Application of an Open Environment for Simulation of Power Plant Unit Operation under Steady and Transient Conditions

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Abstract. The aim of the paper is to present a proposal and discuss an application of an open environment for modeling of a power plant unit. Such an environment is called the Virtual Power Plant (VPP) and is based on a model created in the Matlab/ Simulink environment. VPP provides a framework for incorporating a broad variety of models, ranging from simple system models that run in real-time to detailed models that will require off-line mode to execute. The paper presents the architecture of the VPP and briefly describes its main components. An approach to implementation, including necessary simplification, sub-models encapsulation and integration are discussed and illustrated by schematics and equations. The paper includes a case study, where the 225 MW coal fired unit is modeled.

Keywords: power plant, steam turbine, modeling, Matlab, Simulink.

1. Introduction

Power plant simulators are developed for several reasons. They can be divided into following categories:
- general purpose [1],
- static thermal cycle calculations [2],
- understanding of a power generation process [3],
- ‘what if’ prediction [4],
- virtual prototyping of new software/hardware plant components [5],
- control system optimisation [6,7],
- improving of thermal process performance [9],
- environmental concerns [9],
- studying a system behaviour out of the operating range [10],
- collecting diagnostic relations among process features of classified components conditions for fault detection and isolation (FDI) purpose [11],
- training power plant operators through playing/reconstructing emergency scenarios and case studies [10],
- defining and validating safety operation procedures.

Virtual simulation of advanced systems plays an important role in reducing the time, cost and technical risk of developing new solutions [12, 13].

The core part of a typical simulator is a model developed in one of numerous simulation packages available on the market, such as PowerSim, Aspen Dyn., HYSYS, Massbal, Matlab/Simulink, ProTrax, Sinda/Fluint, Autodynamics, MMS, APROS, gPROMS, SIMODIS [14]. These packages may have different functionality optionally using pre-developed power components libraries [15, 16]. They are used for modeling of coal, gas, or combined power units.

Matlab/Simulink is a very popular modeling environment [17]. Its advantages and shortcomings have been analyzed considering the Virtual Power Plant (VPP) application scope and this package has been finally chosen as the core modeling environment. It provides an open and general-purpose functionality. Therefore, many engineers and scientists are familiar with this package. In addition, availability of auxiliary domain libraries (toolboxes and blocksets) including the PowerSim blockset at reasonable costs is an important advantage. Matlab/Simulink package, in most applications, is used to create simplified physical models suitable for purpose of control system modeling [18, 19] however less applications refer to deep physical modeling. Interesting example is the modeling of 677 MW coal- and gas-fired power plant [20]. Another example is the Simulink model used for training in advanced power plant process dynamics and control loop tuning [4]. It enables simulation of differentiated operational scenarios including transient operation. Literature also considers detailed physical models of steam circuit components regarding fault detection algorithms and performance evaluation [20]. A few Matlab/Simulink applications are focused on an electrical circuits modeling including generator and power grid [e.g. 21].
application is the validation process of a turbine regulator in respect of the settings and hazard management [22]. An automatic controller is tested under different operating conditions to detect disturbances in the system with the use of a simulator attached to the turbine controller I/O signals [22]. In this case the simulator consists of Matlab/Simulink model and Lab-View controlled Input/Output hardware. All those application case studies provide an overview for Matlab/Simulink strengths, disadvantages and implementation process.

From the modeling approach viewpoint, the Matlab/Simulink package enables first-principle and data-driven model development. First-principle modeling uses an understanding of the system's physics to derive a mathematical representation. On the other hand, data-driven modeling uses system test data to derive a mathematical representation. These two approaches can be combined in application to modeling dynamic systems. The advantage of the former approach is insight into the system's underlying behavior and enables performance prediction, while the advantage of the latter is a fast method for developing an accurate model and confidence because it uses data from an actual system. The difficulties of the former approach are coefficients required to be determined, e.g. friction and flow coefficient. The latter approach disadvantage is the need to handle multiple data sets to cover range of system operation. Interesting comparison of modeling based on physical principles and data driven model can be found in [23].

For power generation applications authors in [24] proposed the Virtual Power Plant (VPP), the innovative work environment intended for reconstruction of a power plant unit functionality based on a model and a recorded process data.

The paper is divided into three principal sections. The first section introduces a simulator environment, while the second section presents the structure of the core model developed in Matlab/Simulink. The focus is on the structure and specific features, such as modularity and flexibility rather than specific details. The third section describes the case study, where the 225 MW coal fired unit was modeled. There are three subsections, discussing the approach applied for the modeling of control systems, elements of the steam-water cycle and the dynamic state. Since the subject is very broad, details of chosen elements are presented. The fourth section presents results of calibration and validation of the model. This was particularly difficult task, as the task could be only based on the recorded operational data.
2. Virtual Power Plant environment

VPP, described in details in [25], provides a framework for integrating the range of models, data management system, and visualization methods including plug and play functionality. VPP consists of a few computers, connected by a fast computer network (Fig. 1). The largest part of the system is the database, which consists of two cooperating subsystems. The first one is the typical DCS system. This approach allows to store the data in the same way they are stored in a real plant. It also allows to present data in a user-friendly way and to interact with the VPP from the level of mimic screens, like plant operators use to work. The second database subsystem is a specialized, fast database which is used to store data generated by modules of the VPP. This subsystem is proprietary, efficient database engine, which can also store dynamic data (e.g. vibration waveforms).

![Fig. 1. Structure of the Virtual Power Plant](image)

2. Submission of final version

The Central Bus (CB) is the central 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. The
interface can exchange not only measurement and dynamic data, but also events. Events are used to inform the selected modules about e.g. completion of a task by a module and they are also used to synchronize the whole system. Other computers are used to run models of components of the power plant unit. Number of computers depends on complexity and structure of the model. Important part of the Virtual Power Plant are user interfaces, which are closely connected with relevant 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, delivering possibilities of advanced graphical data analysis.

2.1. Structure of Virtual Power Plant model

The Virtual Power Plant Model (VPPM) uses a module-based and causal architecture having the possibility of referring to external libraries written by domain experts. These libraries can be developed in MATLAB-Simulink, but can be also linked in the form of compiled executable algorithms or open codes developed in C, C++, Java, Fortran, or Ada. MATLAB-Simulink offers a hierarchical object-oriented approach to communicate with OPC server using the OPC Data Access Standard. It allows acquiring live process data directly into MATLAB-Simulink and writing simulation output to the OPC server. The alternative is to exchange data through a temporary file using customized S-function and read-write data converter. The simulation process is synchronized with the system clock of the central bus (CB). The simulation can be performed in on/off line mode dependent on the model complexity and available computational power. In addition, it is feasible to generate and compile C-code, being an equivalent of a developed model, accelerating simulation process. VPPM implements major processes transformation of fuel chemical energy into thermal energy, thermal energy into mechanical rotational energy, and mechanical energy into electric energy (Fig. 2). Water-steam properties are computed using steam tables based on the empirical formulas which are the implementation of the IAPWS IF97 standard [26]. It provides accurate data for water, steam and mixtures of water and steam from 0–1000 bar, and from 0–2000°C. The current operating point of water/steam mixture is propagated through model blocks in the form of a state vector consisting of four state variables: temperature, pressure, mass flow rate, and enthalpy.
VPPM is split into Power and Vibration Module, which contain together more than 25 libraries, 58 mdl-files, 3 s-functions and almost 100 initialization m-files. These modules can be run separately, exchanging control and process data via the OPC server, and providing data simultaneously with a real power generation process. The model must be numerically stable and robust under steady and transient operation. A model parameterization is a significantly time-consuming phase, because of large amount of measurement data, machinery layouts, physical, and geometrical parameters available as engineering specifications, manufacturer documentation, control system manuals, turbine and auxiliary devices’ manuals, and test reports [27]. The model files combine the libraries and initialization files to create a VPPM application of a specific power plant unit. The libraries contain the components’ models.

The auxiliary functions and procedures (e.g. load programs) are stored and in the system folder. Simulink allows to create a library of masked subsystem blocks. This feature has been utilized in VPPM to create customized libraries using the object-oriented data structures [12, 28]. Before starting simulation, the initial conditions, load program, model parameters, controller settings, and trip logic settings are uploaded into Matlab workspace (Fig. 3). PID controllers and trip logic settings are required to initialize the governor system with safety check limits, e.g. overspeed, min/max rate limits for the speed, load, and pressure. The initial conditions are required to run the model at exactly specified operational conditions, e.g. at boiler start-up while the rotor is stopped, before synchronization or at a given steady load. VPPM is parameterized with geometrical and physical parameters including numerous coefficients, constants and characteristics, e.g. valve opening characteristics.
Another key requirement to the model in Virtual Power Plant was the 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 may have arbitrary complexity, depending on the focus of research. Next, models are interconnected to cover larger part of the power plant processes. A control valve model is an example of increasing model complexity, where following models were developed:

(i) basic version: static experimental pressure-flow characteristic,
(ii) mediate version: static physical model including spring stiffness and steam flow equation,
(iii) advanced version: dynamic physical model including mediate version functionality + valve head inertia.

Similar sets of variants are prepared for all modeled 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 a common interface, but they will differ in model parameters. 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 also has its scope of application, i.e. valid range of input parameters.

3. VPPM customization for simulation of 225 MW power unit

The model structure is presented and discussed using example of the model customized for 225 MW power unit. The power unit is equipped with a coal fired wet bottom steam generator driving the three casing turbine with a seven-stage boiler feedwater regeneration system (Fig. 4). Tab. 1 presents basic parameters of the power unit under nominal load.

**Tab. 1. Basic power unit parameters referred to 225 MW operating conditions**

<table>
<thead>
<tr>
<th>Power unit component</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>Power</td>
<td>225.6 MW</td>
</tr>
<tr>
<td></td>
<td>Stator current</td>
<td>9919 A</td>
</tr>
<tr>
<td></td>
<td>Power factor</td>
<td>0.85</td>
</tr>
<tr>
<td>Boiler OP-650</td>
<td>Steam production</td>
<td>650 t/h</td>
</tr>
<tr>
<td></td>
<td>Fresh steam pressure (HP)</td>
<td>13.8 MPa</td>
</tr>
<tr>
<td></td>
<td>Fresh steam temperature (HP)</td>
<td>540°C</td>
</tr>
<tr>
<td></td>
<td>Reheated steam pressure (IP/LP)</td>
<td>2.36 MPa</td>
</tr>
<tr>
<td></td>
<td>Reheated steam temperature (IP/LP)</td>
<td>535°C</td>
</tr>
<tr>
<td></td>
<td>Consumed energy</td>
<td>1230–1835 GJ/h</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>93%</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Cooling water consumption</td>
<td>29 000 t/h</td>
</tr>
<tr>
<td></td>
<td>Cooling water temperature</td>
<td>22°C</td>
</tr>
</tbody>
</table>

The parameters of a turboset shaft line are given in Tab. 2. The rotor critical frequencies are in the range between, i.e. 1300–1450, 1780–2230, and 2700–2880 rpm. The rotor is supported on 7 hydrodynamic bearings, while the total length of the shaft line is 29 meters. The shaft line model consists of 18 nodes. The rotor geometry is introduced in details in reference [29] where the complete 160 nodes model of the similar turboset was described.
Tab. 2. Turbine-generator properties

<table>
<thead>
<tr>
<th>Heading level</th>
<th>High pressure part</th>
<th>Intermediate pressure part</th>
<th>Low pressure part</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass [kg]</td>
<td>7 800</td>
<td>16 300</td>
<td>49 982</td>
<td>42 650</td>
</tr>
<tr>
<td>Number of sections</td>
<td>12</td>
<td>11</td>
<td>4</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Fig. 4. Power block functional scheme with the sample parameters of steam-water mixture (EX – steam extraction port, XW – high pressure heater, XN – low pressure heater, CO – condenser, PZ – main pump)

3.1. Control system

VPPM implements the functional equivalence of a power unit control system. The main part of the system is shown in Fig. 5. The complex functional group consisting of cascaded control blocks implement the control concept of TURBOTROL 6 (PROCOTROL P13 [30]), while ignores auxiliary controller and instrumentation details.

The basic controllers are speed controller, power rate controller and fresh steam pressure controller. These controllers use signals from the fresh steam pressure rate limiter, power rate limiter, speed rate limiter, temperature...
limiter after HP stage and nozzle diaphragm pressure limiter. The auxiliary controllers implemented in the Power Module are as follows:
- reheated steam temperature controller,
- drum level controller,
- excitation voltage controller (AVR).

The automatic controller of Power Module governor, as explained hereinafter by reference to Fig. 5, executes a pre-selected load program based on the available process signals: (n) rotational speed, \( (n_o) \) steady state rotational speed, (N) turbine electrical power, (T) steam and turbine casing temperature, \( (P_{ex}) \) extraction pressures, \( (P_o) \) outlet pressure, and \( (G) \) binary signal command latching the generator to a power grid. A thermal stress limiter operates on the constrains such as the minimum boiler pressure \( P_{min} \) and casing temperature \( T \). The process constrains include the gradients of the rotational speed, power and pressure. Control logic is provided operative in relation to specific stages of the steam pressure and temperature build-up in sequential order and selectively through the duct lines in preparation of turbine latching and loading. This logic switches on/off valves of the low and high-pressure heaters’ banks. The control logic outputs a binary command signal on synchronization line \( G \), which latches a generator to power grid, and disables the speed controller after a specific time. In addition, after the turbine has been synchronized, steam is allowed to enter the low pressure heaters’ bank through extraction outlets, and pipelines denoted as VII, VI, V, IV, respectively to the heaters XN3, XN4, XN5, cf. Fig. 4. Heaters XN1, XN2 assembled in the condensers are in continuous operation with the condensers CO1, and CO2. When the turbine is loaded at a given rate, steam is allowed to enter the high pressure heaters’ bank through extraction outlets, and pipelines denoted as III, II, I respectively to the heaters XW3, XW2, XW1. The regulatory control loops are coupled to the simulated sensors to receive respective signals from the signal bus.

3.2. Power module

The power module (PM) consists of models of a steam turbine, low and high pressure heaters, a boiler, a deaerator, condensers, mills, a control system, a generator and a power grid. To formulate components’ models, unsteady conservation equations for mass, energy and momentum have been used. In order to implement the model in Simulink and to maintain the amount of simulation time within the time available, some models were developed in both advanced and simplified versions. All models’ components are connected through ports enabling and propagating current steam parameters.
(temperature, pressure, enthalpy), and/or mass/energy flow rates (Fig. 6). Advanced models require the access to complete input-output vector, e.g. (T) temperature, (P) pressure, (H) enthalpy, while simplified models use only mass flux (M) and temperature (T) variables. Other components' models are connected to the (M) mass flux port (raw coal, pulverized coal, steam, water), (E) energy flux port (combustion, or mechanical energy), (N) rotational speed, and electrical ports (U,I) (voltage, current).

Fig. 5. Functional scheme of the VPPM control system
The structure of the Power Module is shown in the Fig. 6. Coal is conveyed to a very fine powder in the pulverized fuel mills and mixed with preheated air driven by the forced draught fan. The fuel controller through sequencer regulates the supply of pulverized fuel to the boiler from four mills. This process has a significant response time. A mill model involves first-order dynamics of a conveyor and air-fuel mixture flow in the form of a transfer function described in [18]. A mill control system is equipped with additional sub-controllers and a mill sequencer, which switches on/off the particular mills depending on the demanded load. A hot air-fuel mixture is forced at high pressure into the boiler, where it rapidly ignites [18]. The conservation of the mass in the furnace assumes the ideal leak-tightened balancing of the mass flow rate of the pulverized fuel, oil, air, slag, ash, and combustion gas [18]. This process is captured by a third order model simplified to a transfer function.
The heat energy is generated burning hard coal, and through convection and radiation is absorbed by circulating water. The process of steam production consists of the phases:

(i) heating of water in the economizer,
(ii) evaporation in the drum,
(iii) steam overheating in the superheater.

A reduced steam generator model implements dynamics of evaporation and overheating while it ignores feedwater preparation process in the economizer. The boiler model describes transformation of chemical energy into a heat energy, which is passed to water flows vertically up the tube-lined walls of the boiler, and turns into steam. The investigations presented in [31, 32] show that a drum model can be approximated with a second order model, or optionally including steam and water distribution in the drum and downcomer pipe system in economiser with a fourth order model including momentum balance [31] (Fig. 7). A set of controllers maintains a water level and steam pressure [31]. It is necessary to establish the following assumptions for a drum model (symbols from Fig.7):

(i) the specific enthalpy of steam leaving the boiler is equal to the vapor enthalpy \( h_s = h_{s\text{sat}}(p) \),
(ii) the pressure of feedwater is equal to the pressure of steam,
(iii) heat transfer is dominated by convection,
(iv) ideal heat transfer between the feedwater inside the drum and the surrounding metal is assumed,
(v) the metal temperature is equal to the saturation temperature of water for the pressure inside the drum.

![Fig. 7. Structure of the simplified drum model](image-url)
The steam passes to the superheater, where its temperature and pressure increase to around 12.7 MPa and 540°C. The superheater model has been derived using partial differential equations and then simplified to a series of transfer functions representing the particular sections of a superheater [18]. The superheater model includes a water spraying process for purpose of steam temperature control [18]. A schematic picture of a superheater section is shown in Fig. 8.

![Fig. 8. Superheater model](image)

![Fig. 9. Steam expansion curves](image)
The steam is piped to the high pressure part of the turbine. The steam turbine contains stationary and rotating blades, grouped into three parts: high pressure (HP), intermediate pressure (IP), and low pressure (LP). Stationary blades (nozzles) convert the potential energy of the steam (temperature, pressure) into kinetic energy (velocity) and direct the flow onto the rotating blades. The rotating blades convert the kinetic energy into forces, caused by the pressure drop, which result in the rotation of the turbine shaft [33]. Fresh steam is piped to the turbine inlet through trip throttle valves (safety shut-off valves) driven by independent on-off hydraulic servomotor with rebound springs. These valves are located in the steam supply line ahead of the governor valve. They are operated as the activating element for the overspeed protection and serve as the manual throttle valve, which may be used for testing and startup. They are designed to run fully open under normal operation and are able to close very quickly. Next, the steam is passed through four pipes to the four control valves located in the HP turbine housing and driven by four independent proportional hydraulic servomotors. They are opened with oil pressure and closed with spring force. A physical model of a hydraulic control system has been developed within previous research programs [34, 35]. The whole model has moderately complex structure per a single control valve including a second order servovalve model, a fourth order linear double-side servomotor model, and a mechanical model of a massless opening-closing valve head system. It is possible to simplify this system using a second order linear transfer function per a single control valve. Valve systems models are calibrated with the use of the measured data [27]. From the control valves, the steam is passed to turbine through four nozzles. After the HP part, the steam is reheated in the boiler. The reheated steam is piped to the valve chambers, where safety shut-off IP valves are located. Then, steam is passed to the four IP control valves connected to the shaft cam driven by a single servomotor described by the previously considered hydraulic control system. All auxiliary on-off valves are modeled by approximated static characteristics. The turbine is equipped with seven steam extraction ports, from where steam is extracted for heating up the feedwater. It is also equipped with outlet/inlet ports to/from the superheater where steam is passed for the reheating process. Steam expansion curves are presented in the Fig. 9. The figure shows the steam parameters in the following locations: (1) - before shut-off valve, (3) - exhaust I, (5) - exhaust II, (10) - before IP stage, (11) - exhaust III, (15) - exhaust IV, (17) - exhaust V, (21) - before LP stage, (22) - exhaust VI & VII, (23) - turbine outlet.

Steam turbine dynamics can be modeled using the first principle model. This method uses equations of the conservation of mass and energy in a steam turbine [36] evaluating the work done by the fluid expanding in an elementary turbine volume [36].
The heat exchange between the steam and the turbine’s housing is described by the quasi-static formula [36]

\[ \dot{Q} = A \cdot k \cdot (T_{\text{housing}} - T). \]  

(4)

In the low pressure part of the turbine, wet steam occurs, therefore the state equations are defined in function of pressure and enthalpy, instead of pressure and temperature, avoiding ambiguity. After rearranging, the equations have the form [36]

\[
\begin{align*}
\frac{dH}{dt} &= \sum \dot{m}_i \cdot h_i - \sum \dot{m}_{out} \cdot h_{out} + \dot{Q} - \dot{L}, \\
\dot{L} &= -v \frac{dp}{dt}.
\end{align*}
\]  

(2)  

(3)

The volumes of stationary interblade channels are negligible. The static characteristics provide relations between the input and output quantities of an elementary turbine section based on the Fügl-Stodola equation adapted to the transient conditions [36]. These characteristics allow to calculate steam flow capacity, efficiency, power, and enthalpy drop in function of the input/output pressure, turbine rotational speed, and number of stages [36].

In second version of the model, the turbine dynamics is approximated by a simplified data-driven model. The model introduces time constants derived from the mass conservation principle. The mass continuity equation formulated for a turbine section is written as follows [33]

\[
\begin{align*}
\frac{dm}{dt} &= v \frac{dp}{dt} = \dot{m}_i - \dot{m}_{out} \quad \text{and} \quad \frac{dp}{dt} = \frac{\dot{m}_i}{V} \frac{dV}{dt}.
\end{align*}
\]  

(7)
Thus, the steam flow delay is given by the following transfer function [33]

$$\frac{1}{1 + \tau s} = \dot{m}_i - \dot{m}_{out},$$

(8)

where time constant is

$$\tau = \frac{p_0 \cdot V}{\dot{m}_o} \cdot \frac{\partial \rho}{\partial p}$$

(9)

and where $p_o$ and $m_o$ are linearized values of the internal pressure and mass flow rate, respectively. The delay constants have been applied for the inlet and steam chest delay in the order of 0.3 to 0.35 sec, crossover delay in the order of 0.4 to 0.6 sec and steam extraction pipeline in the order of 0.35 sec. The additional delay is included in a reheater model. The enthalpy drop at each stage of a condensate multiple stage steam turbine (except the last two stages [38]), is assumed constant, based on the Saint-Venant and Wanzel equation [38]. If a steam turbine operates with constant rotational speed, the peripheral speed is constant at each stage. Therefore, the speed coefficients are assumed the same at all turbine stages [36] hence, the turbine section efficiency does not depend on the transient conditions. In the simplified data-driven steam turbine model the energy conservation equations are replaced by static characteristics representing variable operating conditions at different load at particular turbine sections where measurements are available.

$$T = f(m_{in}) \quad \text{and} \quad p = f(m_{in}).$$

(10)

The steam parameters are approximated based on the experimental data (Fig. 10, 11). Steam extraction temperature, and pressure were measured under differing load conditions in the range of 160–225 MW [27]. A steam mass flow rate was measured with the use of a calibrated orifice compliant to the ISO standard [27]. The measurements were performed at the left and right inlet pipelines to the turbine, the water spraying pipelines of the fresh/reheated steam, and after the feedwater pump before the deaerator (see Fig. 4) [27].
The steam is condensing rapidly back into water, creating a near vacuum inside the condenser. The condensers use a general heat exchange model discussed in the next paragraph. The condensed water is then passed by a feed pump through heater banks, powered by a steam extracted from the high, intermediate and low-pressure extractions, respectively. The temperature, pressure and enthalpy of the condensate/feedwater are increased by a series of low- and high-pressure heaters. The heaters with integral drain coolers are the vertically arranged type with U-tubes. A deaerator is a horizontal, direct contact deaerating feedwater heater equipped with a storage tank. The condensate is pumped to the deaerator, through XN12, XN3, XN4, XN5 low pressure heaters bank (Fig. 6). From the deaerator the feedwater is pumped to the steam generator through XW1, XW2, and XW3 high pressure heaters bank. The feedwater heater drain system consists of drain removal path from each heater. The normal drain flow path is cascaded to the next lower stage heater and the alternate path is diverted to the condenser.
Advanced and simplified heat exchanger models [10, 39] have been developed for the purpose of modeling the feedwater heaters’ banks, deaerator and condensers. A three-section advanced heater model is used when accurate results are required. This heat exchanger model consists of three sections including (A) desuperheating, (B) condensing, and (C) subcooling volumes, respectively (Fig. 12). A steam circuit model assumes [10]:

(i) negligible heat exchange between the cavity and the external environment,
(ii) negligible heat accumulation in a water, metal housing of the cavity, and pipelines,
(iii) negligible exchanges of energy and mass, due to surface phenomena at the interface between the condensing and subcooling areas,
(iv) all heat-exchange areas are variable and dependent on the desuperheating, condensing and subcooling volumes,
(v) uniformly distributed and constant pressure in the cavity equals to the inlet steam pressure, uniform and averaged enthalpy distribution inside each area (A, B, and C) based on the boundary conditions for each heater chamber,
(vi) negligible density variations inside the subcooling area.

Fig. 11. Linearized relation between inlet steam mass flow rate and extraction mass flow rates (based on measurements)
A feedwater circuit model assumes [10]:

(i) feedwater is in the liquid state and in a subcooling condition,
(ii) constant fluid pressure in the tube-bundle equals to the inlet feedwater pressure,
(iii) uniform physical properties of the tube-bundle metal,
(iv) negligible longitudinal heat conduction in both the pipe metal and the fluid.

![Diagram of a three section heater model](image)

**Fig. 12.** Layout of the three section heater model

The equations governing internal chambers energy and mass are formulated as follows

\[
\frac{dH_{34}}{dt} = \dot{Q}_3 - \dot{Q}_4 + V_{34} \frac{dp}{dt} - \dot{Q}_{34-56}, \quad (11)
\]

\[
\frac{dH_{23}}{dt} = \dot{Q}_2 - \dot{Q}_3 + V_{23} \frac{dp}{dt} - \dot{Q}_{23-57}, \quad (12)
\]

\[
\frac{dm_{23}}{dt} = \frac{1}{h_3 - h_2} \left( \frac{dH_{23}}{dt} - m_{23} \frac{d(h_3 - h_2)}{dt} \right), \quad (13)
\]
\[
\frac{dH_{12}}{dt} = \dot{Q}_1 - \dot{Q}_2 + V_{12} \frac{dp}{dt} - \dot{Q}_{12-78},
\]
\[
\frac{dm_{12}}{dt} = \frac{1}{h_2 - h_1} \left( \frac{dH_{12}}{dt} - m_{12} \frac{dh_2 - h_1}{dt} \right).
\]

The equations below are formulated for the conservation of the energy in the draining volumes, and they are follow from the assumption of uniform density of the water neglecting variation over time.

\[
\frac{dH_{56}}{dt} = \dot{Q}_6 - \dot{Q}_5 + V_{56} \frac{dp_{56}}{dt} + \dot{Q}_{34-56},
\]
\[
\frac{dH_{67}}{dt} = \dot{Q}_7 - \dot{Q}_6 + V_{67} \frac{dp_{67}}{dt} + \dot{Q}_{23-67},
\]
\[
\frac{dH_{78}}{dt} = \dot{Q}_8 - \dot{Q}_7 + V_{78} \frac{dp_{78}}{dt} + \dot{Q}_{12-78}.
\]

Introducing the weighted (average) steam-water properties, i.e. density, temperature, constant volumes and constant pressure inside the heater cavity, the heater model can be reduced to the two-section or a single chamber heat exchanger model as presented in Fig. 13.

Fig. 13. Layout of the simplified heater model

The PowerSim Blockset toolbox of Simulink has been used for modeling of the generator submodel [25]. A ready to use electro-mechanical model of a synchronous machine and a power grid were parameterized and integrated.
with other VPPM modules [25]. A breaker is operated to connect the generator to the electric grid, when the generator acquires the proper operating point for synchronization. A mechanical model of a turbine-generator considers rotational energy and angular form of vibrations [40]. This model is adequate under assumption of a small deviation in rotational speed and consists of five coupled rotor sections. The rotor section inertias $H$, damping factors $D$, and rigidity coefficients $K$ are assigned to generator, two LP rotor sections, IP section, and HP section. The generator is connected to an infinite power grid.

3.2. Vibration module

The Vibrations Module (VM) is the separate part of the VPPM and models the dynamic behavior of the shaft line. The steam turbine shaft rotates in the casing on hydrodynamic bearings. The steam turbine coupled with generator is a mechanical system of large number of degrees of freedom. Angular and lateral vibration forms are mainly considered referring to generator driving torque and rotor unbalance [40]. These two forms can be decoupled and modeled separately neglecting the mutual influence of rotor eccentricity [40]. This assumption leads to angular vibration model used in the power module (PM) and lateral vibration model used in the vibration module (VM). A torque balance between rotor and generator is an excitation to the angular vibration model, while the eccentricity and other synchronous/asyncronous forces are an excitation to the lateral vibration model. Both models could be coupled, but this would require huge increase in the computation power.

The Vibration Module is mainly focused on testing of different scenarios of early warning diagnostics. It is possible to convert the model response into a hardware unit which generates vibration signals equivalent of real machinery operation [41]. These simulated signals are the inputs to the vibration monitoring system. They allow to validate its sensitivity and robustness under different operating scenarios simulated by the model. Simulation scenarios may contain alignment, balance, and incorrect clearance malfunctions.

A lateral vibration model considers the elastic shaft of the high slenderness ratio consists of several rigid discs, mounted horizontally embedded in hydrodynamic bearings arranged upon the supports [42, 43]. All system mass is concentrated in the nodes. Linear, nonlinear infinitely short and long bearing models have been developed [44]. Inertia, gyroscopic, damping, stiffness forces, and excitation forces are associated with the n-th node as follows:

$$M_{\text{ran}} \dot{\omega} + G_{\text{ran}} \ddot{\omega} + D_{\text{ran}} \dot{\omega} + K_{\text{ran}} \omega + f(\dot{\omega}, \omega) = u_n.$$  \hspace{1cm} (19)
A bearing model can be attached to an arbitrary node using the general expression \( f(\dot{w}, w) \). The vibration module uses signal postprocessing methods [25] to plot vibration trends, cascade complex plots, orbit plots, etc.

4. Model validation

4.1. Static validation and calibration

After proper tuning of the control loops, the dynamic simulation model can be operated in a stable steady state at two load points: 70% and 100% load. The power unit model was calibrated statically using available performance documentation, i.e. power unit energy balance. The calibration procedure of the power module consists of three stages:
(i) module calibration,
(ii) group module calibration including local control-loops calibration,
(iii) final power unit calibration.

The available documentation provides steam/water mass flow rates, temperatures, and pressures for the operating range within 160–225 MW with a step of 10 MW. The model outputs are state variables and other calculated or explicitly given values. The outputs from the model line up very closely with the available data at 70% and 100% (Tab. 3).

**Tab. 3. Basic power unit parameters referred to 225 MW operating conditions**

<table>
<thead>
<tr>
<th>Power unit component</th>
<th>Error at 160 MW [%]</th>
<th>Error at 225 MW [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine inlet</td>
<td>-5.5</td>
<td>-2</td>
</tr>
<tr>
<td>Turbine inlet</td>
<td>-0.19</td>
<td>0.08</td>
</tr>
<tr>
<td>Reheater inlet</td>
<td>-7.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Reheater inlet</td>
<td>0.33</td>
<td>0.1</td>
</tr>
<tr>
<td>Turbine Outlet</td>
<td>6.91</td>
<td>6.88</td>
</tr>
<tr>
<td>Turbine Outlet</td>
<td>0.00031</td>
<td>-0.6319</td>
</tr>
<tr>
<td>XW1 - feedwater after a heater</td>
<td>2</td>
<td>-2.6</td>
</tr>
<tr>
<td>XW3 - feedwater after a heater</td>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>XW3 - steam to heater</td>
<td>-2.7</td>
<td>34.5</td>
</tr>
<tr>
<td>XW3 - steam to heater</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>XW3 - condensate after a heater</td>
<td>10</td>
<td>-6.7</td>
</tr>
</tbody>
</table>
One of the important aspects is model performance under continuous operation, simultaneously to a power unit. A long-term test was prepared to validate the performance of power and vibration modules and available simulation hardware, e.g. operational and cash memory, disk capacity, and processor speed.

The load program is run continuously and it simulates daily or weekly power plant operation under variable load conditions, e.g. combination of the hot startup, steady state and coast down operation. The data produced by the model is gathered and collected at the specified sampling frequency. The basic model can be simulated in real time if it is configured to exchange data through read-write converter. A single workstation equipped with Intel Pentium 2.8 GHz CPU and 4 GB RAM operated under Microsoft Windows XP Professional x64 edition, and Matlab 7.2 (R2006a) was used for simulation purpose. The following solver settings were applied: solver = ode23tb (stiff/TR-BDF2), max step size = auto, min step size = auto, zero crossing control = disable all, relative tolerance = auto, absolute tolerance = auto, data sampling time = 60 [s].

4.2. Dynamic validation

The normal operating conditions were simulated to evaluate the qualitative model accuracy compared to the reference power unit measurements under closed-loop conditions. The steady state operation was simulated with the use of a load program recorded during normal unit operation. The simulation results were compared to the power unit response at exactly the same reference signals, i.e. pressure and power. The power plant operational data and simulation results were compared regarding the steam mass flow and turbine demand load in Fig. 14. The small fluctuations in the data are seen due to the assumed limitations of the power unit control system model, and neglected or simplified components' models. The valve operation pattern is similar to real data as shown in Fig. 15; however, the simulated valve opening waveforms do not follow adequately to the load change. In Fig. 16, the steam pressure simulated waveform is compared to the measurement data. The model resembles the steam pressure trend with acceptable accuracy. The reheated steam temperature comparison is shown in Fig. 16. The model reconstructs the trend, however exact temperature variations are not included in the simulation results. In case of the feedwater temperature, the trend in the simulation is too sensitive to load changes, most likely it is an influence of simplified heater models used in this simulation.
(Fig. 17). In a heater model, the chambers volumes where fixed to simplify the equations and increase numerical model efficiency.

4. Conclusions

The paper presents the usage of the Matlab/Simulink package to implement the model of the power plant unit (VPPM), which is the basis for the Virtual Power Plant (VPP). This environment facilitates virtual modeling approach at component and system levels.
The VPP can be run on standard workstations to play and simulate major power plant processes in conditions close to the real time with accuracy required for qualitative trend-based prediction and sensitivity analysis. VPPM objectives are to decrease the uncertainty during preliminary power block settings selection, better choice of the starting point in case of power block optimization, identification of the most critical physical and geometry parameters contributed to power block performance, and finally reproduction of operational scenarios contained in the measurement data.

As presented in the previous sections the Virtual Power Plant Model (VPPM) structure can be easily maintained and managed, due to introduction of model variants, being model libraries updates. The available models’ equations have been implemented and integrated in Matlab/Simulink. It is possible to use several modules creating a combination of simplified transfer function models and extended advanced physics-based models within the
single VPPM. Such an approach is important whenever model speed and its flexibility are critical. It is possible to implement in the VPP several submodel versions to customize the model to specific needs of a modeling task, e.g. transient or steady-state. A workshop has been organized together with the involved power plant specialists and academic staff to summarize the status of the VPP and the VPPM development after the first phase of the project. Developed VPP architecture was evaluated as fulfilling the project requirements. However, it is necessary to extend the VPPM to cover broader operating range. The control system must involve more elements necessary for good reproduction of all the system events.

The current project results can be divided into software infrastructure and demonstration of the model for the power plant unit. VPP project has included development of powerful software infrastructure, predominantly for data handling, processing and presentation. Further research will be performed in two directions: increase of the computational speed to achieve the real-time operation and further development of the VPPM for better accuracy, especially in transient states.

5. References


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