor core is always operated at these conditions independently of the load requests. The mechanical power regulation is achieved by coordinating the operation of the bypass valve and of the turbine admission valve.

Table 3
Parameters of the HV grid.

Parameter	Value
Phase voltage (kV)	150
Phase angle of phase A (°)	0
Frequency (Hz)	50
Internal connection	Yg
Three-phase short-circuit level at base voltage (VA)	10^8
Reactance over resistance ratio (–)	20

Table 4
Parameters of the breaker.

Parameter	Value
Transition time (s)	100
Breaker resistance (Ω)	0.001
Snubber resistance (Ω)	10^6
Snubber capacitance (F)	inf

Table 5
Parameters of the HV/MV transformer.

Parameter	Value
Winding 1 connection	Yg
Winding 2 connection	Yg
Nominal power (MVA)	130
Nominal frequency (Hz)	50
Voltage, *V*1 (kV)	150
Normalized resistance, *R*1 (–)	10^{-6}
Normalized inductance, *L*1 (–)	0
Voltage, *V*2 (kV)	20
Normalized resistance, *R*2 (–)	10^{-6}
Normalized inductance, *L*2 (–)	0
Normalized magnetization resistance (–)	500
Normalized magnetization reactance (–)	500

In order to outline the mentioned limitations of adopting the reactor follows approach in the operation of ALFRED, in particular as far the primary regulation is concerned, the same operational transient (a 10 MW step on the mechanical power) has been simulated by adopting both the *Reactor Follows* and the *Uncoupled Reactor* approaches. The outcomes of the simulations performed by means of the object-oriented model of ALFRED (Section 3.2) are shown in Fig. 9.

The blue track represents the system response when the load-following PWR approach is employed. As for the control scheme configuration, the turbine admission valve has been adjusted in order to maintain the SG pressure constant, whereas the control rods have been operated so as to achieve the thermal

Table 6
Parameters of the synchronous machine.

Parameter	Value
Rotor type	Salient pole
Nominal power (MVA)	130
Nominal frequency (Hz)	50
Phase voltage (kV)	20
Stator resistance (Ω)	$7.6 \cdot 10^{-4}$
Stator dispersion inductance (H)	$1.27 \cdot 10^{-5}$
Stator magnetization inductance (*d* axes) (H)	$5.25 \cdot 10^{-4}$
Stator magnetization inductance (*q* axes) (H)	$3.84 \cdot 10^{-4}$
Field resistance (Ω)	$1.58 \cdot 10^{-4}$
Field dispersion inductance (H)	$8.7 \cdot 10^{-5}$
Damper resistance (*d* axes) (Ω)	0.0161
Damper dispersion inductance (*d* axes) (H)	$5.45 \cdot 10^{-4}$
Damper resistance (*q* axes) (Ω)	$2.15 \cdot 10^{-3}$
Damper dispersion inductance (*q* axes) (H)	$5.2 \cdot 10^{-5}$
Moment of inertia (kg m^2)	$1.51 \cdot 10^{4}$
Friction factor (N m s)	0.8
Pole pairs	1

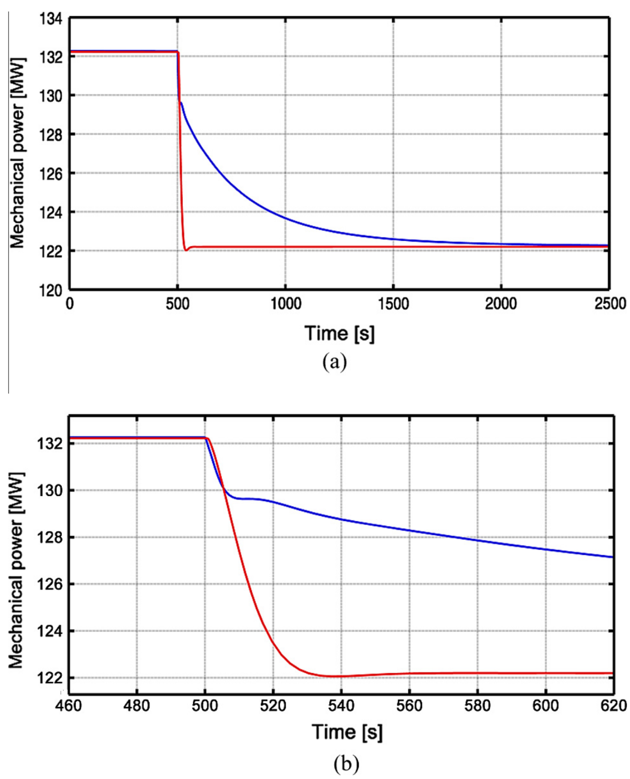


Fig. 9. (a) Mechanical power controlled evolution, simulated by adopting both the "Reactor Follows" (blue curve) and the "Uncoupled Reactor" (red curve) approaches, and (b) detailed view of the simulated transient. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

power variation corresponding to the requested mechanical power drop. The large settling time is due to the primary circuit dynamics. Indeed, the control of the reactor core conditions so as to reach the desired power level is heavily affected by the temperature field whose evolution is particularly slow with respect to the one of PWRs. Conversely, the red track represents the system response when the reactor core is working at rated power conditions and the coordinated control of mechanical power and pressure is achieved by adjusting, respectively, the bypass valve and the turbine admission valve. Such a control scheme turns out to be more effective (the desired power level is reached in less than 30 s), complying with the time requirements of the primary frequency regulation.

5. Simulation results

5.1. Primary frequency regulation

After having designed a suitable strategy to govern the mechanical power produced, a frequency profile with a resolution of seconds has been provided in order to assess the performance of the proposed scheme. In particular, the case study referred to the frequency in the synchronous grid of the Continental Europe over a period of 1000 s. The test data set is referred to the 8 March 2011, between the 6 p.m. and the 7 p.m. [21].

Being ALFRED connected to the synchronous grid, the installed power is much higher than its own rated mechanical power. Therefore, ALFRED cannot succeed in restoring the nominal conditions. For the simulation of the primary frequency regulation, the grid has not been modeled and the frequency regulation process has been represented by means of an open loop scheme (Fig. 8). The aim of this simulation is showing that, thanks to the proposed procedure, it is possible to deal with the grid frequency fluctuations (Figs. 10a and 11a), without being conditioned by the primary circuit dynamics. As shown in Figs. 10b and 11b, the simulation outcomes assess that the proposed control scheme allows adjusting the mechanical power, according to the adopted droop, by operating the turbine admission valve. Though the presented results are preliminary (the modeling of the BoP is not fully characterized), these simulations may help to evaluate the possibility of employing this reactor concept in the primary frequency regulation perspective.

When the reactor is operated at nominal power (300 MW_{th}), in virtue of the feedforward control loop, the value of the feedwater mass flow is close to the rated one (192 kg/s). In this way, the influence of the BoP operation on the primary circuit variables is limited, i.e., the only interferences that can affect the value of the reactor power are the pressure fluctuations due to the instantaneous load variations. However, in addition to the effective pressure controller that operates on the bypass valve, these fluctuations are further damped by other feedback regulators. Thanks to the adopted tuning of the controllers parameters, the disturbances that can influence the values of the primary circuit variables (Fig. 12a) are effectively filtered by the implemented PI regulators. Ultimately, the lead temperatures in the hot and cold leg and the thermal power (Figs. 12b and 13) hardly perceive the experienced load variations, and they can be easily kept closed to their rated values.

5.2. Islanding operational transient

Recently, there has been a relevant deployment of the distributed generation, thanks to the presence of generating units of small or medium size in distribution lines. In this section, the operation of the ALFRED reactor as if it were a generating unit connected to the MV distribution line (20 kV) has been studied. Along with the promptness of the control system in adjusting the mechanical power produced, the frequency elongation due to the lack of contribution provided by the HV alimentation line has been evaluated. Therefore, since the power requested by the loads in the MV grid is lower than the ALFRED power output, the distribution line has been modeled, and the load–frequency control via the NPP has been simulated.

The MATLAB Simulink toolbox *SimPowerSystems* [22] has been adopted. Indeed, the MATLAB simulation environment provides a library for the modeling of electrical components, such as loads,

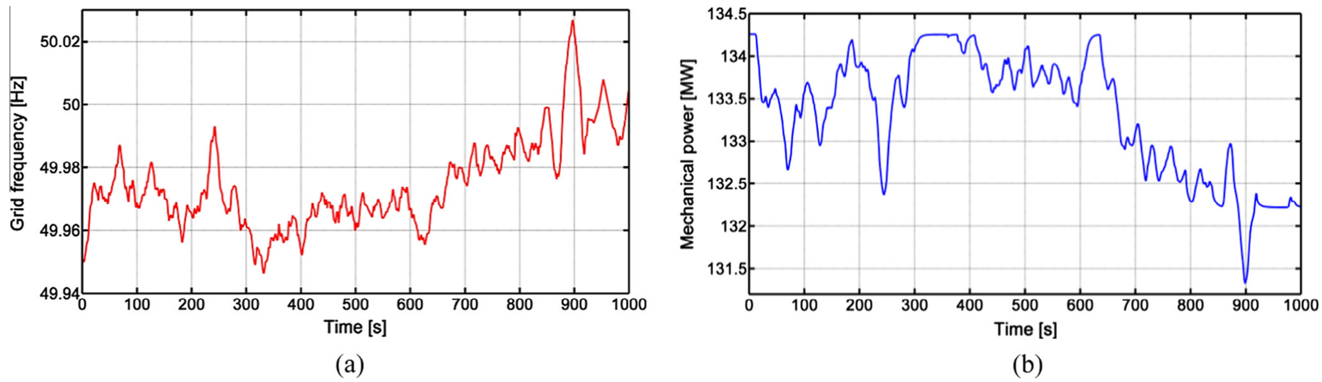


Fig. 10. (a) Case test frequency profile, and (b) mechanical power response to the provided frequency profile.

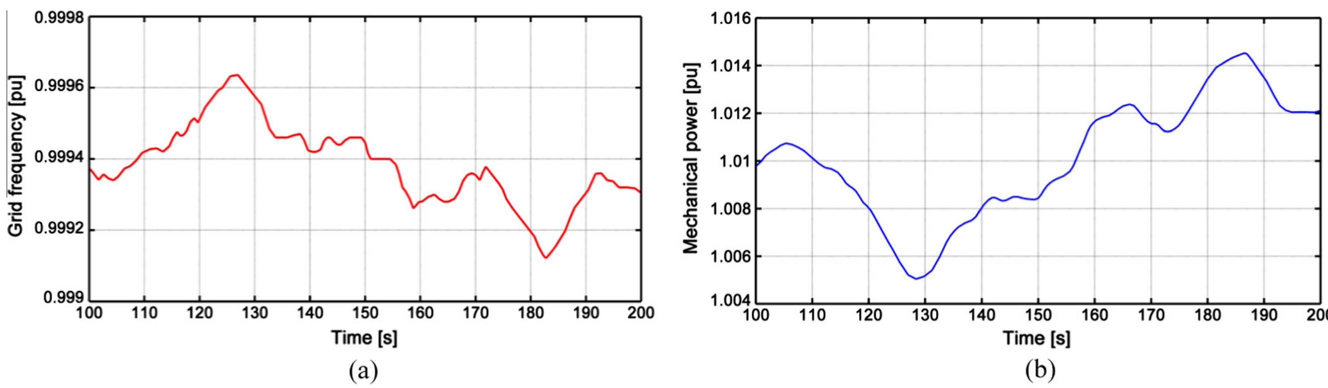


Fig. 11. Detailed view of the (a) frequency profile, and (b) mechanical power response.

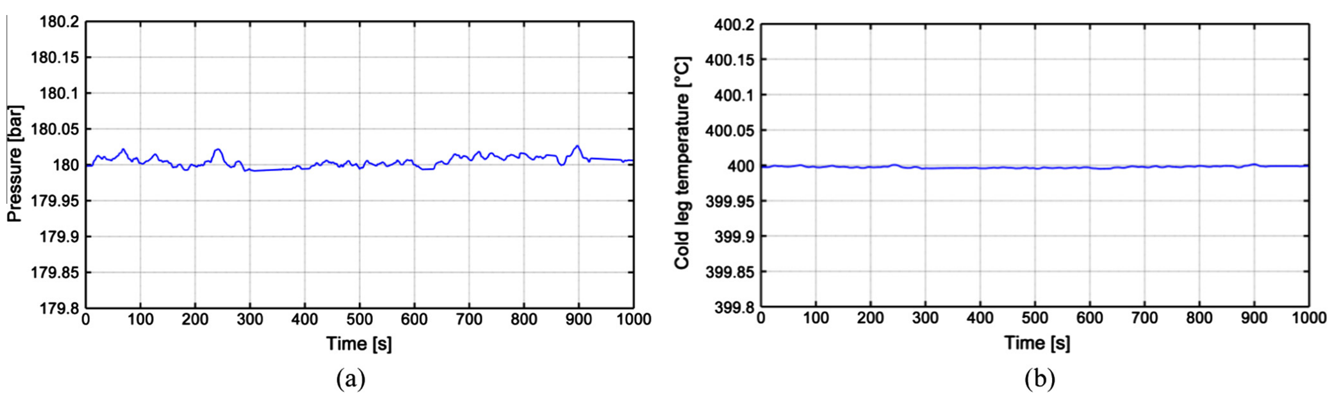


Fig. 12. Evolution of the variables which influence the primary circuit, (a) SG pressure, and (b) lead temperature in the cold leg.

transformers, lines, and generators, and it has been already widely used in the energy power field [23] as well as in the control framework [24].

The configuration of the studied grid is shown in Fig. 14, in which both the HV and the MV grids are represented. The interconnection between them is achieved through a HV/MV transformer, which lowers the voltage of the transmission grid (150 kV) to the one of the distribution grid (20 kV). Downstream of the transformer, a three-phase breaker is envisaged, thanks to which the islanding of the MV grid portion can be performed. In the HV grid, there is a three-phase voltage source that allows simulating the presence of an infinite installed power grid. The main parameters of the grid model are listed in Tables 3–6.

The values of the power absorbed by the loads and the power produced by the NPP have been set in such a way to obtain a net export of power from the MV grid to the HV grid. In order to properly simulate the input–output dynamics of the MV grid, an equivalent load has been added, in place of the generator in the HV grid.

In nominal conditions, ALFRED is connected to the grid and performs the primary frequency regulation. At the time $t = 100$ s, the breaker is opened, and the islanding of the MV grid is achieved. Thereafter, the grid portion downstream of the transformer HV/MV is isolated, and ALFRED must meet the power demand of the connected loads.

The net effect of the islanding is the cessation of the power export from the MV to the HV grid. According to the demands of

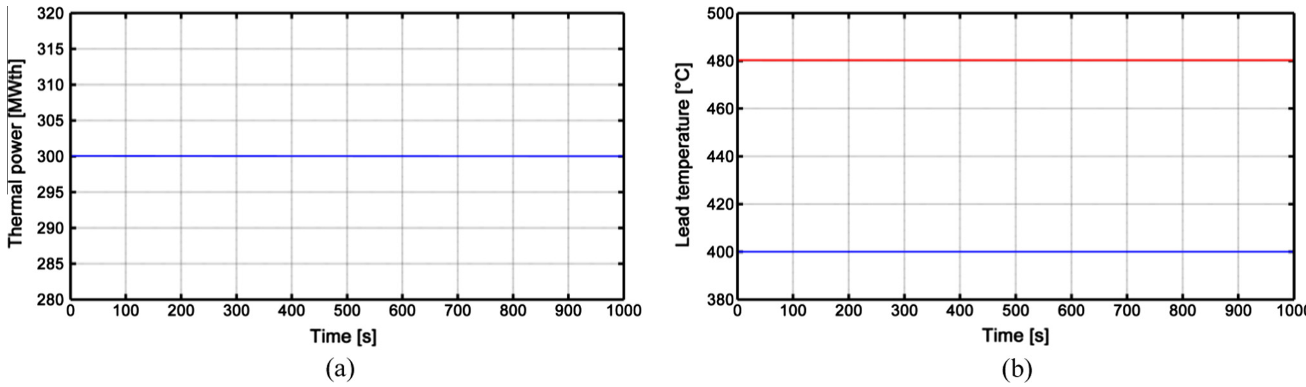


Fig. 13. Evolution of the primary circuit variables during the primary frequency regulation, (a) thermal power, and (b) lead temperatures in the hot (red line) and cold leg (blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

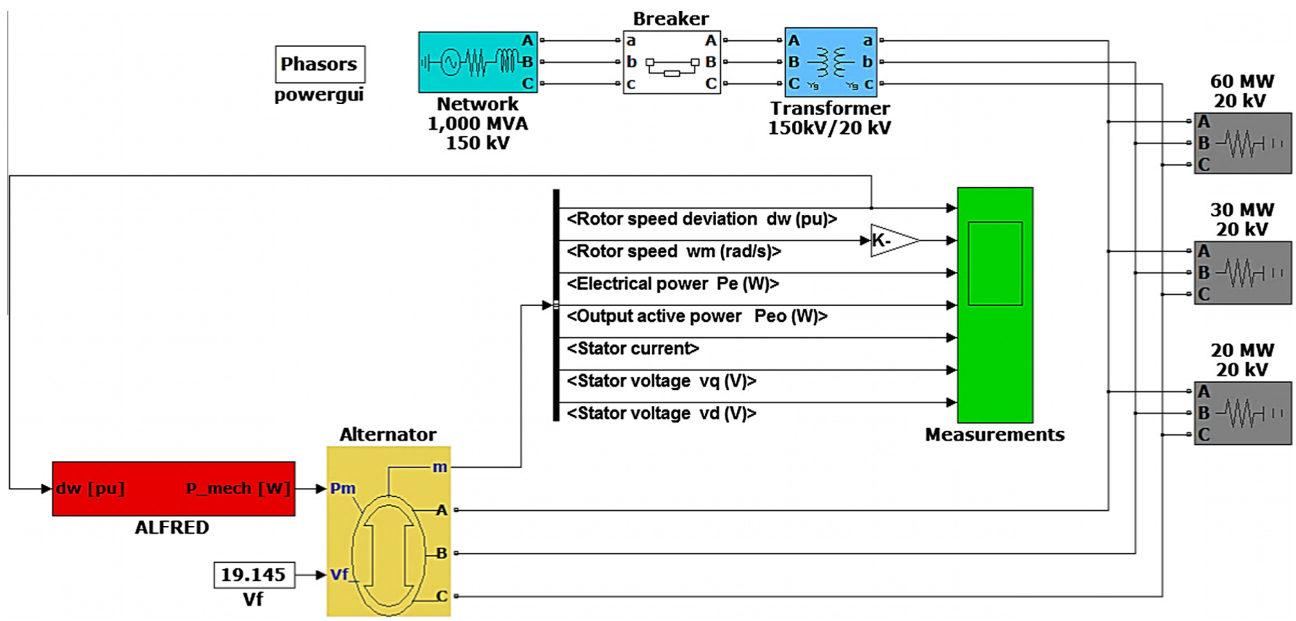


Fig. 14. Configuration of the portion of the grid which performs the islanding.

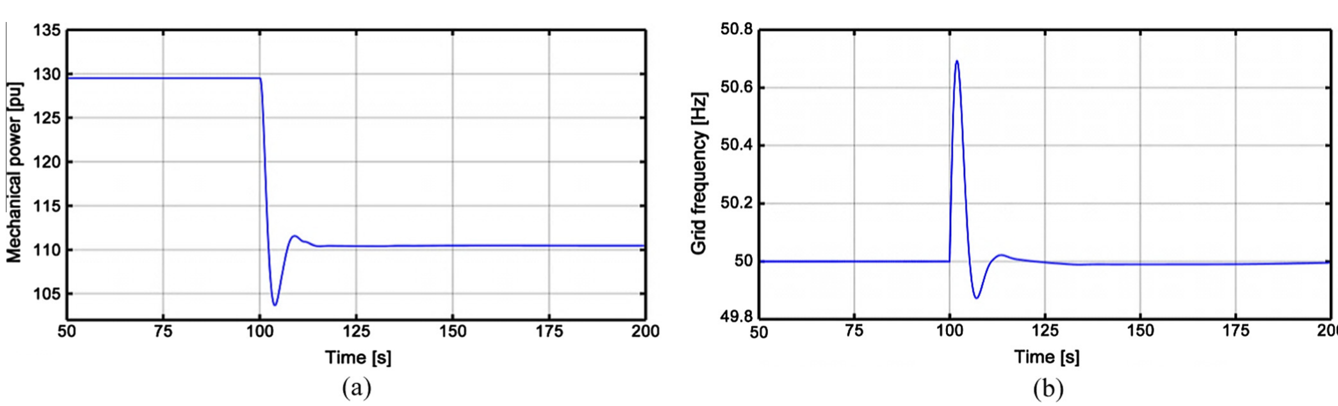


Fig. 15. (a) Mechanical power response to the disconnection from the grid, and (b) evolution of the frequency in the islanded portion of the grid.

the loads connected to the distribution line, ALFRED must achieve a 20 MW power drop within a few seconds so as to maintain the value of the frequency equal to the set-point (50 Hz). Indeed, at the beginning of the transient, the excessive power production (Fig. 15a) leads to an increase in the grid frequency (Fig. 15b). The employed controller cannot prevent a frequency overshoot, even if it remains below the maximum allowed limit (50.8 Hz). In the case of the islanding, the capability of promptly adapting the power plant operating conditions to the new grid configuration is a basic requirement in order to avoid compromising the integrity

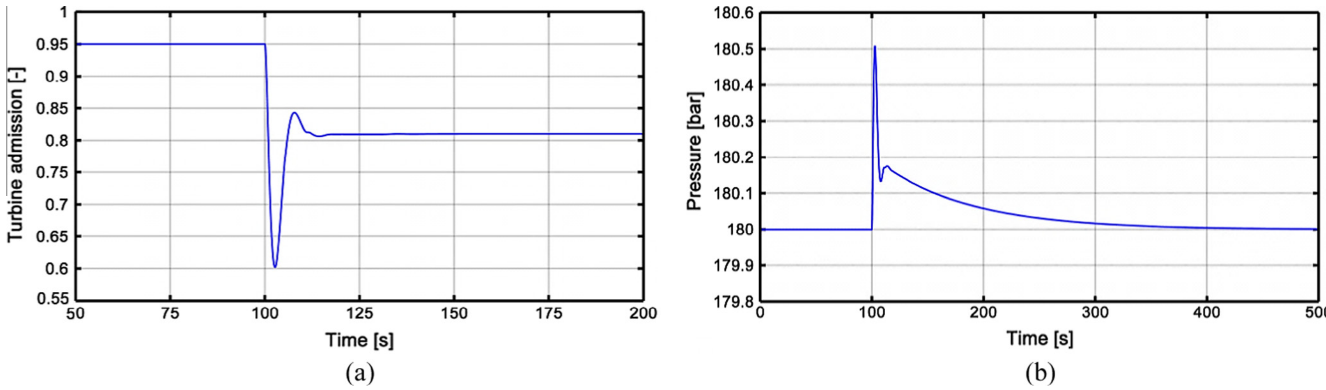


Fig. 16. (a) Turbine admission valve coefficient variation, and (b) SG pressure evolution.

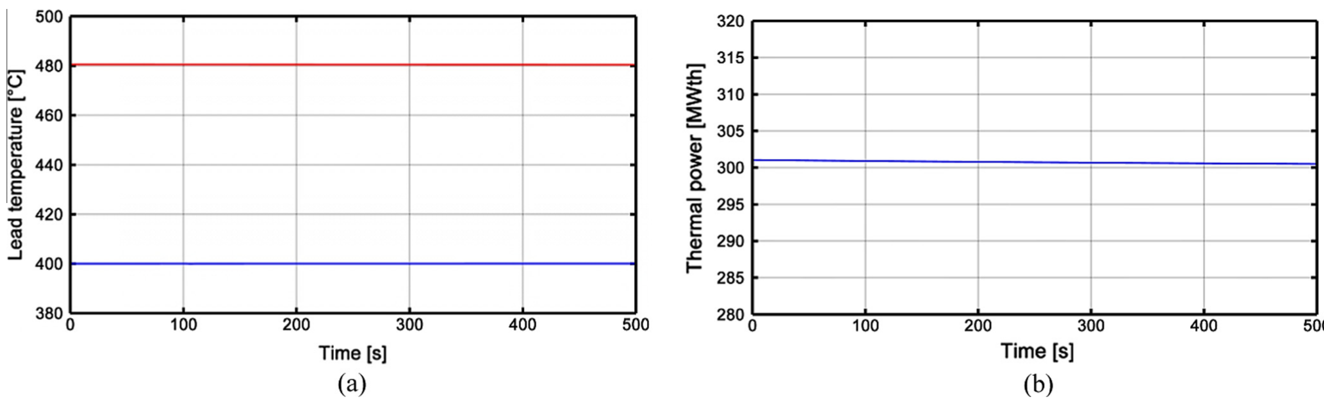


Fig. 17. Evolution of the primary circuit variables during the islanding, (a) lead temperatures in the hot (red line) and cold leg (blue line), and (b) thermal power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the connected loads. It is clear that, in any case, the accomplishment of this transient can take place only if the primary circuit dynamics are decoupled from the BoP operation.

The turbine admission valve has to be promptly operated to adapt to the new requested power level (Fig. 16a). This has an impact on the pressure evolution (Fig. 16b), which is affected by the sudden closure of the valve with an overpressure transient whose amplitude remains contained. As for the BoP induced feedbacks on the primary circuit, the implemented regulators guarantee reliable performance. Indeed, the net impact on the lead temperature in the cold leg (Fig. 17a) is less than one degree of deviation from the nominal value. Thanks to this reduced influence, the feedback control loop devoted the thermal power control achieves maintaining the steady conditions in the primary circuit (Fig. 17a and b).

6. Conclusions

In this work, the possibility of performing the load–frequency control by means of LFRs has been studied, by adopting the ALFRED reactor as a case-study. Being ALFRED a demonstrator whose aim is assessing the feasibility of LFR technology, the system capabilities to adjust the mechanical power output in response to grid frequency fluctuations have been evaluated. Firstly, it has been tried to adapt to ALFRED the *reactor follows turbine* approach. However, such a strategy has turned out not to be suitable since the technological constraints due the adoption of lead as coolant determine strict pairings between input and output variables. Therefore, because of the impossibility of adjusting the feedwater mass flow rate conditions according to the instantaneous load demands, it has been necessary to decouple the operation of the BoP from the primary circuit dynamics. The proposed control strategy foresees to govern the mechanical power produced by regulating the bypass valve and the turbine admission valve, by operating the SG in constant pressure mode so as to balance the frequency fluctuations over few seconds, without affecting the primary circuit. The outcomes of the performed simulations have demonstrated the capability of the studied NPP to promptly adapting the electrical power production to the instantaneous variations of the load demands. In addition, the possibility of operating the NPP in islanding mode has been evaluated. In this way, ALFRED can be regarded as a power plant that can play an important role in ensuring the service continuity in case of accident in the upstream line, in virtue of its reliability features.

As a future development of this work, it would be interesting to interface the simulator of ALFRED with a more realistic description of the power grid. Indeed, at the moment, the developed strategy is suitable for meeting reduced amplitude variations of the power output. Conversely, the possibility of allowing for the presence of wind farms and photovoltaic plants would give the possibility of conceiving a more efficient control strategy, foreseeing the slow varying set-point for the thermal power control as well.

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References

[1] Ruth MF, Zinaman OR, Antkowiak M, Boardman RD, Cherry RS, Bazilian MD. Nuclear-renewable hybrid energy systems: opportunities, interconnections, and needs. Energy Convers Manage 2014;78:684–94.

[2] OECD/NEA. Technical and economic aspects of load following with nuclear power plants. Nuclear Development. <http://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf>; June 2011.

[3] Ela E, Milligan M, Kirby B. Operating reserves and variable generation. Technical report NREL/TP-5500-51978. Department of Energy; August 2011.

[4] Bragg-Sitton SM, Boardman R, Ruth M, Zinaman O, Forsberg C. Rethinking the future grid: integrated nuclear renewable energy systems. In: Proceedings of 9th nuclear plants current issues symposium: moving forward charlotte. North Carolina, US; 2014 December 7–10.

[5] Chou QB. Characteristics and manoeuvrability of CANDU nuclear power stations operated for base-load and load-following generation. IEEE Trans Power Apparatus Syst 1975;PAS-94(3):792–801.

[6] GIF. Technology roadmap update for Generation IV Nuclear Energy Systems. <https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf>; 2014.

[7] Alemberti A, Frogheri M, Mansani L. The lead fast reactor Demonstrator (ALFRED) and ELFR design. In: Proceedings of the international conference on fast reactors and related fuel cycles: safe technologies and sustainable scenarios (FR 13). Paris, France; 2013 March 4–7.

[8] Grasso G, Petrovich C, Mattioli D, Artioli C, Sciora P, Gugiu D, et al. The core design of ALFRED, a demonstrator for the European lead-cooled reactors. Nucl Eng Des 2014;278:287–301.

[9] Bortot S, Artioli C, Grasso G, Peluso V, Ricotti ME. Preliminary core characterization of a Generation IV lead fast reactor DEMO: goals, design rationales and options. Energy Convers Manage 2010;51(9):1806–12.

[10] Tang Z, Zhao F, Wang P, Chen L, Fang H. Simulation of nuclear power units for primary frequency regulation research. In: Proceedings of the 21st international conference on nuclear engineering (ICONE21). Chengdu, China; 2013 July 29 – August 2.

[11] Ponciroli R, Bigoni A, Cammi A, Lorenzi S, Luzzi L. Object-oriented dynamics modelling and simulation for the ALFRED plant. Prog Nucl Energy 2014;71:15–29.

[12] DOE. DOE fundamentals handbook nuclear physics and reactor theory. Volume 2. DOE-HDBK-1019/2-93. Washington, D.C.: U.S. Department of Energy; 2003.

[13] R. Ponciroli. Development of a Model-based approach for studying the system dynamics and control of Gen-IV Lead-cooled Fast Reactors. PhD thesis, Politecnico di Milano, 2014.

[14] UCTE. UCTE Operation Handbook – Introduction (final v2.5 E); 2004.

[15] ENTSOE. Network code for requirements for grid connection applicable to all generators; 2013.

[16] Sterpu S. Power system dynamic performance. Primary governing frequency response. In: Proceedings of the IEEE Bucharest power tech conference. Bucharest, Romania; 2009 June 28 – July 2.

[17] Damiani L, Montecucco M, Pini Prato A. Conceptual design of a bayonet tube steam generator for the ALFRED lead-cooled reactor. Nucl Eng Des 2013;265:154–63.

[18] Dynasim. Dymola Version 6.1. Dynasim AB, Lund, Sweden. Homepage: http://www.dynasim.se/; 2006.

[19] Kundur P. Power system stability and control. McGraw-Hill Education; 1994.

[20] Perez FR. Private communication; 2012.

[21] Measurement of the utility frequency. <http://www.mainsfrequency.com/verlaufen.htm>; 2014.

[22] MATLAB® and SIMULINK® software. The MathWorks, Inc.; 2005.

[23] Mohantya P, Bhuvaneswarib G, Balasubramanianb R, Dhaliwalb NK. MATLAB based modeling to study the performance of different MPPT techniques used for solar PV system under various operating conditions. Renew Sustain Energy Rev 2014;38:581–93.

[24] Mansouri M, Reinbolt JA. A platform for dynamic simulation and control of movement based on OpenSim and MATLAB. J Biomech 2012;45:1517–21.