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INTELLIGENT CONTROL SOLUTIONS FOR STEAM POWER PLANTS TO BALANCE THE FLUCTUATION OF WIND ENERGY

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Abstract: A stable and quality-oriented energy supply in Germany is a pre-requisite for a sustainable national economy. Therefore, also for political reasons, the wind energy as a renewable energy source in on-shore and off-shore wind power plants plays a more and more important role in this context. But this increase in wind power productions generates new and up to now unknown problems in the German energy system concerning energy transportation, the reduced availability of this energy for meteorological reasons and the thereby caused need for so called "Hour Reserve from conventional power plants". Also the fluctuation in wind power production in addition to the fluctuations of the consumer power demand and the not measured production from decentralized sources are resulting in substantially high positive and negative reserve power in the conventional power plants which are up to now not well designed for these new requirements. The analysis of these new burdens for the power plants, the development of new energy services and new strategies of control and the design of new conventional power plants in respect with an optimal operation regime are the main goals of this investigation on behalf of VGB PowerTech.

1. INTRODUCTION

Extreme situations at the wind energy generation like several days of calm or several days in sequence with a relatively even strong wind confront the conventional thermal power stations in Germany with few problems. However, for the grid and the power stations the weather conditional and different large power transients of the wind energy generation are critical, which are hardly predictable. Therefore a positive or also negative reserve power ("Hour Reserve") must be provided and offered on the market independent of the power flow condition. Furthermore whole wind parks can separate from the net in a fault case and lead to a huge spontaneous power deficit. Thus the fluctuating power of the wind parks must be regulated by the available conventional power stations as long as no large energy storages are available yet. This applies to those wind power spectra which show the largest power amplitudes. Due to the size of the planned off-shore wind parks the pumped-storage power plants alone will not suffice for this task. For that reason also conventional thermal power stations must be used. Therefore new energy service products like "Hour Reserve" must be defined for the existing thermal power stations so that these power stations can follow the appearing wind power fluctuations for balancing. Due to the material characteristics of their operational equipment the power plants have a limited minimum load and control ability (thermal stress in the components, wear, control rate of the thermal process etc). Therefore the needed start-up and shut-down cycles as well as the required minimum load and the possible starting and control rate of these plants are examined. In addition, the efficiency and economic utilisation of the power stations will be worse, if the power plant does not operate under design basis conditions. This increases the fuel consumption and extends the maintenance costs. For the technical operation of the conventional power stations in this changed environment the following points are seen as particularly problematic:

- Thermal and mechanical loading capacity due to frequent start-up and shut-down cycles and fast power transients of the power plant
- Reduced demand on the minimum load and with that a higher probability of an outage
- Operation of the power plant with lower efficiency
- Effects of the power fluctuations on the maintenance and life time of conventional power stations

The provision of the energy service "Hour Reserve" to balance the fluctuating wind energy feeding will be a market product in future. Therefore it is in the interest of the operators of conventional power stations to take over this control task. The conventional power stations may not be charged beyond their specific operation characteristics. Particularly the thermodynamic limits regarding thermal stress in the components must be taken into account. This applies mainly for the frequent start-up and shut-down cycles due to the introduction of the energy market service "Hour Reserve". This makes the use of additional control facilities necessary. For the existing power plants it has to be examined, which plants are already suitable for a cost-effective and gentle operation to compensate the fluctuation of the wind energy by means of the energy market product "Hour Reserve". Furthermore it must be clarified, which power stations are eligible for this and which plants are not suitable for this. The following questions have to be answered:

- How do number and speed of the start-up and shut-down cycles change for thermal power plants?
- Which requirements have to be met by the existing power plants and newly built power stations concerning the minimum load?
- Which changes of the utilisation factor are to be expected for the conventional power stations which produce "Hour Reserve"?
- Is a combination of conventional power stations and pumped-storage power plants possible for the provision of the new energy services?
- What is the consequence of the adapted operating method regarding the life time and cycles for maintenance of stressed components like feedwater pump, boiler and collector?
- Which new control system will be necessary to be able to provide the new energy services?

2. WIND ENERGY IN GERMANY AND DENMARK

By the end of 2006 wind power stations with an output of 20,622 MW were installed in Germany. The German wind energy production amounted to approx. 30.0 TWh in the year 2006. The highest simultaneous feeding of all wind power plants in Germany occurred on 12-31-2006 with a power of 16,129 MW. For the year 2020 an installed onshore wind power with approx. 27.9 GW is forecasted. The difficulty will be to maintain the extension of the wind energy use in Germany on high standard even though there will be a saturation in the onshore area. The solution will be to gradually acquire suitable sites at sea. At present, 24 wind parks are planned with an installed power of 22,703 MW in the North Sea and 2,130 MW in the Baltic Sea.

The Danish power system is subdivided into two synchronous zones. Denmark-West belongs to the UCTE and Denmark-East belongs to the NORDEL. The installed capacity of wind power plants in Denmark-West is 2,137 MW, but only 700 MW in Denmark-East. The installed offshore wind capacity amounts to 423 MW where Nysted (165.6 MW, Baltic Sea) and Horns Rev (160 MW, North Sea) are the largest. The Danish wind energy production amounted to approx. 6.1 TWh. The highest simultaneous feeding of all wind power plants in Denmark-West occurred with a power of 2,198 MW and in Denmark-East with a power of 680 MW.

2.1 *Annual duration lines of fed-in wind energy*

If one looks at the number of hours in full-load operation which are important for the economic efficiency, then the advantage of the offshore wind parks compared with onshore wind parks becomes clear. The Danish offshore wind power plants reached an average of 3,230 hours in full-load operation in the year 2006. It must be noticed, that in the North Sea due to higher wind velocities more hours in full-load operation are reached (Horns Rev: 3,727 h, Nysted: 3,123 h). The Danish onshore wind power plants operated 1,749 h in full-load; however the German onshore wind power plants operated only 1,526 h in full-load.

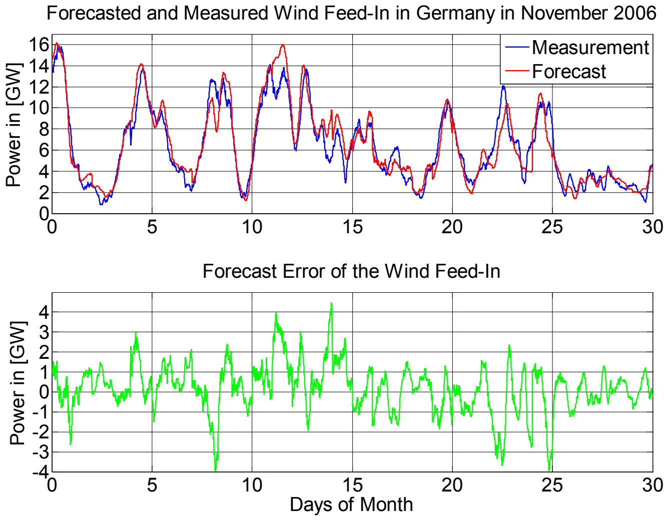

Fig. 1: Forecasted and measured wind data in Germany 11/06

The course of the annual duration line of all wind power plants feeding in the grid is dependent on the wind velocity and particularly dependent on the distribution of the wind velocity over the area of the installed wind power plants. The maximum wind feed-in amounted to 79.1 % of the installed wind power plant capacity in Germany. This is caused by the fact that an important share of the wind power plants is installed in the German midland by now. In comparison with this there are considerably more profitable wind conditions in Denmark. The maximum wind feed-in amounted to 90.2 % of the installed wind power plants in Denmark.

2.2 *Power transients of fed-in wind energy*

Figure 1 shows the forecasted and measured fed-in wind power for November 2006 in Germany. The forecast error of the wind feed-in is depicted additionally which can reach maximum values up to ± 4,000 MW in the ¼-h time period.

The greatest power rise in the ¼-h time period in the year 2006 appeared in May in Germany. The maximum positive power transient (844 MW) of the fed-in wind power was 4.4 % of the installed wind power capacity. The greatest power decrease in the ¼-h time period in the year 2006 appeared in November. The maximum negative power transient (-1,230 MW) of the fed-in wind power was 6.1 % of the installed wind power capacity. The greatest power rise and decrease in the 1-h time period in the year 2006 appeared in May. The maximum positive power transient (2,156 MW) of the fed-in wind power was 11.3 % of the installed wind power capacity (cf. Denmark 14.7 %). The maximum negative power transient (-2,704 MW) of the fed-in wind power was 14.2 % of the installed wind power capacity (cf. Denmark 16.3 %). The greatest power rise and decrease in the 3-h time period in the year 2006 appeared in April. The maximum positive power transient (5,080 MW) of the fed-in wind power was 26.9 % of the installed wind power capacity (cf. Denmark 33.2 %). The maximum negative power transient (-5,444 MW) of the fed-in wind power was 28.9 % of the installed wind power capacity (cf. Denmark 32 %). The power transients in the 12-h time period were between 52 % (positive) and 60.1 % (negative) related to the installed wind power capacity. In the 24-h time period power transients at most 58.7 % (positive) and 68.1 % (negative) were determined related to the installed power. It can be recognized that the duration lines of the wind power transients are not symmetrical. During great changes a strong reduction of the power happens more frequent than a strong increase. In comparison with Germany the values were also higher in Denmark. It is noticeable that the wind power transients increase considerably with time ranges getting larger. Due to the higher wind velocities and the regional higher density of the wind parks in Denmark in all investigated time periods higher positive and negative power transients occur. One would expect similar power transients for offshore wind parks in Germany like in Denmark.

3. UNIT CONTROL SYSTEM OF A POWER PLANT

Unit control systems have the task to coordinate the operation of turbine and boiler as effectively as possible. The structure of the classic closed-loop control of a conventional steam power station results from the operation mode of the power station. The operation mode is determined by the control requirements on the power station which are different in the assignment of the controlled variables.

- generator power p_G and live steam pressure p_D

to the controller output signals

- turbine control valve y_T and fuel mass flow $\dot{m}_B$

The operation modes result from that with the respective power station control systems

- Turbine Following Mode
  (Natural variable pressure operation mode)
- Boiler Following Mode
  (Modified variable pressure operation mode)

3.1 Model based unit control systems

In contrast to the classic closed-loop control an approved concept is considered here with a process model based feed-forward control in combination with dynamic decoupling in the closed-loop control. The determination of process models as well as the design of the controller itself is computer-aided with the help of optimization programs. The advantages of this intelligent and modern solution are particularly:

- Essential improvement in the dynamics without influencing the stability
- Additional degrees of freedom at the optimization of response to set point changes and disturbances
- Reduced control tasks allow a smoother operation of main components like coal pulverisers
- Improved plant efficiency for primary control through reduced throttling of the turbine control valves
- Feed-forward control and closed-loop control can be designed and optimized independently of each other

In figure 2 the model based unit control system concept is represented. It performs these tasks by using the manipulated variables fuel mass flow $\dot{m}_B$ for the boiler and the turbine control valve y_T for the turbine under consideration of internal dynamic models for the live steam pressure p_D and generator power p_G. The unit control system is intended to allow controlled start-ups, shut-downs and load changes of a power plant unit under economically optimized conditions. Within the framework of primary and secondary control, the aim is to deliver the energy produced by the unit on the basis of the dynamic response demanded by the load dispatcher. The unit control system permits primary and secondary load-frequency corrections allowing for high economy and high quality improvements for new and refurbished power plants. The primary grid frequency control of the unit is responsible for the balance between the power generation and consumption. The response time of this control is extremely short (few seconds) and is decisive for the grid stability in case of major disturbances of the power generation. Therefore a dynamic coordination of the grid-frequency error for turbine and boiler load has been introduced into the solution of the unit control system. The grid secondary control is provided by a load dispatcher, who regulates the agreed load exchange between the interconnected power supply partners. Its control response time is in the range of minutes, where the units adapt their power generation according to the dispatcher demand signals. In figure 3 a model of a thermal power station is represented with the unit control system concept introduced here. The modelling was done in MATLAB®.

3.2 Set point control of the unit

The task of the set point control of the unit is the management of a reliable stationary operation of the unit. This includes the realization of target-setting of power through the load dispatcher and the supply of primary and secondary control power. The supply of primary and secondary control power is moreover dependent on the power offered on the energy market for positive and negative values. The closed-loop control of the unit is carried out by the superimposed power set point control with the subordinated set point controls for the boiler and the turbine. The input signal of the power set point control is the power from the load dispatcher p_{PP}. When participating in the secondary control the unit is directly managed by the secondary controller. The limitation of the target-setting of the power has to ensure that the sum signal of the power set point $p_{G\,REF}$ and the request for secondary power p_{SEC} do not exceed the maximum permitted unit load as well as the maximum permitted power transient speed depending on the operating point of the unit. It guarantees the compliance with the permitted thermal and material stress of the turbine and the boiler. Furthermore the availability of the coal pulverisers, pre-heaters and feedwater pumps is considered. The output signal of the power set point control of the unit is the feed-forward control value for the boiler $\dot{m}_{B\,SP}$. The feed-forward control value for the turbine $y_{T\,SP}$ is calculated with the power set point $p_{G\,REF}$ depending on the modified or natural pressure operation mode. When participating in the primary control a value proportional to the frequency deviation is added both to the feed-forward control value for the boiler and the turbine.

3.3 Process model

The power of the unit is changed primarily by feed-forward controlling. The feed-forward signals are affecting the subordinated fuel mass flow control and therefore the feedwater pumps as well as the turbine valves. The effects on the controlled values are reproduced in a respective set point course by the predictors. The controllers are discharged at the response to set point changes and can be optimized on the disturbance response. The control has merely a corrective function. The input signal of the predictors is the feed-forward controlled value for the boiler $\dot{m}_{B\,SP}$. The course of time of the desired set point of the live steam pressure $p_{D\,SP}$ is reproduced with a PT 5 time response and the course of time of the desired set point of the generator active power $p_{G\,SP}$ is reproduced with a PT 4 time response. The time constants in both predictors are adapted depending of the unit load.

3.4 Power, pressure and turbine position control

Depending on the chosen operation mode different regulation concepts and control actions in the thermodynamic process result. In the boiler following mode a distinction has to be made between the pre-pressure mode and the natural variable pressure mode.

- Boiler Following Mode

In the pre-pressure operation mode the live steam pressure is controlled with the turbine valve, however in the natural variable pressure mode the live steam pressure glides unregulated at fully open turbine valves. The pressure controller is designed as a PID-controller. It regulates the changing of measured pressure in relation to the feed-forward control value for the pressure. The derivative part has only an effect on the measured value. The integral-action time of the controller is adapted due to the unit load. The power controller for the boiler is carried out as a PI-controller. It regulates the actual measured generator power in relation to the feed-forward control value for the unit load. The output of the controller is added to the feed-forward control value for the boiler. The control of the generator power is done in both cases via the slowly subordinated fuel mass control. The storage capacity of the boiler is not utilized.

- Turbine Following Mode

In the turbine following mode a distinction has to be made between the constant pressure mode and the modified variable pressure mode. In the constant pressure mode the live steam pressure is independent of the power and is controlled to have a constant value by throttled turbine valves. In the modified variable pressure mode the live steam pressure is proportional to the unit load. This is reached by throttling the turbine valves at such rate that a desired active power reserve is provided. The position controller for the turbine valve is designed as a PI-controller which regulates the changing of the measured position of the valve y_T in relation to the feed-forward control value for the turbine $y_{T\,SP}$. The course of time of the feed-forward control value is reproduced with a PT 2 time response for decoupling. The output of the controller is added to the feed-forward control value for the pressure. The pressure controller is carried out as a PID-controller. It regulates the changing of measured pressure p_D in relation to the feed-forward control value for the pressure $p_{D\,SP}$. The derivative part has only an effect on the measured value. The integral-action time of the controller is stopped in the variable pressure operation. In both constant pressure areas the integral-action time is unrestricted.

The power controller for the turbine valve is made as a PI-controller. It regulates the actual measured generator power in relation to the feed-forward control value for the unit load. The output of the controller is added to the feed-forward control value for the turbine. The regulation of the generator power is carried out in both cases via the turbine valve. In both operation modes the storage capacity of the boiler is used because of throttling of the turbine valves.

3.5 Feedwater control with enthalpy correction

The mutual influence of the two control systems pressure and enthalpy is eliminated with a decoupling network. The decoupling of the pressure controller is achieved by way of injecting the output signal of the enthalpy controller with a PDT time response $\Delta\dot{m}_B$ on the feed-forward control value for the boiler. The output value of the pressure controller $\Delta\dot{m}_{FW}$ is injected analogous to the feed-forward control value for the feedwater pumps. The enthalpy controller is made as a PI-controller. It regulates the actual enthalpy h_D in relation to the desired enthalpy $h_{D\,SP}$. The output of the controller is a quantity of correction of the feedwater which is already included in the feed-forward control value $n_{FW\,SP}$ for the feedwater pumps. The enthalpy of the live steam at the exit of the superheater is a measure for the balance of feedwater supply and heat supply. If at a pre-defined heating the enthalpy of the live steam is too big, the feedwater quantity is increased correspondingly. If the feedwater quantity remains constant, then the heating must be reduced immediately.

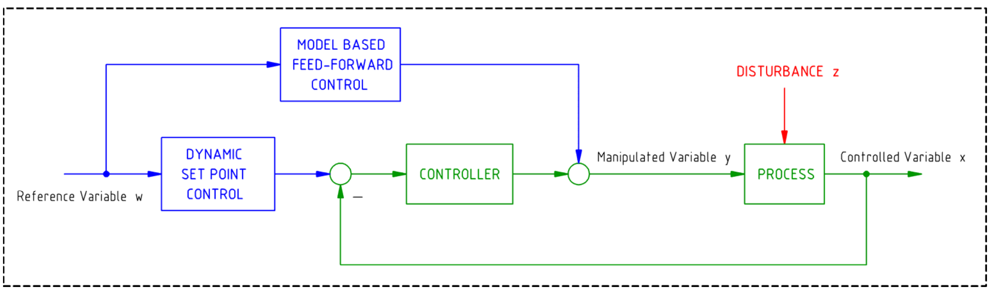

Fig. 2: Model based unit control concept

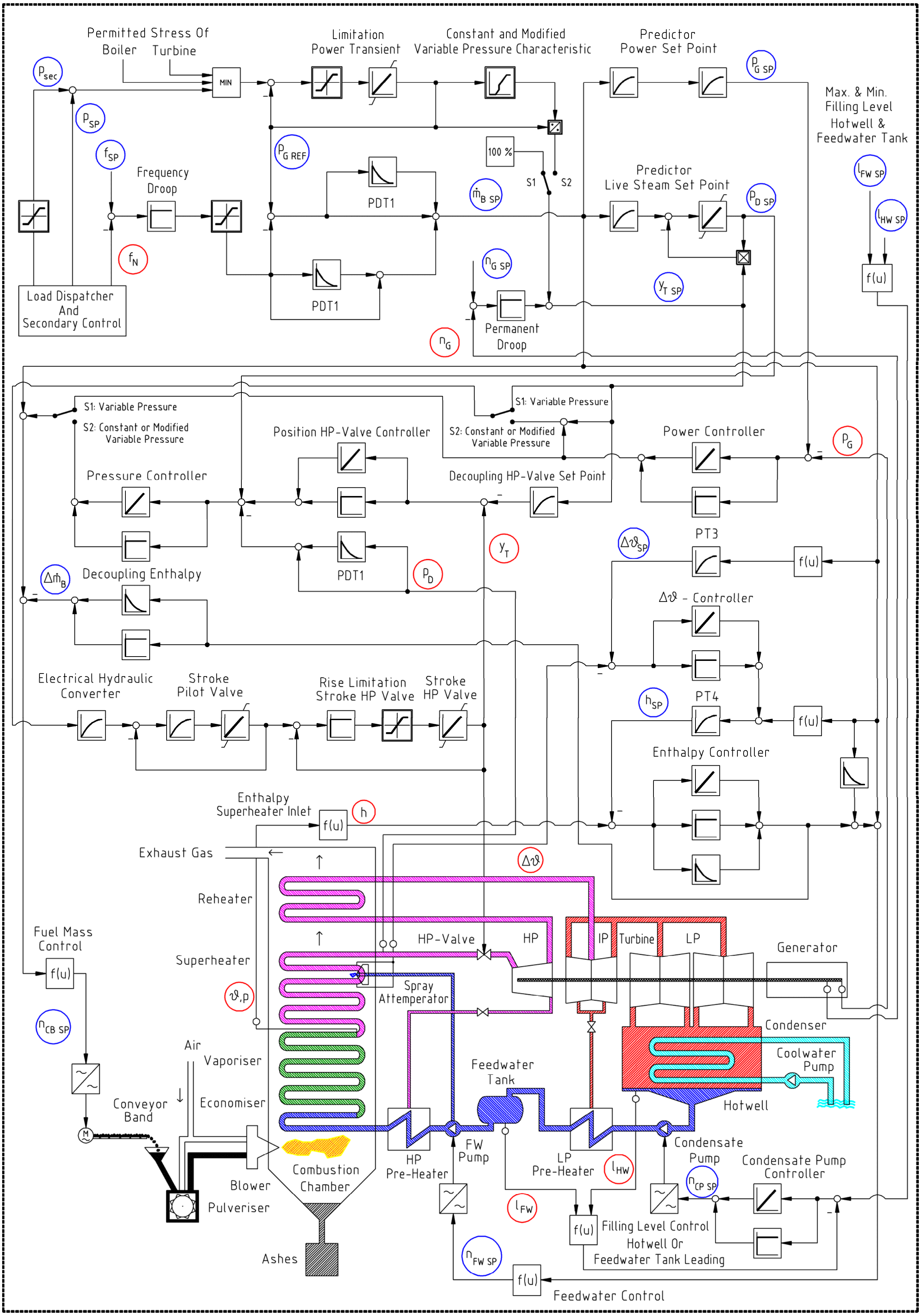

Fig. 3: Simplified Model "Turbine Following Mode"

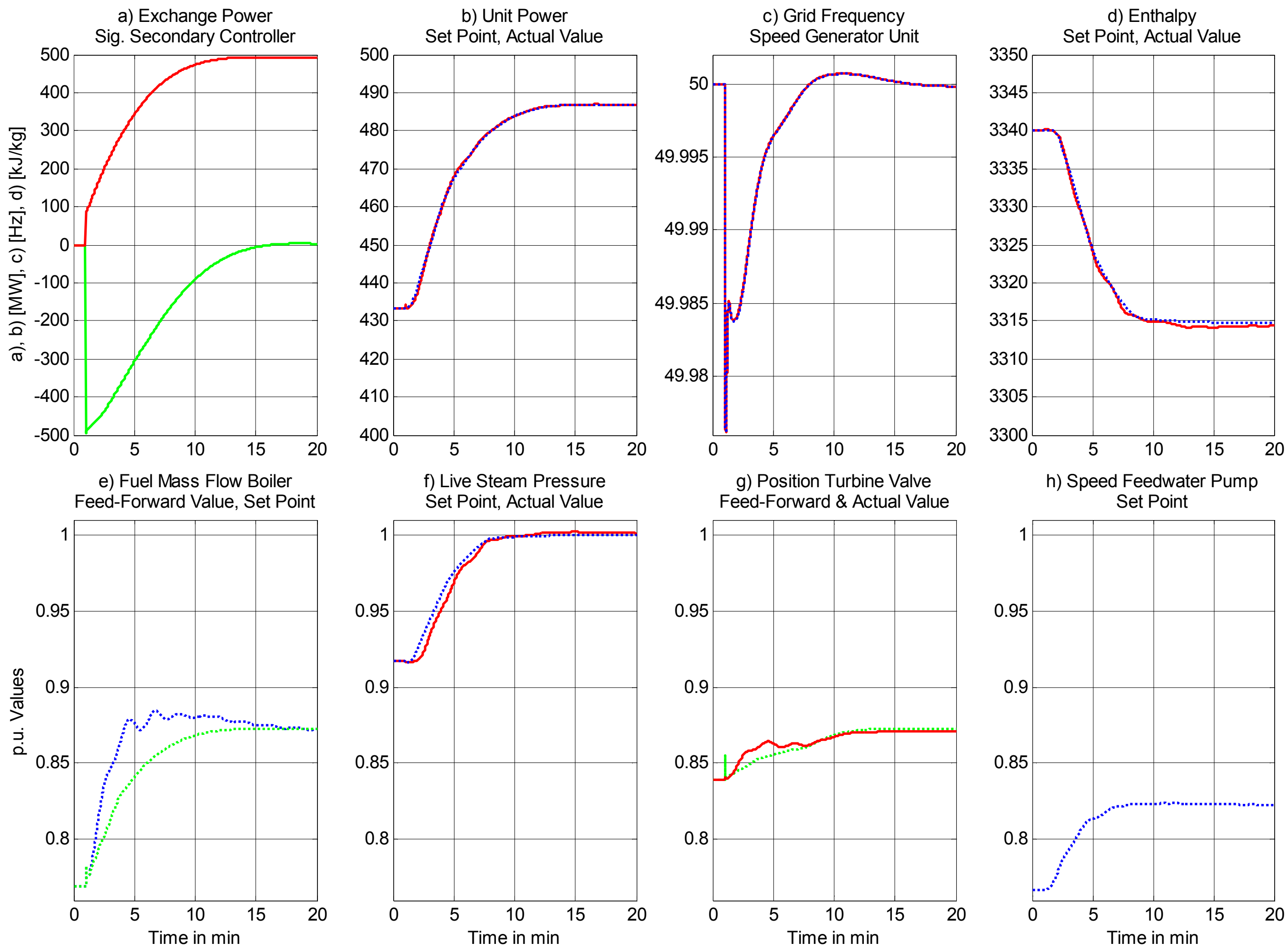

Fig. 4: Simulation results of a load request ······ Set Point —— Actual Value ······ Feed-Forward Value

3.6 Fuel Mass Flow Control

The unit control system determines the number of the required pulverisers and coal allocators due to a load request. The main fuel mass flow controller determines the speed of the coal allocators n_{CB} which are transporting a defined mass flow of coal via a conveyor band to the pulveriser. The output of the pulveriser model is the coal dust which is injected in combination with air into the combustion chamber. Next to the delay in the boiler the inertia of the fuel supply and the storage behaviour of the pulverisers are having a decisive influence to the load change dynamic of the unit.

4. SIMULATION OF THE UNIT CONTROL SYSTEM

The model was tested in the modified variable pressure mode by a load request due to an outage of a 500 MW power plant, which leads to a frequency deviation in the grid, see figures 4 a, c). The unit participates with 10 % in the secondary control so that the unit net power increases by 50 MW (10 % of the nominal net power of the unit). In figure 4 b) there is no difference to be recognized between the desired set point and the actual value of the generator power. The unit increases its power with the pre-defined maximum permitted power transient speed of 2 %/min in order to satisfy the rules of the transmission code. The turbine valve in figure 4 g) opens temporarily and releases thus additionally stored steam from the boiler. Depending on the power the live steam pressure in figure 4 f) glides on the new working point. The enthalpy of the live steam pressure in figure 4 d) gets smaller because the pressure increases. However, the live steam temperature ϑ_D is kept constant by the cooling water injection control. The influence of the inertial fuel mass control and the boiler on the dynamics of the unit can be seen in figure 4 e) at a load request in which the transient behaviour through a feed-forward controlled mass flow is improved.

In conclusion it can be said that the model is able to simulate the operation of the unit during the smoothing of disturbances in the net realistically. In the future the disturbance in the net will be simulated by a fluctuating wind energy feeding based on measured wind data. Thus the participation of the power plant in the energy market product "Hour Reserve" can be investigated.

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