DETERMINATION OF REACTOR THERMAL POWER USING A MORE ACCURATE METHOD

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ABSTRACT

Reactor thermal power is an important operational parameter in many respects such as nuclear safety, reactor physics or evaluation of turbine thermal performance. Thermal power of a pressurized water reactor is determined on the basis of the steam generator thermal balance. The balance can be made in several variants differing from one another by the selection of different measuring circuits whose data are used in the balancing. In principle, no one such variant gives the true value of the thermal power. Among the variant values, the one nearest to the unknown true value of reactor thermal power is probably the value calculated with the lowest uncertainty. The determination of such uncertainty is not easy and its value can make even several percent, which has significant economic consequences.

This paper presents the method of data reconciliation and its application to the data of the third unit of Dukovany NPP. The data reconciliation method allows to exploit all the information which process data contain. It is based on the statistical adjustment of the redundant data in such a way that the adjusted data obey generally valid laws of nature (e.g. conservation laws). Mass and energy balances based on the data not yet reconciled do not obey those laws because of measurement errors. For data reconciliation in Dukovany, a detailed model of mass and energy flows describing the 3rd unit from steam generators to alternator and condenser was set up. Laws of mass and energy conservation and phase equilibrium in water-steam systems are thus fulfilled. Moreover, the user can model momentum balances in pipelines and create other equations, which are respected during calculation. The data reconciliation is done regularly for hourly averages.

As a result of data reconciliation, there is a new data set with more accurate data including the reactor thermal power. Data reconciliation also allows:

- *determination of confidence intervals for results of mass and energy balancing*
- *calculation of unmeasured quantities (e.g. thermal flows in loops of the primary circuit)*
- *detection and elimination of measurement gross errors*
- *design and optimization of measurement systems aimed at the minimization of uncertainty of measured and calculated values and minimization of measurement cost.*

The paper describes the current state of implementation using overall plant information system and the process data warehouse based on the Industrial SQL server database and the InTouch human machine interface. The paper also presents the experience with data reconciliation in 2004 and 2005.

1. DATA RECONCILIATION THEORY [1,2,3,4]

Data validation consists usually of several steps. The first activity is the data pre-processing and screening. In this step raw data are averaged and cleaned of possible apparent mistakes and errors.

The further step – data reconciliation (DR) – can be defined as an adjustment of measured data to obey some mathematical model (mostly a law of nature). The DR procedure minimizes the generalized sum of squares of adjustments constrained by

$$g(z) = 0 \tag{1}$$

where z is the vector of state variables (flowrates, temperatures, …) and g is a vector of generally nonlinear functions of z. Equation (1) represents e.g. a set of mass and energy balances. The vector z consists of three kinds of data:

- Variables x measured with some error
- Unmeasured variables y to be calculated in the DR process
- Constants.

The reconciled solution z' obeys the condition (1) and minimizes the generalized sum of squares

$$Q = v^T F^{-1} v \tag{2}$$

where F is the covariance matrix of measurement errors and v the vector of adjustments of measured values

$$v = x' - x^+ \tag{3}$$

where x' is the vector *of reconciled values* and x^+ the vector of measured values subject to random errors e defined by relation

$$e = x^+ - x^t \tag{4}$$

where x^t is the (unknown) true value of x.

The minimum value of Q will be further denoted as Q_{min}.

The DR procedure is formalized in the next Figure 1.

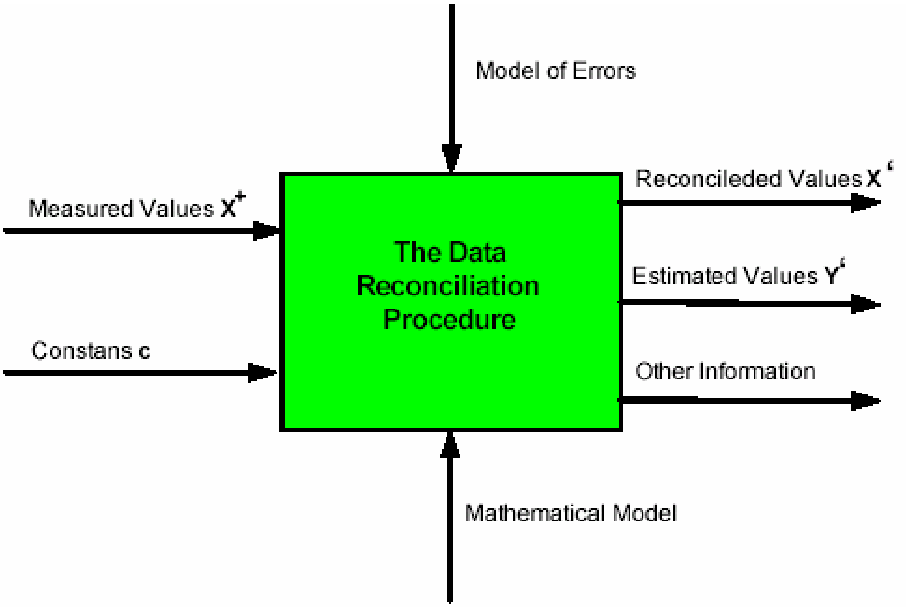

Fig. 1: The Data Reconciliation Procedure

The other result of DR is the (automatic) classification of variables.

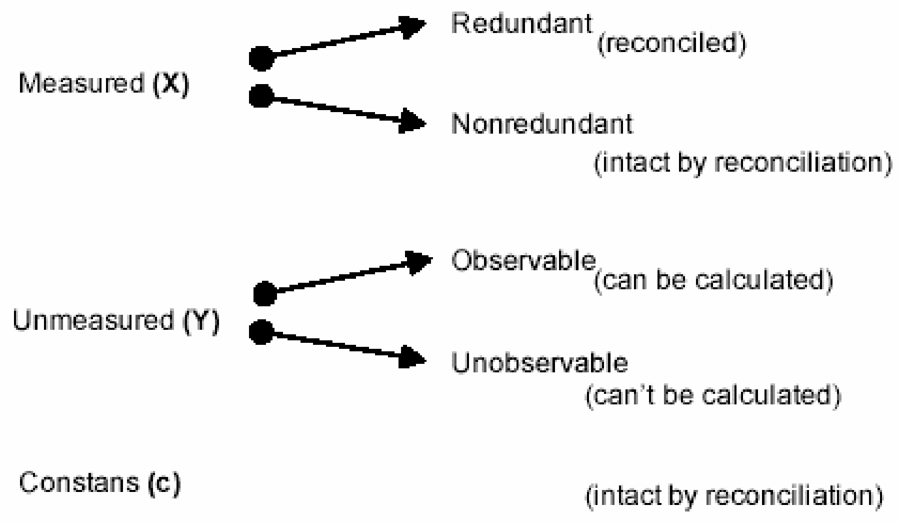

Fig. 2 : Classification of variables

The most frequent model of random errors is the *normal (Gauss) distribution* characterized by the zero mean value and the standard deviation σ. 5 % of errors occur outside the interval $<-e_{max}\,;\, e_{max}>$ where $e_{max} = 1.96\ \sigma$ which corresponds to the 5 % confidence level accepted usually in technical problems. Errors greater than e_{max} are denoted as *gross errors.* e_{max} is sometimes called a *tolerance or uncertainty*.

The other important notion is the *number of degrees of freedom* ν. If all unmeasured variables are observable, ν equals the difference between the number of equations and the number of unmeasured variables, i.e. number of redundant measurements.

Precision of reconciled data

The precision of data can be characterized by their covariance matrices $\boldsymbol{F}$. Between covariance matrices of $\boldsymbol{x}^+$, $\boldsymbol{x'}$ and $\boldsymbol{v}$ holds the following relation [1]

$$\boldsymbol{F}_{\boldsymbol{x}+} = \boldsymbol{F}_{\boldsymbol{x}'} + \boldsymbol{F}_{\boldsymbol{v}} \tag{5}$$

The precision of individual variables (elements of vectors) is characterized by their standard deviations, which are square roots of diagonal elements of respective covariance matrices

$$\sigma_i^2 = F_{ii} \tag{6}$$

As $\sigma_{vi}^2 \geq 0$, the following inequality holds

$$\sigma_i \geq \sigma_{x'1} \text{ (where } \sigma_i \text{ means } \sigma_{x+\,i}) \tag{7}$$

saying that there can be some improvement in precision due to DR. This improvement can be characterized for the *i*-th variable by the so-called *adjustability* a_i

$$a_i = 1 - \sigma_{x'i}/\sigma_i \tag{8}$$

The adjustability of any measured variable represents the reduction of its imprecision caused by DR. As will be seen later, adjustabilities are quite remarkable variables having importance also in area of gross error detection. From the definition follows that any adjustability lies in the interval <0 ;1>.

- value 0 represents so-called *just determined variable,* which is not influenced by DR and is not adjusted at all
- value in the interval (0;1) means *redundant variables* which are adjusted in the process of DR
- value 1 occurs when the standard deviation of a measured variable is approaching infinity. By definition, this is the case of *unmeasured variables.*

Further it is supposed that covariance matrices of reconciled values $\boldsymbol{x'}$ and of estimated values of unmeasured variables $\boldsymbol{y'}$ are available (the already mentioned DR Engine in Fig. 1) thus providing tolerances (confidence intervals) of reconciled values.

Detection of gross errors

Q_{min} is a random variable which is used for testing of presence of gross errors. The gross error is detected when

$$Q_{min} > Q_{mincrit} \tag{9}$$

where $Q_{mincrit}$ is a critical value available in statistical tables (Q_{min} has the chi-square distribution with number of freedom equaling ν, for details see [1]).

The ratio S

$$S = Q_{min}/Q_{mincrit} \tag{10}$$

is called the Status of data quality. Data sets with $S > 1$ are corrupted by a gross error(s) and should not be used until possible gross errors are identified and eliminated.
The identification of a gross error (finding the probable source of it) is based on the *standardized adjustment* z_i , which is introduced as

$$z_i = \frac{v_i}{\sigma_{vi}} \ . \qquad (11)$$

where v_i is the adjustment
σ_{vi} is the standard deviation of the adjustment.

It can be shown that the square z_i^2 *equals* (in the linear case) *or at least approximates* (in the nonlinear case) the *reduction of* $Q_{\min}$ after deleting the measurement x_i . So we can directly look for the largest $|z_i|$ (or z_i^2) identifying the first suspect as source of a gross error. Finding a variable suspect of a gross measurement error is itself a useful result. It is a motivation for *checking the suspect measurement devices* by instrumentation maintenance engineers.

This is a brief statement of the DR problem. The solution proper was described many times in the literature (for example [1,2,3]) and will not be treated here. Further it is supposed that the reader is acquainted with basics of DR. For those not familiar with the DR technology, there is the *Balancing and Data Reconciliation Minibook* [4] available free on the Internet.

2. NUCLEAR POWER PLANT DESCRIPTION

Dukovany nuclear power plant consists of 4 reactor units. The secondary side (conventional island) of each unit consists, among others, of 6 steam generators, 2 high pressure turbines, 4 low pressure turbines, 4 high pressure reheaters, 2 feedwater tanks, 10 low pressure reheaters, 4 moisture separators/superheaters and 4 condensers.

Input data for the data reconciliation model are hourly averages.

3. MATHEMATICAL MODEL OF THE SECONDARY CIRCUIT

The mathematical model consists of the following set of sub-models:

- Mass balance – the basis of the model

- Energy balance – mostly enthalpy balance. Water and steam properties are evaluated according to IAPWS IF 97. Kinetic energy is respected in the case of velocities over 30 m/s. Potential energy is neglected.
- Phase equilibrium applied to situations when both temperature and pressure of a wet steam are measured. These equations are essential for temperature and pressure validation.
- User-defined equations for special models; also used in places of insufficient instrumentation to guarantee full observability of unmeasured variables.

The model contains some artificial streams and nodes representing for example duplicated measurement of flows and other state variables on one stream or heat and power fluxes.

The balancing flow sheet of one reactor unit contains about 130 nodes (units) and 300 streams. The model is fed with data of 191 measuring circuits (43 mass flows, 96 temperatures, 52 pressures). The model has 27 redundancies so far, which is not a final number. Some redundant measurements will be added after data are supplied from overall plant information system at the end of this year.

It is worth mentioning that there are 250 unmeasured variables, all observable. Some of them are variables defined during the model configuration (heat fluxes, heat transfer coefficients, etc.). Anyway, most of them are unmeasured physical variables, like flows or temperatures, which are calculated as results of mass and energy balancing. Thus a complete reconciled balance of the overall system is available to users.

Typical measured variables, describing steam generator condition, and their uncertainties used in the model are shown in the following table:

Type	**Stream**	**Unit**	**Typical value**	**error (uncertainty)**
Flow	feedwater after HP reheater	kg/s	383.4	2 %
Flow	feedwater before SG	kg/s	127.8	2 %
Flow	steam after SG	kg/s	126.1	4 %
Flow	steam before turbine	kg/s	189.1	4 %
Flow	Blowdown	kg/s	1.7	10 %
Temperature	Feedwater	deg C	222	2 °C
Pressure	Feedwater	MPa	4.7	0.05 MPa
Pressure	Steam	MPa	4.7	0.05 MPa

The main target variable is the steam generator output. The tolerance of this calculated variable is 0.56 % of the nominal value (7.66 MW absolutely). The picture of the whole model is shown in Fig. 3.

Data reconciliation of the nonlinear model is of iterative nature (usually 4 iterations are sufficient). The overall calculation lasts about 1 s (on 2 GHz Pentium PC).

As the status of the model mentioned above, in this stage of its development, is sensitive to the changes of less important variables (e.g. temperature of water used for district heating of plant buildings), a simpler model has been developed. This second model describes only the area of steam generators and is used for determination of their thermal power. In comparison with the large model, the smaller one is more robust (not so sensitive to possible problems with the instrumentation) but still powerful as concerns the quality of data validation.

The balancing flow sheet of the second model contains about 19 nodes (units) and 57 streams. The model is fed with data of 36 measuring circuits (20 mass flows, 8 temperatures, 8 pressures). The model has 8 redundancies and tolerance of the output of steam generators is 0.68 % (9.35 MW absolutely). The model is shown in the Figure 4.

The model of the secondary side of the Dukovany third unit has been built in graphic form using RECON software by Chemplant Technology.

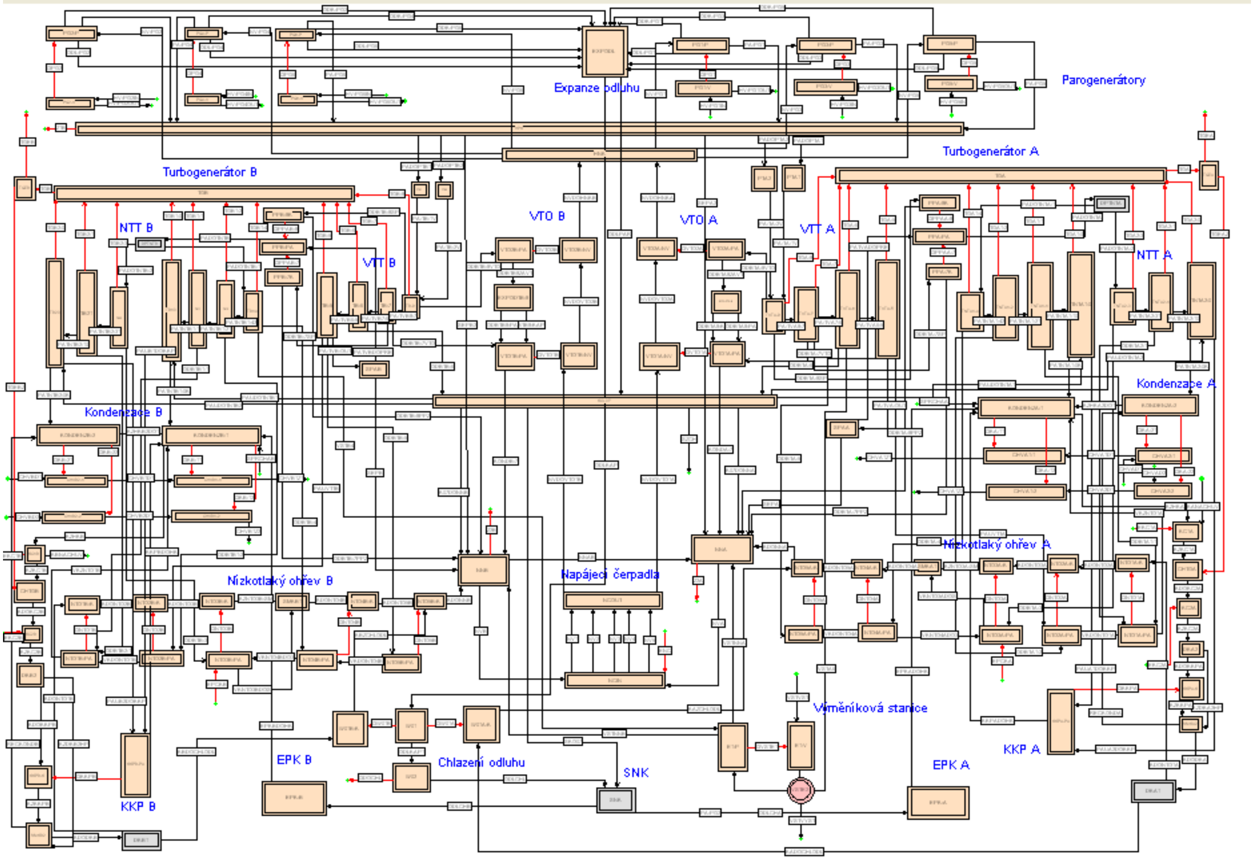

Fig. 3: The model of the secondary circuit

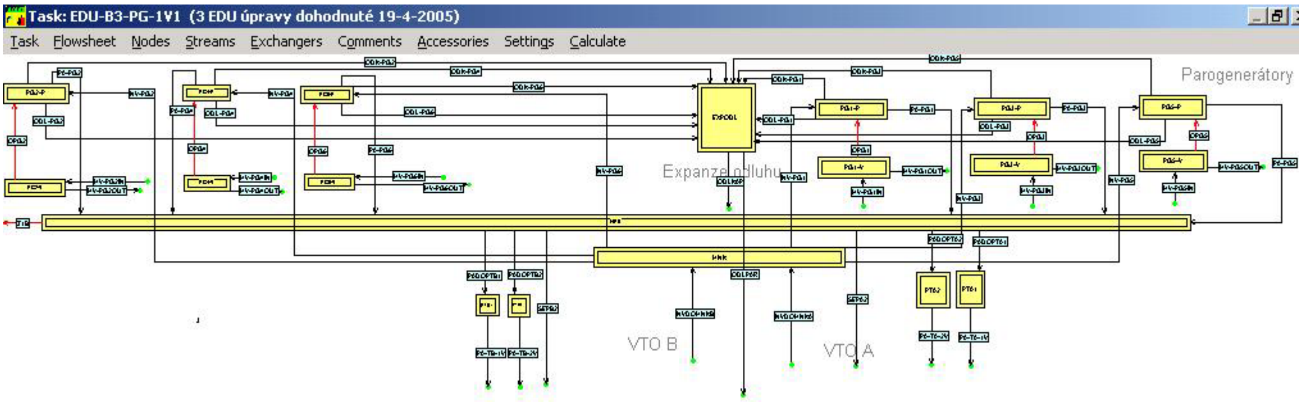

Fig. 4: Model of area of steam generators

4. EVOLUTION OF CHARACTERISTIC DATA

The model was tested on data from the beginning of 2003 to the present. During the outage of the third unit in spring 2004, when the old information system (URAN) was replaced, considerable amount of measurements were added to model input data. Figure 5 shows evolution of status of the larger model after the outage.

Increase of status around 29 April was caused by process computer system operator who introduced an incorrect database of measurements into the computer. Hourly averages used for data reconciliation were calculated on the basis of archive data. These data represented only significantly changed values of variables. Hourly averages calculated from these data were different from those calculated from data regularly read. Thus mass and energy balances were distorted more than usually.

Other increases of status usually mean that real flows are different from those in a model. Another reason is the occurrence of transients or at least unsteady states, whose data reconciliation is rather difficult.

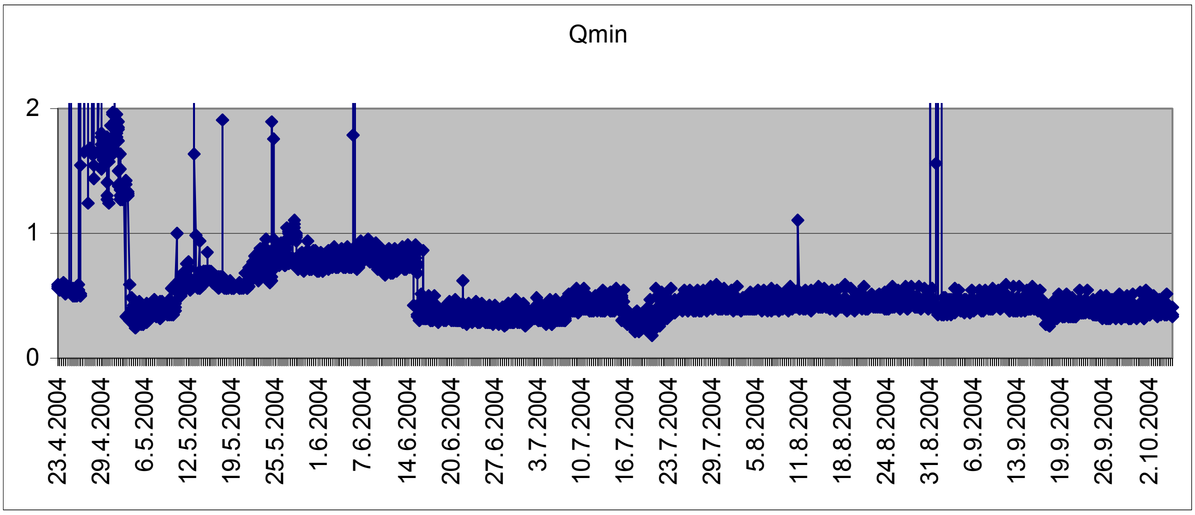

Fig. 5: Status after the outage in 2004

The next Figure 6 shows example of thermal power of steam generators and status determined through the second (simpler) model. After about 5 July, it can be seen slow decrease of the thermal power. Its cause is a degrading measurement of one reactor coolant cold leg temperature, which increased delta t on one loop and resulted to incorrect calculation of the average reactor delta t used for reactor power control.

Thermal power at the point indicating 1379 MW (i.e. more than nominal power) at 6:00 on 27 June is not calculated correctly. At present stage of model development, a periodical blowdown flow for a single steam generator is not yet determined. It requires defining a virtual variable, combining the mass flow through the common pipeline of periodical blowdowns and the state of the valve at the corresponding steam generator, which will be done in the overall plant information system. Thus states when periodical blowdowns are discharged from steam generators will be modelled properly after the data reconciliation is carried out in this overall system (see the next section).

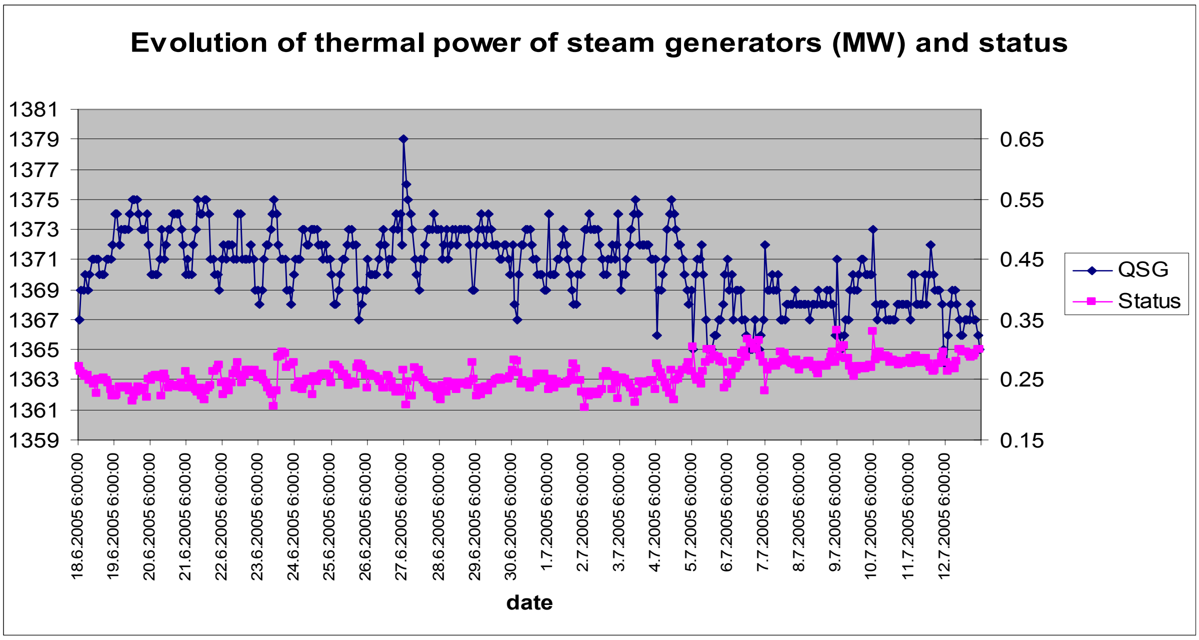

Fig. 6: The steam generators power (QSG) and the Status of data quality

5. INTEGRATION OF THE PROCESS DATA VALIDATION INTO THE OVERALL PLANT INFORMATION SYSTEM

Reconciliation of process data of the Dukovany third unit, as described above, is done with input data files, containing 10 min. averages, from process computer system (PCS). The data from PCS are manually transferred to power plant’s LAN. Hourly averaging and the reconciliation itself is carried out separately in the standard PC by a performance engineer, usually in daily batch. It is not a final state.

The data validation is a part of a larger project, whose final goal is to enable monitoring and evaluating reactor unit’s thermal performance. The control room operator will get the information in quasi-real time (with delay of time averaging interval) about actual condition (characterized mainly with electrical output) of the reactor unit and its should-be condition (i.e. expected in case of good equipment condition) with advice where the cause of the difference could be sought. The same information will be available to the performance technician the next working day. To fulfil such a goal, a new arrangement of data flow and processing is designed.

The solution is based on the Industrial SQL server database and the InTouch human machine interface by Invensys’ Wonderware and the RECON data validation package by ChemPlant Technology. Such solution unifies presentation of validated data with other company applications and minimizes a need of staff training. The overall plant information system, which is now being built, connects and integrates separate and heterogeneous information and control systems, each with its own set of components and internal autonomous databases.

The foundation of the overall plant information system is a Process Data Warehouse (PDW) which gathers data, at high speed and full resolution, from multiple simultaneous and disparate real-time sources. Each data source has data in its own formats maintained in the various databases. PDW handles collection, transformation into unified format, storage and retrieval of numerical, digital, string and other data.

PDW acts as a data server for variety of clients' applications for operators, engineers and managers, generally for role-based individuals in the plant. Data validation is a new layer between the raw data stored in PDW and its users, such as ad-hoc queries and predefined reports, as well as analytical processing where the data quality is an important issue to achieve new level of application functionality. Cleaned and validated results are stored back in PDW for various uses.

Overall plant information system consists of a plenty of hardware and software modules. Figure 7 shows the basic overview of the overall plant information system.

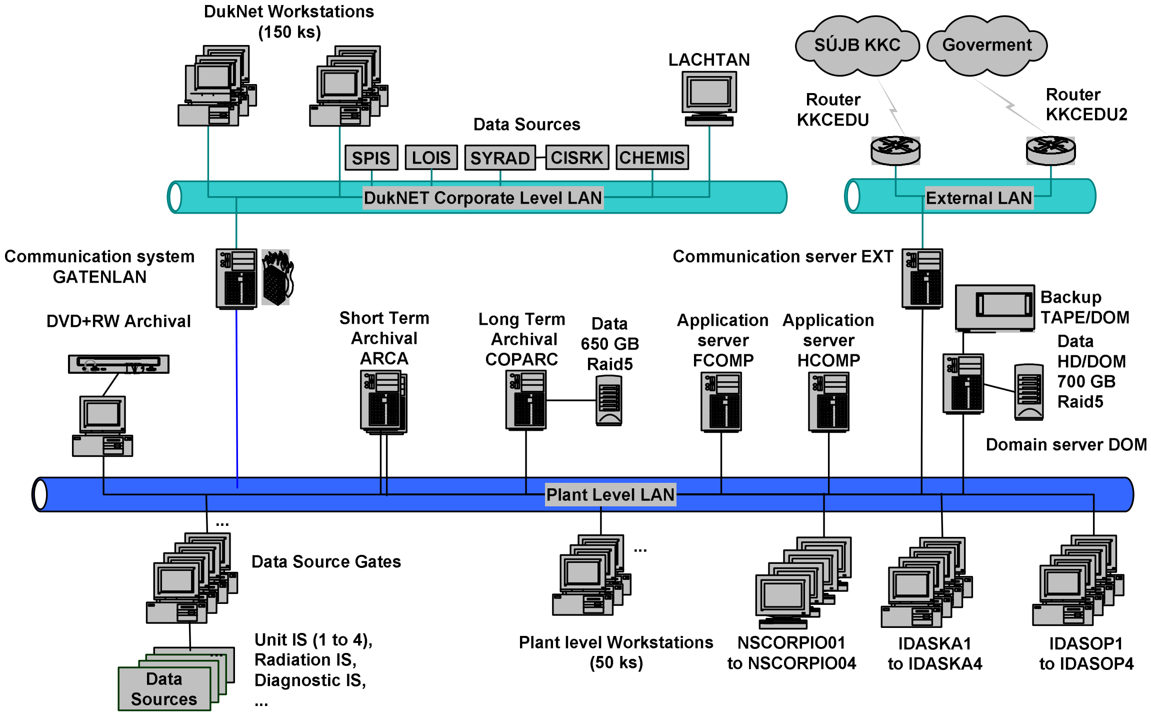

Fig. 7: Overall plant information system

Data collection from disparate data sources is performed by software modules called data acquisition servers (DAS) which provide Dynamic Data Exchange (DDE), SuiteLink and OLE for Process Control (OPC) protocols.

Data pre-processing, data reconciliation and gross error detection functions described above run on Application server. Application server provides current data using DAS in the same manner as any data source.

One of DAS client is Wonderware's Industrial SQL Server historian which uses the Remote Industrial SQL Data Acquisition Service (IDAS) to acquire data from DAS distributed throughout the overall plant information system.

The IDAS is configured to provide Store and Forward functionality for failover of InSQL Server or plant information system network so that those failures do not adversely affect data collection.

Application server provides suitable infrastructure for data validation and also for mathematical model for on-line monitoring, process optimization, component diagnosis and on-line calibration of instrumentation.

6. CONCLUSIONS

The process data validation based on data reconciliation of redundant data is a promising way to enhance quality of data about nuclear power plants. Among its major advantages belong the following features:

- all information present in data is used
- the directly unmeasured variables (as a thermal power of a nuclear reactor) are determined with a minimum uncertainty
- there are well developed methods for detection and identification of possible malfunction of the instrumentation
- the data reconciliation is a part of the overall mathematical model enabling one to get information about the complex behavior of the whole system

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