APPLICATION OF VIRTUAL POWER PLANT FOR CONDITION MONITORING OF POWER GENERATION UNIT

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Summary

The following paper presents the method, called here the Virtual Power Plant (VPP), for the condition monitoring of power generation unit elements. The Virtual Power Plant is the proposal of a group of computers, which model a real power plant unit in the real time. This paper is focused on Virtual Power Plant architecture and procedure to use it for condition monitoring. Such a procedure is based on models of various types tuned to the normal technical state of the plant. Next, this model is used to detect any changes in the behaviour of the plant elements.

The paper present details of the Virtual Power Plant idea: its structure and functionality of key elements. The structure of the model is presented with stress on its modularity and flexibility. Next part of the paper is the case study, where test installation, tuned to a 200MW coal fired unit, was described. Results from operation on the test installation are presented.

Keywords: modeling, condition monitoring, model based diagnostics, power plant.

ZASTOSOWANIE WIRTUALNEJ ELEKTROWNI
DO DIAGNOSTYKI BLOKU ENERGETYCZNEGO

Streszczenie

Artykuł przedstawia metodę, nazwaną Wirtualną Elektrownią (VPP, ang. Virtual Power Plant), zastosowana do oceny stanu elementów bloku energetycznego. VPP jest propozycją zastosowania zespołu komputerów, które będą modelować pracę bloku energetycznego w czasie rzeczywistym. Artykuł koncentruje się na przedstawieniu architektury Wirtualnej Elektrowni oraz na jej zastosowaniu do oceny stanu technicznego. Metoda opiera się na heterogenicznym modelu, dostrojonym do bloku energetycznego w poprawnym stanie technicznym. Następnie model ten jest podstawą wykrywania zmian zachowania elementów bloku.

Artykuł przedstawia szczegóły koncepcji Wirtualnej Elektrowni: jej strukturę oraz główne elementy. Opisano model bloku ze szczególnym naciskiem na modułowość i elastyczność. W kolejnej części artykułu opisano instalację testową, gdzie VPP została dostrojona do rzeczywistego bloku typu 200MW. Zaprezentowano wyniki pracy instalacji.

Słowa kluczowe: modelowanie, ocena stanu, diagnostyka, energetyka.

1. INTRODUCTION

Nowadays, very rapid development of information technologies, especially processing power, enables us to develop innovative methods of condition monitoring of machinery and processes. Among these, power generation equipment is of very significant importance. This significance is the direct consequence of very high construction costs, as well as maintenance and repair costs.

Numerous methods are used to assess the technical state of supervised objects. In general, they are referred to as fault detection and identification (FDI) methods. Comprehensive survey presenting those methods can be found e.g. in [7, 4]. Very successful approach is based on models, either based on analytical equations, either on parametric models obtained during the process of system identification [8, 6]. On the other hand, feasibility of such an approach is limited when it is applied to large, industrial installations, like power plant units. Key problems can be listed as:

- development of the model; in most cases, even if the underlying physical equations are known, the important obstacle is to obtain correct parameters, and thus – correct model behavior; on the other hand, when the system identification approach is chosen – it is extremely important to acquire sufficient data, covering range of operation of the object;
- flexible work environment; the process of model development and next – diagnostics

requires efficient cooperation of specialists from different fields: power plant staff should deliver data and technical documentation, diagnostic experts are responsible for modeling the process and drawing conclusions, results should be presented in a comprehensible way for the power plant experts and management; in practice, those tasks are executed with a set of heterogeneous tools, making the whole process hard to manage and inefficient.

Following paper presents the proposal of the Virtual Power Plant (VPP) - the innovative work environment for technical state assessment of dynamic objects, here applied to elements of the power plant unit. Such an environment should work with performance close to the real time (when necessary and technically possible). Introduction of such an environment facilitates development of models and next – the process of diagnostics. Such an environment has following benefits:

- flexible structure, enabling multiple configurations;
- import of real data acquired at the object;
- possibility to include models in various formats (though Matlab/ Simulink was chosen as the default);
- possibility to store models in different versions;
- presentation of results in two ways: advanced for experts and simplified for power plant staff.

However, applications of the Virtual Power Plant can be much broader than the diagnostics only. It can be also used to achieve the following goals:

- reply of malfunctions to analyze real cases from the plant;
- modeling of faulty behavior of a plant to improve the knowledge about processes in the real plant;
- simulation of various modifications of the unit and effects it will have, for example in the dynamic state;
- huge resource for search of diagnostic rules, thus it will bring advances in FDI techniques
- testing of existing and the development of new models;
- development of risk management algorithms
- verification of diagnostic systems in operation on a plant;
- testing of equipment behavior, also in abnormal conditions;
- testing of concepts of new equipment elements, using rapid prototyping techniques
- very efficient tool to train operators, also in abnormal conditions;
- improvement of safety of existing plants.

The development of the Virtual Power Plant can also be very interesting option for power plants owners to improve their competitive position on the deregulated market. The possibilities mentioned above will be investigated during future research and development works.

2. VPP ARCHITECTURE

Achieving of the main goals of the Virtual Power Plant depend most on its structure. The key requirement is that it should have a modular structure, similar to that one of a real power plant. Such a structure is presented on the figure 1. The Virtual Power Plant is the group of computers, connected by a fast computer network. Each computer plays a role of a VPP component. The largest part of the system is database, which consists of two cooperating subsystems. The first one is the database as in the typical DCS system. This allows to store the data in the same way they are stored in a real system. On the other hand it will allow to present data in user-friendly way and to interact with the VPP, during training of operators. The second database subsystem is a specialized, fast database which is used to store data generated by

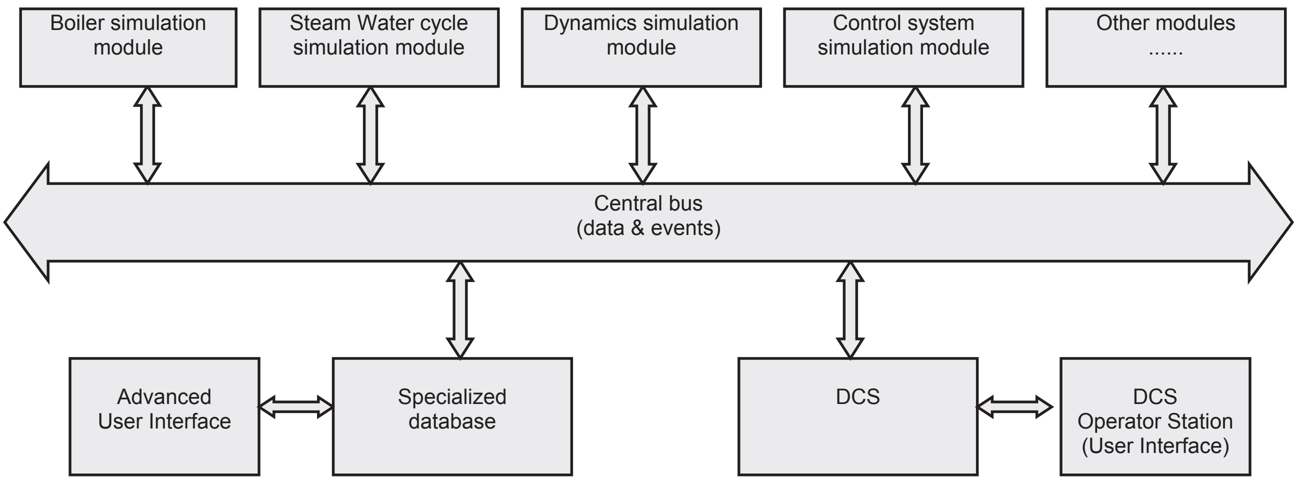

Fig. 1. The structure of the Virtual Power Plant

modules of the VPP. This subsystem is proprietary, efficient database engine, which can also store dynamic data (e.g. vibration waveforms).

The Central Bus is another computer, which is the main data exchange hub in the VPP. It provides common interface for all the modules, which allows to develop each module independent from the others. It is possible to exchange a module, or even to change the structure of the whole system without changes in the software, but only in the configuration. Such an interface is object oriented and thus flexible and very efficient mean of communication. It can exchange not only measurement and dynamic data, but also events. Events are used to inform selected modules about e.g. completion of a task by a module. Events are also used to synchronize the whole system. The Central bus contains several additional components, enhancing it:

- Data Player, which can reply real data acquired on the plant, in order to observe the response of the model and to compare it to the response of the real plant.
- Data Processor, where one can define any calculation, based on other values in the system.
- Limit Checker, which is used to monitor violation of given levels by the chosen variable. It is possible to define several states and to assign limits to states.

The remaining computers are used to run models of the components of the power plant. It is assumed that the model will be developed in the Matlab/ Simulink environment [9]. If the speed of calculation is not sufficient to achieve the operation close to the real-time, the Distributed Computing Toolbox (DCT) [9] may be used. Model of the power plant unit will be described later in this paper.

Important novelty of VPP is application of separate computers to implement all modules of VPP. This will allow to mix even different modeling tools as well as exchange of selected ones with data recorded at the real plant and then replayed. Additional benefit is possibility of data processing distribution between several CPUs.

Important part of the Virtual Power Plant are user interfaces, which are closely connected with the databases. The first one is the user interface native to the DCS system. It implements typical mimic screens of the unit control room. Thus, the process can be monitored in the same way as it is done by operators in their daily work. It may be also used in the future to train operators on the VPP. The other user interface access the data in the specialized, fast database. It delivers more advanced plots:

- detailed browsing of data in form of trend plots and waveform plots (for dynamic channels);
- plot of basic dependencies (XY plots);
- export of result data to other systems for in-depth analysis.

Another important feature of the VPP is the remote access, which will increase its usefulness. Experiments can be configured and then monitored remotely. It is also possible to connect e.g. modelling module from a remote location, like a scientific center to the rest of VPP, though fast and reliable network connection is the prerequisite in such a case. Security of processed data and especially model parameters is very sensitive and important factor in VPP. It is thus necessary, that all data exchange with other computers through the Internet is performed via secure channels. VPN (Virtual Private Networks) technology was applied to achieve this goal.

OPC was chosen as the basic communication interface in the Virtual Power Plant. OPC is the international standard [10], developed for exchange of data in industrial applications. Application of such a standard reduces cost and time of integration of various hardware and software system elements, because interfaces between various components need to be only configured, instead of being developed. Matlab/ Simulink as well as virtually all DCS systems are equipped with the OPC interface. Communication over OPC is also used for synchronization of operation of the VPP.

2. MODEL STRUCTURE

The mathematical model used in the Virtual Power Plant is a compromise between the requirements of the accuracy to the real object and available computing and data processing power [5]. There are many available works focusing on modelling of particular elements [2]. The basic requirements towards the model in VPP were, that the model should allow to model the dynamics of key processes and should have potential for the continuous improvement. In other words, it must be possible to develop models by step improvements in such aspects like accuracy, introduction of more advanced or alternative models of subsystems. Therefore, the model must have modular structure. This structure is presented on the figure 2.

The presented model was prepared for 200MW unit. The unit consists of coal fired boiler, reheat steam turbine and generator. One has to mention that the model assumed in VPP does not impose this structure, so it can be modified for some other units. The communication between the model and other parts of VPP is based on items in OPC protocol, which do not require any special model structure.

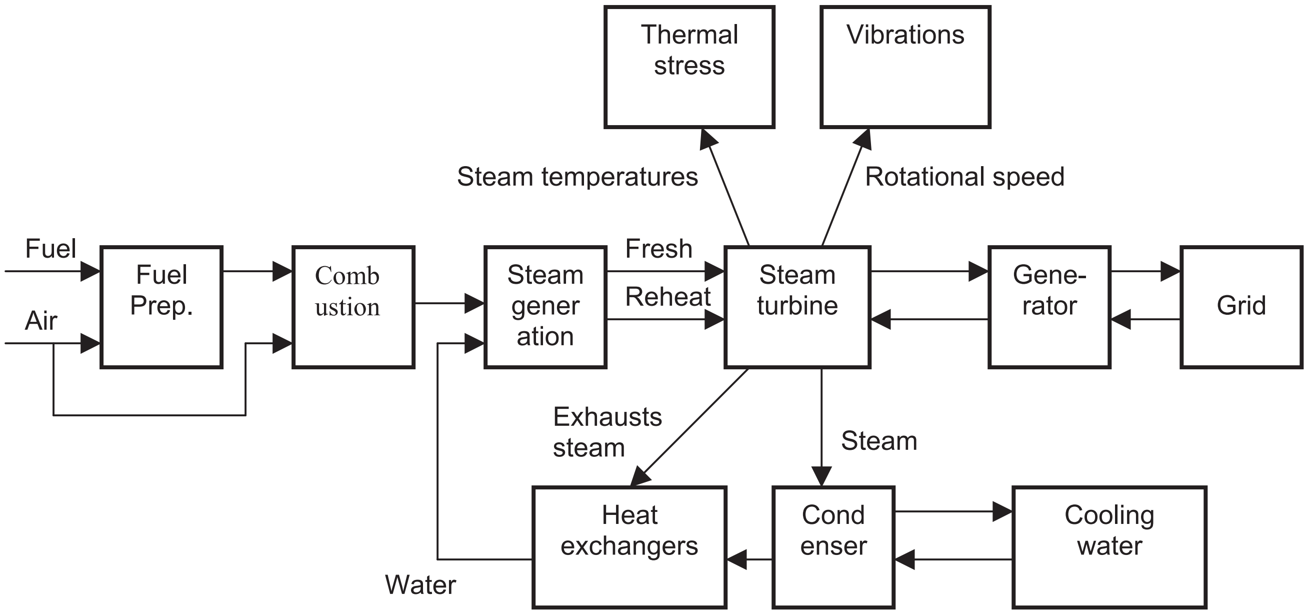

Fig. 2. The structure of the model

The model was focused on main power generation processes, i.e. steam generation in the boiler, steam-water cycle (including steam regeneration in heat exchangers) and generator. Some auxiliary machines were not covered, some processes were only partially implemented. Example of such process is the dynamic state, which depends only on the rotational speed and does not have any feedback to the rest of the model.

Another key requirement to the model in Virtual Power Plant was possibility to keep several variants of model of a given component. It is important, because development of the model is a process, where in the first step independent partial models are developed. Those models have various levels of details, depending on the focus of research. Next, models are interconnected to cover larger part of the power plant processes. The figure 3 presents possible variants of a model in the case of steam control valve.

|- **Virtual_Power_Plant_Model_V001**
|
|- VALVE (steam flow control valve)
|
|- V001 (static model, e.g. spring + turbulent flow equation)
|- model.mdl
|- model_parameters.m
|- V002 (V001 + dynamics, e.g. mass of a head, friction)
|- model.mdl
|- model_parameters.m
|- V003 (V002 + fluid flow dynamics, e.g. oil/steam acceleration)
|- model.mdl
|- model_parameters.m

Fig. 3. The structure of variants of sample element model

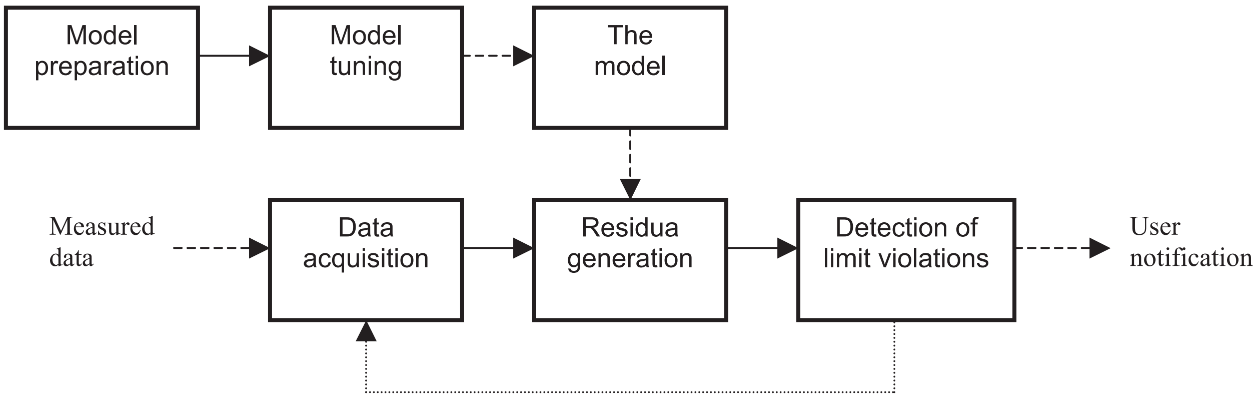

Fig. 4. The process of condition monitoring, based on the mode

All models approximate the same element, namely the steam flow control valve. Each one is another variant, increasing complexity and accuracy. Similar sets of variants are prepared for all modelled components.

As a result of the described process, to create the final unit model, the model of a component can be chosen from a list of available model versions. All such models must have common interface, but they will certainly differ in model parameters. It should be possible to adapt models to the chosen goal of simulation (e.g. response to a load change) by changing model parameters, which in case of Matlab/ Simulink models can be stored in m-files. Preparation of the model should consist of choice of models of subsystems. For each subsystem the model can be chosen out of a library of available ones.

The fundamental distinction is between steady-state and transient models. Whereas the first one can be linearized, the latter is inherently non-linear and thus, is much harder to develop. Therefore, each submodel should have also defined its scope of applications, i.e. valid range of input parameters.

3. APPLICATION FOR CONDITION MONITORING

The application of the Virtual Power Plant, which is presented in this paper is condition monitoring of the power generation unit. The process of condition monitoring, based on the model, is presented on the figure 4.

The process is divided into two subprocesses, shown in the fig.4 as separate levels. The first subprocess is preparation of the tuned model. It starts from choosing the model type and structure. In the next step, the chosen model is tuned to the real object. The tuned model is the input to the second subprocess, which is condition monitoring of the object. It is periodically (which can mean off- or on-line) activated. The approach presented here is based on residua generation, which are next checked against the allowable limits. The presented process is a typical one, the detailed description can be found e.g. in [3].

There are several advantages, which can be achieved, when the described process will be implemented within the Virtual Power Plant environment. Possible advantages are presented in the table 1.

Tab. 1. Advantages in the process of condition monitoring achieved by application of the VPP

Process	**Advantage gained by application of Virtual Power Plant**
Model preparation	The model preparation can be much faster, when the library of typical power plant unit elements are used.
Model tuning	The model tuning can be based on the real data from the object, stored in the database of VPP. Sets of parameters can be assigned to particular object operating points (when linearized models are used).
Data acquisition	Data acquisition can be simplified in both off- and on-line modes. In the off-line mode, the possibility of the Central Bus to reply stored data can be used. In the on-line mode, it is possible to acquire the data directly from the Distributed Control System (DCS). In such a case, the VPP can form a part of a monitoring and diagnostic system. Due to complexity of the VPP, it is rather expected, that it will work remotely, acquiring the data via a phone line or network connection.
Residua generation	Another part of the Central Bus – the Data Processor, can be used to calculate any set of chosen mathematical expressions. Every residuum should be configured and will result in creation of new data source (or tag in

	the system). The value of this tags will be updated with every refreshed data input.
Detection of limit violations	Limit Checker, yet another part of the Central Bus, can be directly applied to detect limit violations of residua. Prior to limits configurations, states can be defined. Each state is detected based on values of chosen tag. Limits can be assigned to states, and thus it is easy to achieve residua checking only in certain operational states, e.g. full load, transient.
User notificatio n	For user notification the DCS-like user interface in VPP can be used. One can upgrade the user screens with additional controls, showing the status of particular components.

It is very important that all mentioned functionality can be achieved only by configuration of the VPP, without the need to develop any software.

4. CASE STUDY

The Virtual Power Plant was applied to the real 200MW coal-fired unit in one of Polish power plants. This action was planned as the verification of the concept of the Virtual Power Plant. According to the agreement with the chosen power plant owner, following data were transferred to the research team:
- technical documentation of selected components;
- locations of measurement sensors;
- DCS system configuration;
- DCS screen set with assignments of measurement channels to screen controls;
- data acquired by DCS during the operation of the unit;
- know-how and consulting from power plant experts.

The developed model contained all main elements of the unit, i.e. boiler, steam turbine and generator. The model structure followed the structure shown on fig. 2. The model also contained auxiliary equipment, such as preparation of fuel (coal mills, boiler fans, air heaters), steam water cycle (heat exchangers, condenser, deaerator), cooling water and control systems. The model included submodels of dynamic state and stress, but they had no feedback to the other components. The division of three basic types of model variables is presented in the table 2. Those types are shown as in the DCS system.

Tab. 2. Division of model variables on the sample installation on a 200 MW power generation unit

Variable type	**Number of implemented variables**
Binary input	81
Analogue input	1072
Binary output	689

The majority of binary output channels had fixed value, since it was sufficient to model only certain states of the power plant. In the user interface system 40 screens from the original DCS were implemented. The figure 5 presents one of implemented screens, presenting overall view of the turbine with steam regeneration and the generator with connection to the grid.

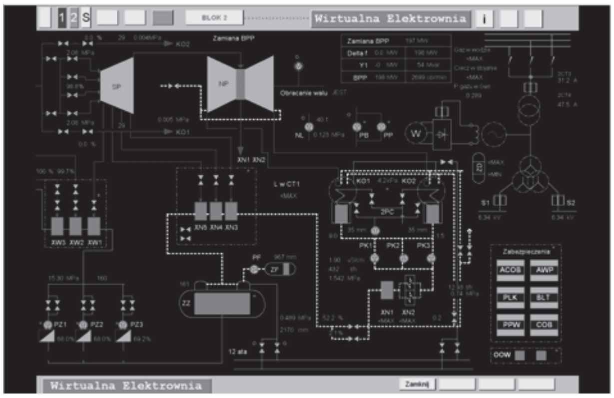

Fig. 5. One of DCS screens implemented in the Virtual Power Plant on a 200 MW unit

In most cases physical equations were used to model the behavior of the plant. However, such an approach resulted in huge CPU consumption and large excession of real-time conditions. Therefore, the hybrid approach was applied [1]. In this step another version of the model was prepared, in which all heat exchangers were implemented as sets of linearized models. Heat exchangers were chosen for linearization, as it was the part of the model, which caused the highest CPU load. This version of the model had worse accuracy, but was much faster, even up to 150% of the real-time in comparison with over 1000% for the analytical model.

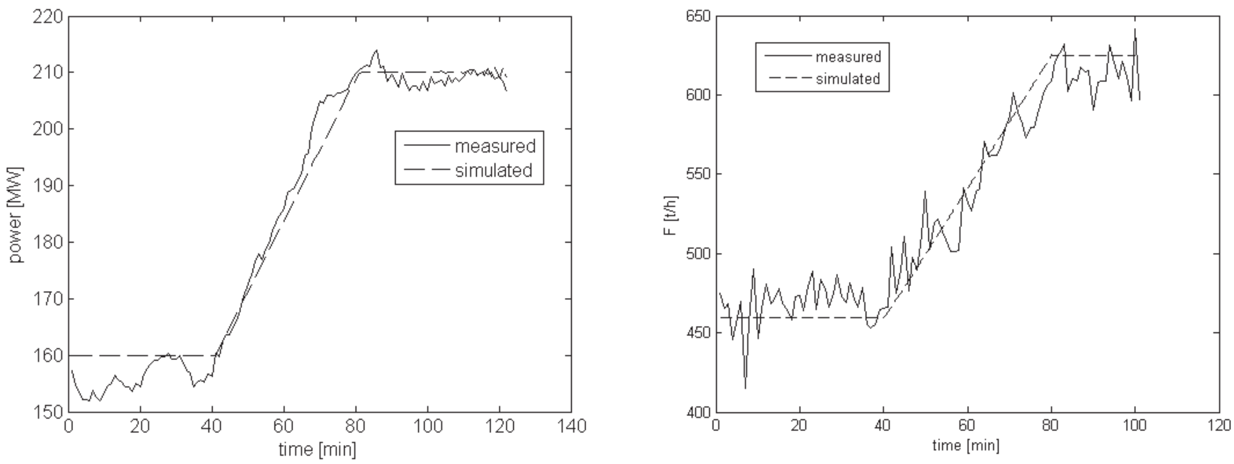

Fig. 6. Comparison of the model output and the real output for load and fresh steam flow

In order to work, the model had to implement several control systems. Following subset of control loops was implemented:

- combustion controller;
- steam pressure controller;
- rotational speed controller load controller;
- water injection controllers;
- heat exchangers controllers (controlled steam exhausts).

Due to very high complexity, only basic functionality of those controllers was implemented. For modelling, large sets of data from real operation of the unit were loaded into the VPP database. For presentation in this paper a part of data as chosen, presenting ramp load change from about 160MW to 210 MW. The fig. 6 presents comparison of the model response to the real data for load and fresh steam flow. It is visible, that only part of the system dynamics was modelled. There were three principal reasons for such a behavior – first, presented results were obtained for the model consisting of set of linearized models. Second, there was no access to the noise acting on the object, so only the basic dynamics was shown by the model. Third, several control systems were implemented with significant simplifications, which again limited the response of the model to only the basic behavior.

Other interesting plots (fig. 7 and fig. 8) present the performance of the model. It shows timeslices required for simulation and the time actually needed for calculation of one step.

One timeslice was 10s of real time and it is shown as the straight horizontal line. As shown above, in the complete model case, VPP required from 15 to 25s to model 10s of the real time a time. The performance was measured during modelling of load change, shown on fig. 6. As expected, during the transient process, CPU load is increased. On the other hand, during steady state operation, the model requires only 50% more time than the real time. In the second case of linearized model, the performance was much better, requiring 4 to 9s of the real time. Note, that there was some increased load at the start-up, with few periods, where the 10s timeslice was exceeded by approximately 1s.

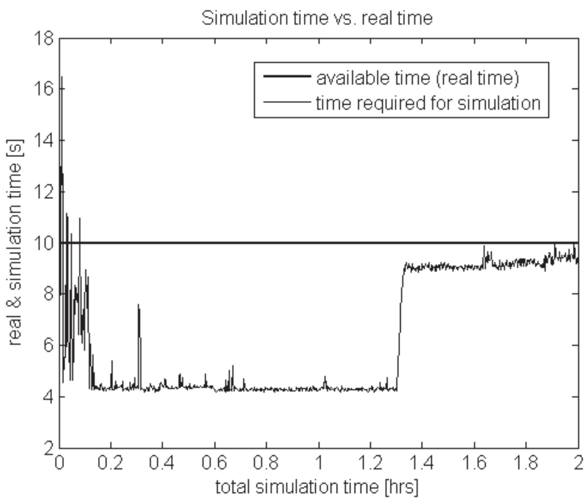

Fig. 7. Performance of model during the simulation of transient process for the complete model

Additionally long term simulation tests were performed. The test duration was 65 hours and the unit was going periodically through states of run-up, steady state, run-down and turning gear. The performance measures were recorded and are presented on the fig. 9.

As shown, the average performance of the model was around 60% of available time, i.e. modeling took only 60% of the real time. This result is very satisfactory.

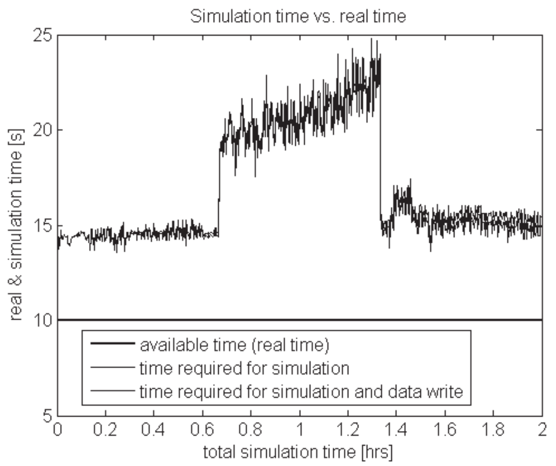

Fig. 8. Performance of model during the simulation of transient process for the linearized model

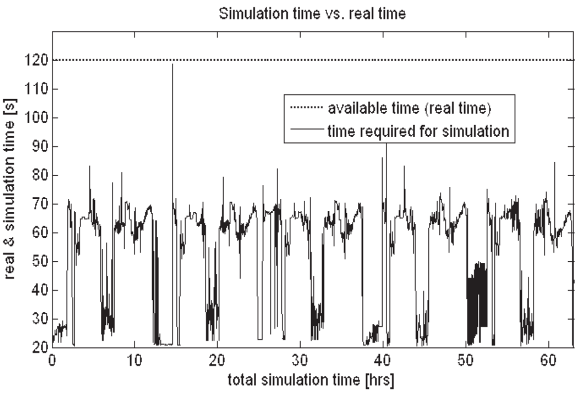

Fig. 9. Performance of model during long term test

SUMMARY

The paper presents the concept of the Virtual Power Plant and its application to the condition monitoring of power plant components. The VPP is a distributed environment, which joins modelling, databases and user interfaces. It is possible to reply the data acquired from a real unit and record the response of the model.

In the next chapter the architecture of the VPP and its main components are described. Two types of databases and their corresponding user interfaces are presented. The condition monitoring algorithm uses the VPP, previously tuned to the power plant unit in good conditions. Next, the data from an unknown conditions are replayed and residua are generated. This classical approach can be facilitated by the use of the VPP.

The following chapter describes structure of models used in the VPP. It is possible to implement several submodel versions to adapt the model to specific need of a modelling task (e.g. transient or steady-state). Example of such an approach for a steam control valve is presented.

The concept was verified on the case of real 200MW power generation unit. The model generated over 1000 channels and presented the data on 40 mimic screens. There were two models developed: the analytical model, which had good accuracy, but was unacceptable due to very long calculation times and the second one, consisting set of linearized models of most CPU-consuming components. The second model is close to the real time operation. Further research will be performed in the direction to extend applied models to improve accuracy, especially in transient states.

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Dr inż. **Tomasz BARSZCZ** pracuje jako adiunkt w Katedrze Robotyki i Mechatroniki Akademii Górniczo – Htniczej. Obszarem jego zainteresowania jest konstrukcja i zastosowania układów monitorowania stanu maszyn. Jest autorem monografii o systemach monitorowania i diagnostyki, wielu artykułów o charakterze naukowym oraz wielu wdrożeń w przemyśle.