Improving automated load flexibility of nuclear power plants with ALFC

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Abstract

In several German and Swiss Nuclear Power Plants (NPP) with Pressurised Water Reactor (PWR) the control of the reactor power was and will be improved in order to be able to support the energy transition with increasing volatile renewable energy in the grid by flexible load operation according to the need of the load dispatcher regarding the power system stability. Especially regarding the mentioned German NPPs with a nominal electric power of approximately 1,500 MW, the general objectives are the following automated grid-relevant operation modes (Figure 1):

- Primary frequency control (1) with load jumps up to –200 MW (asymmetric downwards within 30 seconds and with a duration of max. 15 minutes and back to full load within 30 seconds).
- Remote secondary control (2) by the load dispatcher; hereby stochastic load changes with gradients of 30 to 40 MW/min within a power range of ∆PG ≈ 600 MW can be required. In this case the load dispatcher directly governs the target setpoint of the turbine load within the mentioned range (which is limited in the turbine control); whereas the load gradient is set by the reactor operator according to the need of the load dispatcher and the actual possibility of the NPP. The reaction time of the load dispatcher is 15 minutes and typically the NPP gets a new setpoint every 15 minutes according to the needs of the grid and the prices in the electricity stock exchange.
- “Classic” load following operation (3) via telephone contact with the load dispatcher with gradients up to 40 MW/min within a power range of APG = 1,000 MW. In this case the load dispatcher communicates via telephone with the reactor operator regarding all aspects of the load ramp (gradient, target load) and often including the duration of the part load situation. The reaction time is more than one hour.

- Generally the primary frequency control can be combined with the other mentioned grid operating modes.

In all these operating modes, the reactor of a PWR follows via the control of the Average Coolant Temperature (ACT) of the primary side. The ACT is an indicator of the energy balance of the PWR; similar to the frequency in the grid, as mentioned before. This ACT is controlled by Control Rods (CR), which mainly compensate the power-relevant so-called “Doppler” reactivity (reactivity describes the relation between production and loss of neutrons), whereas subsidiary controls are mainly responsible for the axial power density distribution in the reactor core and the entire reactivity management (including ensuring sufficient shut down reactivity; controlled with boric acid and demineralised water = BODE).

The new possibilities of digital automation (as TELEPERM® XS) enable the complex automation of these operating modes on the reactor side – and, if needed, also on the turbine side, provided that manual support is nearly no longer necessary. These possibilities were and will be implemented by AREVA with its ALFC-product (ALFC: Advanced Load Following Control). Its main feature is a new adaptive reactor control and gave the related German projects the name ALV (ALV: adaptive Leistungsverteilung- und Bank-Stellungsregelung/adaptive power density control). Manifold adaption algorithms to the reac-

Fig. 1. Grid relevant operation modes for ALFC.
tor physical variations during the nuclear load cycle enable mainly a precise control of the axial power density distribution in the reactor core and of the reactivity balance. Finally, this is the basis for highly automated load flexibility with the parallel respect and surveillance of the operational limits of a PWR.

This technical paper shows the impressive operational results after the implementation of ALFC in four German NPPs. It also gives perspectives for the approach to ALFC projects for PWR other than those of AREVA/SIEMENS-KWU.

Additionally, an implementation of ALFC in other NPPs can have further benefits, such as the following:
- The variation of low-leakage core loadings to minimise fuel costs and/or
- Nominal integral reactor power uprates can be possible.

These increased challenges led to several projects in PWRs to implement the ALFC:
- KKP 2 (Philippensburg NPP unit 2); utility EnBW; implementation in 2008
- KKI 2 (Isar NPP unit 2); utility E.ON; implementation in 2014 (August)
- KBR (Brokdorf); utility E.ON; implementation in 2015 (May)
- KKW (Grohnde); utility E.ON; implementation in 2015 (October)
- KKG (Gösgen-Däniken in Switzerland); utility ALPIQ; project started in October 2015; implementation will be in 2017.

Regarding the three E.ON-projects and the project in Gösgen there was/is only an ALFC software upgrade necessary; the needed digital I&C platform was implemented in forerunner projects. Before the implementation of the ALFC in the mentioned NPPs itself, the ALFC software was tested at the plant-specific training simulators together with the shift personnel (reactor operator, shift leader), the responsible engineers of the NPP and the AREVA design engineers.

Basics regarding the new adaptive reactor control concept

The possibilities of digital TELEPERM® XS technology have been fully employed with these ALFC projects and the possibility of physical parameterisation – adaptation to the reactor core – is being used. The reactor power control receives a new set of reactivity coefficients by the Service Unit (SU) with every new core loading. These coefficients and their changes are determined for each fuel cycle as a function of the reference boric acid concentration which decreases during the fuel cycle.

Knowing these coefficients, in conjunction with more precise calculation methods in the form of physical balances, allows a more accurate control
- With the power distribution fine control mode at full load operation and
- At part load during load cycles.

Near full load the relevant dead bands of the control rod bank position control can be reduced. This assures high control quality near the full load point which is important if the driving margins regarding power density peak limitation (Figure 2) are very low. These peak relevant limit values consider mainly the “Departure of Nucleate Boiling” (DNB), Pellet Cladding Interaction (PCI) and condition limit values for the LOCA accident analysis (LOCA: Loss of Coolant Accident).

An adaptive Power Distribution (PD) controller driven by a 2-point Xe-calculation (Xe: Xenon-135, a fission product which influences the reactivity balance) for the upper and lower core half helps to keep the spatial power distribution shape nearly constant for the whole fuel cycle which inhibits the beginning of any axial Xe oscillation. This helps to return to the conditioned full load situation – after having part load conditions. Furthermore, reactivity balances – including the calculation of the integral Xenon reactivity (regarding to the complete core) and dead time effects in the Chemical Volume Control System (CVCS) – help to return to full-load operation.

These mentioned ingredients are the basic necessities for a fully automated flexible load operation. Besides all these technical aspects, we had a first positive response in the German press (e.g., in the “Frankfurter Rundschau”) after implementation of ALFC in the NPP Brokdorf (KBR):

“[…]the control of the reactor power was improved to be able to support the energy transition with increasing renewable energy in the grid by flexible load operation according to the need of the load dispatcher[...].”

Self-adapting power distribution controller

Deborating the reactor coolant system in order to compensate the fuel burn-up leads to a redistribution of the power density into the lower core half. This redistribution means the plant engineers have to consider the following as part of their operating strategy:
- This redistribution can, in principle, be compensated by withdrawing the entire L-bank (= power distribution relevant control bank) in the first fuel cycle phase so that the axial power distribution signal of the in-core instrumentation remains constant.
- If the L-bank has reached a strategic upper position (either top of the core or a strategic upper position in which it is still capable of moving in both directions), further power density redistributions downwards can no longer be compensated.

The power distribution controller does not detect this redistribution as a xenon oscillation. This – slightly changing – equilibrium power distribution, which is important as target value for the part load transients, is automatically memorised in equilibrium conditions which occur between the begin Of fuel Cycle (BOC) over the Mid Of Cycle up to the End Of Cycle (EOC); see Figure 2. The situation in which it can be automatically memorised is the constant load operation with Xe-equilibrium. Normally this condition occurs every fortnight for physical calibration/measurement activities.

As a result, manual actions are not needed at all to adjust the power distribution controller because the controller adapts itself to the equilibrium power distribution. Therefore, only the corresponding L-bank manual set point adjustment is needed to define the long-term nuclear strategy within a fuel cycle. Regarding further future optimisations this shall also be automated. That means that in stationary conditions the PD-controller adapts the L-bank setpoint with the focus to optimise all margins to relevant limitation margins in the upper and lower core-half.
If load changes have to be carried out, this memorised equilibrium power distribution shape shall be kept as constant as possible (Figure 3) to inhibit any axial Xenon oscillation in the beginning. Following this objective, it is the best prerequisite to reach full load without any conflict with limitation values. This is managed impressively by the new PD-controller of ALFC, which is triggered by an axial 2-point Xe-calculation and which has (compared with older solutions) a very fast dynamic behaviour which is additionally adapted to control rod positions and to load gradients. After damping the Xenon oscillation to nearly zero, the PD controller adjusts the actual axial power density distribution to the above-described memorised shape exactly. Principally, the axial power distribution in the reactor core is disturbed by the control rod movement which is needed on the one hand to compensate the reactivity effects due to reactor power change and on the other hand to local reactivity effects due to the reactor coolant temperature changes caused by the temperature part load diagram. Principally, this triggers an axial Xenon oscillation; which can increase in larger reactor cores.

Summarised, all these measures allow:
- Maintaining the control of the PD do not require manual intervention of the reactor operator because the adaptive PD controller keeps the – automatically memorised – axial equilibrium PD shape nearly constant and hereby inhibits any axial Xe-oscillation – even in load following operation.
- And hereby the operation of the reactor within very small margins to the limit values of the limitation system (Figure 3) is possible.

ALFC ensures the very fast damping of any PD oscillation which is the prerequisite for accumulative stochastic load changes — even with small operating margins — as you will see in the following.

In parallel the reactivity management of ALFC ensures the optimal bank position with boric acid and demineralised water (BODE) injections considering the integral Xe-reactivity effects.

For cases in which a sufficient margin to limitation values cannot be ensured by the normal control algorithms the ALFC automatically uses the possibility to stop the load increase in the setpoint generation module in the turbine load controller as long as the normal control algorithms are able to increase the margins again. After this the turbine controller continues with the desired load increase.

Operational experience

Regarding the remote secondary control the load dispatcher changes or can change the load set point of the plant every 15 minutes according to the load balance of the grid and the prices in the electricity stock exchange. The experience in this operating mode is very impressive:

- Figure 4 shows this operation mode with a time scale of one day. The graph depicts the stochastic changes of the generator power within a band of approximately 500 MW and the fully automated compensation of the short term reactivity effects with the control rods of the D-bank (D: Doppler relevant reactivity) and the control of the axial power distribution mainly with the L-bank.

- Figure 5 shows this operation mode with a time scale of nearly one month. The graph depicts the stochastic changes of the generator power within a band of approximately 600 MW and the fully automatic compensation of the long-term reactivity effects of the Xenon reactivity with boric acid and demineralised water (BODE) according the basic design of any PWR. Additionally, the impressive correlation of Xenon in upper and lower core half is to be noted as the result of the new ALFC PD-controller.

- The increase of the demand for demineralised water – to compensate the marked integral Xe-oscillation (Figure 5) – depending on the reference boric acid concentration C_b is shown in Figure 6 in relation to the capacity of the evaporator in the coolant treatment system. Here you can see that there is no limitation for this operation mode up to the end of the fuel element cycle with approximately 80 ppm boric acid concentration.

Besides the remote secondary control of the plant by the load dispatcher the primary frequency control with larger load jumps becomes more and more important and well-paid by the electricity stock exchange. Figure 7 shows the successful qualification test of a -200 MW (–14 % at 1,460 MW) load jump downwards within 30 seconds and after 15 minutes back to 100 % – also within 30 seconds – and after a break of 15 minutes the same again. This qualification test – which is a worldwide record was carried out in in the EnBW Philippsburg 2 NPP, which has a nominal generator power of 1,460 MW.

The quantity of load changes during the last entire fuel cycle of KKI 2 (2014/2015)
is shown in Figure 8. Besides the impressive behaviour of new implemented ALFC, the increasing plant stress is considered by the manufacturer and the utility:

- The general German plant design by the manufacturer considers load following operation from the beginning. A part load diagram with a constant Average Coolant Temperature ACT minimises thermal stress and is optimal regarding reactivity effects; the in-core instrumentation with SPND (Self Powered Neutron Power Detectors) ensures an optimal surveillance of the power density in the reactor core, a fatigue monitoring system allows the surveillance of the thermal stress of relevant components, a reasonable quantity of load collectives is the basis of the plant design, etc. The licensing situation also considers this.

- The utilities are checking the load and stress collectives, observing the relevant measurements and adapt/modify – where required – the maintenance concept.

Benefits

Besides the described technical benefits of improved load flexibility, there are further economic benefits:

- Often a more precise reactor control allows a nominal power uprate and/or saving of fuel elements, as it was shown in the KKP2 NPP (the first ALFC project), because this control can operate with smaller margins regarding the discussed limitation values. Both – namely the nominal power uprate and/or saving of fuel elements – lead to an increased local power density.

- A load following operation with more part load conditions reduces the fuel burn-up and can lead to the minimisation of loading new fuel elements. According to actual experience of E.ON, it can be possible to save a quartet of fuel elements.

- The prices which can be obtained for the discussed grid operating modes lead – besides the two above-mentioned benefits – to a further economic benefit. This benefit alone allowed amortisation of the ALFC software upgrades of the three mentioned E.ON NPP within one year.

Additionally, there is a benefit for the nuclear safety:

- by minimising the needed manual interventions,
- by an automatic reactivity management with special process computer diagrams which inform the reactor operator,
- and by the automated flexible navigation depending on limitation margins regarding Pellet Cladding Interaction (PCI), analysis of Loss of Coolant Accident (LOCA), analysis of Reactivity Insertion Accidents (RIA).
**Perspective**

Besides the capability for further increased load gradients and jumps, which can lead to a further increased economic benefit, a feasibility study of a “predictive Xe-reactivity calculation input” for the reactor control shall be the next step to improve the reactivity management. This reactivity management leads to further minimisation of boric acid and demineralised water injection. An improved visualisation of the complete reactivity balance shows how the target power (e.g. 100%) can be reached from a part load situation.

**Start of a new ALFC project**

All the new ALFC projects started with a small feasibility study which analysed mainly the following aspects:
- I&C architecture,
- process analysis,
- possible load range and gradients for the several grid-relevant operating modes,
- suitable load controller for the turbine control,
- control rod movement concept,
- core instrumentation – capability regarding surveillance and control of the local power density,
- condition limitations regarding the relevant accident analysis,
- automatic sliding limit values for each core half regarding Pellet Cladding Interaction (PCI),
- part load diagram regarding ACT, main steam pressure, pressuriser level,
- load collectives regarding thermal component stress in the plant design,
- fatigue monitoring system,
- license situation of the NPP regarding load following operation,
- plant-specific simulator for training and test aspects,
- training needs,
- stepwise modular implementation of ALFC, e.g., implementing a reactivity management control regarding BODE-injection first.

The utility E.ON, which implemented three ALFC-projects in their NPPs Isar 2 (KKI 2), Brokdorf (KBR) and Grohnde (KWG), would support new ALFC projects – if desired – with its experience and know-how regarding:
- operation,
- maintenance,
- licensing of the NPP,
- evaluating component stress.

**References**


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