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Testing and Utilization of Loviisa Full Scope Apros Model in Engineering and Development Simulator

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ABSTRACT

Loviisa Nuclear Power Plant (NPP) includes two PWR units with VVER-440 reactors. The Plant units are commissioned in 1977 and 1980 and have operating license for 50 years. The plant has been in operation over 30 years using mostly original Instrumentation and Control (I&C) systems. A large I&C renewal is needed to guarantee the availability of the plant until the end of the plant lifetime.

Simulators are used extensively in Loviisa automation renewal project. Alongside the automation renewal project also Training Simulator will be updated with new state of the art Apros based process models. Apros is a multifunctional simulation software tool developed by Fortum Nuclear Services Ltd and VTT Technical Research Centre of Finland.

A full scope Apros model of Loviisa NPP including process, automation and electrical power system models has been developed. Virtual copy of operational I&C provided by Siemens and the safety I&C system provided by Areva has been connected to the Apros model.

The Engineering and Development (E&D) simulator plays an essential role in development and testing of process models and simulation software tools that are utilized in the project. The E&D simulator also provides an excellent environment for testing and development of Human Machine Interface (HMI) and operating procedures.

Exploitation of a full scope E&D simulator in Loviisa NPP automation renewal project is described in this paper. Software tools developed and used in E&D simulator are introduced and methods used for testing Apros model are discussed. Finally the benefits from multifunctional full scope E&D simulator are concluded.

1 BACKGROUND

Loviisa Nuclear Power Plant (NPP) operated by Fortum is located about 100 kilometres east from city of Helsinki. In Loviisa NPP there are two PWR units with reactors of type VVER-440. The first unit has been in operation since year 1977 and the second was commissioned in 1980. In year 2007 a new operating license until 2027 and 2030 was issued for both reactors. Long operating license presumes continuous inspections, enhancements and also large renewal projects to ensure availability and safe operation of the plant.

1.1 Loviisa NPP I&C Renewal Project

Loviisa automation renewal project [1] was started in year 2005. The original analogue I&C system will be replaced with digital I&C. The supplier in the project is a consortium consisting of Areva NP GmbH and Siemens AG. Digital I&C consists of Areva Teleperm XS (TXS) safety I&C system and Siemens SPPA T2000 operational I&C. Hardwired manual backup will be implemented to back up digital I&C in most safety critical functions. Loviisa NPP main control room will also go through remarkable changes. Hardwired desks and panels will be replaced by monitor based Human Machine Interface (HMI). A Qualified Display System (QDS) delivered by Areva will be used to control and monitor TXS safety I&C. For T2000 operational I&C OM690 control and monitoring system is used.

The I&C renewal in Loviisa NPP will be done in stages. The first stage included limited parts of both safety classified and non safety classified I&C systems. The first stage was executed in unit 1 in 2008 and in 2009 in unit 2. The installations are carried out during the normal annual outages. In this way loss of production will be minimized and the renewal can be realized economically.

1.2 Simulators in Loviisa NPP Training Simulator Renewal

Simulators are used extensively in Loviisa I&C renewal project. Simulators are used for engineering, development, testing and training. All the simulators in the renewal project are based on Apros simulation software [2].

Alongside the I&C renewal project, a new Loviisa NPP Training Simulator will be built next to the old training simulator. The new training simulator will include process models implemented with Apros and virtual I&C provided by Areva and Siemens, the suppliers of the I&C renewal project. When I&C renewal is implemented in stages, also training simulator renewal must adopt to it. Having two separate training simulators during the I&C renewal makes it easier for the renewal project to organise the simulator updates. When the old simulator with the old configuration is still used for training the operators the new simulator can be updated to next stage of the I&C renewal. In this way it can be ensured that there is always an almost plant identical training simulator and adequate training can be provided to plant operators.

The Engineering and Development (E&D) simulator located in Espoo Finland plays an essential role in the development of the new Loviisa NPP training simulator. Utilization of E&D simulator in Loviisa NPP training simulator update and in I&C renewal is introduced in this paper.

Testing simulator is used to perform closed loop testing of the digital I&C. Testing simulator is located in Germany in the premises of Areva and Siemens. The process models are the same as those used in the E&D simulator. Process models are connected to the real or virtual I&C. The safety critical automation is tested both in real hardware and virtual configurations. Utility automation is tested in virtual configuration only. In the Testing simulator I&C system is connected to the process simulator so that it acquires the measurement signals and sends control commands to the field devices. Testing simulator has been operated in co-operation with Fortum and I&C suppliers to complement other test methods in the factory acceptance tests. Simulation assisted automation testing was perceived to be effective. Such errors were found that would have been very difficult to find with other means. For instance such errors were found that originate from faults in the initial data of the I&C renewal. Errors were found because I&C system got a realistic process response from the simulation model. [3]

1.3 Apros – Advanced simulation software

Simulation models describing the process will be developed using Apros (Advanced PROcess Simulator) [2]. Apros is multifunctional simulation software created by Fortum Nuclear Services Ltd and VTT Technical Research Centre of Finland for full-scale modelling of dynamic processes. Apros is used in 25 countries. Users are e.g. nuclear and combustion power plants, automation suppliers, paper mills, safety authorities, universities and solid oxide fuel cell system developers. Also automation and electrical systems can be modelled using the comprehensive model library.

The function of the device models are one-to-one analogous with the function of the real devices. Solution algorithms are hidden to components and needed calculation level objects are generated automatically when process level components are created through graphical user interface. Users own modules can be included in the calculation using Apros external models.

Apros thermal hydraulic model library contains several different thermal hydraulic models e.g. one dimensional water/steam/gas flow, single phase flow, containment and one for the steady-state flow with tank dynamics. Different thermal hydraulic models can be mixed to the same Apros model.

Apros can be connected to I&C systems and human machine interfaces with standard OPC DA and OPC XML DA communication interfaces. Apros provides also lower level Apros Communication Library (ACL) for fast communication.

Apros has been used successfully in many solutions e.g. for safety analysis, training simulators and simulator assisted automation testing. [2]

1.4 Apros models used in the simulators

During the Loviisa NPP training simulator update a full scale NPP model utilized in all the simulators in the project is developed. Process components, electrical systems and also most parts of I&C systems are implemented in Apros model.

In a training simulator, real time simulation speed is expected in every case. Reaching real time simulation speed with a full scale training simulator equipped with six-equation models and 3-Dimensional model of the reactor is found out to be a challenging task. To achieve this goal, the process model is divided into four applications. Secondary side, primary side, containment and reactor core are all implemented in separate Apros models that run in different computers. In Primary side model and in secondary side model all the main loops and safety systems are modelled.

In the primary side, one-dimensional two-phase flow model (six-equation model) is used. Six-equation model simulates the behaviour of a system containing gas and liquid phases. The six-equation model is based on the one-dimensional conservation equations of mass, momentum and energy. From the equations pressures, void fractions, phase velocities and phase enthalpies are solved. When the equations are applied to both the liquid and gas phases, a total of six partial differential equations are used. The phases are coupled to each other with empirical friction and heat transfer terms which strongly affect the solution. The partial differential equations are discretized with respect to time and space, and the resulting linear equation groups are solved by the matrix equation-solving system of Apros [4]. In the secondary side, the process is modelled with homogenous three-equation model. It cannot solve gas and liquid phases separately but it calculates faster than six-equation model [5]. Anyway, sufficient accuracy for the secondary side is achieved with three-equation model.

Training simulator will include a 3-Dimensional model of the reactor. Prior to building of the simulator core model, an extensive comparison was carried out between Apros and VTT's in-house reactor analysis code HEXTRAN that has been widely used in Loviisa licensing calculations by the Finnish safety authority STUK. The agreement between Apros and HEXTRAN calculation results was generally acceptable. It was concluded that Apros core model was suitable for modelling the training simulator core. On the basis of previous experience on the speed of various Apros core models a model with approximately 100 thermal hydraulic flow channels divided into 10 axial sections was assumed to be realistic for real time performance. Various alternatives were studied resulting into a model with 111 channels. The simulator core model has been tested with comprehensive set of test cases against data from current Loviisa training simulator, data from some plant transients and calculations carried out with other models. The results indicate that the new 3-D simulator model is suitable for application in the training simulator. At the moment the simulator core and process model can be run in real time in parallel combination either with separate computers or using a multi core computer [6]. The models communicate with each other using ACL data transfer.

2 ENGINEERING AND DEVELOPMENT SIMULATOR

E&D simulator is used in several tasks in Loviisa automation renewal project. E&D Simulator plays an essential role in testing and development of new Loviisa NPP training simulator. It has been used also for Human Machine Interface (HMI) development and Operating procedure testing.

Figure 1: E&D simualor is used in several tasks in Loviisa Automation Renewal Project

2.1 E&D Simulator configuration

The heart of the E&D simulator is the Apros models. Models described in chapter 1.4 are tested and utilized in the E&D simulator.

In the E&D simulator most parts of the I&C systems are implemented in the Apros models. Currently Loviisa plants are operated from hard wired panels. Process Monitoring System (PMS) by ABB is used for monitoring purposes at the plant. PMS has been modified for the E&D simulator so that it can be used for operating the process model. PMS is connected to Apros with ACL.

Some I&C systems of auxiliary processes are already implemented with virtual copy of T2000. The virtual I&C system is also connected to Apros with ACL. A part of safety I&C system, Preventive Protection System (PPS), is implemented with emulated TXS model provided by Areva. It is connected to Apros as an external model, which means that it has direct access to some specified variables of Apros model. The first parts of T2000 operational I&C and TXS safety I&C are installed in the E&D simulator in order to test the interfaces between Apros models and I&C systems provided by the suppliers.

After the I&C renewal some analogue I&C system will still exist in Loviisa NPP. In the plant hardwired safety panels will be used to backup some safety critical functions. In the E&D simulator virtual panels are used for testing and validation of the new hardwired panels (Figure 2). By using virtual panels instead of real hardwired panels configuration can be modified easily. Using virtual panels is also a cost effective solution since no IO-system for hardware is needed.

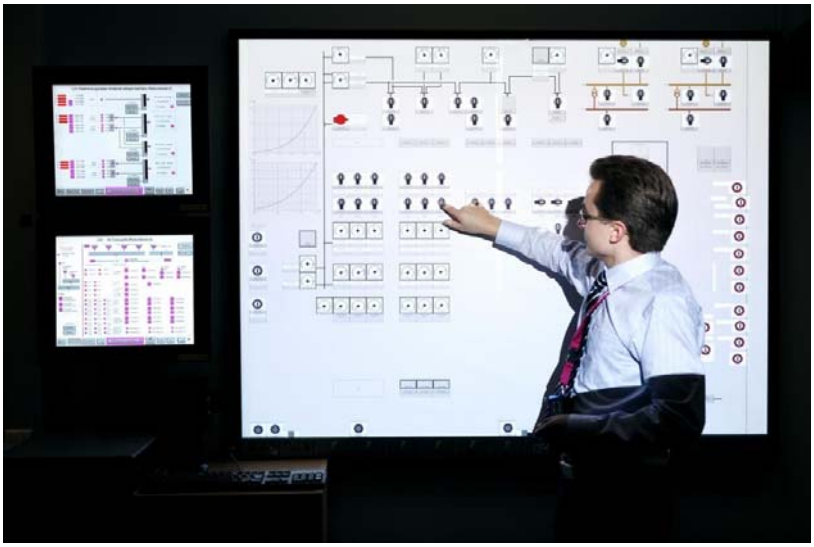

Figure 2: Virtual Panels can be used to imitate hard wired panels.

E&D simulator contains tools for controlling and managing the Apros models and I&C systems. In Loviisa NPP Training Simulator renewal project a new instructor station software Training Station is developed [7] in co-operation with Fortum Nuclear Services Ltd and VTT Technical Research Centre of Finland. In E&D simulator the Training Station is used for managing and controlling the simulator. Simulation control commands can be issued concurrently from the Training Station to all components in the E&D simulator. Also overall status of the simulator can be monitored from the Training Station. Most of the testing done for Training Station software was carried out in the E&D simulator. The components implemented in the E&D simulator are presented in figure 3.

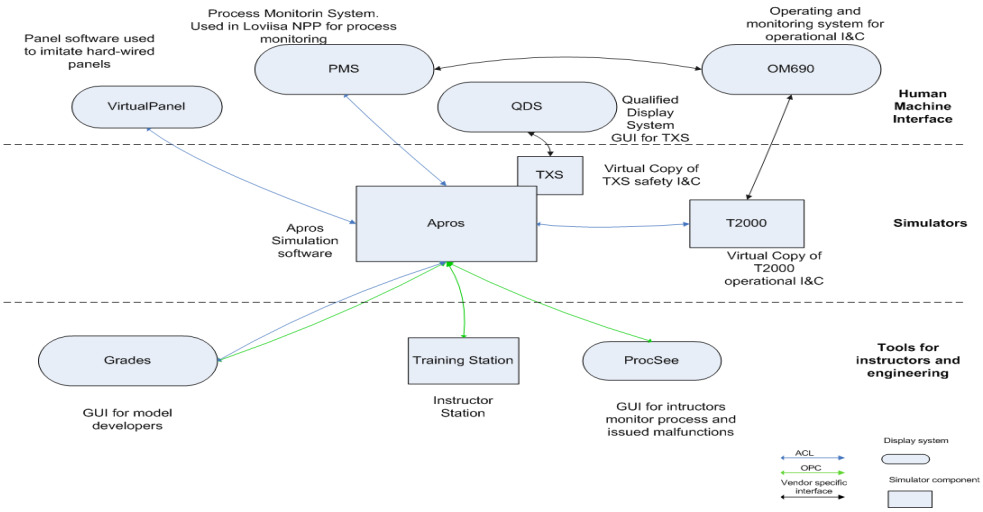

Figure 3: System configuration in E&D simulator.

2.2 E&D Simulator integration

At the moment most parts of the I&C systems are implemented in the Apros models. When the project goes forward, the I&C systems will be implemented in the Training Simulator using virtual copies of TXS and T2000 I&C systems.

Tight schedules in Loviisa I&C project affects also to Loviisa NPP training simulator project. Due to schedules Fortum's strategy in the training simulator project is to make the integration phase and the commissioning in the Loviisa NPP Training Simulator as fast as possible. In this strategy E&D simulator plays an essential role. Fortum is aiming for the goal by following methods:

1. Make the process models as ready as possible before they are connected to virtual automation provided by the supplier.
2. Test the interfaces and the communication between the components properly with help of small applications before the final integration.

Model testing is done by extensive integrated process model tests carried out in the E&D simulator. Model development and testing in described in more detail in chapter 3.

The first parts of the I&C Systems provided by the supplier have been used to test the interfaces between Apros models and virtual copies of the I&C Systems. All the other components that will be used in the training simulator are implemented first in E&D simulator. Much important information about the systems and co-operation of the different systems is received with limited applications.

3 APROS MODEL DEVELOPMENT AND TESTING IN E&D SIMULATOR

When the full scale Loviisa NPP model is developed each subsystem of the process is tested separately. The basic tests are done always after changes are made to the process model to ensure that the dynamics of the whole process model remain the same during the development process. The tests are executed automatically with help of the model testing features implemented in the Training Station.

In the integrated process model tests several, test cases that examine the whole process models are executed. The tests vary from long lasting cases where the process model is at first run from full power to cold shut down stage and then back to full power to short cases where for instance a design-basis accident cases are run. The integrated process model tests are executed in co-operation with Loviisa NPP operators. In the tests the operators control the process like they do in the real plant. In addition to this, the operators also measure the process and give feedback of the behaviour of the models compared to the real behaviour of the plant.

In addition to feedback received from the operators, the dynamics of the model is examined by comparing results to other analysis models [8]. The data from plant is used as much as possible. Integrated tests are carried out in iterations. The same carefully defined tests are executed several times. If errors in Apros model are met, they will be corrected and tested in the next iteration. This way it can be tested that the changes that are made do not cause other problems.

Due to complexity of the process the operators are needed to run predefined scenarios in the simulator and compare the dynamics of the model to the real dynamics of real plant. When the same display systems that are used in the plant are used also in the E&D simulator, monitoring and evaluation of the dynamics of the process becomes much easier to the operators (figure 4). Therefore full scope E&D simulator provides an excellent environment for model testing. In E&D simulator manual operations done by the operators can be issued from the process computer. This enables possibility to execute long tests where operators are assumed to control the process.

After two of fours iterations are done altogether 656 errors in process models are reported. Before the third iteration of the integrated tests starts 381 of those errors are fixed. Several of the errors have been reported during the tests where operations from operators are needed. During the test where the Apros models were run from full power to cold shut down stage and then back to full power 450 errors were found. In this test, manual operations done by the operators are needed. Therefore tests can be carried out only in a full scale training simulator or in a full scale E&D simulator.

Results shows that using E&D simulator in testing the Apros models has been useful and it will make the time needed to integration of the virtual I&C systems and commissioning in the training simulator shorter. When the virtual copies of TXS and T2000 I&C systems will be connected to the Apros models, it can be assumed with higher respect that the dynamics of the Apros models are

correct and the found errors are due to mismatch of the process models and the virtual automation, not because of the errors in the process models.

Figure 4: E&D simulator provides authentic environment for Apros model testing.

4 HUMAN MACHINE INTERFACE AND OPERATING PROCEDURE DEVELOPMENT

In Loviisa NPP I&C renewal project Fortum is responsible for the Human Machine Interface (HMI) design and control room basic design. Control room will be based almost completely on digital HMI. All the content of the displays used in the QDS and OM690 systems are designed by Fortum.

E&D simulator provides an excellent environment for testing and development of HMI. New concepts used in control room can be evaluated in a safe and illustrative way in E&D simulator. Comprehensive study of using Large Screen Displays (LSD) in nuclear power plant control rooms was carried out in the E&D simulator. The first fully functional Information Rich Design (IRD) LSD was installed in the E&D simulator. It was recognized that large screen overview displays will be needed in tomorrow's nuclear power plant control rooms in order to support crews' situation awareness. [9]

The goal of the operating procedure development is to produce instructions for the operators for all operating situations, including abnormal and emergency situation. Procedures help operators in complex operations (e.g. shutdown and startup) in aid troubleshooting, support emergency identification and give guidelines how to run plant into safe state in transients and accidents. Tested, validated, trained and up to date procedures are an important part of a NPP and its accident management concept.

In procedure development Apros models have been be used to test plant response (initial analyses), to create and test operating strategies, to test actual procedures and their use in a control room environment (e.g. technical flawlessness, ease of operations, clarity, ergonomics etc.), and to validate procedures.

Plant I&C, control rooms and operating procedures form an entity that is used in operating the plant. Therefore they should be developed and tested with strong co-operation. The E&D simulator is used when operating procedures are tested together with new control room and HMI.

5 RPS HUMAN MACHINE INTERFACE PRE-VALIDATION

When HMI is developed for safety related systems the quality of the HMI can not be tested nor validated in the plant. In May 2010 E&D simulator was used for pre-validation of the HMI of the Reactor Protection System (RPS). In the RPS pre-validation the E&D simulator is used to evaluate how the operators are able to control the process in simulated accident scenarios using the new QDS displays, hard wired panels and the new operating procedures. The Finnish safety authority STUK

expects that expert estimation about the HMI is created [10]. Evaluation is based on pre-defined requirements and expert opinion by systems usability experts from VTT Technical Research Centre of Finland. The expert estimation was formed based on the results and observations done in the pre-validation.

Pre-validation is done with help of Loviisa NPP operators. Two groups of operators took part of the tests. Group 1 consisted of a reactor operator and a turbine operator. Group 2 consisted of two experienced shift supervisors. In the pre-validation five tests were carried out. Basic functionality of the displays was tested in the first tests. In the last tests different kind of accident scenarios were simulated.

In the fourth test a fault in alarm logic was simulated. An Alarm signal indicating low pressure in the primary loop was simulated. After couple of second the same signal was simulated back to normal position. From the displays the operators were able to see that the alarm signal had been on. They were also able to see that the alarm was not active anymore.

The fourth test provided good information about how the operators construe and follow the operating procedures. Group 1 first discussed whether the procedure should be performed or not whereas group 2 departed from the procedures. When the operators from group 2 were interviewed they told that they had a clue what might be the reason for the alarm and wanted to have evidence to their assumption. Information like this is essential for the HMI developers. Even thought different groups had different strategy the both group made the same operations. This was strong evidence that operator procedure testing and HMI development had succeeded.

According to systems usability experts, the Fortum E&D simulator is a very suitable tool for the testing of systems usability of the new design at those stages in which the training simulator is not yet available. The first evaluation of the new RPS concept and the new HMIs could be carried out rapidly and efficiently in a quite realistic setting. The tests provided useful information for the further development of the HMIs and gave valuable insights of the ways the operators monitor and control the process according the new concept

In the pre-validation the model of RPS was implemented in the Apros models. In the tests in was seen that even for small-scale tests extensive part of the process and I&C systems need to be implemented in Apros models used in E&D simulator. That is because in the accident cases the operators were willing to use all the available information in order to get better understanding about the state of the process. This brings challenges to environments where the tests are carried out.

6 CONCLUSIONS

Full scale simulation models of Loviisa NPP are developed during the Training Simulator update project. An Engineering and Development (E&D) simulator is used extensively in Loviisa NPP I&C renewal project for training simulator update and for the development of the new HMI.

Fortum's strategy in the Training Simulator renewal is to develop the Apros models as ready as possible before they are connected to virtual I&C systems provided by Siemens and Areva. In this strategy, E&D simulator plays an essential role when it is used for testing the Apros models and the connections between the components before the final integration.

In order to test the Apros, models extensive integrated process model tests are carried out. In the integrated process model test several errors in the process model were found. Many of the errors were such that those could not be found without a full scale E&D simulator.

E&D simulator is also used for HMI and operating procedure testing. In May 2010, pre-validation of HMI of the RPS system was carried out. Based on the results of the pre-validation an expert opinion about the quality of the HMI design was produced. In the pre-validation representative part of the RPS system was implemented in Apros models. With the help of this arrangement, the HMI pre-validation was carried out even before the actual RPS system provided by the supplier existed.

Because of different usages of the process models, both accuracy and speed is required from the Apros model. Sufficient accuracy and speed are gained by dividing the whole Apros model in to separate Apros models that run in different PCs.

Different purposes of use bring several requirements to the E&D simulator. At the same time they also bring several benefits. The full scope NPP model makes it possible that dynamic tests can

be used to test and validate the HMI design and operating procedures. Process model testing has also benefit from the HMI development and testing. The latest displays developed are also available for the model testing.

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