Advancing load following control

Thanks to new innovation the Advanced Load Following Control system can become the autopilot for a reactor. Andreas Kuhn and Konrad Schirrmeister, explain the concept

The increase in renewable energy with discontinuous, fluctuating electricity feed-in means nuclear plants have to operate flexibly. The challenge to nuclear is to operate as secondary grid control. In this case the load dispatcher controls the generator power remotely, with stochastic load changes and gradients of 30-40MW/min varying power by up to 600MW in total at a typical 1500MW Konvoi pressurised water reactor (PWR).

Several German and other PWRs have implemented Advanced Load Following Control (ALFC) developed by Areva in recent years. They include Philippsburg 2 in 2008, Isar 2 in 2014, Brokdorf in 2015, Grohnde in 2015 and Gösgen-Däniken in Switzerland in 2017. ALFC improves their load following behaviour for efficient and cost-optimised electricity generation.

ALFC-Predictor technology is an upgrade of ALFC that greatly expands its capabilities and allows more automation. It has the following benefits:

- More sustainable and profitable plant operation, due to enhanced capabilities for grid stabilisation operations.
- Very high reliability in making the power changes demanded by the load dispatcher, using fully-automated operation of the reactor to avoid any penalties imposed for not achieving the ramps – especially upwards to 100% power – requested by the load dispatcher.
- Increasing load flexibility at the end of the fuel element cycle by minimising boron and demineralised water injections.
- Increasing nuclear safety by an adequate visualisation of the automated reactivity management for the reactor operator, which is a WANO (World Association of Nuclear Operators) requirement.

These capabilities are achieved by the ALFC-Predictor technology on the basis of automated predictive reactivity management, which calculates all reactivity effects. That includes the transient time-dependent Xenon reactivity regarding the future "maximal load increase", which can be requested at any time. This ALFC-Predictor technology was installed at Isar 2 in July 2017 after extensive tests in the plant simulator. Isar 2 has since run nearly continuously in secondary grid control mode, with stochastic load changes.

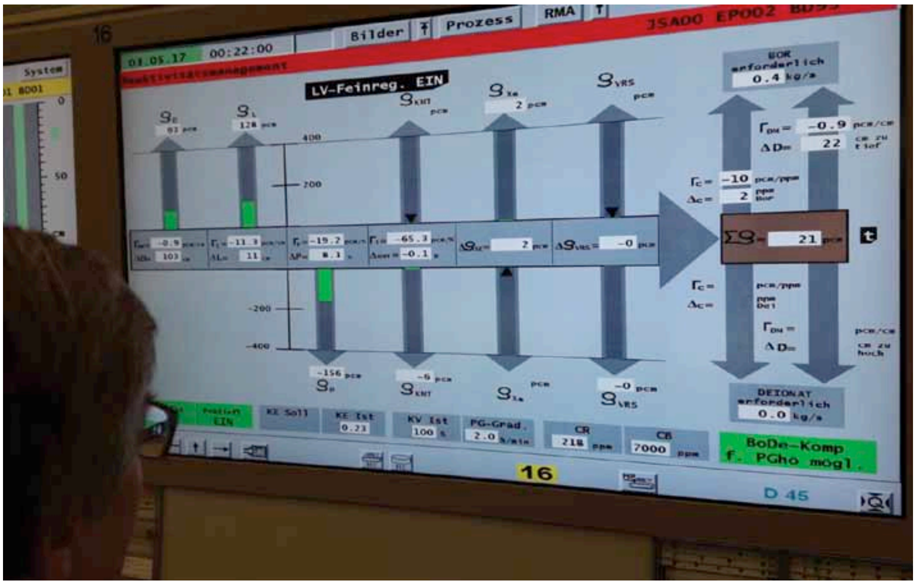


Figure 1. Visualisation of predictive reactivity management to illustrate potential performance limits to the reactor operator

In the basic version of ALFC algorithms adapt relevant coefficients to the reactor's physical changes during the nuclear load cycle. That allows precise control of the axial power density distribution in the reactor core. Finally, ALFC guarantees highly automated load flexibility, while respecting and monitoring the operational limits of a PWR.

Basics of the ALFC concept

The possibilities of digital Teleperm® XS (TXS) technology have been fully employed with all ALFC projects, for example adapting the physical parameters of the reactor core. The reactor power controller receives a new set of reactivity coefficients via the TXS service unit 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 for more accurate control of the axial power distribution (PD) of the core, using control rods. The relevant reactivity coefficients – which are used in a linearised way – are:

- Boron reactivity coefficient (Γ_C),
- D-Bank reactivity coefficient (Γ_D) for power distribution fine control near full load point,
- Average D-Bank worth for reactivity balances in conjunction with load cycles (Γ_{DA}),
- L-Bank reactivity coefficient (Γ_L),
- Coolant temperature coefficient (Γ_T),
- Power reactivity coefficient (Γ_P) – basically Doppler reactivity).

The reactivity coefficients – related to L- and D-Bank – are given related to the possible bank movement sequences, which are changed typically every fortnight.

An adaptive power distribution controller driven by a two-point Xenon-135 calculation for the upper and lower core-halves helps to keep the axial power distribution shape nearly constant during load-following operations, which inhibits the beginning of any axial Xenon oscillation. This helps to return to the conditioned full-load situation after being in part-load condition. A selfadaption algorithm of the power distribution controller automatically memorises the fuel burnup-dependent power distribution in Xenon equilibrium conditions as an orientation value during load changes. No manual power distribution setpoint is needed any more.

While monitoring the axial power distribution, all relevant condition limits are considered automatically – including Departure of Nucleate Boiling (DNB) during loss of flow events and loss of coolant accidents (LOCA) and pellet-cladding interaction (PCI). There is also automatic consideration of shut-down reactivity and reactivity insertion accidents.

The autopilot - an upgrade to ALFC predictive technology

The combination (in the predictive version of ALFC) of these reactivity coefficients with a predictive tandem Xenon simulation of the integral Xenon reactivity for the complete core allows for automatic integral reactivity management. This tandem Xenon simulation calculates the reactivity change by Xenon during the maximum ramp required by the load dispatcher at any time. Specifically it calculates:

- the actual concentration of Iodine-135 and Xenon-135 depending on the load change history,
- the predicted Xenon reactivity change within a maximal generator load ramp, which is defined by the maximum load gradient and the maximum power that can be requested by the load dispatcher at any time.

Automatic integral reactivity management includes also dead time effects in the chemical volume control system (CVCS). The reactivity effects automatically determine – via a reactivity balance – the necessary bank position as a setpoint at part load. No manual intervention is needed except for extra-long part load operation, when the bank position setpoint would be set manually into a control-rod-free position. A parallel reactivity and mixture balance controls, whether boric acid or demineralised water (BODE) injection can be avoided or whether reactivity deviations can be compensated for during a maximum load ramp by a boric acid or demineralised water injection. If compensation is not possible, the ALFC first starts BODE-injection and if this is not sufficient the reactor operator will be informed.

The reactivity balance can be visualised in the process computer by the diagram "reactivity balance for maximal load increase". The reactor operator can see the automatic setpoint settings and any actions taken by the reactor control. If the automatic predictor influence is switched off, the diagram proposes manual setpoint adjustments.

Operational experience

In remote secondary control the load dispatcher can change the load setpoint of the plant instantaneously, according to the load balance of the grid and electricity prices. Figure 2 shows this operation over a month at Isar 2 in 2014. The graph depicts stochastic power changes within a band of approximately 600MW and the automatic compensation of the long-term reactivity effects of the Xenon with boric acid and demineralised water (BODE), according to the basic design of any PWR. The impressive correlation of Xenon in the upper and lower core-halves (blue and green lines) is the result of the ALFC PD-controller.

Figure 3 shows an excerpt of the ALFC-Predictor commissioning test at Isar 2 in August 2017, with a ramp from 100% to 47% to 100% with a power gradient of 2.1%/min and a part load time of 6 hours. The diagram shows the reactivity balance at the end of this part-load period (Xe-maximum) and all the reactivity effects in reaching full load.

- The inserted banks at part load can deliver positive reactivity – L-Bank 184 pcm and D-Bank 757 pcm – based on their insertion depth and reactivity coefficients. The L-Bank is inserted to keep the power distribution shape constant (governed by the PD-controller) and will be withdrawn again during a load increase, whereas the D-Bank-Sum (ΣD) mainly compensates the reactor-power-dependent "Doppler"reactivity.
- Increasing the reactor power to full load will cause a reactivity loss of 782 pcm due to the "Doppler"-effect with 14.8 pcm/%PR.
- Increasing the average coolant temperature by 4.8K, according to their load dependent setpoint (shown in an additional process computer diagram) will cause a reactivity loss of 202 pcm with reactivity coefficient of -42.6 pcm/K.
- The predictive calculated Xe-burnout will deliver a positive reactivity of 94 pcm.
- The reactivity contribution of CVCS follow up flow is zero pcm.
- The reactivity sum of 56 pcm is equivalent to the control margin at full load with a slightly inserted bank. Therefore, the correction of the boron concentration is nearly zero. Full load can be reached perfectly.

To get a feeling of the time dependent behaviour of this reactivity balance in the part load situation, the last five hours part load and the beginning of the load increase are shown:

- Due to Xenon increase at part load the reactivity profit (ΔRHO-Xe) increases if the maximal load ramp starts.
- Therefore, the bank insertion at part load can be decreased, which is automatically done via the variable "setpoint influence" or SI.
- Starting the load ramp the integral contribution of the Xenon reactivity profit (ΔRHO-Xe) regarding the rest of the ramp decreases. The L-Bank will be withdrawn according to the needs of the PD controller, so the needed reactor power related contribution of the Doppler relevant D-Bank increases. This causes increases of the "setpoint influence" or SI.

Since implementation in July 2017 and after commissioning tests of the ALFC-Predictor

Figure 2. Xe-Predictor optimises stochastic load changes ΔPG by load dispatcher

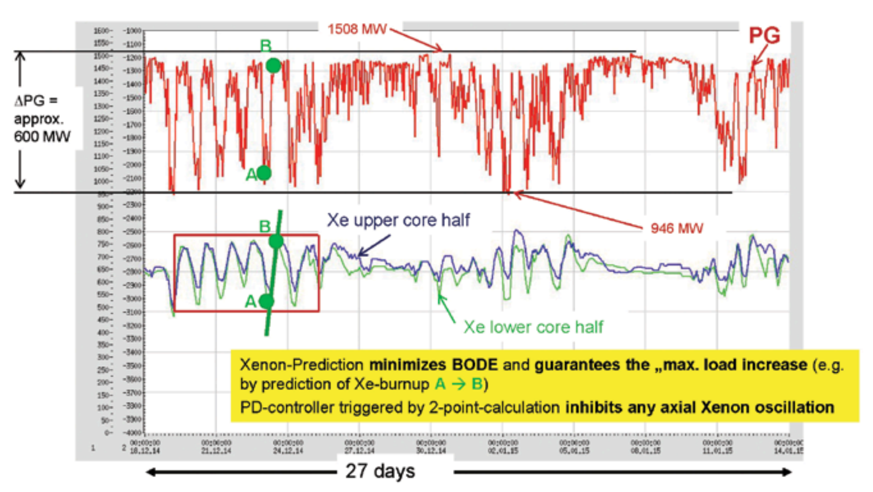
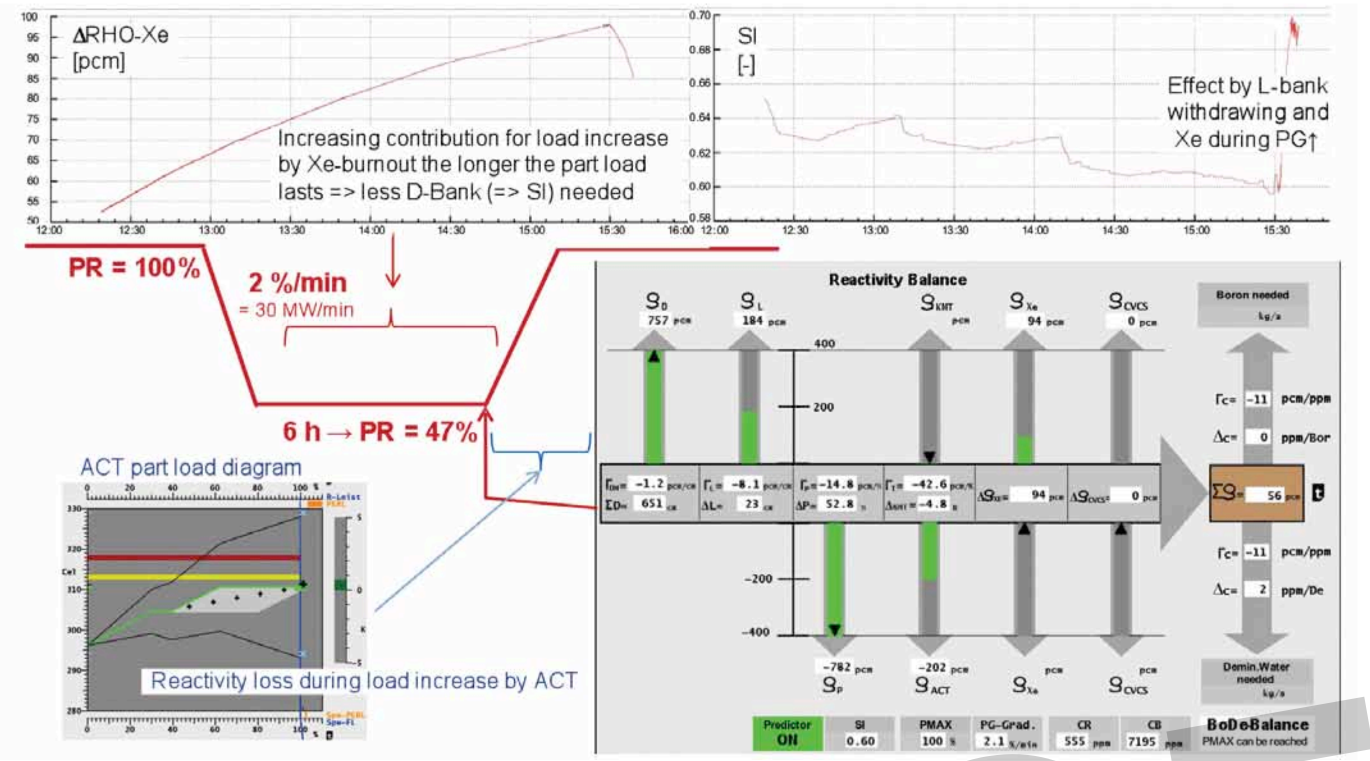


Figure 3. ALFC-Predictor commissioning test at Isar 2 in 2017



upgrade Isar 2 has been operated nearly continuously in the remote controlled stochastic secondary grid control mode, with positive feedback received from the customer.

Benefits of system

The ALFC ingredients guarantee a fully automated flexible load operation and ensure that the plant can return to full-load operation at any time, if required by the load dispatcher.

Additionally, nuclear safety is increased because:

- Fully automatic operation considers all safety relevant limits without any manual intervention, which minimises human errors.
- If any safety relevant limit cannot be automatically ensured a load increase will be stopped automatically. If necessary staggered countermeasures will be activated, e.g. automatic load decrease.
- Process diagrams keep the reactor operator informed.

As well as the technical and safety benefits of improved load flexibility, there are economic benefits:

- Often precise reactor control allows a nominal power uprate or saving of fuel elements, as happened at Philippsburg 2 (the first ALFC project), because this control can operate with smaller margins. Both increase local power density.
- A load following operation with more part-load reduces fuel burnup and reduces the need for new fuel elements. According to experience at PreussenElektra GmbH saving a quarter of fuel elements may be possible.
- The revenue from grid support services is considerable. This revenue allowed the ALFC software upgrades to be amortised in the three PreussenElektra plants within one year.

Starting a new ALFC project

Each of the ALFC projects started with a small feasibility study, which analysed the relevant boundary conditions to other automation systems, to the control room, the affected software modules, the required process-related tests, etc.

In order to use the ALFC in PWRs other than those from Areva/Siemens-KWU the approach should start with a more detailed feasibility study. This would look at the I&C architecture and define the process (e.g. possible load range and gradients, control rod movement concept, core instrumentation, fatigue monitoring system and others). The feasibility study should also consider the licence application for load-following operation, the use of a plant-specific simulator for testing, training needs and the potential for step-wise implementation of the system. A step-wise approach could include initial implementation of the reactivity management control with BODE-injection, followed later by additional steps.

PreussenElektra, which implemented three ALFC-projects at Isar 2, Brokdorf and Grohnde, would support new ALFC projects with its experience and know-how regarding operation, maintenance, licensing and evaluating component stress. ■

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