REQUIREMENTS ON MECHANISTIC NPP MODELS USED IN CSS FOR DIAGNOSTICS AND PREDICTIONS

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Abstract

Mechanistic models have for several years with good experience been used for operators' support in electric power dispatching centres. Some models of limited scope have already been in use at nuclear power plants. It is considered that also advanced mechanistic models in combination with present computer technology with preference could be used in Computerized Support Systems (CSS) for the assistance of Nuclear Power Plant (NPP) operators. Requirements with respect to accuracy, validity range, speed, flexibility and level of detail on the models used for such purposes are discussed. Quality Assurance, Verification and Validation efforts are considered. A long term commitment in the field of mechanistic modelling and real time simulation is considered as the key to successful implementations. The Advanced PROcess Simulation (APROS) code system and simulation environment developed at the Technical Research Centre of Finland (VTT) is intended also for CSS applications in NPP control rooms.

INTRODUCTION

Mechanistic model based diagnostics and prediction techniques have already extensively been used in electrical network dispatching centers. It has been considered important that the operators have a possibility to test their intended operations with a simulator before operating the real network. The electrical network models used are very detailed, including models of interlocks and automation systems. the required measurements have been available for the estimation of the initial conditions needed for the predicting simulation runs. This has been possible because of the linear behavior of the electrical network itself. The first attempts to predict thermohydraulic processes were realized by linearized state equations resulting however in very short accurate predicting time span because of the process non-linearities that not were taken into account. In fact it has previously not been possible to make the accurate enough much faster than real time situations needed for long term predictions. Furthermore, the use of thermohydraulic codes has traditionally required access to experts. Now, when sufficiently easy to use simulation environments are available, the efficiency/price ratio of computers has increased rapidly, and the numerical methods for solving this kind of problems have improved considerably, it has been feasible to study a possible introduction of mechanistic model based support systems in the NPP control rooms. The requirements for such models with regard to accuracy, validity range, speed, flexibility, level of detail, verification and validation are discussed.

The quality assurance aspects, both with respect to the development and maintenance of the simulation tool itself and also concerning the consistency of the model specification, are discussed. A systematic updating procedure of the mechanistic model according to changes at the plant state, as for instance caused by the manual operation of a valve, is definitely needed. The mechanistic model specification is in fact a computerized the real-time documentation tool for notation and evaluation of the detailed state of the plant. Verification and validation procedures are essential for the quality assurance of the simulation tool. Modeling of a large set of international test requirements and subsequent simulation of the recorded experiments made at each site form an important but laborious part of the verification work. The test matrix has to be reprocessed after each change in the code of the simulation tool. Also documented experience and working procedures of the development team of the simulation is of importance. For reference, the experiments in mechanistic modeling of NPPs at VTT is described. The following concepts have been applied on the development of the Advanced PROcess Simulation (APROS) environment and code system.

GENERAL REQUIREMENTS

Accuracy and validity range

The concept of accuracy with respect to mechanistic model is dependent on the physical and chemical mechanisms taken into account as well as the accuracy of the material properties and correlation used, and the construction data available. The validity range concerns the extent of the temperature, pressure and concentration regions where the mechanisms, material properties and empirical correlation are valid. The achievable accuracy is also dependent on the spatial discretization of the fluid circuit and heat structures, and on the length of the time-step used for the numerical integration. Numerical methods used and truncation errors may also have a large impact on the resulting accuracy.

Speed

The speed requirements is real-time for tracking mode simulation as well as for training applications in general. However in predictive simulation, more than 100 times faster than real-time may be required for feasible application. Ten times faster than real time can presently be achieved with an affordable desk-top work station computer and efficient code.

Level of detail

The level of derail is considered as the portion of components and processes simulated. Usually an integrated system should be simulated as a whole. The exact replication of control system functions is very important. Auxiliary systems may not be needed to model in detail, if their impact is not specifically studied.

Flexibility

The flexibility requirement is perhaps one of the most demanding. The flexibility includes easy and formally consistent model specification. It should be possible for the operator to easily make changes in the model. It should be convenient to isolate a part of the model to study only local interactions. It should be easy to assign any suitable variable as a boundary condition for the model, e.g. for attaching a tracking mode simulator to process measurements. Change in mode structure should be possible to do on-line.

MECHANISTIC MODEL BASED OPERATOR SUPPORT

Three applications of mechanistic models for advanced CSS systems in the control room will be discussed. The on-line tracking mode simulator used for non-linear state estimation. the faster than real time predicting simulator for extending measured curves on process computer displays, and the off-line what-if simulator for experimentation of operational procedures. All these tools include the same identical mechanistic model of the plant, which also may be used for plant analysis or training purposes: Only one model to update!

State Estimation

One such model is used for state estimation running as a tracking model in real time and having some important measured variables as boundary conditions. These variables are either of integrating type, such as levels, temperatures, and pressures, or are external such as cooling water temperature, electrical grid voltage and plant electrical power set-point. This model produces input for a diagnostics tool evaluating differences between measured and calculated values.

Prediction

A copy is made from the tracking model state variable data-base for use by the predicting model, running without any implied boundary conditions and much faster than real time, and providing calculated extensions to the measured curves for the operators' displays in the control room. The predicting simulator is started with pre-defined time intervals and each time provided with a fresh snap-shot from the tracking mode simulator, including all state variables and parameters needed. The predicting simulator is supposed to calculate a scenario of sufficiently long time to show how the process is proceeding from the present state without any interventions from the operators. That means that all involved automation systems, such as sequential automatics, also shall be included in the predicting simulator model.

Scalar or Parallel Processing

A full scope analyser model with one dimensional reactor and turbine plant models included runs presently on a desktop workstation computer about ten times faster than real-time with a time step of 0,2 seconds. The same plant model provided with a detailed fully three dimensional reactor representation runs just in real time. To run the one dimensional model 100 times faster than real time, either we have just to wait for some years to have available a single workstation at affordable prices, or to make extensive use of parallel processing. The problem is that general code made for sequential computing usually not can benefit much from traditional, medium grain vectored or parallel processing. The algorithms used have to be adapted for parallel processing and the code reprogrammed, which is a major effort. Also distributing the overall model on several computers for coarse grain parallelism requires advanced computerised tools for efficiency and consistency.

An interesting feature is that code optimised for parallel and vector processing also runs more efficiently on a single processor. This will be more evident in future as the single processor architecture develops with inherent fine grain parallelism. Old scalar Complex Instruction Set Computers (CISC) processed the instructions strictly sequentially, needing several clock cycles for an operation. They were improved with pipelined functions, such as floating point operations, and even combined with attached vector processors. The Reduced Instruction Set Computers (RISC) managed to initiate operations in parallel, reaching about one operation per clock cycle. Super scalar RISC processors, such as Pentium Pro, reaches 3-4 operations per clock cycle. Future Very Long Instruction Word processors provides already for massively parallel operation. In addition to this we all have experienced the 25% increase in clock cycle speed each year. The hardware needed will be available.

Experimenting

An additional workstation with the identical model may be provided for off-line what-if simulations in close connection to the control room or for studies in the technical support centre, as well. It should be possible to make copies of the real-time state value data-base to this simulator on request. The what-if predicting simulator makes it possible for the operator to check off-line the impact of manual operations before invoking them at the real plant. The operator may then like to run the simulator in real time mode, faster than real time, slower than real time, or interrupt the simulation, and also include manual operations in the scenarios. A separate workstation should be assigned for the what-if simulation. This workstation may with preference be used by the operators for self directed training studies of the operational performance of parts of the plant or the whole plant.

MODELLING REQUIREMENTS

The Paradigm Used

Power plants are intrinsically very non-linear, the automatics introduce discontinuities in the operation, as well as certain events in the process itself, mostly because of the non-linear and even discontinuous nature of the thermodynamics and transportation properties involved. Also, simulation of a plant at continuous full power is not very interesting. The estimator should survive operations from cold shutdown to full power, and also assist in accidental situations. This means that only a non-linear mechanistic model of the process is useful, and that a reasonable complete model of the control system also is needed. In fast transients a linear adaptive estimation model has neither the time nor the information to reconstruct its parameters. A non-linear estimator may also have adaptation of some of its parameters, however, the adaptation should always be user controlled, not continuous, since an adapting model might not find developing errors in the process itself.

The Mechanisms Considered

Only a mechanistic model may comply with these requirements. It is always important for the user to know which physical and chemical mechanisms are considered in each part of the model, and what restricting assumptions are made such as:

- noncompressibility or compressibility considered
- flow only in pre-defined direction or change of direction is considered
- single phase flow only or homogeneous multiphase flow considered
- velocity of sound considered or not
- separated phases may have different flow velocities and directions or not
- transportation of solid phase considered or not
- diffusion considered or not
- separation considered or not
- non-equilibrium thermodynamics considered or not
- non-condensable gases considered in vapour flow or not
- solubility of gasses in liquid phase considered or not
- momentum considered or not
- momentum flux considered or not
- relocation of heat structures considered or not
- penetration of pressure vessel considered or not
- equilibrium chemical reactions considered or not
- chemical reaction kinetics considered or not
- electrolytic effects considered or not
- residual heat dependent on operational history or not

Material Properties Presentation

Also the calculation of thermodynamic and transportation properties of materials included, and the validity range of such properties is of vital importance for a reliable result. The user should definitely know the valid operational range of pressures, concentrations, entalphies, void, and temperatures. The accuracy of the calculated outputs should be presented, for e.g.

- mixture density
- mixture temperature
- mixture entalphy
- void fraction,
- liquid density
- gas density
- liquid entalphy

- gas entalphy
- liquid phase concentrations
- gas phase concentrations
- solid phase concentrations
- viscosity
- friction between phases
- heat transfer coefficients, between phases and between fluid and solid structures
- derivatives such as compressibility and specific heat

Flexible Boundary Conditions

In a tracking mode simulator it is essential to have a large variety of variables possible to choose as boundary conditions for the calculation, preferably such variables that usually are measured with reasonable accuracy, and are of integrating type, such as

- temperature
- level
- pressure
- concentrations
- integrating controller outputs

The derivative type of inputs, however, such as flows are usually not very precisely measured, and may merely be used for diagnostics purposes. Of course if they are real boundary conditions to the real model, as for example water to and from water treatment system, they have to be considered. In fact one of the main sources for discrepancy between model and real process is accumulated to the total water inventory. It is also the place where to look for pipe breaks, considering feed and bleed control, besides possible measurements from the drainage system.

On-Line Model Configuration

Extreme flexibility is needed of the tracking model. Measurements may be found incorrect and can not longer be used as boundary conditions, some part of the plant may be operating abnormally and should be excluded from the overall model, until the model has been changed accordingly. A leakage should for instance be possible to introduce anywhere in the model. All these changes should be possible to introduce on-line between the simulation time-steps of the tracking mode simulator. There are a lot of parameters in a simulation model that are based on constructional data that may need an adjustment when measurements are available from the plant. So is that case e.g. with the total heat exchange coefficients of heat exchangers. The tracking mode simulator should allow for adjustment of the heat exchangers, provided suitable measurements are avai lable.

A very important aspect is the updating of the simulation model. The model needs prompt updating of data according to procedures, which may well promote the overall quality control of the work orders performed at the plant. All changes in the plant, e.g. as simple as operation of manual valves, should be included in the model specification. This means that there is a current model specification of the plant, which is the basis for the tracking mode, predictive mode, and what-if mode simulations. In addition it serves as consistent a plant state data-base. The tool for updating the model shall be computerised process and automation diagrams. There shall be access to the states and parameters of the different components directly from the diagrams, by activating the component of interest. Changes in the model is done by updating the diagrams and component parameters according to changes in the real process. All parameter data should be traceable: who has introduced a parameter, found from which document, who has updated the parameter, and when. All this improves the consistency.

The Model Data-Base

Several types of data shall be available in the model data-base that is reached directly from the graphics. In addition to the model component parameters themselves and the state values from the simulation data-base, there may be references to other databases, possibly including such information as the functional descriptions of the components, the source document for the specification of each parameter, the design criteria for the components, reference to maintenance database, operational history of the components, and specific current remarks on the use of the component to be considered. That is, the model data base is a part of the plant documentation system, having its role in transferring consistent knowledge to the operators and the maintenance personnel, much originating from the design phase of the plant. It is also a place to update data later on, as changed during backfitting and re-engineering efforts.

Design Evaluation

When available, the simulator is also a tool for evaluation of different design alternatives when planning for changes to the process. Specific design copies are made from the current database only for this purpose and are used by the design and maintenance personnel at their own computer systems.

Technical Support Simulator

A copy of the current model should also be available at the computer system in the technical support centre, making it possible to independently run what-if scenarios starting from the present situation. A copy could also be available at the office of the national nuclear regul ator.

Training Simulator

The plant full scope training simulator could benefit from the current model philosophy. If the same model specification is used at the simulator, the training simulator will always be up to date. This is also the correct place to introduce changes in the process design for training of the operators just on time before they are taken into use at the real plant.

Quality Assurance

Nuclear power plant analyser codes are usually very extensive, and developed of a team of several specialists during a long period of time. They nowadays tend to be commercial grade proprietary codes. The quality of such common code for the different simulation purposes may be assured with a consistent verification program. The correct performance in different configurations of the lowest level building blocks of heat structures, flow structures and physical and chemical mechanisms is checked. If there is made any changes in the kernel of the code, the whole verification program has to be renewed. The verification program consists of a large set of modelled test equipment, each having available several measured transient tests, with will be compared to simulated tests. It is assumed that the code is calculating correctly the target process if it performs correctly in the test cases. Also the validation of the software with measured data from the simulated target plant is important. Both model and specification data correctness are considered.

THE ADVANCED PROCESS SIMULATION SOFTWARE

Graphics Based Model Specification

In order to achieve a consistent specification of plant and automation systems, suitable for concurrent engineering by several persons, a suitable graphical interface is needed. A graphics clients' and data-base server based approach enables consistent model development and updating procedures. The plant model is formed by a hierarchical set of pictures, including process and automation system diagrams. Several persons may develop and test their own models independently, which easily are combined to a single model. The model may be run on several computers concurrently. The models are easily connected to emulated or real control system equipment over TCP/IP connections.

Computer Platform

The simulation server code is presently maintained on a large set of computers and operation system versions The development environment includes new Silicon Graphics, Hewlett Packard, Sun, and DEC Alpha computers, having UNIX operating systems with X-Windows and Motif libraries available. Also a VMS version is available for DEC Alpha, and soon also Windows NT. The graphics server software runs presently in X-Windows environment, but soon in PC environment.

Layered Software Structure

The software quality is maintained applying a layered software structure, enabling easy transportation of the software between software platforms, easy transportation of the model specifications to new versions of the software, and easy connection to new types of graphical interfaces [1]. It is important to keep the following two layers separated: Mechanistic Model Building Blocks, and higher level Technological Process Building Blocks.

APROS has a software kernel developed and maintained at VTT. This includes the real-time database with the basic sparse matrix solvers, the thermohydraulics calculation, heat structure calculation, the electrical system solvers and the automation system solvers. Also basic correlations and material properties are included. The kernel level mechanistic building blocks have been heavily verified. A large set of international thermohydraulics test equipment have been modelled [2]. Reliable operation in the test cases implies reliable operation also in other configurations. After changes in the code the tests have to be repeated. APROS application models have been also validated against measurements from real plants and compared to calculations made with other codes [3]. It is possible for the user to define own component models such as steam generators, only by specification in the database, using the mechanistic building blocks of flow and heat structures provided for by the kernel. This technological level enables the user to develop added value to the APROS, maintaining his own component libraries, and quality assurance procedures.

The APROS Project

In 1986 it was decided from software quality assurance point of view to develop a completely new modelling and simulation environment for inclusion of new, more advanced codes for demanding simulation studies. The Advanced PROcess Simulation (APROS) software was developed as a more than hundred man-year effort in close co-operation with IVO International Ltd. The consistently verified and validated product has reached a mature level with respect to nuclear plant dynamic analysis. The next features under development concern more severe accidents including possible relocation of heat structures in the core. Separate research aiming on implementation of capability to calculate scenarios including penetration of pressure vessel is presently going on.

APROS is now in use at about 20 sites, including applications from full cope simulators to design workstations. The CSS application area was considered from the beginning of the development of APROS. Model based operator support systems, such as state estimators, predictive simulators, or so called "what if" simulators, are provide for. The CSS requirements for the models and the simulation environment were accordingly considered in detail.

Accumulated Mechanistic Modelling Experience at VTT

Extensive experience on modelling of nuclear power plants has been built up since the early seventies at the Technical Research Centre of Finland (VTT). At VTT Automation the first larger efforts concerned modelling of the Loviisa pressurised water VVER 440 nuclear power plants for the purpose of validation of the total control system concept. The model was later on used for on line tests of some parts of the real control system, as e.g. the plant and turbine controllers, which were connected to the model instead of the simulated controllers. The model was also equipped with a control desk for initial training purposes of the Loviisa operators. A similar model with one dimensional reactor calculation was also developed for the Olkiluoto boiling water nuclear plants of ABB type. At the same time VTT Energy was involved in making detailed analysis of the Finnish nuclear reactors, as required by the authorities, using at that time available codes, but also developing completely new codes for the purpose. This was the start of the long term generation of the critical mass of know how in the development of real time simulation and nuclear plant analyser tools.

This experience was refined during the years in different contexts concerning full scope training simulators. VTT was providing software tools, modelling and consulting services during the construction of the Loviisa full scope training simulator together with a department of ABB Power in Finland, and has later on been directly updating and improving the Loviisa simulator for the owner Imatran Voima Company (IVO). The Loviisa simulator was one of the first full scope simulators where a primary circuit small brake accident could be calculated in real time and included in the training program. ABB has subsequently used codes with roots in Finland for its training simulator development, as for example in the PAKS simulator in Hungary. An other implementator of VTT developed codes has been Eurosim AB in Sweden. Accordingly, several Swedish, Japanese and Korean NPP simulators have thermohydraulics codes developed at that time in by VTT in Finland. This was a good starting point for the APROS project.

CONCLUSIONS

The technology provides for introduction of computerised model specification tools serving the plant from its design phase, during the commissioning and operation of the plant, until the decommissioning. Very soon, affordable standard computer systems are on the market enabling the introduction of advanced mechanistic model based CSS to the control room. Fortunately experimental tracking mode simulators have been implemented with real plant measurements, and also experimental control rooms are built enabling studies of the use of predicting simulators and model based diagnostics in power plants[4].

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