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E. Végh, J.S. Jánosy, V. Ozerkov, I. Soldatov: Compact simulators for VVER-440 type nuclear power plants. KFKI 1991-25/G

ABSTRACT

This paper describes a Compact Simulator for VVER-440 type Nuclear Power Plants. The simulation of the process covers the whole operating range: from cold shut-down state to nominal power level. The simulator can be used to train normal and abnormal operating procedures, moreover, a great ammount of emergency scenarios can also be practised.

Э.Вег, Я.Ш.Шебештьен, В.Озерков, И.Солдатов: Компактный тренажер для АЭС типа ВВЭР-440. KFKI-1991-25/G

АННОТАЦИЯ

Описывается компактный тренажер, разработанный для АЭС типа ВВЭР-440. Симуляция охватывает все режимы работы АЭС от холодного состояния до состояния работы на номинальной мощности. Тренажер используется для обучения персонала обслуживанию реактора как в нормальном режиме, так и в переходных режимах, далее,позволяет продемонстрировать большое количество аварийных ситуаций.

Végh E., Jánosy J.S., Ozerkov V., Soldatov I.: Kompakt szimulátor a VVER 440 típusú atomerőművek számára. KFKI-1991-25/G

KIVONAT

A dolgozat ismertet egy Kompakt Szimulátort, amelyet a VVER 440 típusú atomerőművek számára fejlesztettünk ki. A szimuláció érvényességi köre felöleli az erőmű teljes működési tartományát: a hideg állapottól a névleges teljesítmény szintig. A szimulátor alkalmas az erőmű normális és üzemzavari kezelésének oktatására, továbbá nagyszámú baleseti helyzetet is lehet vele bemutatni.

1 ABSTRACT

This paper describes a compact simulator for VVER-440 type plants. Up till now three simulators have been delivered: to Paks Nuclear Power Plant (Hungary), and to Kola and Rovno NPPs (Soviet Union). In this compact simulator the modelling complexity of the plant is almost similar to that of a full-scope one apart from the Control Room being replaced by a Control Desk and four colour graphic display units. The simulation of the plant covers the whole operating range: from cold shut-down state to nominal power level. The simulator contains up to 32 different initial conditions. Moreover, every 5 minutes the simulator produces so called "snapshots", i.e. disc images of the Data Base. Using these snapshots the instructor can go back in time (called backtracking) in order to repeat some previously passed events. The most important part of the training is to teach the plant behaviour and the necessary actions to be taken by the trainees during transients caused by equipment failures and malfunctions. The simulated malfunctions are divided into groups according to the technological systems of the plant. A maximum of 64 malfunctions can be active at a given time.

2 INTRODUCTION

Training simulators for Nuclear Power Plant operating staff have gained increasing importance over the last twenty years. The need for training simulators was clearly recognized as a result of analysing the operators' errors that led to severe accidents at Three Mile Island and Chernobyl.

In compact simulators the modelling complexity of the plant is almost similar to that of a full-scope one, but the similar appearance to the real control room is not required. In general interfacing of compact simulators to the operating staff consists of a control desk and several colour display units. For this reason this device is considerably less expensive than a replica simulator and its hardware is much smaller.

A compact simulator for the VVER-440 type (Model: V-213) PWR plants was originally constructed for Paks NPP; it then was adapted to two Soviet NPPs.

3 MAIN FUNCTIONS

This Compact Simulator is used both for initial training and retraining of the personnel of VVER-440 Nuclear Power Plants. In this simulator all the important operating modes are simulated, including the start-up procedures from cold state to full power and the shut-down procedures back to cold state. Moreover, with this device a very wide range of abnormal situations can be simulated in order to practice different emergency scenarios. In the operators' training this device plays an important role and it is used in the following fields:

* to teach the dynamic behaviour of the plant,
* to analyse different transient states,
* to develop emergency procedures for abnormal situations,
* to train normal and abnormal operating instructions,
* to test different emergency scenarios,
* to test different repair procedures,
* to evaluate the trainees' performances.

3.1 MODELLED TECHNOLOGICAL SYSTEMS

In this simulator all the main technological units of the plant having any effect on the plant dynamics are modelled. The technological models can be divided into three groups viz.

- reactor and primary circuit,
- turbine and secondary circuit,
- generator and grid.

In the first group the reactor, the pressurizer, the cooling loops, the main circulating pumps, the steam generators and the make-up water system are modelled.

In the second group all stages of the turbine, the low- and high-pressure preheaters, the moisture separators, the condensers, the feedwater tanks, piping and pumps are simulated.

In the third group the electrical generator, the excitation system, the main transformers and breakers, and the grid are calculated.

All of the systems listed above include their control-, safety-, plant logic- and measuring systems, as well.

3.2 OPERATING MODES

In the simulator practically all of the normal operating modes of the plant, moreover, a wide range of transient states can be studied. The validity limits of the models are determined by the flow modelling, which is valid only for one-phase flows, thus boiling in the primary circuit is excluded. The most important operating modes are the following:

* normal operating modes
  - warming from cold state to warm state,
  - reactor power increase from critical state to minimum controllable power level,
  - pressurizer operation with nitrogen and steam cushion,
  - reactor power increase to any permitted level,
  - power decrease and block shut-down,
  - operation with residual heat removing system.

* transient states
  - load rejection of the generators,
  - turbine trip,
  - stop of one or more main circulating pumps,
  - air break into the condenser,
  - trip of feedwater pumps,
  - trip of a high-pressure preheater, etc.

* emergency states
  - leakage of the pressurizer safety valve,
  - leakage of the steam generator safety valve,
  - break of the main steam line,
  - break of the feedwater line, etc.

4 HARDWARE STRUCTURE

The hardware of this simulator consists of a simulation computer, a control desk, four colour graphic terminals and an instructor's station. The computer is a Hungarian megamini with the computing power of a microVAX-2. It has 9 Mbyte operating memory and 300 Mbyte disc storage.

The Control Desk provides an interface for the trainee. On this device all the important parameters of the plant are displayed and it contains the most important controlling equipment to control the actual plant. The desk contains a modular mimic diagram with meters, LEDs and alarm windows mounted into it. The plant mimics is engraved into the mosaic system, displaying the state of all valves, pumps and heat exchangers. The state of these elements are presented by LEDs. Alarms are indicated by alarm windows. The Control Desk has its special input/output microprocessor based electronics, operating 10 times in a second, thus the time resolution for input/output events is 0.1 sec. This electronic system scans the input devices 10 times a second and controls the appropriate elements on the mimic diagram at the same rate. In this way the Control Desk provides an immediate change in the state of the control elements when a controller is manually operated. However, the actual states of the control devices are sent to the simulator computer only once a second when this is requested by a polling sequence. The Control Desk - as a special terminal - is connected to the simulation computer via two asynchronous serial lines.

Since the Control Desk is small, its mimic diagram cannot display the technology in every detail. For this reason colour graphic displays are used to present detailed plant mimic diagrams. Two display terminals are used for mimic diagram presentation, one display simulates the operation of the neutron flux controller and one display shows the time history of different variables. Up to 6 curves can be seen at the same time on this device.

The Instructor's station contains an alphanumeric display terminal and a colour plotter for plotting the time history of the given transient.

5 SOFTWARE STRUCTURE

5.1 DATA BASE

The software structure of the simulator is based on the Global Common concept. The Global Common is installed as a "shared image" in the operative memory, and all communication between the simulation and communication software is evaluated by reading and writing this memory partition. The Data Base contains every input/output variable, state variable and parameter which should be easily accessed during simulation and which is necessary to determine the state of the simulator.

The Data Base is divided into a dynamic and a static part. The dynamic part is modified during the simulation sessions, whereas the static part remains constant.

Since the Data Base determines fully the state of the models, this area represents the Initial Condition (IC) for the simulator as well.

5.2 REAL-TIME EXECUTIVE

A real-time simulator executive supervises the entire operation of the simulator. This executive is specifically developed for the needs of a training simulator environment, and it controls the execution of the technological models. The executive can operate in normal, slow and fast modes. In normal mode most of the models are executed once a second, except the neutronic part which runs four times a second. In slow time mode the execution of the models is slowed down by a factor of 5. In fast time mode the Xenon model is accelerated by a factor of up to 240, in order to produce the Xenon transient in a convenient time scale.

5.3 COMMUNICATION SYSTEM

The communication system transfers the information between the data base and the man/machine interface system (Control Desk and display terminals). The communication can be divided into two main parts:

- control desk communication
- colour display communication

The communication input program sends a polling sequence to the Control Desk once in a simulation cycle and it sends back its new state if it has changed from the previous polling. The input program modifies the data base according to the received information. In the same way, the communication output program sends back the values of the output elements of the Control Desk at the end of a simulation cycle.

Since the Control Desk is much more simplified in comparison with the real Control Room some subsystems cannot be shown in the necessary - and simulated - details. The actual parameters of the most important subsystems are collected into mimic diagrams, and displayed by colour graphic displays. The refreshment cycle of the mimic diagrams is the same as the main simulation cycle.

5.4 INSTRUCTOR'S SYSTEM

The Instructor's System is a very important part of the simulator since this provides a tool for controlling the whole simulation process. Long operating sequences are avoided in order to help the instructor on controlling, teaching and evaluating the trainee's performance.

The instructor communicates with the simulator via a standard alphanumeric display terminal. A menu-driven selection is provided on the display screen, which makes the control of the simulation session very simple.

With the Instructor's System the following services can be requested:

- Initial state loading/saving
- Start and freeze simulation
- Save snapshots
- Backtrack snapshots
- Change time scale
- Control manually operated components
- Initiate malfunctions
- Control parameter monitoring

5.4.1 INITIALIZATION -

The system contains the following initial states:

- 32 normal initial states;
- 32 backtrack initial states, or snapshots.

Each initial state is a disc file containing the image of the data base. The normal initial states are permanently stored whereas the snapshots are preserved only during the simulation session. Snapshots are stored automatically every 5 minutes or on manual request at any time. Simulation always starts from an initial state. The instructor selects the required initial state from the appropriate list on his display screen. The described simulator was delivered with the following initial states:

- cold shutdown state,
- hot standby state,
- operation with one turbine,
- nominal power level.

5.4.2 BACKTRACKING -

Using this feature the instructor can go back in time and can repeat events. During backtracking, snapshots are used as initial conditions and the simulation continues from the stored moment.

5.4.3 DATA MONITORING -

The system can collect the values up to 32 variables into a buffer at every simulation cycle. From this file the Graphic Display System produces trend curves. The instructor may select up to 32 variables for collection and any 6 of the monitored variables to be displayed. Time history curves are generated with different ranges and time scaling. The time scaling can be selected in the interval from four minutes to one hour.

5.5 PLANT SYSTEM MODELLING

The structure of the model software closely follows the organization of the actual plant. These models are FORTRAN programs thus they can be modified easily. Structured programming methods and thorough standardization support any future changes.

5.5.1 REACTOR AND CONTROL RODS -

A point model is used for the reactor core model. No spatial distributions are calculated. The model contains equations for power distribution, delayed neutrons, coolant and fuel temperatures, xenon and iodine concentrations and decay heat. The control rod banks and associated drive mechanisms are modelled in sufficient detail so that they respond accurately in all manual and automatic modes of operation. It is assumed that all rods which form a bank have the same position and they cannot move independently from other rods in the same bank.

The in-core and out-of-core detectors respond correctly over the full operational range of the reactor. The reactor protective and automatics systems are also simulated. All relevant time delays are included in the model.

5.5.2 PRIMARY COOLING SYSTEM -

The reactor coolant models simulate the thermal hydraulics of the coolant loops, including the reactor vessel, all hot and cold legs, steam generator tube sides and reactor coolant pumps.

The hydraulic model, which computes flows and pressures around the reactor coolant system, utilizes a model based on conservation of mass and momentum. No assumptions are made regarding the direction of coolant flows. The model adequately caters for reverse flows, natural circulation and thermal expansion of the coolant. The model calculates the flows and pressures simultaneously through the use of an "inertia matrix" solution. Core thermodynamics are simulated with coolant thermodynamic properties, temperature, density, fuel and cladding temperatures and heat transfer being calculated.

5.5.3 PRESSURIZER AND RELIEF TANK -

A non-equilibrium stratified model is used for the pressurizer. The model covers the following operation modes:

- normal operation,
- pressurizing with nitrogen,
- pressurizer filled completely with water,
- pressurizer is empty.

Both gas/vapour and liquid phases are modelled as control volumes separated by a moving boundary, with condensation and flashing between the phases.

The pressurizer relief tank model simulates the piping system between the pressurizer and the relief tank, the cooling circuitry, the phases in the tank itself: water, steam and nitrogen. The following conditions are modelled:

- normal operation,
- blowdown from the pressurizer (nitrogen and/or steam).

5.5.4 STEAM GENERATORS -

The steam generator model dynamically calculates pressure, level, and steam generation. A lumped parameter approach is used. The model responds correctly to swell/shrink, uncovered tubes, coolant boiling, partial draining and natural circulation.

5.5.5 TURBINE, CONDENSER AND FEEDWATER HEATERS -

A dynamic turbine model is used, which covers all of the HP and LP stages, the control system, moisture separation and reheating. The auxiliaries such as turbine generator lubrication and gland steam sealing, are not modelled in every detail.

The main condenser is represented by a two phase model with condensation and evaporation between the phases. The model calculates condenser pressure, hotwell level and other properties for all required operating conditions - including normal operation, bypass under trip conditions, during shutdown, and in case of failure of the air evacuation systems. The model responds correctly to normal, transient and emergency operations of the cooling water system.

All the HP and LP preheaters, and the feed water tank are simulated by a unified Saturated Tank model. This model can handle the filled state as well as the emptied state of the mentioned tanks. The process of deaeration, and the gas carrying capacity of the water are not modelled.

5.5.6 WATER AND STEAM LINES OF THE SECONDARY CIRCUIT -

The flows, pressures and temperatures are calculated by a flow network package. The lines, which can carry steam and water at different operating conditions, are supported with some auxiliary calculations and water/steam library routines.

5.5.7 ELECTRICAL SYSTEMS -

The main generator and exciter models operate only in synchronous mode. The interaction of the generator and exciter models with the grid remains realistic even under load rejection and island conditions, as well. A dynamic model is employed for the grid, with an equivalent generator representing the other units. Control and protection logic for the plant electrical distribution system is also modelled.

5.6 MALFUNCTION MODELLING

The instructor can select the desired malfunctions through his display terminal using the Malfunction Selection Display Formats.

The simulated malfunctions are divided into groups according to the technological systems of the plant. A maximum of 64 malfunctions can be active at a given time. Each malfunction has the following attributes:

- address
- parameter (optional)
- delay time

The address specifies the affected object or component of the plant. The parameter may specify the severity of the malfunction. The delay time specifies the remaining time to malfunction activation.

The most important malfunctions of the simulator are as follows:

- control rod failure,
- pressurizer heater and/or spray valve failure,
- pressurizer safety valve failure,
- reactor trip,
- turbine trip,
- stop of main circulating pumps,
- feedwater pump failure,
- leakage in the steam generators,
- turbine safety valve failure,
- turbine bypass valve failure,
- loss of generator load,
- stuck control valves,
- spurious alarm signals,
- measurement drift, etc.

The malfunction events can be preprogrammed and saved as a part of the initial condition. In this way the instructor can concentrate attention on the trainee's performance, moreover, the work of different operators can easily be compared.

6 ADVANTAGES OF THE COMPACT SIMULATOR

The described simulator is a result of the joint efforts of KFKI (Hungary) and VNIIAES (USSR). The advantages of this device can be summarized in the following:

1./ The simulator was developed, installed and put into operation in less than two years for two Nuclear Power Plants.

2./ Practically every normal operation of the plant can be simulated with this device as can a very wide range of emergency situations.

3./ The operation of the simulator is simple and inexpensive. Special services are not needed, the whole device can be installed in a normal classroom.

4./ The Control Desk and the colour display terminals provide a compact and clear picture of the plant. The physical relationships and control rules can be easily understood.

The described simulator has been operating in Paks NPP since June 1989, in Kola NPP since November 1990, and in Rovno NPP since February 1991.

7 FURTHER DEVELOPMENT

In this report a VVER-440 Compact Simulator was described. However, a Compact Simulator is planned for the VVER-1000 type power plants, as well, and the results of the existing VVER-440 simulator can easily be used in the planned VVER-1000 compact simulator. In the planned VVER-1000 Compact Simulator the most important further developments are as follows: the safety system should be included and in the primary circuit two-phase flow modelling is needed. It is logical that this development should be based on the existing cooperation of KFKI and VNIIAES.

In our opinion this device can be used parallely with the full-scale simulators, because both the price and the operating cost of the Compact Simulator is very low compared to the full-scale one, and at the same time its possibilities are very wide.

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