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Minimum Throttling Feedwater Control in Vver-1000 and PWR NPPs

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ABSTRACT

This paper presents an approach for the design and implementation of advanced digital control systems that use a minimum-throttling algorithm for the feedwater control. The minimum-throttling algorithm for the feedwater control, i.e. for the control of steam generators level and of the feedwater pumps speed, is applicable for NPPs with variable speed feedwater pumps. It operates in such a way that the feedwater control valve in the most loaded loop is wide open, steam generator level in this loop being controlled by the feedwater pumps speed, while the feedwater control valves in the other loops are slightly throttling under the action of their control system, to accommodate the slight loop imbalances. This has the advantage of minimizing the valve pressure losses hence minimizing the feedwater pumps power consumption and increasing the net MWe. The benefit has been evaluated for specific plants as being roughly 0.7 and 2.4 MW. The minimum throttling mode has the further advantages of lowering the actuator efforts with potential positive impact in actuator life and of minimizing the feedwater pipelines vibrations. The minimum throttling mode of operation has been developed by the Ukrainian company LvivORGRES. It has been applied with great deal of success on several VVER-1000 NPPs, six units of Zaporizhzha in Ukraine plus, with participation of Westinghouse, Kozloduy 5 and 6 in Bulgaria and South Ukraine 1 to 3 in Ukraine. The concept operates with both ON-OFF valves and true control valves. A study, jointly conducted by Westinghouse and LvivORGRES, is ongoing to demonstrate the applicability of the concept to PWRs having variable speed feedwater pumps and having, or installing, digital feedwater control, standalone or as part of a global digital control system. The implementation of the algorithm at VVER-1000 plants provided both safety improvement and direct commercial benefits. The minimum-throttling algorithm will similarly increase the performance of PWRs. The paper summarizes an actual VVER-1000 plant modernization experience and the demonstration of applicability to PWR plants.

1. INTRODUCTION

Feedwater control systems remain the center of attention for the control system experts in the Commonwealth of Independent States (CIS) and Western countries. The reason for such interest is their importance in power units' safety, which is reflected in classification of these systems, that is, 3N class according to the classification for Russian-design plants (Ref. [2] and [3]) and category B per IEC 1226 (Ref. [1]), i.e. systems important for safety. In fact, failure of these systems, even in unit steady operating modes, could lead to initiation of events sequences such as reactor trips or turbine trips and, for VVERs, reactor coolant pumps trips, which challenges the operators and impact unit availability. Since their stability and regulation effectiveness determine whether the transient would result in a unit shut-down, heavy burden is imposed on these systems in dynamic modes.

Feedwater control systems, including steam generators level regulators and turbine driven feedwater pumps regulators, affect the unit safety as well as its efficiency and other operational behavior issues.

This article introduces an innovative feedwater control system developed for VVER reactors by the Ukrainian company LvivORGRES and being jointly studied by LvivORGRES and Westinghouse for VVER and PWR reactors.

2. MINIMUM THROTTLING ALGORITHM FOR VVER PLANTS

VVER-1000 reactors are equipped with four horizontal steam generators. One characteristic of these important reactor features is the dynamics in level variations in case of imbalance transients between steam and feedwater flows, and strict requirement to regulating control effectiveness. Units' performance requirements are greatly significant because VVER units should remain operational when one or two loops are cut off, one of two turbine driven feed water pumps are off, in cases of net load trips, partial load drops and turbine runbacks. Accordingly, prescribed accuracy of level regulating control must be achieved during all design normal operation transients.

The VVER units level regulating control task becomes even more complex as a result of certain operational features of feed water control valves manufactured in Russia. These are the unbalanced vane valves having an asynchronous three-phase motor actuator with a power of 5.6 kW that does not allow for frequent ON-OFF cycles.

Currently most VVER units are equipped with analog control systems hardware, which do not allow the implementation of complex regulation processes. At these units, steam generator regulating system performs marginal functions; therefore, not providing automation in all operational modes. At such units, the turbine driven feedwater pump speed regulators act to maintain pressure drop at the feedwater control valves. Pressure differential allows for certain margin of flow for balancing the disturbances. In order to reduce steam flow to turbine driven feedwater pumps, thus, increasing power generation, even in analog control systems, LvivORGRES suggested maintaining pressure drop proportional to load squared, as opposed to keeping it constant.

The transition from analog to digital regulating control hardware has led to the control algorithms upgrade. First implementation of digital steam generators control system for

VVER-1000 units was performed in 1985, utilizing ASYT-1000-2 hardware manufactured by Monolit, a Ukrainian company in Kharkov (Ref. [4]).

At that time, the first system, which used feedwater control valves minimum throttling concept, was applied. In essence, steam generators feedwater control is being performed with almost wide-open feedwater control valves.

The valve of the most loaded steam generator, or of the steam generator with the highest hydraulic resistance of the feed water line, is wide open, and the level in this steam generator is maintained by controlling the turbine driven feedwater pumps output, while the valves of the other steam generators are slightly throttling under the action of their control system.

During this process, at rated load, pressure drop at the feed water control valves is reduced which allows increasing the unit power output (0.7 MW and 2.4 MW in specific examples) due to the steam supply decreasing to the turbine driven feedwater pumps.

Therefore, it was for the first time for a VVER unit that the modulating control system performs its function of plant parameters control and, at the same time, generates power by itself. In addition to this, minimum throttling is important as far as safety is concerned. That is, reduction of pressure differential at vane valves decreases adjustment forces applied to the actuator, which increases its lifetime and reliability. The absence of throttling in valves reduces feedwater pipelines vibration and erosive wear of valve gates and seats.

For example, at Khmelnitsky NPP, commissioned in 1987 and equipped with an analog control system, the erosive wear reached its limit, which necessitated the valve replacement, while no such action was required due to no erosive wear detection at Zaporizhzha NPP, commissioned three years earlier and since 1985 using the digital feed water control system in minimum throttling mode.

Starting with first implementation of the minimum throttling mode, several enhancements have been introduced, specifically

- Load range, for which minimum throttling is performing reliably, was defined
- System automatic readjustment, following load change, was implemented
- Automatic transition from minimum throttling mode to pressure differential control mode, in case load decreases, was implemented.

The most significant improvement in the base concept was its modification for unit safe performance in case of failure of a fail-as-is feedwater control valve. If a malfunction of one of the main feedwater control valves is detected, the system switches from controlling the level in the corresponding steam generator to maintaining its level in the steam generator by controlling turbine driven feedwater pumps output. Furthermore, to provide control margin that allows to compensate disturbances for the remaining steam generators, the system opens the bypass feedwater control valves for these steam generators and closes the bypass feedwater control valve at the steam generator with failed main feedwater control valve. The enhancement described above has prevented several unit trips.

This digital steam generator regulating control system has been implemented at commercial units with K-60/1500-2 turbines and proved itself in a long run. Such commercial units include six (6) units at Zaporizhzha NPP in Ukraine and two (2) units at Kozloduy NPP in Bulgaria.

However, there are several drawbacks related to the minimum throttling systems original design process by LvivORGRES. The major shortcoming is that all technical issues have been resolved empirically through conducting multiple tests at power production units and accumulating the operational experience over the years. No stability rated analysis were performed, nor was the process dynamics verified using scaled models. Moreover, hardware and software, intended for the corresponding type of scale modeling, were not developed at that time either. It is worth noting, though, that LvivORGRES has participated in startup and adjustment activities at many power units and gathered vast experimental data related to VVER unit operational dynamics, which established the basis for subsequent research.

3. ADVANCED STEAM GENERATOR FEEDWATER CONTROL SYSTEM FOR VVER PLANTS

The cooperation between LvivORGRES and Westinghouse began in 1994. The first joint project was the replacement of the feedwater control valves with Western-type pneumatic valves at two Kozloduy power units. Westinghouse defined the feedwater control valves design, while LvivORGRES developed Technical Specification for new control system interface and performed system adjustment.

In 1996 within commission of European Community TACIS scope, a tender was opened for feedwater system modernization for South-Ukraine NPP Units 1 and 2. In preparation to this tender, Westinghouse Electric Belgium (WEB) realized that the best technical solution would be the application of digital control system with LvivORGRES functional design along with the improvements which are the basis of Westinghouse advanced digital feed water control system implemented at a number of European and US NPPs. Such innovative approach to algorithms became one of the decision elements for the Tacis experts to grant this project to Westinghouse.

The WEB project involved the supply of motor operated feed water control valves, with two French subcontractors, Emerson (Fisher-Rosemount) for the valves and Bernard for the motors (pneumatic operator was excluded by the specification). The valves are pressure equilibrated, which permits to minimize the power of the actuator. The design of combination of valve with motor actuator was developed specifically for this project. The motor actuator is specified to introduce no limit on the number of actuations. Nevertheless, endurance qualification was performed. The positioner is designed to respond to a continuous position demand 4-20 MA (as opposed to ON-OFF design). Positioning speed is a function of position error, decreasing for small errors.

The control cabinets were manufactured in European community with the WDPF design and programming was performed by the Ukrainian company Westron.

The modern design process was utilized for the project. It included several revisions of the functional design by WEB and by the Tacis experts, system verification and validation. A plant model was designed for the system closed loop testing. This model includes all unit equipment and unit control systems that may affect the feed water control system in transients such as:

- Reactor with rod control, power regulator and power limiting protection system
- Reactor coolant loops and pumps

- Steam generators
- Steam collector with relief valves to atmosphere and to condenser and with appropriate regulators
- Turbine with digital electro-hydraulic governing system
- House steam supply collector with interlocks and pressure regulators
- Deaerators with level and pressure regulators
- Turbine driven feed water pumps
- Feed water pipelines and feed water control valves with actuators and positioners

The plant model performance under different transients was verified using experimental dynamic of VVER-1000 units. Special model verification report shows high model accuracy and its suitability for feed water system closed loop testing.

Plant model interfaced with target controller cabinet in real time mode using the reflective memory tools. This allowed control system adjustment and closed loop testing on the design stage. It made it possible to minimize scope of system testing on site after first successful transient tests proved the model accuracy.

The design package which includes more than 40 documents was submitted to Tacis experts and to Ukrainian nuclear authorities. As the result of licensing the system design, the system was approved for installation and commissioning (Ref. [5]).

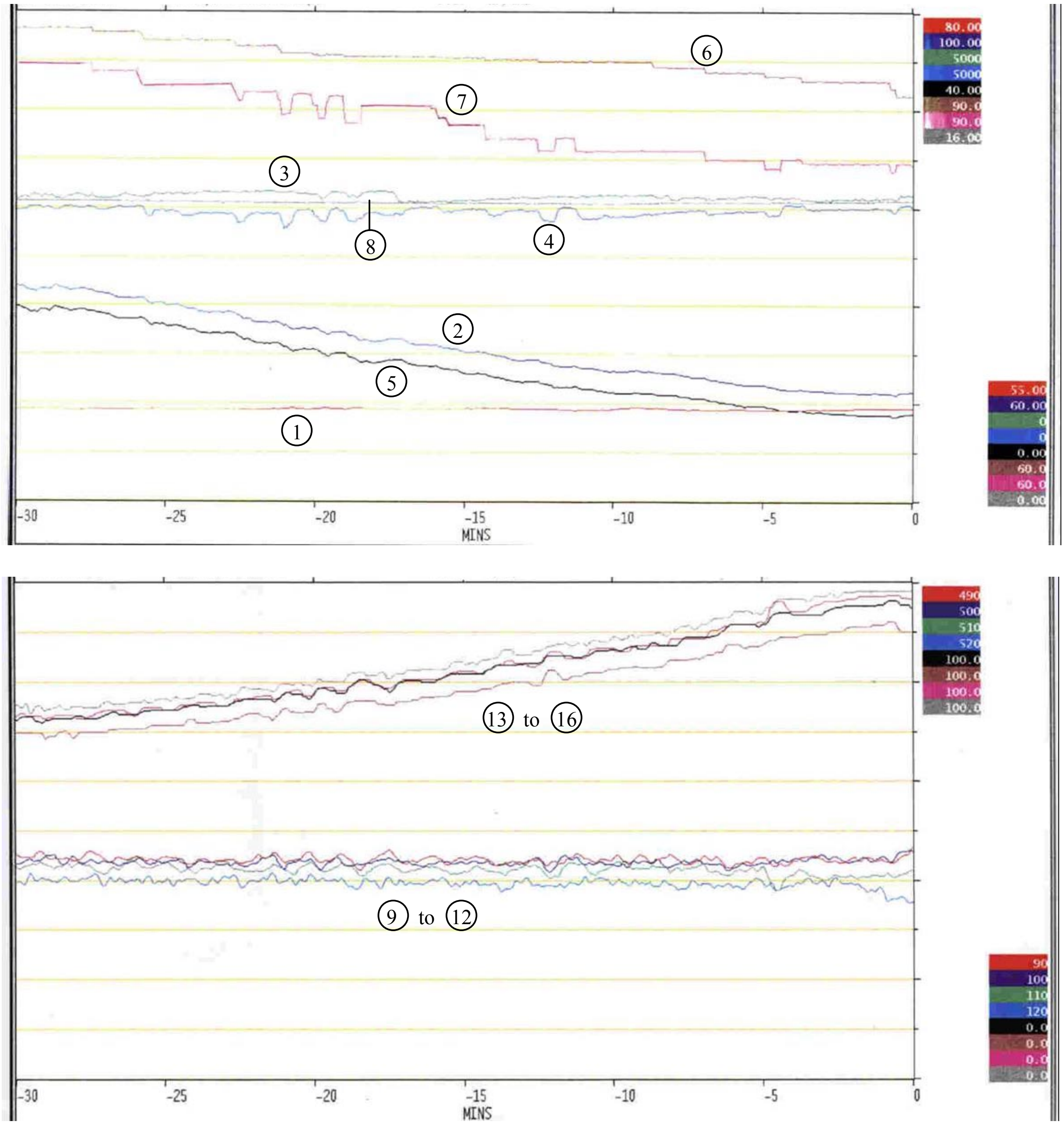
During system commissioning at South-Ukrainian NPP units 1 & 2, the reactor coolant pump trip operation mode switchovers and turbine 300 MW load reduction transients were tested. During these tests and during a real turbine trip transients in the period of system trial operation, the control system ensured control of the steam generators level in the design limits.

Figure 1 illustrates the performance of the minimum throttling algorithms during the control system switchover from pressure drop regulating mode to minimum throttling mode at South Ukraine NPP. During the transfer process the feed water pumps admission valves closed from 85 to 79 percents, the feedwater control valves opened from 75 to about 100 percents and pressure drop decreased from 16 kg/cm^2 to 8 kg/cm^2. Steam generators levels during transfer did not change.

The feedwater control system and feed water control valves now operate on South Ukraine NPP units 1 and 2 after successful completion of the startup following their installation. This unit is expected to have, as a result, significantly increased availability. Unreliable ON-OFF valves requiring motor water spray cooling are replaced by very reliable continuous positioning control valves with low power actuator and no limit on number of actuations. A very sophisticated control system permits the unit to operate with minimized losses in the minimum throttling mode and enables to accommodate without reactor trip and without operator action a large number of situations, operation with loop out of service, operation with feedwater control valve failure in one loop, reactor coolant pump trip and startup, feed water pump trip, load variations, partial turbine trip, turbine trip, net load trip, sensor failure and processor failure.

A design approach similar to the one described above was adopted for South-Ukraine NPP Unit 3. The successful implementation of Unit 1 and 2 systems was the basis of the intention of the NPP management to apply analogous reconstruction at Unit 3. Similar feedwater control valves were purchased and Westron was ordered to supply the digital system for which a new hardware platform based on Westron's "Vulkan-M" complex was applied. LvivORGRES carried out functional design and functional software design. The activities at Unit 3 included the complete set of design modeling test tasks since Unit 3 differs from the rest of the South-Ukraine units and Zaporizhzha units by the turbine type K-60/3000 and secondary side technological process. System implementation was accomplished in 2003, proving the applicability of the minimum-throttling mode to all types of VVER reactor units.

Figure 1: Minimum Throttling Transition Process



Recorded Parameters

N°	Recorded Parameter	Units	Scale
1	Steam pressure	kg/cm²	55-80
2	Feedwater pressure	kg/cm²	60-100
3 (4)	Feedwater flow after feedwater pump A (B)	m³/s	0-5000
5	Feedwater/steam headers Δp	kg/cm²	0-40
6 (7)	Pump A (B) steam control valve lift	%	60-90
8	Steam pressure at turbo-pump inlet	kg/cm²	0-16
9	Steam generator 1 level	mm	90-490
10	Steam generator 2 level	mm	100-500
11	Steam generator 3 level	mm	110-510
12	Steam generator 4 level	mm	120-520
13 to 16	Loop 1 (2) (3) (4) feedwater control valve lift	%	0-100

4. DEMONSTRATION OF APPLICABILITY OF MINIMUM THROTTLING FOR PWR PLANTS

The minimum-throttling mode implementation experience at VVER power units and obvious commercial benefits in using such mode of operation, as well as interest expressed by certain PWR NPPs managements, were the bases to initiate a demonstration program for the PWR reactors by Westinghouse, with the participation of LvivORGRES. Besides the apparent differences in dynamic factors between horizontal and vertical steam generators, the following issues have been considered with respect to system stability.

- Use of the cascading control algorithms for steam generator feed water control as opposed to three-signals algorithm customary for VVER units
- Implementation of pneumatic and hydraulic fast-acting actuators for feed water control valves and turbine driven feed water pumps.

A first step has been conducted in which a simplified steam generator and control system prototype, implemented in Mathlab Simulink environment, has been employed. The results of the modeling research at this stage prove the possibility of system applications for the PWR units. Especially beneficial for system stability is absence of the dead zone in control systems with pneumatic/hydraulic actuators which are mandatory in control systems with ON-OFF electrical actuators. Minimum throttling mode successfully interacts with cascading algorithm of the steam generator feed water control which allows to minimize redesign to currently used PWR units control systems. As a result of the first stage, the system structure has been defined for implementation at the second stage of demonstration on the Westinghouse simulation platform. This second stage, which is ongoing, consists of the further demonstration with full-scale computational model by Westinghouse.

5. CONCLUSIONS

For VVER-1000 NPPs, the minimum throttling feedwater control algorithms are demonstrated to operate successfully and achieve a unit output power increase while minimizing the duty of the feedwater control valves and the feedwater piping vibrations. Work for demonstration of applicability to PWR reactors, is in good progress.

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