Co-published by
Institute of Fluid-Flow Machinery
Polish Academy of Sciences
Committee on Thermodynamics and Combustion
Polish Academy of Sciences

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ARCHIVES OF THERMODYNAMICS

Optimisation of the control curves of load-changing nuclear power units taking into account thermal stress

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Received: 22.01.2025; revised: 22.10.2025; accepted: 21.12.2025

Abstract

Besides the increasing share of uncontrollable renewables in the energy mix, the consumption/production balance of the grid must be permanently assured. Additionally, the successive stopping of traditional, fossil-fuelled power plants necessitates the controllability also of nuclear power plants. The major drawback of the load-following operation of such units is the side effect of load changes. They are, namely, carried out via non-stationary transitions, during which the temperature changes result in thermal stresses. The most critical, practically unchangeable part of the plant is the reactor pressure vessel, which is a thick-walled component of complex geometry. Hence, determining the optimal curves of the unit's available control inputs is a crucial issue. For this, several tools are needed, such as a dynamical model of the entire power unit, a dynamical description of the thermal stress in the most critical points, a practical system of criteria of the optimisation condition, and numerical method for seeking the optimal pathway. The results demonstrate that optimised actuator trajectories can reduce thermally induced stress in the nozzle corner of the reactor pressure vessel during load-following operation.

Keywords: Thermal stress; Load change; Optimised control; Nuclear power plant; Reactor pressure vessel

Vol. 46(2025), No. 4, 41–48; doi: 10.24425/ather.2025.156835

Cite this manuscript as: Pudleiner, B., Szentannai, P., Désesquellesc, L., Matter, C., & Fekete, T. (2025). Optimisation of the control curves of load-changing nuclear power units taking into account thermal stress. *Archives of Thermodynamics*, 46(4), 41–48.

1. Introduction

The major bottleneck of electrical energy is well known, as its storage is still not solved in an efficient way and in an appropriate amount. Consequently, a permanent balance between actual consumption and production is a must. Because the consumption side practically cannot be influenced and because some uncontrollable elements have also been appearing on the production side, the rest of this side must satisfy the entire burden of controllability. As highlighted by Marusic et al. [1], the growing share of uncontrollable renewables, together with the decreasing amount of easy-to-control fossil-fuelled power plants, results in the need for the load-following operation of rather large power-generating units. The difficulty is that such units were traditionally handled as permanent-load ones.

Nuclear power plants (NPPs) are typical examples of this type, as discussed in the study by Raskovic et al. [2], and they are characterised by outstandingly high relevance of security, economic, and ecological issues. Just because of these reasons, a basic question is whether they are capable of load-following operation at all.

Nomenclature

c – specific heat capacity, J/(kg K)
E – total internal energy, J
E – Young's modulus, Pa
$\boldsymbol{F}$ – force vector, N
h – specific enthalpy, J/kg
$\mathbf{I}$ – identity tensor
J – dimensionless cost function
m – mass, kg
$\dot{m}$ – mass flow rate, kg/s
p – pressure, Pa
$\mathbf{Q}$ – weighting matrix for the control accuracy
$\dot{Q}$ – heat transfer rate into the system, W
$\dot{q}$ – volumetric heat transfer rate, W/m^3
$\boldsymbol{r}$ – reference signal
$\mathbf{R}$ – weighting matrix for the manipulated variable change
t – time, s
T – temperature, K
$\boldsymbol{u}$ – local fluid velocity vector, m/s
$\Delta\boldsymbol{u}$ – manipulated variable change (between two time steps)
$\boldsymbol{v}$ – velocity vector, m/s
V – volume, m^3
$\dot{W}$ – work done by the system, W
$\boldsymbol{y}$ – controlled variable (process output)

Greek symbols

$\boldsymbol{\varepsilon}$ – strain tensor
κ – thermal conductivity, W/(m K)
ν – Poisson's ratio
ρ – density, kg/m^3
σ – stress, Pa
$\boldsymbol{\sigma}$ – stress tensor, Pa
$\boldsymbol{\tau}$ – shear stress tensor, Pa

Subscripts and Superscripts

1, 2, 3 – first, second, third
ext – external
in – incoming
l – liquid
ls – fluid and solid
out – outgoing
s – solid
T – transpose of the vector
VM – von Mises
I – first scalar invariant

Abbreviations and Acronyms

FEA – finite element analysis
normd. – normalised: divided by the maximal value*
NPP – nuclear power plant
PID – proportional-integral-derivative
Pos. – position
Rel. – relative: deviation from the point of linearization*
RPV – reactor pressure vessel
vlv – valve

* Note that most numerical results are shown as 'rel., normd.'as deviations from the point of linearisation in a normalised (dimensionless), hence have an easy-to-compare form.

A high number of operational experiences definitely answers this question with a yes. Germany is a well-documented example, where several units operated in a load-following mode nearly continuously throughout the year, as confirmed by Ludwig et al. [3] and Grünwald and Caviezel [4]. This operational flexibility is often referred to as 'manoeuvrability', a term borrowed from aviation, where faster control typically comes at the cost of higher structural stress [5].

The most critical technical challenge of manoeuvring operation in NPPs is the thermal stress induced in thick-walled components, especially in the reactor pressure vessel (RPV). Among its regions, the nozzle corner is widely recognised as the most vulnerable due to geometric complexity and stress concentration effects [6–8].

While the control side of load-following has been extensively studied, the structural integrity side – particularly the dynamic modelling of thermal stress – has received less attention. Recent studies [5] have proposed integrated modelling approaches that combine fluid dynamics, heat transfer and solid mechanics to derive time-dependent stress functions suitable for control-oriented optimisation. Furthermore, the long-term impact of thermal stress is material ageing, which can be assessed using either cycle-based (Palmgren-Miner) or time-dependent (Lorenzo-Ray) damage models [9,10]. These models are increasingly being incorporated into control strategies to extend component lifetime while maintaining grid compliance.

For investigating the potential of NPPs to participate in the load control, it is necessary to determine their optimal behaviour. For this, these dynamical systems must be mathematically described, that is, modelled. If a model is ready and programmed, it can be easily turned into a linearised one. Because of some practical reasons, for simplicity, throughout this study, we consider the linearised model and the linear ramp of the load change as the expectation of the grid operation.

The main contribution of this study is to introduce a new procedure for determining the optimal route of the plant's real inputs, i.e. the actuators, while also considering the side-effects, i.e. the caused thermal stresses. The resulting trajectories can then be used as reference pathways for traditional proportional-integral-derivative (PID) controllers or as benchmarks for assessing any controller performances.

2. Dynamical model of the power unit

The power unit itself has to be modelled in the first step, and, on this basis, a model for calculating thermal stress must be built. Both model parts are needed for the optimisation of the control curves of the entire system. The first part of the dynamical model is introduced in the current section (Sec. 2), while the second one is presented in the subsequent one (Sec. 3).

The inputs of the model of the power unit are the variables that also serve as inputs in reality, that is, the control rod positions and the main steam valve positions. Similarly, all those variables are modelled as outputs that may be used as measured values for any control strategies, such as temperatures in both the primary and secondary circuits, flow rates, neutron fluxes, water levels, etc. Further, the process variables that can act as the inputs for thermal stress calculations are also handled as outputs in this model part.

A central item in any lumped dynamical model is the state variable. This variable defines the model's internal state at any given time and serves as the foundation for describing time-dependent processes. Accordingly, these models are often referred to as state space models, and their dynamical nature arises precisely from the evolution of state variables over time. At the heart of lumped models lie the fundamental conservation laws, which form the primary differential equations governing the system's behaviour. These include: conservation of mass, conservation of momentum and conservation of energy.

The general form of these conservation laws can be expressed as follows:

Conservation of mass:

$$\frac{dm}{dt} = \Sigma\dot{m}_{in} - \Sigma\dot{m}_{out}, \qquad (1)$$

where m is the total mass within the control volume, $\dot{m}_{in}$ and $\dot{m}_{out}$ are the incoming and outgoing mass flow rates, respectively.

Conservation of momentum, which is typically omitted in lumped models unless forces or accelerations are of primary concern; if required, it takes the form:

$$\frac{d(\rho V \boldsymbol{v})}{dt} = \Sigma \boldsymbol{F}, \qquad (2)$$

where ρ is the fluid density, V is the volume of the control region, $\boldsymbol{v}$ is the velocity vector and $\boldsymbol{F}$ is the force vector acting on the control volume. However, in the current model, momentum conservation is not explicitly included.

Conservation of energy:

$$\frac{dE}{dt} = \Sigma\dot{Q} - \Sigma\dot{W} + \Sigma\dot{m}h, \qquad (3)$$

where E is the total internal energy of the control volume, $\dot{Q}$ is the heat transfer into the system, $\dot{W}$ is the work done by the system (e.g. shaft or flow work), $\dot{m}$ is the mass flow rate and h is the specific enthalpy of the inflowing or outflowing fluid.

A well-balanced mathematical model was set up by targeting accuracy and numerical effectiveness at the same time. It was achieved by our in-house model, which includes 12 state variables covering the above conservation laws as per Table 1.

Table 1. Conservation equations in the dynamical model of the power unit.

Type	No.	Applied for
Mass conservation	4	Neutrons, delayed neutron precursor atoms, steam (several locations)
Momentum conservation	0	–
Energy conservation	8	Thermal energy stored in the fuel rods, cladding, moderator (several locations), steam generator and pipe (several locations)

Besides the above conservation equations, their internal variables also have to be calculated. It can be done by algebraic equations (no differential equations) and their sources are rather diverse. Throughout setting up the lumped model, its parts can be taken from the basic physical rules, reliable approximations and phenomenological equations, and their selection and formulation are exciting aspects of model building. Textbooks can be beneficially used here (see, e.g. Walter et al. [11] for the most relevant systems of the current topic, and Corriou [12] for additional insights), along with tables or calculation methods for material properties and often also the latest publications and own measurements. It should be noted that this way of model development is referred to as theoretical or first-principle model building, in contrast to the empirical method. The latter relies on input-output data measured on the existing full-sized facility. A mixed use of these two basic directions is also possible, as demonstrated by Rossi et al. [13].

Accordingly, the first-principle modelling approach was applied in the actual work, and because control systems may sense and act on discrete points only, the proposed model class is that of the lumped models, as introduced in more detail by Szentannai et al. [14].

3. Dynamical calculation of thermal stress at the most critical point

Non-stationary states cause thermal stresses in the structural materials of nuclear power plants. Among these, the RPV is of particular concern due to its large wall thickness, complex geometry, and the fact that it is practically irreplaceable. Within the RPV, the nozzle region – especially the nozzle corner – has been consistently identified as the most critical location in terms of stress concentration and fatigue vulnerability. This is supported by multiple studies.

Li et al. [6] conducted an engineering critical assessment of RPV nozzle corner cracks under pressurised thermal shocks and highlighted the nozzle corner as the most vulnerable area due to geometric stress intensification. Liu et al. [7] and Cheng et al. [15] further confirmed that the nozzle-cylinder intersection is highly susceptible to crack initiation and propagation, particularly under transient thermal loads. Trampus [8] emphasised that the nozzle corner's geometry and material constraints make it the limiting factor in manoeuvring operations. Additionally, Rabazzi et al. [16] performed a detailed structural integrity assessment of the nozzle during thermal shock events, reinforcing its criticality.

Based on these findings, the nozzle corner was selected as the focus of our analysis. To quantify the thermal stresses in this region, we developed a dynamic model through an in-depth investigation.

A finite element analysis was carried out, which consisted of three main steps:

- fluid mechanical calculations,
- numerical modelling of heat transfer phenomena, and
- computation of stress-strain fields within the steel body.

The fluid flow in the analysed region was modelled using the Navier-Stokes equation and the continuity equation, both applied for incompressible fluids:

$$\rho_l \left(\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u}\right) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \boldsymbol{F}_{ext}, \quad (4)$$

$$\nabla \cdot (\rho_l\, \boldsymbol{u}) = 0, \quad (5)$$

where $\boldsymbol{u}$ is the local fluid velocity vector, ρ is the fluid density, p is the pressure, $\boldsymbol{\tau}$ is the local shear stress tensor and $\boldsymbol{F}_{ext}$ summarises the external forces.

The fluid flow governs the heat exchange between the fluid and solid domains. The energy equation for the fluid phase is

$$\rho_l c_l \frac{\partial T_l}{\partial t} + \rho_l c_l (\boldsymbol{u} \cdot \nabla) T_l - \nabla \cdot (\kappa_l \nabla T_l) = \dot{q}_{ls}, \quad (6)$$

where T_l is the fluid temperature, c_l is the fluid specific heat capacity, κ_l is the fluid thermal conductivity and $\dot{q}_{ls}$ is the volumetric heat transfer rate between fluid and solid.

In the solid domain, where there is no convective motion, the energy equation simplifies to

$$\rho_s c_s \frac{\partial T_s}{\partial t} - \nabla \cdot (\kappa_s \nabla T_s) = -\dot{q}_{ls}, \quad (7)$$

where T_s is the solid temperature, ρ_s is the solid density, c_s is the solid specific heat capacity and κ_s is its thermal conductivity. In regions away from fluid contact $\dot{q}_{ls} = 0$.

The steel structure is considered to behave as an isotropic, linear thermoelastic material. The stress tensor $\boldsymbol{\sigma}$ is given by the following formulation [19]:

$$\boldsymbol{\sigma} = \frac{E}{1+\nu}\left[\boldsymbol{\varepsilon} + \frac{\nu}{1-2\nu}\varepsilon_I \mathbf{I}\right] - \frac{E}{1-2\nu}\alpha\left(T - T_{ref}\right)\mathbf{I}, \quad (8)$$

where E is Young's modulus, ν is Poisson's ratio, α is the thermal expansion coefficient, $\boldsymbol{\varepsilon}$ is the strain tensor, ε_I is the first scalar invariant of the strain tensor, T is the local temperature, T_{ref} is the reference temperature and $\mathbf{I}$ is the identity tensor.

The principal stresses σ_1, σ_2, and σ_3 are calculated as the eigenvalues of $\boldsymbol{\sigma}$. From these, the von Mises stress is determined as

$$\sigma_{VM} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]}. \quad (9)$$

This scalar quantity characterises the effective stress at each point in the material. The regions of highest σ_{VM} values align with the expected stress concentrations. Due to symmetry, only one critical zone is considered for further calculations.

As a result of the above series of finite element calculations, the stress field around the critical point inside the steel body could be obtained, as shown in Fig. 1.

The time-dependent maximum of the thermal stress was then calculated as a consequence of a (theoretically applied) stepwise change in the input. This time function is the *step response function* [12] of this subsystem, which can already be integrated with the dynamical model of the power unit, as discussed in the previous subsection.

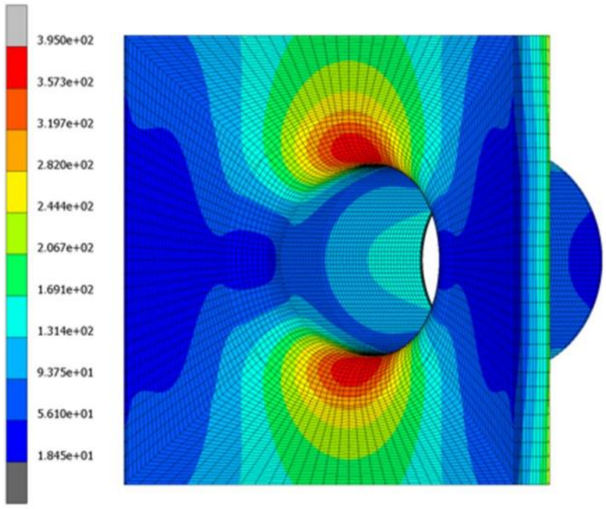

Fig. 1. Von Mises stress field around the critical point in the course of increasing the unit load; 300 s after stepwise temperature increase.

4. System of criteria for the optimisation

The consumer of the product that a power plant offers is the electrical grid, hence, the criteria formulated on this side are the first ones to be considered. In the synchronous area of Continental Europe, it is clearly formulated and summarised by a regulation of the European Commission [17]. According to this, limiting curves are given, between which the electrical power output must be kept throughout any load-changing transients. Although this regulation allows a certain freedom between the two limiting curves, throughout this study, we simply follow the more remote limiting line. This is because our preliminary investigations show that the optimum is in the very close proximity of this line (Fig. 2), hence, this simplifying decision does not result in any noticeable influences on the global optimisation result.

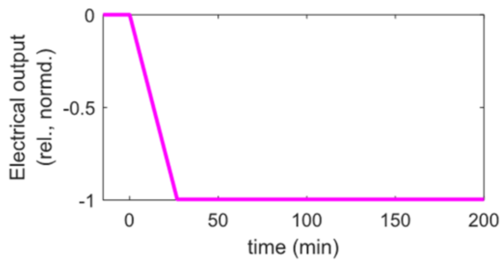

Fig. 2. The setpoint of the electrical power output vs. time as one of the criteria for transient load change formulated by the grid operator.

A first attempt at solving the control problem could be a proportional, purely linear moving of both actuators within the prescribed time interval from their original positions to the final ones, determined by the final desired operating point (Fig. 3). In the presence of a dynamical plant model (see Sec. 2), the plant outputs can be calculated as functions of time, as shown in Fig. 4. These plant outputs are the electrical output, the steam pressure

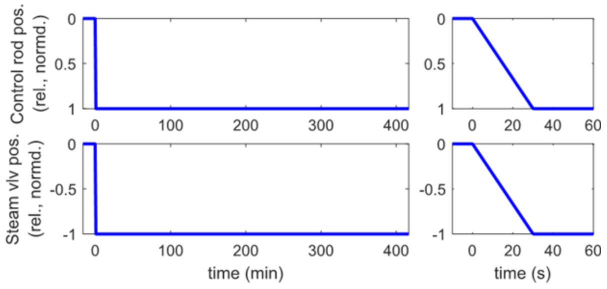

Fig. 3. Purely linear control of the actuators between their initial and final positions with filling the allowed time frame – to be used as the reference case throughout the present study.

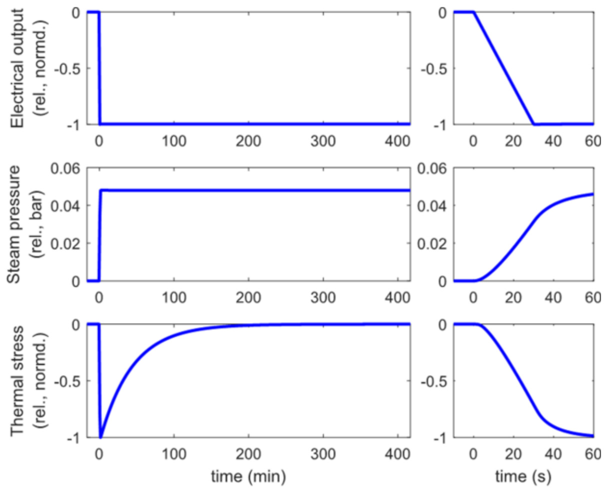

Fig. 4. Plant outputs as functions of time as consequences of the basic control strategy – to be used as the reference case throughout the present study.

in the secondary circuit and the von Mises stress at the most critical point. As visible in the top right high-time-resolution graph in this figure, this control concept fulfils the first criterion. Note that this scenario will be used as the reference one with the same normalising values throughout this study.

Further optimisation criteria come from the capabilities of the plant itself. As the first one, the speed of the control rods is limited to 0.2 m/s in the investigated plant. For formulating the next one, the degree of freedom of such plants must be considered. Based on these thoughts and based on the two known modes of traditional reactor control, either the live steam pressure in the secondary circuit or the average coolant temperature in the primary circuit can be freely chosen and kept constant. Throughout this study, we consequently apply the former one, as this seems to be the more often implemented one. Finally, all criteria together must be formulated in an integrated form. For this, we apply the quadratic cost function:

$$J = \int_{\text{time frame}} (\boldsymbol{r} - \boldsymbol{y})^T \mathbf{Q}\, (\boldsymbol{r} - \boldsymbol{y}) + \Delta\boldsymbol{u}^T \mathbf{R} \Delta\boldsymbol{u}\, \mathrm{d}t. \quad (10)$$

This form is extensively applied in both theoretical and practical control applications due to its analytical tractability and effectiveness in balancing multiple objectives. The definitions of the vector variables and matrices are as follows: $\boldsymbol{r}(t)$ − the reference signal (desired output trajectory), $\boldsymbol{y}(t)$ − the actual process output, $\boldsymbol{u}(t)$ − the control input (e.g. actuator positions), $\Delta\boldsymbol{u}(t)$ − the rate of change of the control input (i.e. actuator speed), $\mathbf{Q}$ − weighting matrix for the control accuracy, penalising output tracking error, $\mathbf{R}$ − weighting matrix for the manipulated variable change penalising control effort.

This quadratic optimisation problem can also be numerically solved while considering several constant or time-dependent constraints. The cost function defined by Eq. (10) is a widely used quadratic form in optimal control theory [18]. Its application in nuclear reactor control has also been demonstrated in recent studies, where it enables the simultaneous consideration of control accuracy, actuator effort and thermal stress.

Based on the above possibilities, also for considering thermal stress, the same optimum-seeking procedure can be applied in two ways: either by putting a constraint or by making the thermal stress more marked. These two methods are detailed and commented on below.

4.1. Weight on thermal stress

To follow established practices, the pressure should return to its initial value after the transitory state. In order to do so, a weight can be put on this output to be stricter on the correspondence between this value and its reference, which remains unchanged. A time-varying weight is applied to the pressure value to make it slowly but surely reach the right value. This weight on the pressure, increasing linearly over time, assures stabilising the pressure at its initial value at the end of the transient.

Of course, thermal stress must also be weighted. A very large weight was applied throughout the transient period, which can then be removed later. An appropriate set of these two time-dependent weights was applied, as shown in Fig. 5.

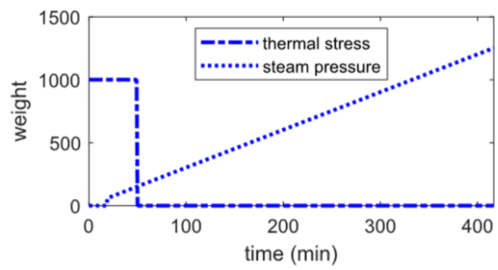

Fig. 5. Time-dependent weights applied in the cost function for fulfilling the system of criteria.

4.2. Constraint on thermal stress

Another possibility offered by the quadratic optimisation method is to apply constraints on thermal stress. This approach is useful in cases when material ageing is considered to be negligible by low thermal stress values, while it becomes harmful after overstepping a certain limit.

5. Numerical method for seeking the optimal pathway

Effective numerical optimum seeking procedures have been available for many decades. In the current study, its realisation within the Matlab framework, as demonstrated by Bemporad et al. [18], was applied. According to its hints, we applied a simplification to achieve a numerically very cheap and effective solution. It is based on a step-by-step optimisation of Eq. (10) and constraints, in such a way that it always seeks the next optimal move of the process inputs, instead of doing the same for the entire set of future time instances.

Throughout the dynamic optimisation procedure, the σ_{VM} thermal stress was considered as one component in the $\boldsymbol{y}$ output vector of the process. This σ_{VM} was calculated by means of the *step response function*, which had to be achieved once as the final result of the finite element modelling, as described in Section 3.

6. Results and discussion

The optimisation procedure presented in this study aimed to determine actuator trajectories that minimise thermally induced stress in critical components of nuclear power plants during load-following operation. The focus was on the nozzle corner of the reactor pressure vessel, which is widely recognised as the most vulnerable region due to its geometric complexity and stress concentration effects. Two optimisation strategies were investigated: one treating thermal stress as a constrained variable and another, incorporating it as a weighted term in the cost function. In both cases, the optimisation was performed using a two-scale time framework: a fast scale (seconds) to satisfy grid-side ramping requirements, and a slow scale (minutes to hours) to capture the evolution of thermal stress.

6.1. Weight on thermal stress

The optimisation was carried out for two cases to demonstrate the effect of changing the weights. In the first one (dashed blue line in Figs. 6 and 7), there was a bigger weight on the steam pressure, while in the second one (thick, solid blue line), the thermal stress was more heavily weighted. As visible in Fig. 7, the latter one results in a fairly acceptable deviation in the main steam pressure, which allows a significantly lower absolute peak in the thermal stress.

The basis for the proposed weight functions for both pressure and thermal stress lies in the physical interpretation of the transient process and the optimisation strategy used in predictive control frameworks. As can be observed, in the case where there was a higher weight on the thermal stress (solid line), in exchange for a lower peak in the thermal stress, we had to allow

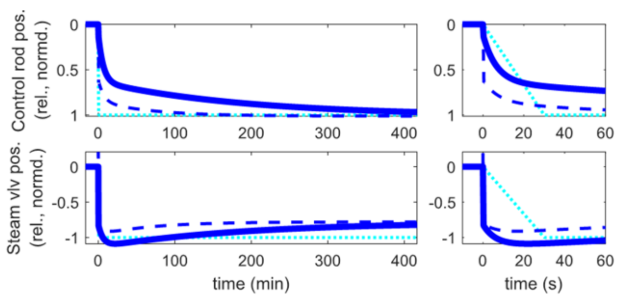

Fig. 6. Optimised control of the actuators (solid and dashed blue lines), together with the pure linear control (dotted, light line) – by means of diverse weighting of plant variables.

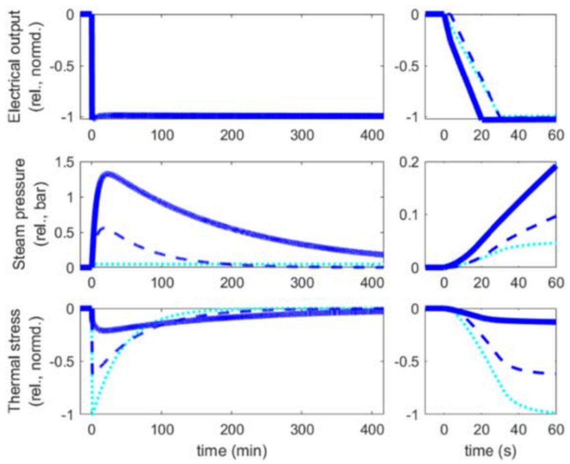

Fig. 7. Results of optimised control – by means of diverse weighting of plant variables. The absolute thermal stress can be significantly reduced at the expense of a larger (but still fully acceptable) deviation in the main steam pressure (dotted, light line: no optimisation; dashed blue line: slight weight on thermal stress; thick, solid blue line: greater weight on thermal stress).

a much larger deviation in the main steam pressure. While the peak thermal stress was reduced by more than 50%, the peak value of the main steam pressure increased by almost 1.5 times compared to the first case (dashed line). However, this is in our favour as the thermal stress is more significant for the ageing of the structural materials. Compared to the purely linear actuator control, the optimised trajectories achieved the same load-following performance while significantly reducing thermal stress.

6.2. Constraint on thermal stress

To demonstrate the effectiveness of constrained optimisation, two cases will also be shown with two different values as the constraints of thermal stress. In Figs. 8 and 9, these cases were marked consequently by a dashed blue line (less strict constraint) and a thick, solid blue line (more strict constraint). The figures show a similar trend: less absolute thermal stress can be achieved at the price of a higher transitional pressure peak.

6.3. Overall observations and causes

The results show that the optimised control curves significantly reduce the peak thermal stress compared to heuristic or linearly ramped control actions. In the constrained case, the stress was

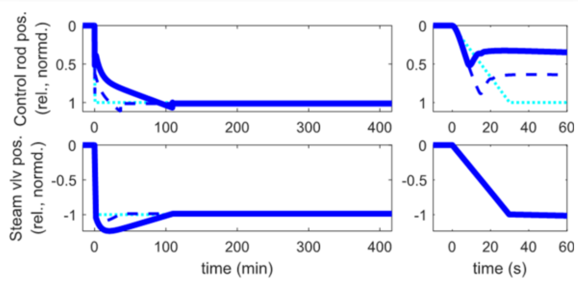

Fig. 8. Optimised control of the actuators (solid and dashed blue lines), together with the pure linear control (dotted, light line) – by means of constraining the resulted thermal stress.

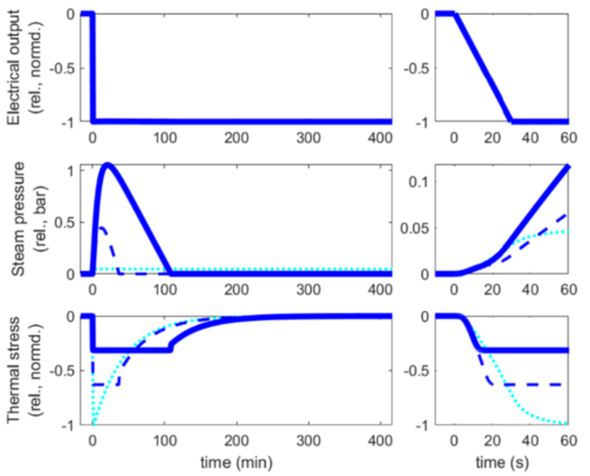

Fig. 9. Results of optimised control – by means of diverse constraining the resulted thermal stress. The absolute thermal stress can be significantly reduced on the price of larger (but still fully acceptable) deviation in the main steam pressure (dotted, light line − no optimisation; dashed blue line − slight constraint on thermal stress; thick, solid blue line − more strict constraint on thermal stress).

kept below the predefined limit throughout the transient. In the weighted case, although the peak stress was slightly higher, the overall stress-time integral – representing accumulated fatigue – was reduced. This demonstrates that the optimisation not only limits instantaneous stress but also mitigates long-term material degradation. Importantly, the optimisation did not rely on a uniform slowing down of the load change. Instead, the algorithm exploited the plant's internal flexibility – such as the thermal inertia of the primary loop and the buffering capacity of the steam pressure – to decouple the fast electrical response from the slower thermal dynamics. This allowed the control rods to move more gradually, reducing stress, while the steam valve compensated for the required power output.

The optimised trajectories also showed improved smoothness and coordination between actuators, which is beneficial for mechanical wear and control stability. The results confirm that the proposed method provides a non-trivial improvement over conventional control strategies, offering a viable path toward extending component lifetime while maintaining operational flexibility.

Although the study focused on a specific reactor configuration and nozzle geometry, the methodology is generalisable. The derived stress transfer function and optimisation framework can be adapted to other critical components and reactor types. Future work may include the integration of fuel behaviour models and the extension of the optimisation to multi-unit coordination.

7. Conclusions

This study demonstrated that the practically required load-following operation of nuclear power plants can be realised in a way that significantly reduces reactor-side thermal stresses – thus mitigating material ageing – while still fulfilling the grid operator's dynamic power delivery requirements.

By integrating a dynamical system model with a detailed stress-strain analysis of the reactor pressure vessel, the proposed optimisation framework enables a balance between fast electrical load manoeuvring and reactor-side structural integrity. In numerical simulations, thermal stress peaks were reduced by up to almost 50% compared to a standard linear control approach. Importantly, this reduction was achieved without exceeding acceptable deviations in steam pressure.

The resulting actuator trajectories adhered to physical constraints, including control rod speed limits (≤ 0.2 m/s), and showed smoother, more predictable behaviour, minimising high-frequency mechanical load changes. This confirms that stress-aware optimisation not only supports flexible plant operation but also contributes to long-term component reliability.

This method provides a practical and scalable solution for adapting existing nuclear power plants to modern grid demands with a high share of intermittent renewables. It supports lifetime considering control and paves the way for health-aware optimisation strategies, offering a path toward more resilient, sustainable nuclear power operation in the future energy mix.

Acknowledgements

The kind help of Dr. Á. Horváth and DSc. J. Gadó, as well as L. Tatár and D. Antók, are gratefully acknowledged.

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