Upgrading the Reactor Power Control Concept with a Modern Digital Control System

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Abstract. Within the framework of a retrofit project, a reactor power instrumentation and control system (REALL) — consisting of a limiting system and the respective reactor control systems — was retrofitted and modernized in a 1450-MW-nuclear-power-plant in Baden-Württemberg. The REALL process control functions were implemented within a modern and completely digitized control system that has been designed for use in safety I&C applications. Along with the installation of the digital control system, the associated hardware was adapted to today's state of the art. At the same time, the given potential for improvement, as revealed during the plant's operation so far, was taken into account in the programming. In order to provide for transparent and quality-assured project management, the implementation was based on a stage plan consisting of several steps, along with specific milestones. Final commissioning of the modern digital control system took place during the 2008 plant overhaul. Despite the complex commissioning procedure, it was possible to avoid a major prolongation of the plant's downtime and to keep within a rough 4-week timeframe that had originally been defined for the plant overhaul to adequate structuring of the project, goal-oriented implementation of preparatory infrastructural measures and adequate scheduling of the coordinated activities of the installation and commissioning teams entrusted with the commissioning of the digital control system during the overhaul activities.

1. PLANT DATA

The plant is operating with a pressurized-water reactor of the 2nd generation from what is referred to as the 'pre-convoy series', using four loop lines. The plant was erected in Baden-Württemberg in Germany originally by KWU-Kraftwerksunion. The erection began in July 1977. Its commercial operation started in April 1985. The plant's electrical nominal gross output is approximately 1450MW. When it was built, the plant was equipped with I&C components that were in line with the latest state of the art at that time. In many cases, analog technology was used.

In nuclear power plants, which are engineered and commissioned nowadays, digital systems are used almost exclusively for the I&C functions. In the nuclear power plant we are looking at, more and more digital control systems were installed over the last 10 years, intended to handle an increasing number of operational and even safety-related tasks. The extremely positive experience gained with these systems — as far as the engineering, commissioning and operation were concerned — was the pivotal criterion for using a digital control system for retrofitting the reactor power instrumentation and control system as well as the in-core neutron flux measuring system. In order to be able to fulfill the requirements in these areas, the retrofit project was executed with a modern, type-tested digital control system that was designed for safety I&C tasks.

REASONS

What were the most important reasons for retrofitting the existing reactor power instrumentation and control system?

The starting point were evaluations of the plant's performance and of the operating experience gained in other plants. The process-related potential for improvement was supposed to be utilized and taken into account by the new instrumentation and control concept in order to optimize the plant's operational performance. Additional aspects of improving the procedures in the event of disturbances or failures and of providing for better identification of abnormal operating states were also to be taken into consideration. Furthermore, the messages and displays from the reactor power instrumentation and control system were to be optimized. Interfacing the system to the process computer system was believed to assure better monitoring and documentation of the reactor power instrumentation and control system.

Altogether, the primary objective of these measures was to achieve an increase in reliability, safety and availability of the overall plant.

Besides that, the future reactor power instrumentation and control system was to support automated testing procedures during regular load operation and overhauls.

In order to avoid potential problems with spare parts deliveries — a discontinuation of supply of the previous operational equipment was announced — the new technology was also intended to serve as a new resource and thus facilitate future repair procedures. And of course, the new technology was expected to upgrade the plant to be in line with the latest state of the art. The goal was to use a modern digital control system that would permit to effectively integrate the envisioned plant improvements into the reactor power instrumentation and control concept from the programming perspective.

2. BASIC STRUCTURE OF THE "REALL" REACTOR POWER I&C SYSTEM

The basic structure of the reactor power instrumentation and control system, abbreviated as REALL in German, is shown in this figure.

The reactor power I&C system includes the limiting system and the reactor control systems. The limiting functions can be found both in the switchgear building and in the emergency building. However, the limiting functions implemented in the emergency building differ from the ones engineered for the switchgear building. Since they are implemented in the secured area, they are also referred to as 'secured' limiting functions.

Basically, the limiting system is of a four-fold redundant design. With regard to the structure of the limiting system, this means that in each one of the four sections (sections 1 through 4) of the switchgear building, the same limiting functions have been implemented.

The same applies to the part of the limiting system that has been implemented in the emergency building. Again, all four sections (section 5 through 8) each cover the same functionality, however, in this case, the 'secured' limiting functions.

The reactor control systems have been implemented only in the four sections of the switchgear building. The control functions have been distributed to the four sections of the switchgear building depending on the respective actuators involved. Unlike in the case of the limiting system, the functions implemented in the individual sections for reactor control purposes are different.

For the purpose of data exchange, the limiting system implemented in the switchgear building is linked to the limiting system implemented in the emergency building. There is also data exchange between the limiting system and the reactor control systems.

3. CONTROL EQUIPMENT STRUCTURE OF THE REACTOR POWER I&C SYSTEM (SINGLE REDUNDANCY)

Since the control equipment for the new digital reactor power I&C system is structured in the same way for all four redundancy levels of the plant, the basic structure can easily be explained looking at the schematic drawing of one redundancy level. This schematic shows the structure of the reactor power I&C system based on the given plant organization.

The limiting functions are implemented both in the switchgear building and in the emergency building. The I&C components of the limiting system are highlighted in the diagram in a slightly blue shade. The reactor control systems are implemented solely in the switchgear building and are shown in a slightly red shade. Besides that, the in-core neutron flux measuring system is located in the switchgear building. The functionality of this system was integrated into the digital control system as well.

This measuring system provides information that is needed for the performance calculation and relates to the power distribution in the reactor core. The 48 power distribution detectors installed in the reactor core are evenly allocated to the four subsystems installed in the respective sections of the switchgear building.

The data acquisition and processing computers and the so-called voter computers or 'voters' are important control system components within the limiting system.

Data acquisition and processing computers include a dual computer system with host and subsystem that is used for signal acquisition and processing as well as for processing the control limiting functions. The result signals formed in the data acquisition and processing computers are then passed on to the voters.

Each voter consists of two redundant and synchronized subsystems. These subsystems monitor each other based on the master/checker principle and together they form an interconnected unit. The voter is used for activating the actuators, e.g. the drives and the control rod groups. The respective tripping signals are generated in the voters.

These components are networked in order to enable data communication. The I&C components of the in-core neutron flux measuring system and of the reactor control systems are included in the network as well. From the equipment perspective, the reactor controls implemented in the switchgear building are processed per section — two mutually redundant subsystems each time. However, both subsystems form an interconnected unit.

A monitoring and service interface (abbreviated as MSI) has been implemented in each section of the switchgear building and is shown in the figure in a slightly green shade. This interface is used for generating and processing the process and control messages coming from the digital control system. For this purpose, the interface is networked with all I&C components of the system. Message output, for instance, takes place through interfacing to the conventional annunciation system or via a gateway connection established by the plant process computer. In addition, this interface can directly activate status indications and other annunciations in the control room.

The digital reactor power I&C system is housed in six control cabinets per switchgear building section. Data acquisition and processing computers are installed in one of the control cabinets as well. The two voters required two control cabinets. Separate control cabinets were necessary for the reactor controls, the subsystems of the in-core neutron flux measuring system, and for the monitoring and service interface (MSI).

Due to the limited signal volume in the emergency building, the data acquisition and processing computer and the voter there were installed in the same control cabinet. As a result, for all four redundancy levels, a total of 28 control cabinets and 2 additional gateway cabinets were needed for setting up the system.

4. STRUCTURE OF THE REACTOR POWER I&C SYSTEM (ALL REDUNDANCY LEVELS)

This figure shows the control equipment structure of the entire system, including all redundancy levels. This is a rather impressive representation of the complexity of the new digital reactor power I&C system. You can recognize the section-internal and the intersectional networking of all the control components. The networking is established by means of visual bus systems (fiber optics), thus assuring proper decoupling.

Via the network, any signal information is therefore available to all of the data acquisition and processing computers. This allows the data acquisition computers to additionally perform signal validation procedures. Thanks to the networking concept, the processing computers can process the complete scope of control functions of the limiting system.

Since the processing computers output their result signals to all of the four redundancy levels, the voters can carry out a 2-out-of-4 evaluation of these result signals when generating the tripping signals. In this respect, this type of control equipment structure provides for a highly available and reliable digital system.

Operating this complex system is done with the help of a special service device which is linked to the monitoring and service interface (MSI).

5. OPERATION OF THE CONTROL SYSTEM

The service device for maintaining and operating the digital control system serves as an interactive user interface. The device can be used to visualize status information received from the individual processing units. In addition, it allows the user to call up function charts. By way of dynamic modification, the signals in the charts are updated with online values. The functionality of this device also includes convenient screen forms which can be used for performing parameter setting and calibration procedures, as well as for recurrent testing procedures.

6. PHASE PLAN

The project was started in 2004. It was implemented in several phases or subphases based on a phase plan.

This phase plan defined a project phase, a simulator phase, an engineering phase, a manufacturing phase, and finally an on-site installation and commissioning phase. The phase plan defined certain milestone dates when the work results of the phases or subphases were to be verified. The next subphase was started only after the respective preceding milestone was successfully accomplished. As quality-assurance measures, the respective testing and acceptance steps were carried out in each phase — in the presence of the officially appointed inspector performing an accompanying checking function.

The project phase included superordinated activities, such as project organization, project management and project monitoring.

The simulator phase served as a phase for testing the overall functions of the new digital reactor power I&C system and ended with the respective acceptance tests on the plant simulator.

The engineering phase served as a phase for generating the control functions. Quality-assured engineering of the system was achieved by pre-manufacturing tests and inspections of the process-specific and control concepts and of the functions compiled in system folders, as well as by analyzing the functions specified.

In the manufacturing phase, the manufacturing of the components took place. Subsequent factory and acceptance testing with the aid of inspection and test computers in the testing station in Erlangen then verified the quality and proper functioning of the components.

During the installation and commissioning phase, the system was installed on site and commissioned. Comprehensive final acceptance tests during the 2008 plant overhaul verified and assured the proper overall functionality.

This way, the phase plan provided for a transparent and quality-assured implementation of the entire project.

What were the tools that were used to engineer such a complex digital control system?

7. SYSTEM ENGINEERING

The basic procedure of system engineering is shown in this figure.

The system engineering was carried out using SPACE (SPecification And Coding Environment) which is a system-specific tool system. For project engineering and software development, this tool system primarily provides a graphic editor, code generators and testing tools.

First, the graphic editor was used to specify the envisioned process tasks in the form of function charts based on the control functions. These function charts were archived in a project database. The control functions shown in the function charts offer the advantage that they can be understood easily by process engineers as well as by I&C engineers. On the basis of the project database, executable programs were then generated automatically for the computers, using the code generators. After that, the control functions were checked using the analysis tools SIVAT and REDIFF.

8. SIVAT

The performance of analyses using SIVAT is shown in this figure.

SIVAT is a simulation and validation tool which provides a simulation environment for the system platform of the control system. Following the code generation, SIVAT performed discrete tests on the process control functions engineered with the help of SPACE.

The test specifications were generated on the basis of the function charts. In order to verify the specified process control functions, the simulation procedures were run, based on test scripts. These test scripts contain defined and discrete simulation steps for varying the input variables and the output variables of function charts that need to be looked at in this case. After a simulation run, the result files are archived in a database and are then output in the form of plots. A setpoint/actual-value comparison following the simulation run helps to identify and eliminate project engineering errors at an early phase.

9. REDIFF

The performance of analyses with the help of REDIFF is explained in this representation.

REDIFF provides a redundancy comparison tool for testing the control functions at the function chart level. The redundant function charts generated with the help of SPACE are checked for consistency. The tool shows the discrepancies between redundant function charts and then documents them in error reports. This tool can help to recognize and eliminate project engineering errors early on as well.

These analyses were complemented by further quality-assurance measures. One of the measures was the ATHLET simulator program.

10. ATHLET

The ATHLET simulator program enables computer-aided modeling of reactor protection functions, limiting functions and major control functions. Based on the results of the modeling, it is possible to simulate defined transients by specifying process variables and thus examine and recalculate their trends. In order to be able to examine the effects that changes in the reactor power I&C system might have on transient trends, the changed reactor power I&C system functions were implemented in the simulator software. After the adaptation, a total of 35 transient trends was examined and recalculated.
The tests and analyses showed that the transient trends fulfilled the criteria defined in the RSK (Reactor Safety Commission) Guidelines and that the reactor protection was not impaired in any way by the changes that were made. The tests and analyses revealed improvements in the plant behavior and in the plant availability.

11. PLANT SIMULATOR

Another important quality-assurance measure were the simulator tests that were carried out on the plant simulator in Essen.

In order to be able to carry out the simulator tests, the plant simulator in Essen had to be adapted first to the system and peripheral specifics. The system-specific adaptation was achieved by porting the control functions contained in the function charts into the software of the plant simulator. By means of hardware measures, the simulator environment was adapted to the peripheral specifics.

After the adaptations had been completed, the integral test of the interactions between the control functions was carried out by simulating the process variables. The testing procedures were generated on the basis of the function charts. In this context, the simulations included the performance of plant transients.

The simulations verified the functions specified and the improvements made for an operational plant optimization. Experience has shown that testing procedures performed with the plant simulator can considerably contribute to identifying possible project engineering errors. Furthermore, testing on the plant simulator also helps transferring specific know-how to the on-plant personnel.

12. PREPARATORY INFRASTRUCTURAL MEASURES

In addition to numerous implementation measures carried out in the course of the project, preparatory measures were performed in advance in the course of other projects. For instance, such measures aimed at an upgrading of the plant's infrastructure so that the integration of the new reactor power I&C system would be facilitated.

13. REPLACING THE PLANT PROCESS COMPUTER

In a preceding project, the plant process computer was replaced. The existing single-computer systems, e.g. the monitoring computer, the reactor protection monitoring computer and the additional display computer were taken together. Their functionalities were integrated into a redundant high-performance and consistent process computer system. The integration project was carried out gradually from 2003 until 2006. For this purpose, a consistent data model was created for approximately 15,000 signals and the necessary system interfacing was established.

Furthermore, the human-machine-interface was improved by the use of modern on-screen-based operating and visualizing techniques and the control room design was optimized.

14. UPGRADING OF THE POWER SUPPLY SYSTEM

In another project, the power supply system was upgraded prior to the actual integration of the new reactor power I&C system.

At first, calculations were performed in order to identify the power and space requirements of the future digital control system. Based on the calculation results, the battery rooms were retrofitted to be suitable for an increase in capacity. The batteries were installed and connected between 2002 and 2005.

The existing batteries were replaced with new battery types that provide an overall capacity of 4640Ah.

Moreover, the 24 Voltage switchbays were manufactured and installed with additional outgoing circuits and a discharge inverter for the batteries.

15. MARSHALLING CABINET

One of the hardware measures carried out during the actual project for modifying the reactor power I&C system was to install marshalling cabinets.

Such a marshalling cabinet has two terminal sides, a system connection side and a plant connection side. Both terminal sides are linked via the planned transverse connections. One marshalling cabinet was integrated into each section of the switchgear building.

This way, following the installation of the control cabinets, it was possible to connect the system supply cables for the digital control system to the system connection side of the marshalling cabinet. It was thus possible to perform signal-specific preliminary tests (cold test) of the I/O modules of the control system up to the plant connection side of the marshalling cabinets — independent of the overhaul activities. And it was possible to detect wiring errors even before the overhaul activities started, which resulted in more time for the remaining overhaul activities.

During the overhaul, the cables connected to the old reactor power I&C system were disconnected close to the modules, pulled back to the marshalling cabinet and then connected to the cabinet's plant connection side. Due to the smaller signal volume in the emergency building, the supply cables there were moved directly from the old system to the new system. Marshalling cabinets were not necessary in this case.

16. COMMISSIONING OF THE DIGITAL CONTROL SYSTEM

The following representation gives a general overview of the commissioning phase of the digital control system.

The overall system was put in operation step by step. After the control system cabinets, including the marshalling cabinets, had been installed, the system was hooked up to the power supply. After the cold test of the control equipment, the system was operated in island mode for several months in order to verify the system's stability prior to the overhaul. During the overhaul activities, the hot commissioning of the control equipment was carried out with the help of a special service device. Upon completion of the intersectional fiber-optic signal connections and after the system had been interfaced to the plant process computer via gateways, intersectional signal and annunciation tests were performed. Upon completion of the commissioning tests on the control components, various process-specific commissioning tests followed in order to provide an integral verification of their proper functioning. These tests included testing procedures during plant standstill, during startups and during plant operation.

Upon successful completion of the process-specific commissioning tests, the plant went on line again in August 2008. The operating experience gained with the new digital reactor power I&C system since has been very positive.

16. ORGANIZATIONAL AND ADMINISTRATIVE MEASURES

In the following some measures are described, which resulted in an optimization of the commissioning time that was needed for the control system while the plant was at a standstill.

17. MANPOWER PLANNING

In order to assure maximum utilization of the plant downtime, the installation and commissioning teams worked shifts on a continual basis. In the shift change meetings, the current work status was communicated to the next team taking-over. Disturbances of the work activities, as they might be caused by recurrent testing activities for overhauling, were avoided. Regular updating of the work status within the project workflow through the installation and commissioning team made it possible that the project management was always able to closely track and monitor the progress of the project.

18. MONITORING OF THE PROJECT IMPLEMENTATION

In order to assure adequate monitoring of the project implementation during the 2008 overhaul, regular project meetings were held during the daily morning meetings. Including shift staff who is familiar with the project has proven to be helpful. This also helped to assure timely releases of job orders. The progress status was identified during the project meetings in order to be able to counteract any deviations from the schedule as soon as possible. The progress was documented in status reports and logs.

Altogether, these measures had a positive effect on the commissioning time and resulted in a quality-assured and traceable implementation of the project.

19. SUMMARY

Thanks to the consistent documentation of the project execution and the phase-specific tests, which were carried out in the presence of the officially appointed inspector, it was possible to fulfill the stringent quality assurance requirements applicable to such a complex system.

Despite the large volume of replacement work, this project is a good example of a successful complex system retrofit which was accomplished thanks to selective preparatory measures and the necessary quality assurance measures without causing a relevant extension of a periodic plant standstill.