Nuclear Industrial Applications of SIMTONIA

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ABSTRACT

In this paper we present three different nuclear industrial applications of the SIMTONIA framework developed by CER. First, we demonstrate how we could utilize SIMTONIA's sequential engine for the verification and validation of the new control rod and reactor power controller system of Paks NPP. In our second example, the application of SIMTONIA's visual engine for system monitoring in the VERONA core monitoring system of Paks NPP will be presented. Finaly, the critical safety monitoring system and electronic operational rules of the plant computer of Paks NPP will be briefly introduced focusing on the application of SIMTONIA's sequential engine as an evaluation tool of logic diagrams.

INTRODUCTION

Centre for Energy Research of Hungarian Academy of Science (CER) has developed a new set of graphics tools for the development of numerical models of nuclear power plant simulators (NPP). The result of these developments is called SIMTONIA (SIMulation TOols for Nuclear Industrial Applications), which is a simulator development framework providing a modern, comfortable, graphics environment for simulator developers. The elements of this framework has been introduced, recently (Páles et. al., 2017). It might be worth noting that similar simulator development platforms were developed by other simulator suppliers (e.g. the Orchid by L3-MAPPS). However, our approach differs significantly from the one used by most of the suppliers, since we do not use old-fashioned code generation strategies, but our model engines utilize DLL based object libraries.

Using three examples, we demonstrate that the applications of the flexibe engines of SIMTONIA's framework are not limited to simulator model developments, but they can be exploited in a number of fields of nuclear industry, too.

In the next Section we demonstrate how we could utilize SIMTONIA during the verification and validation (V&V) procedure of a new, safety related control systems of Paks NPP.

Then, the replacement of GE's iFIX Intellution human machine interface by SIMTONIA's visual engine used in the VERONA core monitoring system of Paks NPP will be discussed, as a cost effective, highly reliable solution.

Finaly, we discuss how SIMTONIA's sequential engine is utilized in the plant computer system of Paks NPP for the evaluation of the so-called critical safety functions and electronic operational rules of the plant, inluding the automatic detection of the plant's operation mode.

VALIDATION AND VERIFICATION OF NEW CONTROL SYSTEMS BY SIMTONIA

In 2015, Paks NPP initiated a public procurement procedure for reconstruction of the instrumentation and control of the Rod Control System (RCS) and the Reactor Power Controller System (RPCS) of plant. The purpose of the reconstruction has been to improve the RCS and RPCS with respect to instrumentation and control to today's standards by applying modern methods and solutions and by ensuring that the safety and reliability criteria related to the planned extension of the nuclear plant's lifetime are met.

SKODA JS was awarded by end user in the procurement procedure and CER as a subcontractor of SKODA JS has been taken part in the project by focusing on the simulator related activities of the project. In particular, CER has been responsible for the implementation and integration of the simulator models of the new RCS and RPC to the full-scope simulator (FSS) of Paks NPP. Beside the implementation of the new models, CER has also been supported the verification and validation procedure of the new RCS and RPCS by performing tests in the simulator in order to demonstrate the reliability of the new system.

Functions of RCS and RPCS

Without going into details, let us summarize what are the roles of RCS and RPCS in an NPP.

Basicaly, the reactor power in an NPP can be controled by introducing neutron absorbers into the reactor core where the chain reaction takes place. For rapid control of power, so called control rods are introduced into the core. Paks NPP has 37 control rods and these are organized into six groups. The groups and the individual rods can be moved up and down by the reactor operators, and in automatic mode the groups can be

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driven by the RPCS, too, keeping the neutron flux or the turbine pressure in a certain level depending on the operation mode of RPCS. Finaly, we note that the reactor protection systems can also drive the control rods in case of abnormal operation modes, e.g. dropping down all the rods into the core by gravity, if it is necessary. During the reconstruction, the underlying principles of RCS and RPCS had to be retained, but the plant personel also requested some new functions to be introduced. For these new features some operational panels of the main and emergency control room (MCR and ECR) of the plant had to be modified, introducing new switches and displays into the panels.

Modeling RCS and RPCS in the FSS of Paks NPP

The refurbishment procedure of these systems is a long procedure in the four real units of the plant, rougly four years, because it can be done only when the reactor is shutdown between two reactor cycles, which are 15 months long. Due to the long-continued refurbishement procedure, there is a period of time when the old system is used in some units and the new one is in action in the others. Since reactor operators must be trained in the simulator for both kind of systems, therefore it had to be guarented that the models of both systems be available in the simulator and a simple way had to be provided to switch over from one model to the other. Also, the differences between MCRs and ECRs had to be represented somehow. Therefore these panels have been modified making possible to replace the control rod actuators and displays rapidly by a screw mounted new panel when the new system is used for training.
Considering the models, a software switch was introduced to jump from the old system model to the new one.
In the FSS of Paks NPP, the old RCS and RPCS were simulated by models written in Fortran subroutines. It was requested that during the reconstruction, the models of the new system be implemented by GRASS, a graphic logic diagram modeling tool developed also by CER and used earlier during the refurbishment of the reactor protection system of Paks NPP (Jánosy et al., 1994). Since GRASS has been developed by more than 20 years ago, its user interface does not suit with present standards. Therefore we have decided to apply a multi-step procedure during the implementation of the new model:

1. Implementation of the new logic elements (60 building blocks) by SIMTONIA's element editor according to the description of SKODA JS' system designers.
2. Implementation of 130 new logic schemes of the new design by the user-friendly environment of SIMTONIA's diagram editor, using the previously developed building blocks (see an example in Fig. 1).
3. Off-line testing of SIMTONIA models.
4. Automatic conversion of SIMTONIA's building blocks and diagrams to GRASS icons and pictures.
5. Coupling the GRASS models with our replica simulator of Paks NPP's FSS.
6. Model code generation by GRASS.
7. On-line testing of the new models in our FSS.

Applying this procedure, the implementation of the new RCS and RPCS system was seamless and requested only two months including both off-line and on-line testing.

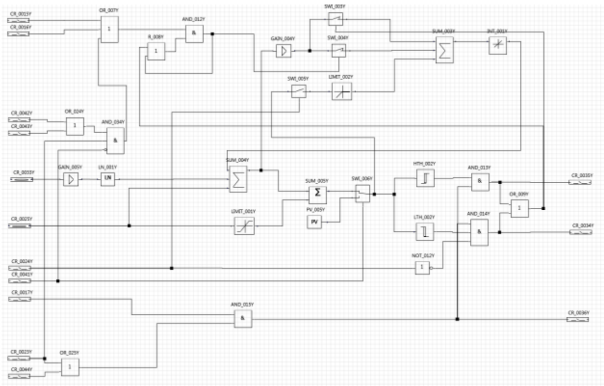

Figure 1: A diagram from the RPCS model

A priori testing of the new MCR and ECR panels

In order to *a priori* test the actuators and displays of the new systems from ergonomic point of view, we also utilized SIMTONIA. Using its visual engine, the old and the new MRC and ECR panels have been implemented as animated pictures and our touch-screen based virtual control room panel shown in Fig. 2 was coupled with the old and new simulator models, respectively.

Figure 2: Touch-screen based control room panel

Using again a software switch, we provided a simple way, to switch from the old panels to the new ones (parallel with the change of models).

Verification and validation of the new models

Setting up this environment a Factory Acceptance Test (FAT) had taken part in my Institute. This V&V procedure followed a very simple scenario. First, all basic functions of the new systems, e.g. individual control rod movements and control rod group operations were tested by the operational personal of the NPP, then more complex situations (e.g. automatic reactor power control at different power levels and during normal and abnormal operations) were simulated by both the old and new systems. Parameters of the controllers were tuned by comparing the obtained relevant physical parameters with each other during these simulations.
After successful FAT, the models were introduced in the FSS of Paks NPP and Site Acceptance Test (SAT) was carried out in a similar manner than the FAT procedures. After successful SAT, a nearly one-year trial period of the new system started, using the new RCS and RPCS in the simulator by the training personel and operators of the plant one day per each week.
Finaly, the new system was first introduced in the 2nd unit of the plant at the end of 2016.

PROCESS MONITORING BY SIMTONIA

In NPPs so-called core monitoring and surveillance systems are used to extract as much information about the state of the nuclear reactor core as possible (Végh et. al., 2008). Although only a limited number of detectors can be installed in a core, using advanced numerical calculations the relevant physical quantities can be obtained with very high resolution. For instance, the core of a VVER-440/213 type NPP consists of 349 fuel assemblies, but it has only 210 thermocouples at the outlet of the assemblies and only 36 assemblies are equipped by neutron flux detectors. In spite of these limited number of measurements, utilizing the available measured data and using well-established neutron physical and thermohydraulical calculations, the temperature, the neutron flux and several other derived quantities can be obtained in more than 10000 equidistantly distributed computational points of each fuel assembly.
In Paks NPP, the VERONA on-line monitoring system has been responsible to determine the relevant reactor physical quantities and associated safety margins (e.g. distance from saturation temperature) of the reactor core since the late eighties (Végh et. al., 2008; Végh et al. 2015). This system was gradually improved in the last three decades as the performance of computational techniques drastically improved allowing more and more sophisticated numerical computations. It is also worth emphasizing that these developments were needed to establish the application of a new, more economic generation of VVER fuel assemblies while keeping or even increasing the safety level of operation.
In 2012, Paks NPP decided to change its operational practice extending the fuel cycles from 12 to 15 months increasing the enrichment of Uranium in the fuel assemblies. Some preliminary calculations revealed that the amount of on-line core monitoring calculations increases significantly due to the changes of fuel, i.e. developments were needed in the core monitoring system. It is also turned out that the increasing amount of computational work cannot be managed by the old hardware and software platforms while keeping the same high level availability (99.9%) of the system than before. Since the hardware and software platform of VERONA became also obsolete in the last decade, the NPP decided to initiate an overall reconstruction work of VERONA core monitoring system and the required major developments can be summarized as follows:

- application of a new generation but proven hardware devices (high performance servers, thin clients for monitoring, new local area network devices, network attached storage for archives),
- application of a new generation but proven software platform (Windows Server 2012 R2),
- application of a new generation of software development tools (Visual Studio 2014, Embercadero XE7, Visual Fortran Composer XE 2013),
- application of VMware virtualization technology,
- extension and acceleration of reactor physics calculation using Graphics Processing Units (GPU),
- replacement of the GE's Intellution iFIX based HMI for process monitoring.

In this paper we focus on the last item. The replacement of iFIX SCADA solution for process monitoring was motivated by the fact that the old version of iFIX used in VERONA system was not supported under the new software platform, therefore new licences would have been purchased by the plant. However, GE's iFIX licence policy basicaly did not allow the plant to initiate such a purchasing, therefore the plant management decided to replace iFIX with some other process monitoring solution. CER suggested to apply SIMTONIA's visual engine as a HMI of VERONA and this proposal was awarded.

VERONA's architecture

Paks NPP has four reactor units and each unit has its own local VERONA network. The principal users of VERONA are the reactor operators and the unit supervisor, who work together in the control room of the unit, where two displays of VERONA system are installed for on-line core monitoring purposes.

Although the local networks of VERONA are independent from each other, all of them are connected to the technological network (TN) of the NPP, which are separated from other networks (e.g. informatics network) of the plant by a data diode (Fig. 3).

The connection of local VERONA networks to TN assures external accessibility of VERONA data from the Control Centre of the plant and from some dedicated places supporting remote maintenance. Such an important place is the Computer Centre of the 3rd unit, where the VERONA-t test system has been installed. This is a kind of test bed of VERONA system, since it can be driven by the measurements of any of the units.

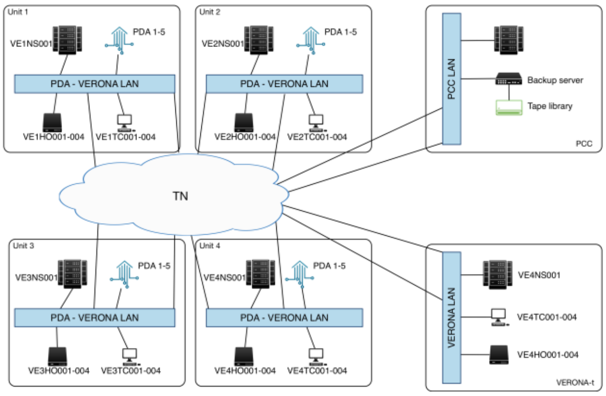

Figure 3: Connection of local VERONA networks to the technological network of the plant.

Since VERONA-t has exactly the same hardware and software components than the units, therefore the investigation of any event happening in the units can be done by VERONA-t without disturbing the normal operation of the units. It might be worth emphasizing here, that the operational regulations of the plant have strict rules for operation without the VERONA on-line core monitoring system (power must be reduced etc.), therefore any operational problem of this system can lead to significant economic loss. This is why, such events should be avoided or at least their occurrence must be reduced as much as possible. The application of VERONA-t test system is not the only way to reduce such an events. A more important approach to achieve high availability and safe operation of VERONA is the application of redundancy. In Fig. 2 one can see the architecture of the local network of VERONA for a reactor unit. PDA (Polyp Data Acquisition) is responsible to provide more than 2000 raw measurement data for VERONA. These raw data are processed in the very same way with two, redundant VDP (Verona Data Processing) servers VExHO001, VExHO003, where x={1,2,3,4} is the identifier of the reactor unit. After data processing VDP servers send the relevant reactor physical quantities to the two, redundant RPH (Reactor PHysics) servers (VExHO002, VExHO004), which are doing exactly the same time-consuming calculations by the support of built-in Tesla GPU cards. After finishing the calculations, the RPH servers send back the results to their VDP pair and the results are processed further by the VDP servers finishing one on-line data processing cycle.

A part of the measured and computed data are saved into the local archive of VDP servers and the archives are saved to NAS (VExNS001) periodically.

Data are displayed by thin clients (VExTC001…TC004), which are in connection with both physical VDP servers.

In the reactor unit 2 and 3, both local networks of VERONA have an additional server (VExHO005), which is called EXD (EXternal Display) server. Their role is to provide the possibility to connect any local VERONA network for ten external users and to display the actual processed data.

VERONA is in connection with the TN of the plant by two switches (VExSW001, VExSW002).

It is worth noting that not only the servers are redundant, but the structure of network also provides redundant connections between the servers and thin clients. Therefore, the malfunction of a system component could not lead to any degradation of high-level functionality of the system, i.e. the system is single-failure proof.

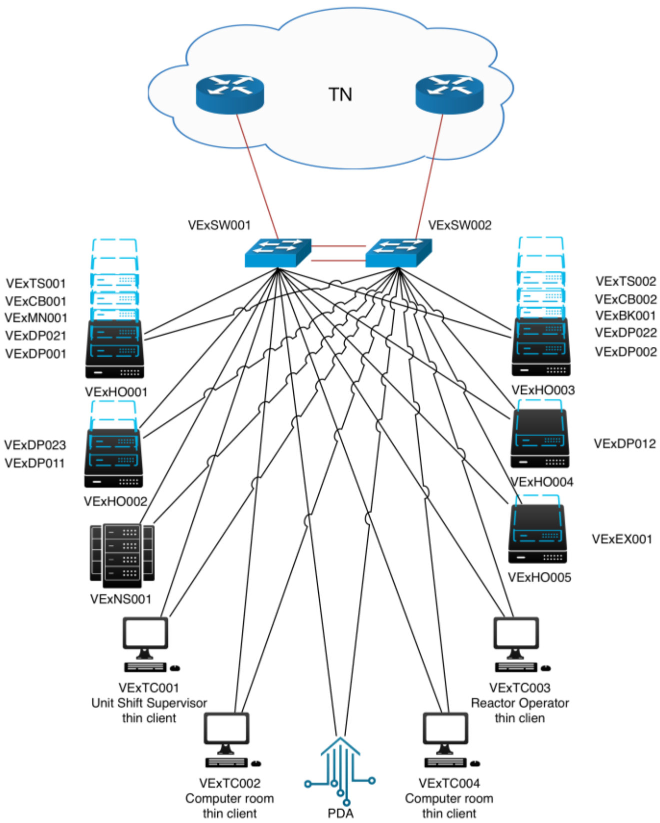

Figure 4: Local VERONA network.

In spite of its obvious benefits, virtualization has not been widely used in the nuclear industry, yet. However, during the reconstruction of VERONA, the application of virtualization was an important requirement from the plant's personal. The major motivations behind this request were to remove dependency on particular hardware vendors, to improve and speed-up disaster recovery, and to extend the lifecycle of applications.

Therefore VMware's virtualization platform (ESXi 6.0) has been used in each physical server, but its advantages of virtualization were especially utilized in the real VDP servers. In the new version of VERONA, one real VDP server hosts five virtual servers integrating the functions of display (VExTS001, VExTS002), data processing (VExDP001, VExDP002), database (VExDP021, VExDP022), system management (VExMN001), backup (VExBK001) and connection broker servers (VExCB001, VExCB002) into one physical hardware (see Fig. 4). In the old system, physical display servers were used to monitor the measured and calculated data. In the new system, the results are shown by thin clients, which are connected to the virtual display servers.

Process monitoring in VERONA

In VERONA 7.0 the process monitoring of data is done by the visual engine of SIMTONIA instead of iFIX.

The visual engine is responsible for visualization of process variables, to receive and process user's interactions.

Each process picture is built up by SIMTONIA's diagram editor using some complex and several simple process elements developed by SIMTONIA's element editor. Each element has its own appearance, behaviour, animation and interaction procedure.

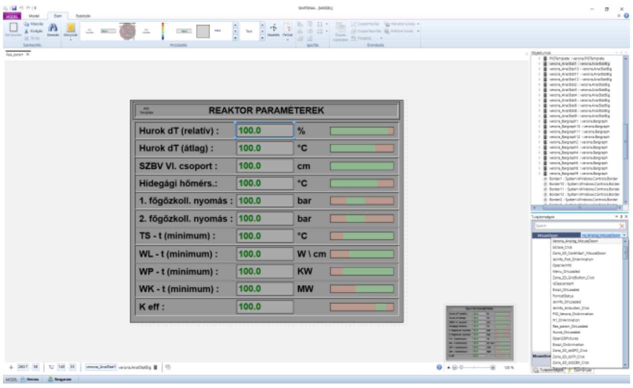

Figure 5: SIMTONIA's element editors during the development of a process monitoring display

A program called VDBIOServ runs in background in the virtual display servers. Its role is to request information from the OPCSend program running in the virtual VDP server. The visual engine of SIMTONIA communicates with VDBIOServ via the ProcessIO Application Programing Interface (API).

This API requests the data in very similar manner than an OPC DA interface using functions like AddGroup, AddItem, ReadItem, etc..). Basicaly it is a simpler version of OPC DA, but it does not use DCOM technology, simplifying the configuration of application programs. Regarding operation, its functions can be divided into two major categories:

- ProcessIO server functions,
- TCP server functions, which assure remote access to the VDB, VERONA's online database.

Functions belonging to these two major categories run in two different threads and they communicate with each other via some shared memory tables.

The ProcessIO server functions belong to SIMTONIA's ProcessIOSrv library, which provides an easy way to write programs, which can communicate with SIMTONIA's engines. The ProcessIOServ registers and provides data to the ProcessIO clients (display programs in this case) in an automatic manner.

For the proper operation of ProcessIO server, the VDBIOSrv has to create a data cache based on the data need to be displayed and some callback functions, which run when a new variable should be displayed (e.g. for checking the availability of variable in the database, or to add a new variable).

It is worth emphasizing that in contrast with the old system, where an individual set of process pictures had to be developed for each reactor unit by iFIX, SIMTONIA uses a single set of pictures and database variables can be accessed through a template resolving logic. It means that template pictures can be created by SIMTONIA's diagram editor and the variables defined according to this logic will be resolved and displayed in the picture. So, only the template has to be modified for a change in pictures, not each individual picture of each unit.

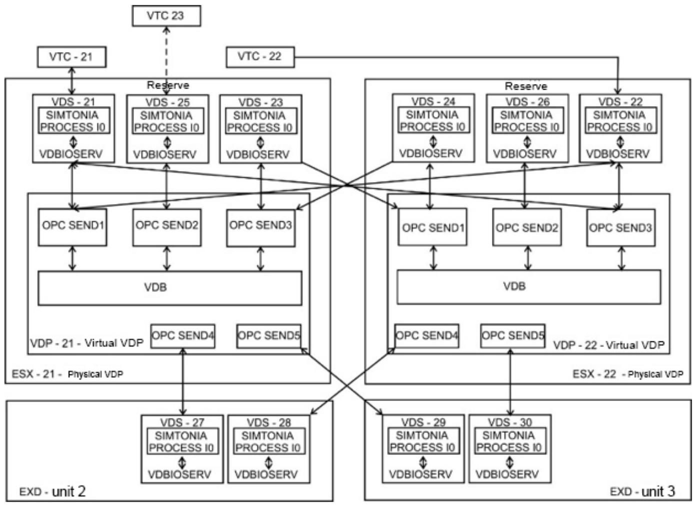

Figure 6: Software modules of process monitoring in VERONA

In Fig. 6 the connections between virtual VDP and display servers are shown focusing on the above mentioned software components. Here the connection of external display servers with the VDP servers can be seen, too.

Fig. 7 shows the main display screen of the VERONA system. The screen is made up of SIMTONIA elements, and each element has its own set of template variables. The data visualization elements placed on a picture are using these templates for the resolution of their database references. When a template variable change occurs in a picture, the visual engine automatically resolves the new references used on that picture by communicating with the VDBIOServ program.

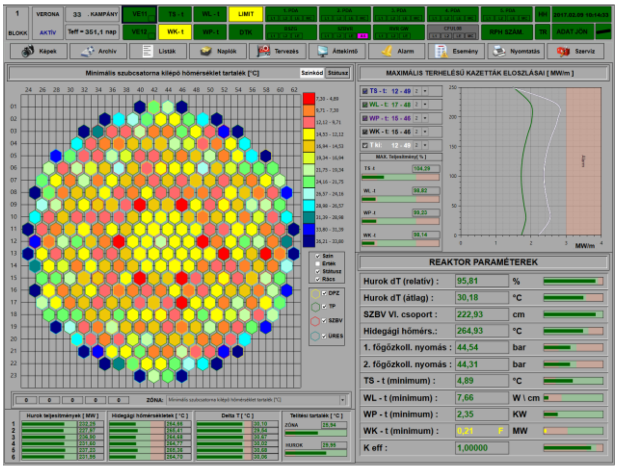

Figure 7: Main process picture of VERONA

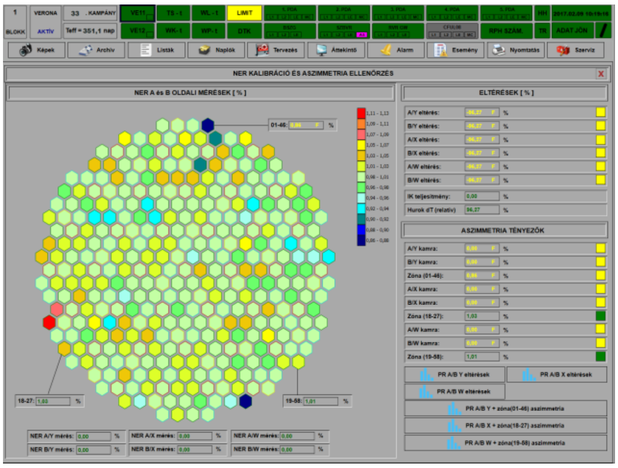

Figure 8: Neutron detector calibration picture

Verification and validation of process monitoring

VERONA is a so-called safety level 3 information system in the plant, which means that it must have a very high level of availability (99.9%) during a reactor cycle. In case of its failure, there is only one hour to recover it. If the recovery is unsuccussful during this periof of time, the reactor power must be decreased and considering a longer time-scale of unavailablity the reactor nust be shutdown. Oviously, such events in an NPP have very tough ecomic consequences, therefore the replacement of VERONA's process monitoring subsystems was established with a detailed and carefuly planed test procedure. This test procedure included an important speedup test, in which we changed VERONA's 2s display cycle time to 2ms and drove VERONA by random input signals in order to study the stability and reliablity of process monitoring subsystem. After successful FAT, first the system was put into operation in the FSS of Paks NPP. The successful simulator trial period was followed by the installation of the VERONA-t test system in the 3rd unit. After VERONA-t's trial period, the new system was introduced at the end of 2015 in unit 3 and the other units in 2016.

EVALUATION OF CRITICAL SAFETY FUNCTIONS BY SIMTONIA

Nuclear reactor units has a so-called plant computer, which system gathers and evaluates all relevant physical parameters of the power plant.

The evaluation has two levels: The first level evaluation contains simple procedures, like signal conditioning, filtering etc. and focuses on individual signal processing. In the second level, more specific operational and safety parameters are derived (e.g. operation mode of the plant, complex safety margins of the unit etc.) from a set of signals processing them together. This kind of evaluation includes complex calculations, e.g. calculation of saturation temperature at the measured reactor power, and determination of relations between measured discrete signals using complex logic sequences.

In the past, this evaluation was carried out by an Excel table driven description of the evaluation algorithms in Paks NPP. Based on these tables a C source code was generated, compiled and linked to an executable file, which was run by the plant computer system.

There were several drawbacks of this approach. First, the modification of an algorithm was ponderous and time consuming. Furhermore, the resulting algorithm was not transparent for the end users, the operators, who were not able to identify easily, why a derived quantity takes its value in a certain situation.

In 2016, a refurbishment project of the old plant computer system has been started in Paks NPP and as part of this project the plant operational personal requested the introduction of a transparent second level process evaluation procedure. CER proposed to apply SIMTONIA's sequential engine for this purpose and the proposel was awarded.

Second level process evaluation by SIMTONIA

The altering of the old system to the new one included the following phases:

1. All complex calculation modules and simple logic elements used in the second level process evaluation of the old system have been implemented in a new element library of SIMTONIA.

2. The evaluation desciptor Excel tables were automaticaly converted to SIMTONIA logic schemes using the elements of the library.
3. SIMTONIA's sequence engine has been built into the new plant computer for second level process evaluation.
4. For each derived quantities (calculated in second level and shown in process monitoring displays), the corresponding evaluation scheme has been made available visualy for the users. That is, by clicking to a displayed derived quantity, SIMTONIA's corresponding logic scheme used for evaluation appears on the process monitoring screen and the animated picture makes it transparent, how the sequential engine derived the given quantity (Fig. 9).

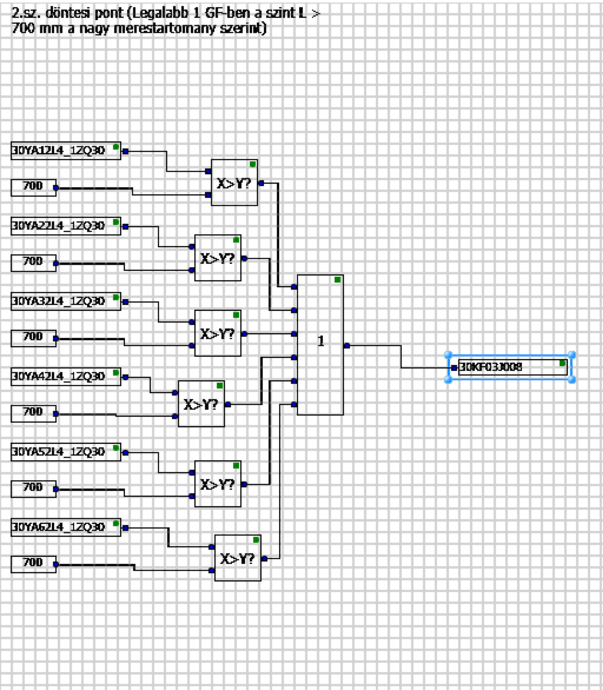

Figure 9: Evaluation of 30KF03J008 signal in SIMTONIA

CONCLUSIONS

Although SIMTONIA framework has been developed for building simulators of NPPs, its well established structure let us to apply its tools in other fields of nuclear engineering very efficiently.

In this paper, we have presented three industrial examples for its application. These successful applications and favourable operational experiences prove the stability and reliability of this system.

Since we provide a flexible licencing policy for the framework, we hope that in the near future we will find other possibilities for its application in other industrial fields.

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