A GPU accelerated nuclear reactor core monitoring system in virtual machines

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Abstract: The core monitoring and surveillance system of Paks nuclear power plant has been replaced recently with a new version of the system VERONA utilizing virtualization technology and GPU accelerated numerical computations. In the new system, the process variables are monitored by the visual engine of a new simulation platform SIMTONIA (SIMulation TOols for Nuclear Industrial Application). In this paper the hardware and software architecture of the new system is presented in details enlighten the advantages of the application of state-of-art computational technologies.

Key–Words: Process monitoring, Graphics Processing Units, Virtual machines

1 Introduction

In nuclear power plants (NPP) so-called core monitoring and surveillance systems are used to extract as much information about the state of the reactor core as possible [1]. Although only a limited number of detectors can be installed in a nuclear reactor core, using advanced numerical calculations, the relevant physical quantities can be obtained in the core with very high spatial resolution. For instance, the core of a VVER-440/213 type NPP consists of 349 fuel assemblies, but only 210 of them have thermocouples at their outlet 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, 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 core monitoring system has been responsible to determine the relevant reactor physical quantities and associated safety margins (e.g. distance from saturation temperature at the outlet of each assembly) of the reactor core since the late eighties [2–8]. 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 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 month. Such an extension requires the application of higher 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 development tools of VERONA became also obsolete in the last decade, the management of the NPP decided to initiate an overall reconstruction work of VERONA. The required major developments can be summarized as follows:

- application of a new generation of proven hardware devices (high performance servers, thin clients for monitoring purposes, new local area network devices, network attached storage for archives),

- application of a new generation of 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 Intellution's iFIX based process monitoring system because of the lack of further support.

In 2014, after some underlying preliminary work, MTA EK in strong cooperation with the reactor physicists of the plant have started the development of a new version of the system: VERONA 7.0. The first reactor unit started its operation with the new fuel cycle and with this new version of core monitoring system in 2015.

In this paper the latest developments of the system will be introduced focusing, in particular, on the computational aspects of the developments. More information about the physical background of calculations can be found in [8].

2 Hardware 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. 1). 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. Since VERONA-t has exactly the same hardware and software components than the units, therefore the investigation of any events 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. That 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.

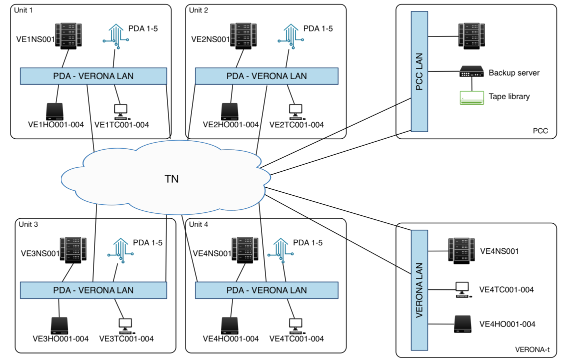

Figure 1: Connection of local VERONA networks to the technological network of the plant.

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 the very 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.

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-

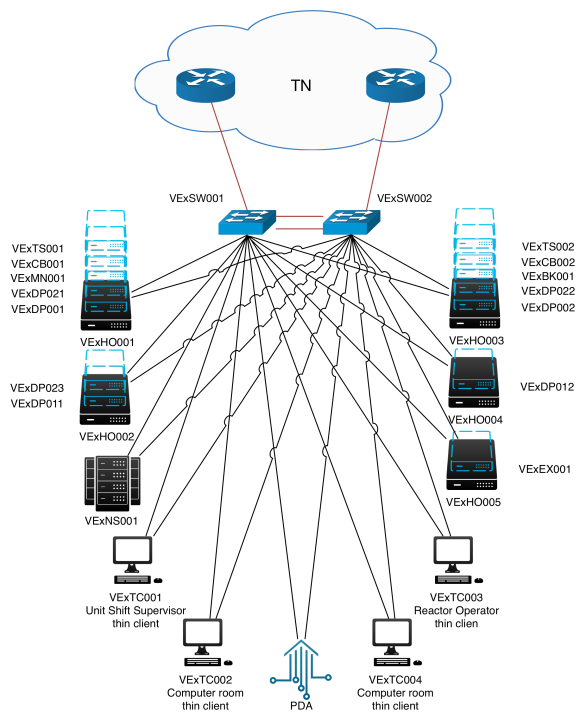

Figure 2: Local network of VERONA of a reactor unit.

failure proof.

3 Virtualization

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. 2). In the old system, real 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. In the old system the SQL based off-line database and archive management of VERONA ran directly on the data processing servers. Unfortunately, this approach sometimes led to the overload of the CPUs of the data processing servers, when some special data processing, e.g. complex data filtering of the archive has been started by the reactor operators to study some events. Therefore, virtual database servers has been introduced in the new system, and all off-line SQL based operation has been moved to this server limiting its available resources by the VMware kernel. In such a way the overloading of the on-line data processing servers could be avoided. The virtual system management server can be used to manage the resources, startup and shutdown of each virtual machines belonging to one reactor unit. Backup and recovery of any virtual machine of the farm can done by the virtual backup server. Finally, the virtual connection brokers are responsible for the load balancing of display servers. They equally distributing the number of connections between thin clients and display servers if both servers are available, or in less than 10 seconds redirect the connection of a thin client to the other display server, if its original connection is lost for a reason or another (e.g. malfunction of the physical VDP server).

4 Software architecture

4.1 System components of the virtual VDP servers

The most important components of VERONA 7.0 can be found in the virtual VDP servers. Fig. 3. shows how these components are coupled with each other.

The static information of the measured and calculated data (description, encoding of data processing, units of measurements, limit values etc.) are stored in a relational off-line database managed by DBM (Database Manager). It is worth noting, that the on-line database is always created from this database in automatic manner.

The Data Communication Subsystem (DCS) receives the raw measured data from the PDA units and shares them with other system components using the on-line VERONA Database (VDB). These subsystems also can be used to share data with other technological information systems of the plant (e.g. Plant Computer or Control Centre of the plant).

Data processing is executed by the PROC subsystem in two phases. In the first phase some standard data processing are performed:

- investigation of plausibility of measured data,

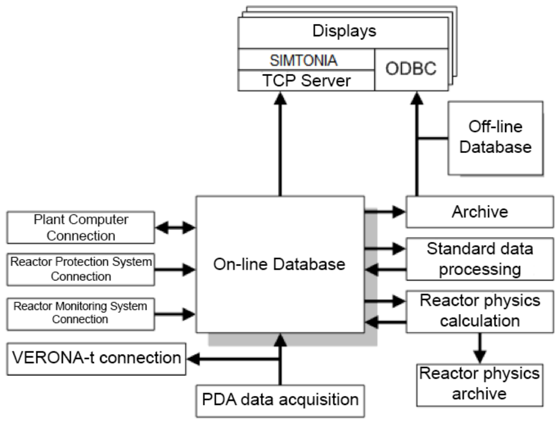

Figure 3: Connections of systems components in virtual VDP servers.

- evaluation of duplicate measurements,
- conversion of units,
- checking of limit violations,
- generation of alarms and events based on measured data,
- storing measured data in archives.

After the first data processing phase, the processed data are transferred via the RPH communication (RPHC) subsystem to the RPH servers, which start to perform a so-called synchronous reactor physics calculation.

The second phase of data processing is started in the virtual VDP servers, when the RPH servers has been finished one synchronous calculation and the calculated data have been sent back to the virtual VDP servers by RPHC.

The most important functions of data processing in the second phase are given as follows:

- investigation of plausibility of calculated data,
- checking of limit violations,
- determination of reactor operation mode,
- determination of the number of living (properly operating) thermocouples and neutron detectors,
- determination of some safety margins of the reactor,
- generation of alarms and events based on calculated data,
- storing calculated data in archives.

The events and alarms generated by any server and subsystem are managed and distributed between the servers by the Event subsystem of VERONA. This subsystem is also responsible to manage the user's acknowledgement of alarms.

The Archive subsystem can be used to restore, filter and analyse the measured and calculated data of archives.

The Diagnostic and Supervisory subsystems are responsible to diagnose and supervise the state of all virtual machines of the system. The diagnostic subsystem has the following components:

- process diagnostics checks periodically that all necessary processes run in a virtual server,
- hardware diagnostics checks periodically the available hardware resources (CPU, memory, hard disc etc.),
- network diagnostics checks periodically the network connections between virtual servers,
- monitors monitor programs for diagnostic information (local and global information).

Based on the available diagnostic information, the Supervisory subsystem chooses the VDP-RPH pair, which is in better condition from diagnostic point of view. This pair will be the active one, while the other pair will work in background mode. For process monitoring always the active pair is the default data source. However, from the user interface of VERONA the user also can choose the background pair for monitoring purposes (to check, for instance, the reason of degradation). In normal operation, both pairs have to be in the same diagnostic condition and in this case, the first pair is active.

The Master Calendar connection subsystem (MC) is responsible for the synchronization of the clock of all virtual servers with the master calendar of the plant, which are connected to the real VDP servers via RS232 series connection cables.

The previous version of VERONA used Intellution's iFIX for displaying process information. The data source of the iFIX based schemes was an OPC server, which queried the data to be displayed from the VDP servers. For the new version of VERONA a new data displaying system has been introduced and a new OPC like server (VDBIOServ) has been developed. These servers also provide information for displaying process data from the VDP servers through TCP/IP connection. More details about process monitoring will be provided later on.

Finally, we note that there are several other system components, such as the Startup subsystem (responsible to start the subsystems at system startup time), Action subsystem (which can be used to monitor e.g. user's interactions) running on the virtual VDP servers but not discussed here in details.

4.2 System components of the virtual RPH servers

The reactor physical servers perform the numerical computations, which are needed to obtain information in the overall reactor core. To be more precise, it calculates $349x48x126$ pin-wise core nodes, since each fuel assembly contains 126 fuel pins and each of them is divided into 48 axial levels.

The reactor physics calculations are categorized into two classes according to their repetition time. The so-called synchronous tasks run in the 2s in-core measurement cycle processing every measured data packet, while the asynchronous tasks, working in a change sensitive manner, run less frequently with a maximum of one hour repetition time.

So, the amount of calculations is significant and the information is needed on-line. Therefore, part of the computations are accelerated by the means of a GPU card (Tesla K40).

To enjoy the benefits of GPU accelerated computation without significant code modifications, we used the parallel computing platform and programming model of CUDA.

Without going into details, using GPU accelerated calculations in the reactor physics algorithms for parallel matrix manipulations, the time consumed for calculations could be reduced with one order of magnitude.

Due to the reduced calculation time, we were able to regroup the asynchronous and synchronous tasks significantly, moving almost all on-line tasks to the synchronous group. Only a part of the node and fuel rod level analysis remained in the asynchronous cycle, while the complete 3D nodal diffusion calculation, the nodal burn-ups calculations, isotope concentration tracking and extrapolation were moved to the 2s synchronous cycle. A consequence of this improvement that now, the on-line calculations are able to follow rapid power excursions showing the effect of power exchange immediately in each reactor physical parameter. On the contrary, the effect of power increase or decrease on the calculated parameters was delayed with 3 or 4 asynchronous cycle in the old system.

4.3 System components of the virtual display servers

As we have already mentioned, in VERONA 7.0 the displaying of data is done by the visual engine of SIMTONIA instead of iFIX. SIMTONIA is a simulation platform for nuclear industrial applications. It contains a number of simulation engines for modeling of different technological systems and its visual engine is responsible for visualization of process variables and for the simple implementation of user interactions.

A program called VDBIOServ runs in the background in the virtual display servers. Its role is to request information based on the scheme to be displayed from the OPCSend program running in the virtual VDP server. The visual engine of SIMTONIA communicates with VDBIOServ via the ProcessIO application interface (API).

This API requests the data in a very similar manner than an OPC DA interface using functions like AddGroup, AddItem, ReadItem, etc. Basically it is a simpler version of OPC DA, which 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 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 needed 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).

Another advantage of using ProcessIO API is that database variables can be accessed through a template resolving logic. It means that the template variables can be used in the names of database variables referenced on SIMTONIA pictures. The actually used variable names are defined according to this logic, and will be resolved when a template variable changes in the picture.

In Fig. 4 the connections between virtual VDP and display servers are shown, focusing on the above mentioned software components. The connection of external display servers with the VDP servers can be seen, too.

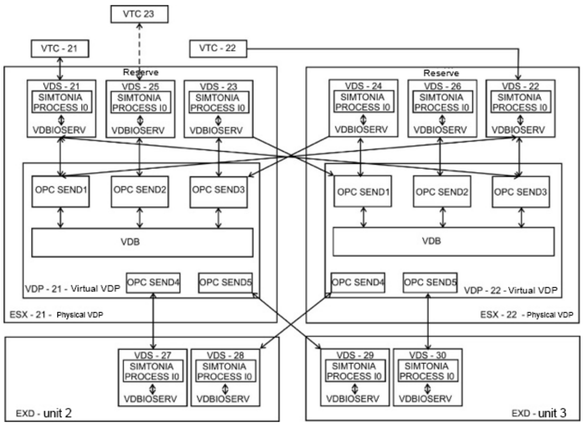

Figure 4: Connections of virtual display servers.

Fig. 5 shows the main display screen of the VERONA system. The screen is made up of separate SIMTONIA pictures, and each picture 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.

The application of templates in database references made possible to use a single set of SIMTONIA pictures for all units in the plant. It also helped to make a seamless switch in the visualization when an automatic active-background server changeover happened in the background.

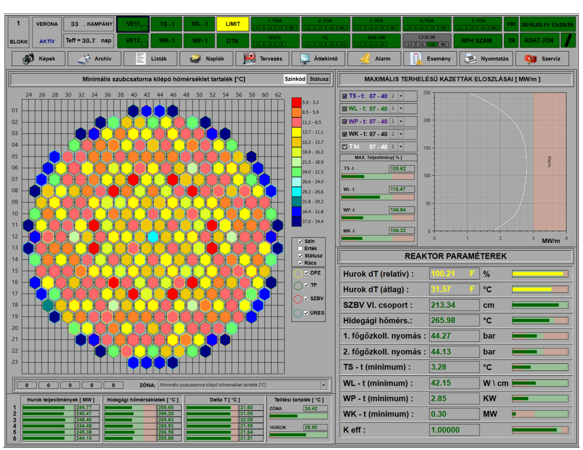

Figure 5: SIMTONIA based display of process data

5 Conclusion

Here we outlined the main features of the new VERONA core monitoring system of Paks NPP. Details of the new hardware architecture, system and application software were given together with some development experiences.

Advantages of the application of GPU accelerated computations and virtualization have been highlighted.

With the new developments, the reactor physics calculations supply the control room operators with reliable and accurate on-line data for core loads containing the new, 15-month cycle compatible fuel assemblies.

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