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Technical Framework Conditions to Integrate High Intermittent Renewable Energy Feed-in in Germany

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1. Introduction

The first part of this chapter gives a short overview about the general problems of integration. Therefore a control theory based description of the basic fundamentals of the power system control concepts is given.

The second part of the chapter concentrates on the technical framework conditions of conventional power plants to follow the intermittent power feed-in because as long as no large-scale storage systems are available these conventional power plants will be necessary to integrate the renewable energy at least for the next 20 years. Therefore different methods and tools to analyze and simulate the power plant scheduling and to determine the additional life time consumption of highly stressed components of fossil fueled power plants will be presented and illustrated by different scenarios.

2. German ambitions for renewable energy until 2050

In Germany the existing electrical generation system is going to be essentially influenced due to the continuously increasing influence of intermittent renewable energy sources. Because of the massive expansion of the total number of wind turbines, especially in the northern part of Germany within the last years, wind power now plays the most important role concerning the renewable energy sources in Germany.

At the end of 2010 the installed capacity of wind turbines amounted to more than 27.2 GW. Besides the photovoltaic capacities are increasing so fast, that at the end of 2010 there was more than 17.4 GW of installed capacity for photovoltaic systems. In the photovoltaic sector this was an increase of about 80 % compared to 2009.

Despite of a stepwise reduction of the legal refunds for the electrical energy produced by photovoltaic systems and wind turbines in Germany within the next 10 years, current predictions yield to about 50 GW of installed capacity for photovoltaic systems and an installed capacity of wind turbines of more than 51 GW in 2020. This means that there will be probably more than 100 GW of wind and solar power generation installed in Germany by the end of the decade. Therefore the share of electrical energy produced by these two

renewable sources could increase from 8.6 % in 2010 to more than 35 % in 2020 of the German electrical net energy consumption.

In regard to a peak load of 85 GW and an off-peak load of only 45 GW there will be new challenges to integrate such a high intermittent power feed-in into the existing electrical generation system. Until now there are only the fossil and nuclear power plants available to balance the renewable energy production and to follow the wind and solar power production in a complementary way. But due to the increasing fraction of intermittent renewable energy sources within the generation system the number of available synchronized conventional power plant generators will be reduced continuously especially in periods with high renewable power feed-in. Since the system stability depends on the availability of flexible power stations, sufficient spinning reserves and certain system inertia, the robustness of the electrical power system will reduced towards suddenly appearing disturbances of the power balance.

Due to the limited fossil and nuclear resources that we use today and the high carbon dioxide emissions and nuclear waste production to produce more than 80 % of the German electrical energy, Germany has to exploit new energy sources that are available in an unlimited way. Therefore in the 21st century the renewable energies will become the most important field of research in several domains of technology. Wind and solar energy are available nearly everywhere in Germany. But it will depend on several economical boundary conditions which kind of technology will be the best to gain an efficient access to this unlimited energy supply.

Of course in regard to the relevance of solar energy it would be the most efficient way to generate the electricity where the solar energy supply is naturally the highest. But unfortunately these regions are often far away from the areas with the high population and consumption density. For example it would be possible to cover the total worldwide energy consumption by just covering a very small fraction of the desert areas like the Sahara in North Africa, but a very powerful transportation system for electrical energy is needed that has to consist of various high voltage transmission lines that can deliver the energy to the consumers. In Europe for example the consumers are several thousand kilometers away from the desert areas and of course Europe is separated from the continent of Africa by the Mediterranean Sea. So it would be necessary to use cable systems to connect this intercontinental sea distance which are very cost-intensive compared to overhead lines.

These new transmission line systems will cause very high capital expenditures that can't be raised in the near-term future. This funding, on the one hand for the transmission line systems and of course on the other hand for the solar generators like Concentrated Solar Power (CSP) stations or photovoltaic (PV) systems, has to be invested in the long-term future. Although in Europe there is a first ambitious entrepreneurship called Desertec, that proposed to it selves that it could be possible to build up such a renewable solar and wind generation system in North Africa within the next decades, earliest in 2050 almost 15 % of the electrical energy consumption of entire Europe could be covered. But in regard to the security of supply it has to be mentioned that there is always a certain risk in dependence to other countries especially when the political systems are not stable in these countries.

So to fulfill the German goals and to be less dependent from foreign political issues it is necessary to use the renewable energy sources that are available on the German land and sea area to increase the fraction of renewable energy in the electrical energy system from 18 % today up to 40 % until 2020 and up to 80 % until 2050.

The potential especially for wind energy is very high in Germany. Naturally the solar energy potentials aren't as high as in southern Europe or North Africa but nevertheless it is still worthwhile to exploit this renewable energy source with photovoltaic systems. In

Germany hydro power is already exploited to a great extent and biomass and geothermal energy aren't capable to contribute big proportions of the energy consumption. Therefore only the intermittent energy sources like wind and photovoltaic power can be used to deliver a high proportion of the total energy demand.

But unfortunately these two energy sources have a very disadvantageous characteristic. They occur in an intermittent way and they aren't reliable. Furthermore the energy supply of wind and solar generators do not correlate to the overall energy consumption. From the consumers point of view this makes it impossible to operate an electrical generation system without any backup power plants that are supplied by big storage systems. Besides these backup power stations are necessary to ensure the safety of supply at any time even when the system is disturbed by suddenly appearing technical outages of any electrical equipment of the generation system. Moreover fast reacting generators are essentially needed especially when the wind and solar energy occurrence is decreasing due to changing meteorological conditions.

3. The electrical generation system as a controlled system: frequency – active power – control

To understand the fundamental problems of the integration of intermittent renewable energy sources into the electrical generation system it is very important to understand the control structure of the system. Therefore in the following subsections a more detailed description of the electrical generation system, which is precisely a controlled system, will be given.

Worldwide the electrical energy supply is operated with a three-phase network. Three-phase rotary current is used instead of single phase Alternating Current (AC) because its behavior towards the transmission of energy is similar to a rotating mechanical shaft which is continuously delivering power. But this virtual "electrical shaft" is not emitting noise nor is it necessary to lubricate it. From the powered generator shaft to the slowing down motor shaft the three-phase rotating current network therefore behaves like a warped torsion shaft under workload that rotates with 50 rotations per second. Hence the electrical switch- and transformer-stations act like mechanical gearboxes that are connected to several distribution shafts which are connected with the consumers. The consumer can use these distribution shafts to perform mechanical work or to produce light or heat by the cause of friction. The shafts are driven by different mechanical power drives which care for the n_T=50 rotations per second and provide the torque M_T which is required for the delivered power P_T according to:

$$P_T = M_T \cdot \Omega_T = M_T \cdot 2 \cdot \Pi \cdot n_T \tag{1}$$

This torque is produced by turbines that are classed into thermal, gas fired and hydraulic. To ensure a long life time of the power drives the rotational speed n_T has to be kept as constant as possible. Therefore only the torque M_T can be adjusted which means more or less steam, gas or water onto the turbine. The turbines consist of rotors which have an inertia Θ. But a rotating mass is only able to change its rotational speed if the sum of working torques is changed according to:

$$\Theta \cdot \dot{\Omega}_T = (M_T - M_V) \tag{2}$$

Here M_T is the delivered load torque: If M_T increases the system accelerates, if M_V increases the system slows down. The rate of acceleration or deceleration of the whole system is significantly determined by the inertia Θ. Hence if the inertia would be reduced the rotational speed change rate would increase, too.

To summarize this first part it can be outlined that if the mechanical system wouldn't emit noise and if it wouldn't be necessary to lubricate the components, the energy supply systems could be realized with pure mechanical components. To understand the frequency – active power – control loop it is therefore sufficient to understand the controlled mechanical energy supply system.

In control engineering usually per unit (p.u.) values are used for different physical values. These per unit values are referenced to their nominal value. If furthermore is assumed that the rotational speed n_T and therefore Ω_T isn't changed noteworthy, equation (2) can be constituted as:

$$\Theta \cdot \Omega_N \cdot \dot{\Omega}_T = (P_T - P_V) \tag{3}$$

If the nominal values P_G and Ω_N are introduced, equation (3) can be written as:

$$T_G \cdot \dot{f} = (p_T - p_V) \tag{4}$$

The values indexed with G stand for values referenced to the whole network. Here f is the per unit system frequency or rotational speed. T_G is called the acceleration time constant and it is calculated by:

$$T_G = \frac{\Theta \cdot \Omega_N^2}{P_G} \tag{4a}$$

The acceleration time constant, which is calculated by the inertia of the generators and motors, commonly states how much time it takes from standstill to accelerate an inertia that is driven by its nominal torque or power until the nominal rotational speed is reached. Within the electrical energy system the inertia is of vital importance, since only the inertia is able to stabilize the network frequency at an acceptable value in the first moment after a disturbance of the power balance. Normally wind turbines are connected to the system via frequency inverters and photovoltaic systems are always connected via DC/AC converters, so they are mechanically and electrically decoupled from the system and can not increase the acceleration time constant. Therefore it is has to be lined out that the acceleration time constant is reduced if more and more wind turbines and photovoltaic panels are connected to the system when at the same time the number of conventional power plant generators with masses are displaced by these intermittent generators while the total nominal power value of the whole system remains constant.

3.1 The primary control

With the use of the Laplace transform equation (4) can be stated according to:

$$\Delta f = \frac{1}{s \cdot T_G} (\Delta p_{G_E} - \Delta p_{G_V}) \tag{5}$$

The values indexed with G stand for values referenced to the whole network, index E for the generation and V for the consumption. This equation of motion is the basis of the control orientated modelling structure of the primary control of a total network shown in Fig. 1. Here the frequency f is stated as the deviation from the desired network frequency that is 50 Hz in Europe. Furthermore the following assumption was made: All power plants and consumers are connected to a single node network model; this means the transmission lines or transmission shafts between them are neglected. Therefore only one network frequency exists. The losses are allocated to the consumers. p_{GE} describe the total power generation and p_{GV} the total power consumption in per unit values. With this kind of model the whole European generation system of the ENTSO-E from Portugal to Poland and Denmark to Turkey with a total nominal power of $P_G = 300$ GW can be described.

Due to the dependency of the power consumption of motors on the network frequency the real absorbed power p_{GV} is corrected by the frequency dependent change of power Δp_{GVf} according to:

$$\Delta p_{GV_f} = \frac{1}{\sigma_{G_V}} \cdot \Delta f \qquad (6)$$

This behaviour is called the consumer self-controlling effect which is expressed by σ_{GV}. The mean value for this value is 200 % in Germany. Therefore the consumers itself acts like a control loop because they reduce their power consumption if the frequency decreases and they increase their power consumption if the frequency increases. Hence in Fig. 1 the magenta-hued total consumer has three single paths:

1. The actual operating point of the consumed power
2. The always occurring disturbance of the system because of consumer re- and disconnections from the system
3. The frequency dependent power consumption of the motoric consumers

The operating point "consumed power" is the forecasted power demand of the total network at a certain hour of the day. All deviations from this value result in the disturbance signal "consumer re- and disconnection". The operating point "consumed power" has to be covered by the existing power plants. In Fig. 1 this is symbolized by the "scheduled power". The operating point "secondary control power" will be described later. For now it can be assumed to be zero.

If now is assumed that only the consumer self-controlling effect would take effect, the deviation of the network frequency from the nominal value of 50 Hz would increase to a non-permissible extent. In Fig. 2 this deviation is illustrated by the green line for a step disturbance of the consumed power of 1 % of the nominal power. For the European network with a nominal power of $P_G = 300$ GW this is equal to a disturbance of 3 GW. The primary control is designed to handle such a disturbance at the maximum and to compensate the power deficit completely. This maximum disturbance is equal to the outage of two French nuclear reactors of the nuclear power plant Tricastin. As withdrawn in Fig. 2 the frequency deviation amounts to $\Delta f = -0.02$ pu $= -2$ % or -1 Hz. In the case of such a high frequency deviation first consumers would be automatically disconnected from the system to ensure the safety of supply and to protect electrical components.
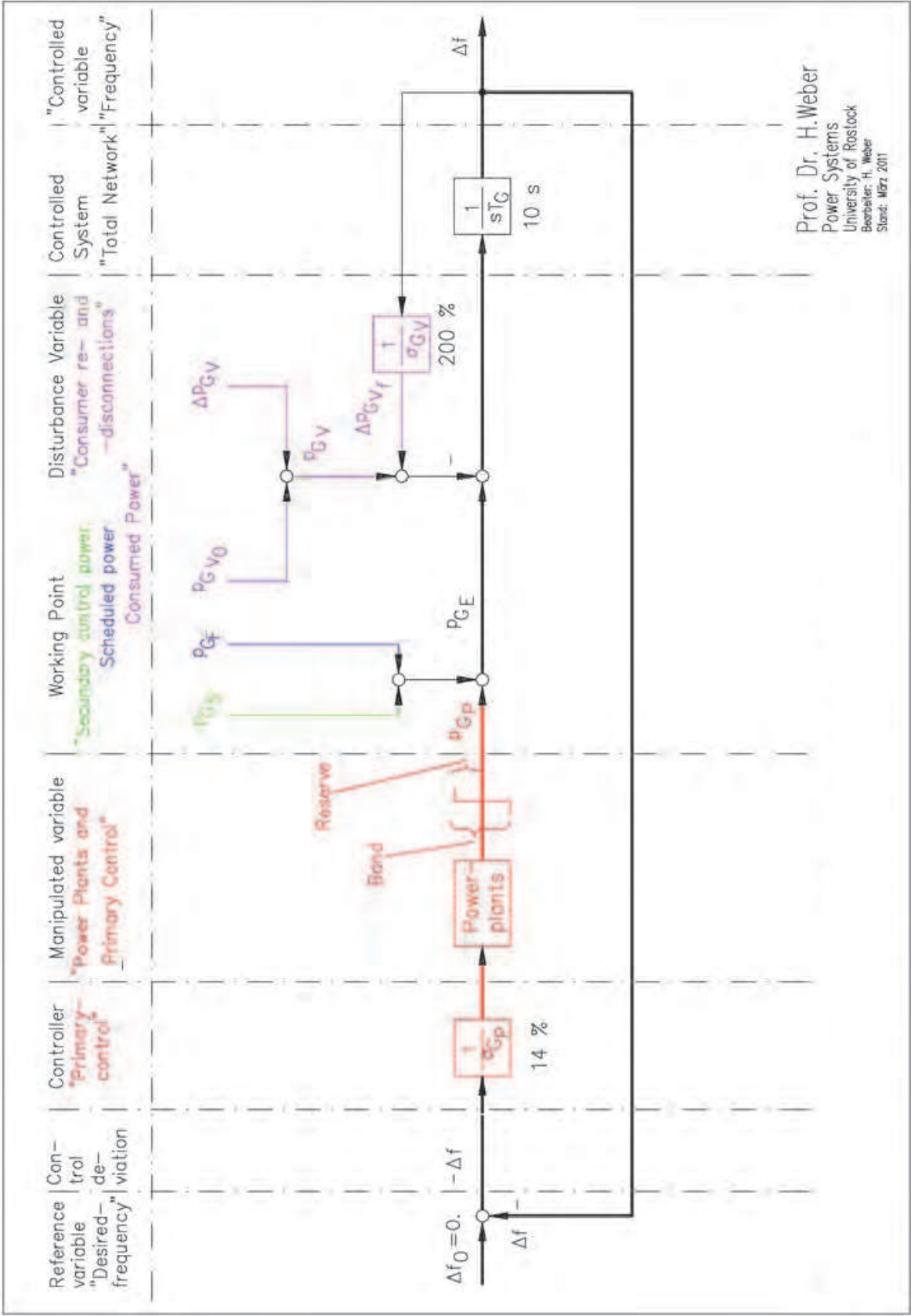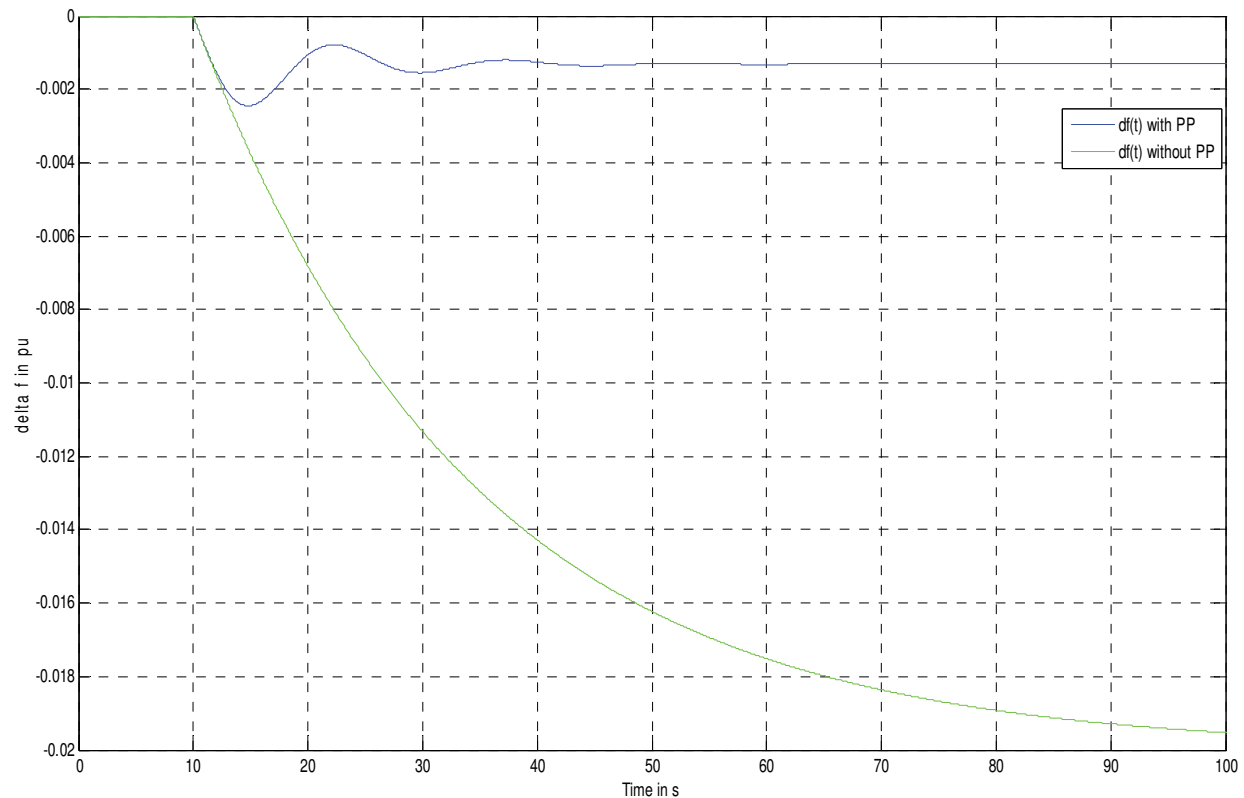
Fig. 1. Control oriented scheme of the primary control

Fig. 2. Frequency deviation in pu while Δp_{GV} = +1 %

The step-shaped disturbance of the consumed power of 1 % has to be covered at any time. In Fig. 3 the different types of power are shown that cover this additional consumed power: The blue line shows the reduction of the real consumed power due to the consumer self-controlling effect according to equation (6), the green line shows the accelerating power that is delivered by the inertia of each rotating mass that slows down corresponding to equation (7). As outlined by this graph in the first moment the required power is delivered by the accelerating power that is provided by the decelerating rotating masses and later by the consumer self-controlling effect which is reacting due to the decreasing frequency.

$$p_{G_{acc}} = -T_G \cdot \Delta \dot{f} \qquad (7)$$

In the future the electrical generation system will be characterized by inertia-free energy converters like frequency inverter controlled wind turbines and photovoltaic panels, so the accelerating power has to be generated synthetically with power electronics to safe the grid control and to ensure the system stability any longer.

In the control orientated structure of Fig. 1 the controller "primary controller" and the manipulated variable "primary control power" are shown. This primary reserve power has to be reserved in all power plants that are connected to the system. Due to this primary reserve power the frequency deviation is kept in an acceptable tolerance range which is illustrated by the blue line in Fig. 2. Here the frequency deviation remains within -200 mHz in regard to a steady state evaluation if a σ_P of 14 % is assumed.
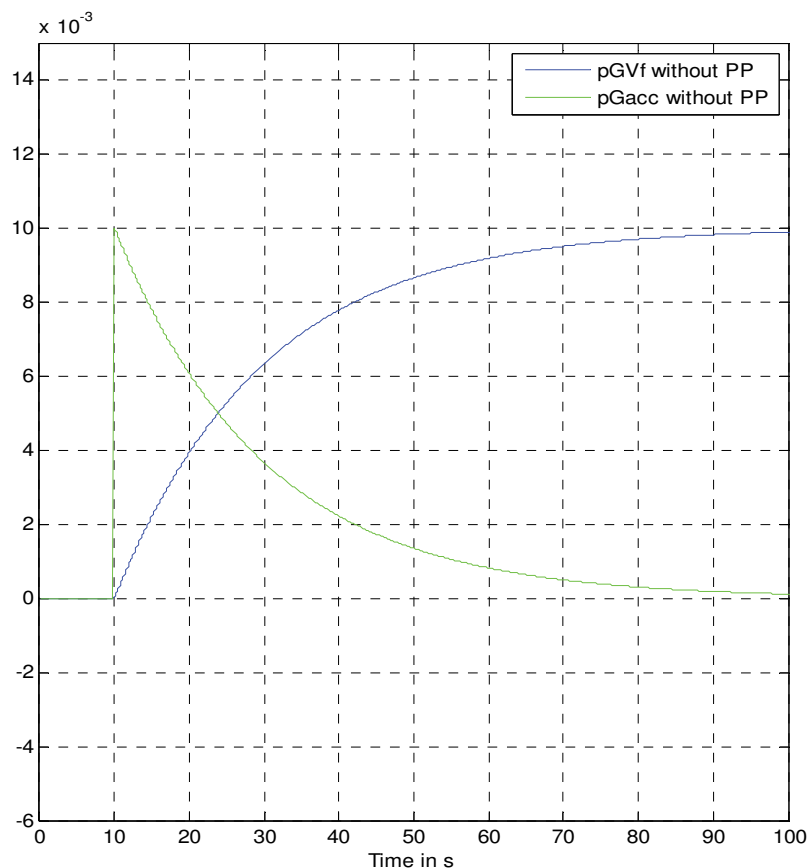
Fig. 3. Disturbance of the power balance covered by accelerating power and the consumer self-controlling effect

In this context in Fig. 4 the accelerating power is shown again. Here now the primary control (red line) almost entirely takes over the disturbance slightly supported by the consumer self-controlling effect. This transition process proceeds oscillating as well as the corresponding frequency change. The related power plant model was simplified to two PT1-elements with the time constants T_{K1} = 0,8 s and T_{K2} = 6 s.

In the future as mentioned before the acceleration time constant T_G will be reduced due to the increasing amount of renewable generation from wind and photovolaics because of the loss of inertia. In Fig. 5 is shown the effect of a reduced inertia. Therefore the network acceleration time constant is reduced from 12 s to 6 s and then to 2 s. As illustrated in the three lines of diagrams at the beginning the frequency deviation increases, the network behaviour gets "softer", although the disturbance remains constant in all three cases. This behaviour will continue until the primary controller stability is lost completely in the third scenario due to the lack of sufficient inertia.

3.2 The secondary control

The operating point "secondary control" in Fig. 1 remained zero in case of the aforementioned primary control action which acts in the domain of seconds. This caused a remaining steady state deviation of the frequency as shown in Fig. 2. This deviation is now corrected by the secondary control within the domain of minutes whereby this process has to be finished after 15 minutes.
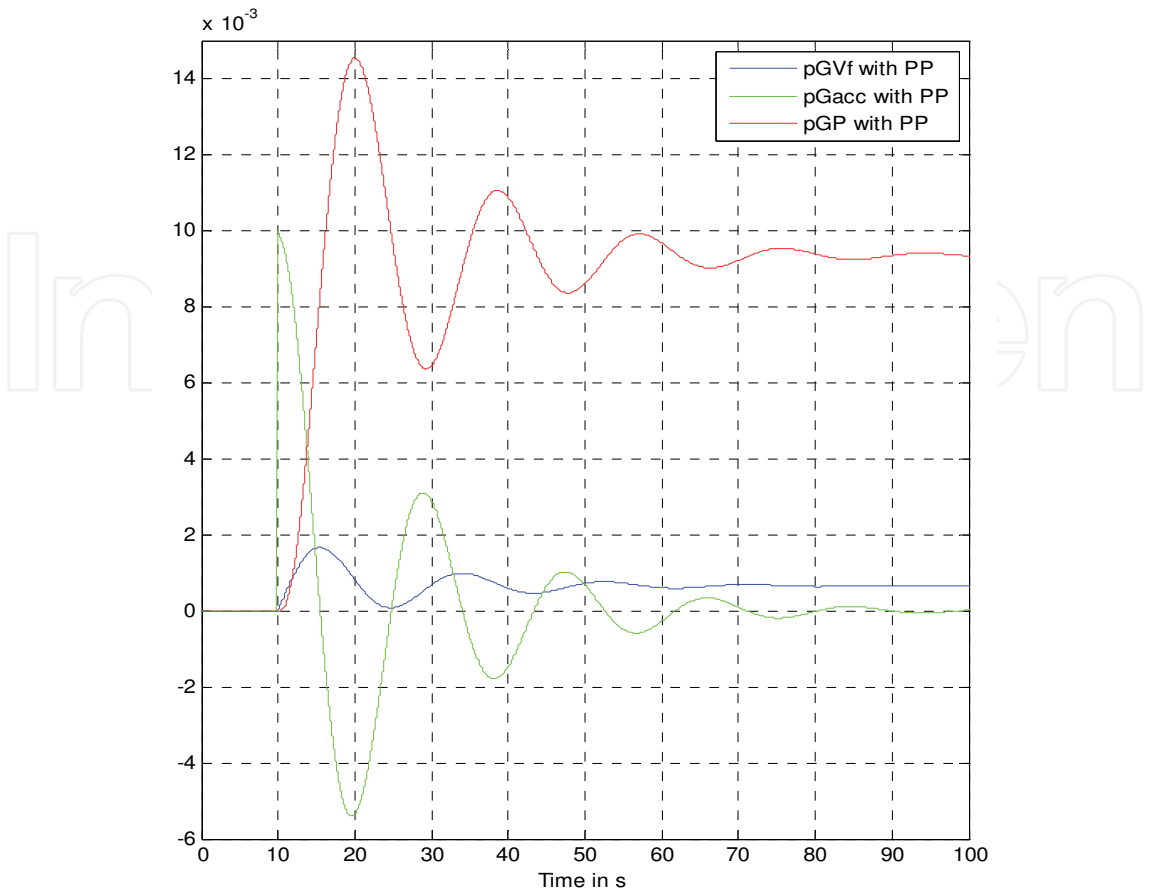
Fig. 4. Disturbance of the power balance covered by accelerating power, the consumer self-controlling effect and the primary control
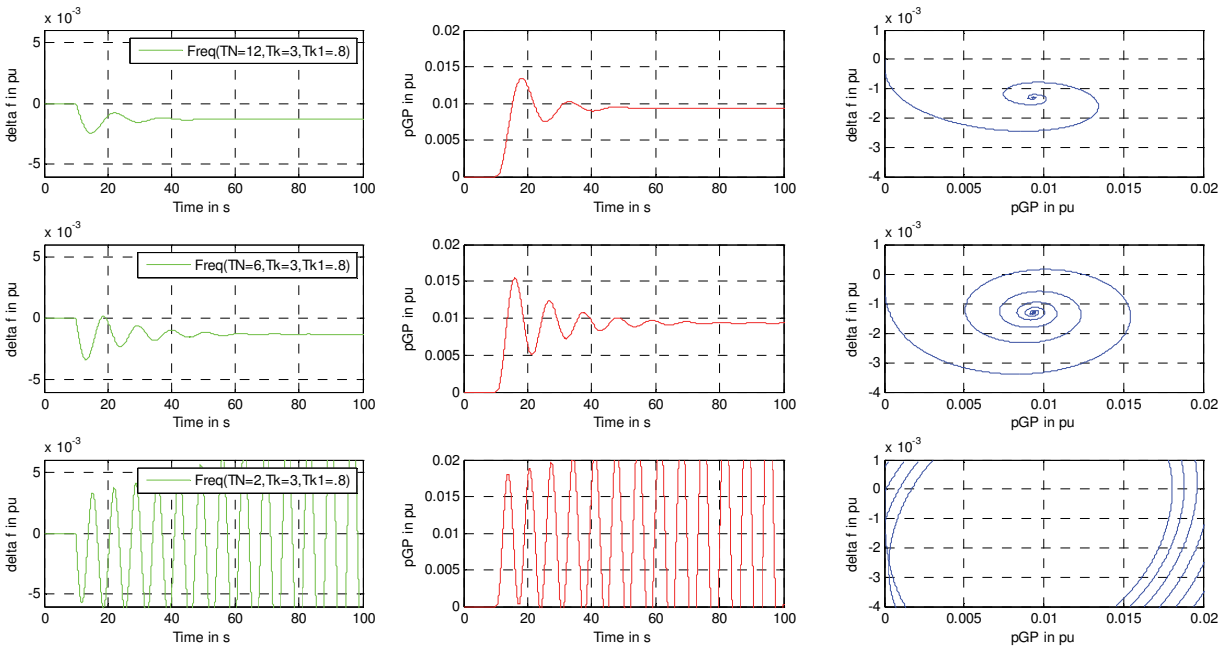

Fig. 5. Effect of a reduced acceleration time constant due to reduced inertia onto the primary controller stability

Furthermore the secondary control has to determine in which control area of the system the disturbance occurred because only the disturbed control area should compensate the disturbance. In this context it is important to consider the scheduled exchange power between different control areas, too. The secondary control detects the disturbance by the use of the Area Control Error (ACE). After the transient oscillation of the primary control the ACE is zero in a non-disturbed control area and in the disturbed control area the ACE is equal to the sum of the power balance (import positive, export negative). Basically the following equation has to be fulfilled for every control area after the transient oscillation of the primary control:

Zero = deviation of primary control power – deviation of exchange power -
             disturbance power

In the case of a consumer reconnection the disturbance power is positive; in case of a disconnection it is negative. If now the equation above is transposed it reads as follows:

disturbance power = -ACE = deviation of primary control power –
                   deviation of exchange power

or

$$-ACE = -K_T \cdot \Delta f - \Delta P_{T_A} \ oder \ ACE = K_T \cdot \Delta f + \Delta P_{T_A} \qquad (8)$$

The Area Control Error ACE of the secondary control reads as follows:

$$ACE = K_T \cdot \Delta f + \Delta P_{T_A}$$

Here values with index T belong to the part-networks and index A for the exchange power. By the estimation of the deviation of the primary control power and by measuring the deviation of the exchange power the each time appearing disturbance power can be determined. The coefficient K_T given in MW/Hz necessary for this estimation is determined by the measurement of the real network coefficient of the primary control of a part-network Λ_T, whereas this coefficient is about $\Lambda_G = 20$ GW/Hz for the whole ENTSO-E network in non per unit values today. Generally for the total network it reads as follows:

$$\lambda_G = \Lambda_G \cdot \frac{f_N}{P_G} \ and \ \sigma_G = \frac{1}{\lambda_G} \qquad (9)$$

The inverse value of the network coefficient λ_G is called the network statics σ_G. The per unit value of network coefficient λ_G is calculated by the per unit values of the network coefficients of the part-networks according to:

$$\lambda_G = \sum_i \lambda_{T_i} \cdot \frac{P_{T_i}}{P_G} \ oder \ \frac{1}{\sigma_G} = \sum_i \frac{1}{\sigma_{T_i}} \cdot \frac{P_{T_i}}{P_G} \qquad (10)$$

For the steady-state frequency deviation of the primary control of the total network in Fig. 1 in the case of steady-state considerations the deviation is calculated by:

$$\Delta f = -\sigma_G \cdot \Delta p_{G_V} \qquad (11)$$

σ_G describes the statics of the total network including the self-controlling effect of all consumers. Under consideration of this relation the control oriented block diagram shown

in Fig. 6 of a secondary controlled part-network within a total network can be given. In this figure the ACE is the controlled variable, the steady-state primary and secondary controlled part- and total network is the controlled system and the secondary control power of the power plants are the manipulated variables. The controller itself is the integral acting secondary control, which splits into the different control reserve ranges of each contributing power plant of the secondary control according to the coefficients c_i. The operating point "scheduled power" of the power plants is created by the exchange power schedule of the part-network and the hourly load forecasts as well as by the forecasts for the renewable energy generation. The forecasts of the renewable energy generation are commonly differentiated into the day-ahead and intra-day forecasts to minimize the final forecast error as far as possible. The schedules of all power plants are generated according to the demand and supply characteristic which is traded via the European Energy Exchange (EEX) in Germany. This process is described by the tertiary control. The forecasts and forecast errors of the load and the renewable energy generation compose the so called "residual load". The sum of all forecast errors results in the disturbance variable of the controlled system. Therefore it is the job of the secondary control to automatically compensate the disturbance variable. If in the future this disturbance variable will increase due to the increased fraction of renewable energy sources within the system the actively controlling conventional power plants have to be designed for high control reserves and therefore higher ramping rates. This will cause higher stress and thermodynamical wear and it will increase the maintenance costs. Hence the undisturbed part-networks do not contribute to this control because indeed their exchange power P_{TA} and the network frequency will change but with a well conditioned $k_T \approx 1/\sigma_T$ both paths "primary controlled part-network $1/\sigma_T$" and the network coefficient network controller k_T compensate each other and therefore the ACE_T remains zero.

In Fig. 7 the principle of operation of the secondary control with steady-state primary control is shown for a total network that consists of two identical part-networks 1 and 2. In part-network 1 occurs in the left case a step-shaped and in the right case a sine-shaped disturbance of 0.01 pu. In the case of the step-shaped disturbance the frequency deviation amounts to:

$$\Delta f = -\Delta p_{T1_V} \cdot \frac{P_{T1}}{P_G} \cdot \sigma_G = -0.01 \cdot 0.5 \cdot 0.14 = -7 \cdot 10^{-4} pu \ oder \ -35 mHz \tag{12}$$

The ACE_{T1} (blue line) is changed according to the disturbance in the first moment and returns back to zero after the secondary control p_{TS} has reacted and compensated the disturbance. Whereas the signal ACE_{T2} (red line) remains zero during this process. In the first moment part-network 2 supports the compensation of the disturbance by the use of the frequency deviation and the primary control by delivering an exchange power of 5×10^{-3} pu to the part-network 1 (red line). Therefore part-network 1 receives this power of -5×10^{-3} pu shown by the blue line.

The sine-shaped excitation is used to illustrate the influence of the forecast error of the renewable energy production and the consumers onto the secondary control: A permanent frequency deviation occurs and the part-network 1 is continuously delivering secondary control reserves by its power plants (blue line) which will lead to increased wear in these plants. Besides the undisturbed part-network 2 continuously delivers an oscillating amount of power by the use of the primary control (red line). So the power plants of these

undisturbed control areas are stressed and wear at a higher extent, too. This effect is even higher as much more the acceleration time constant is reduced.
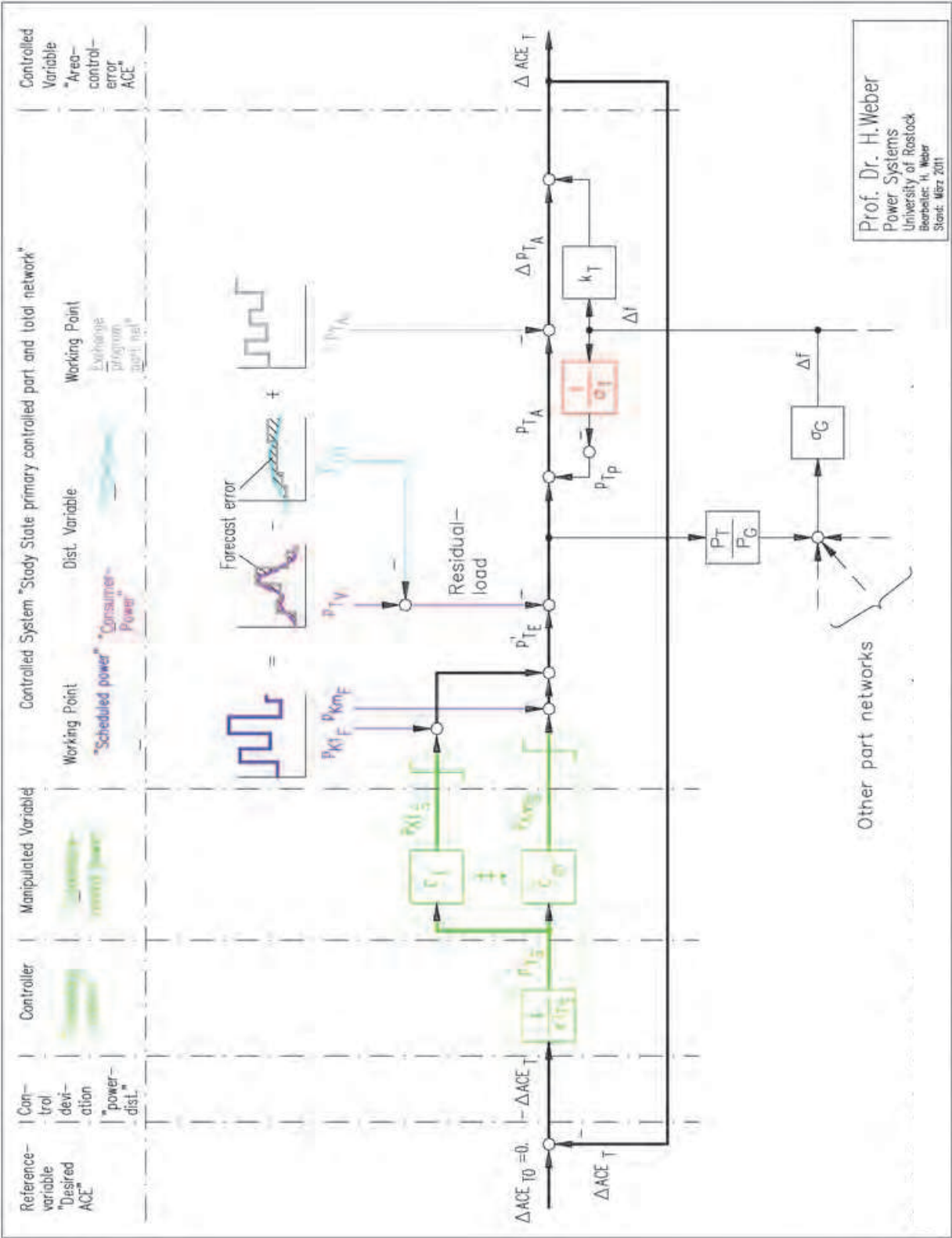

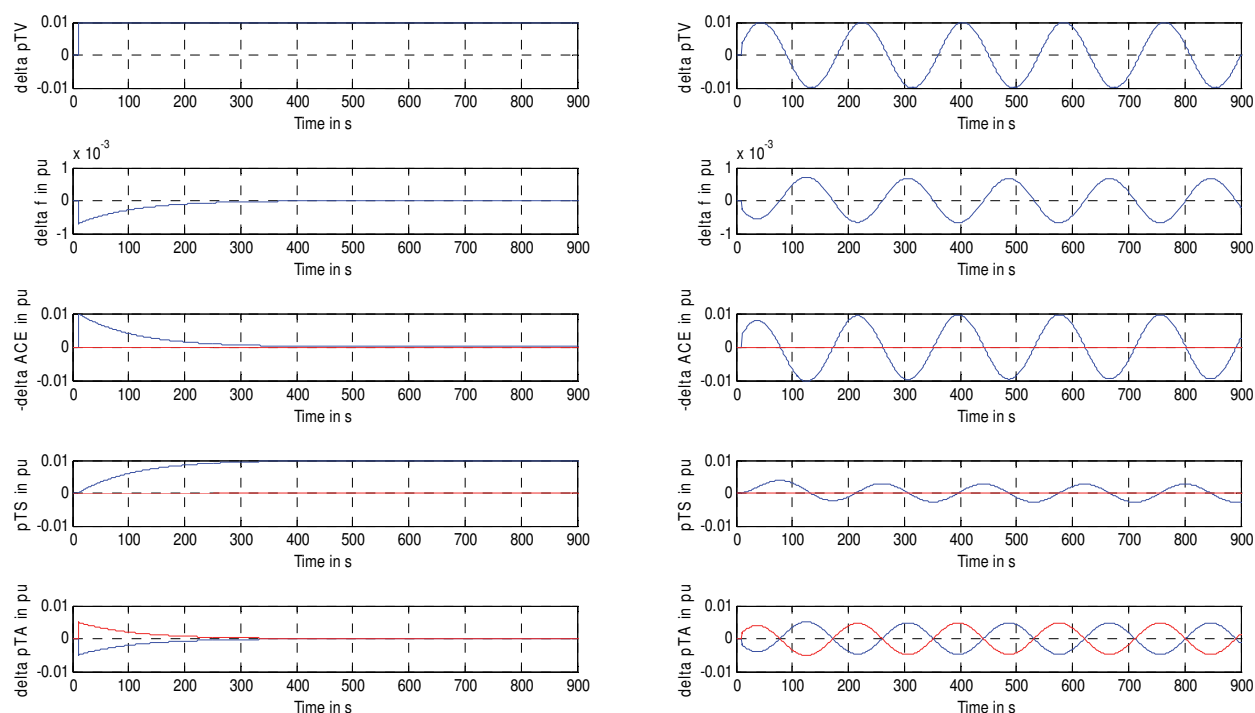Fig. 6. Control oriented scheme of the secondary control

Fig. 7. Principle of operation of the secondary control if a step-shaped (left) and a sine-shaped (right) disturbance occurs

3.3 The tertiary control

The primary task of the tertiary control is the allocation of power into the power plant schedules of a part-network according to the forecasts for the load, for the renewable energy generation and the exchange schedules with other part-networks. In this context it is not a kind of automatic control like the secondary control because these schedules are generated on the basis of stock exchange contracts at the EEX. The control oriented structure of the tertiary control is shown in Fig. 8.

The main task of the players that trade the electrical energy at the EEX is to minimize the costs of generation and to maximize the profit. Therefore it is attempted to minimize the losses and at the same time ensure the safety of supply. This means amongst other issues that the secondary control signal returns back to zero at the end of each quarter-hour. Furthermore the forecasts for the load and the renewable energy generation have to be refreshed continuously and the exchange schedule with other part-networks must be ensured. Therefore the inadvertent exchange power of every week has to be included into the next-week delivery in such a way that all MWh are compensated. Here the controlled system is the "primary and secondary controlled part-network" which is disturbed by the load curves and the real renewable energy generation. The manipulated variables are the schedules of each conventional power plant which can be adjusted with a quarter-hour resolution. In addition to these adjustments of the scheduled power output even warm and cold start-up cycles of conventional power plants can occur to follow the intermittent renewable power feed-in in a complementary way.

This kind of dynamical operation will increase in the future if more and more uncontrolled renewable power feed-in is added to the system. Therefore the effect of this higher dynamic and more pretentious flexibility requirements are discussed in the next sections.
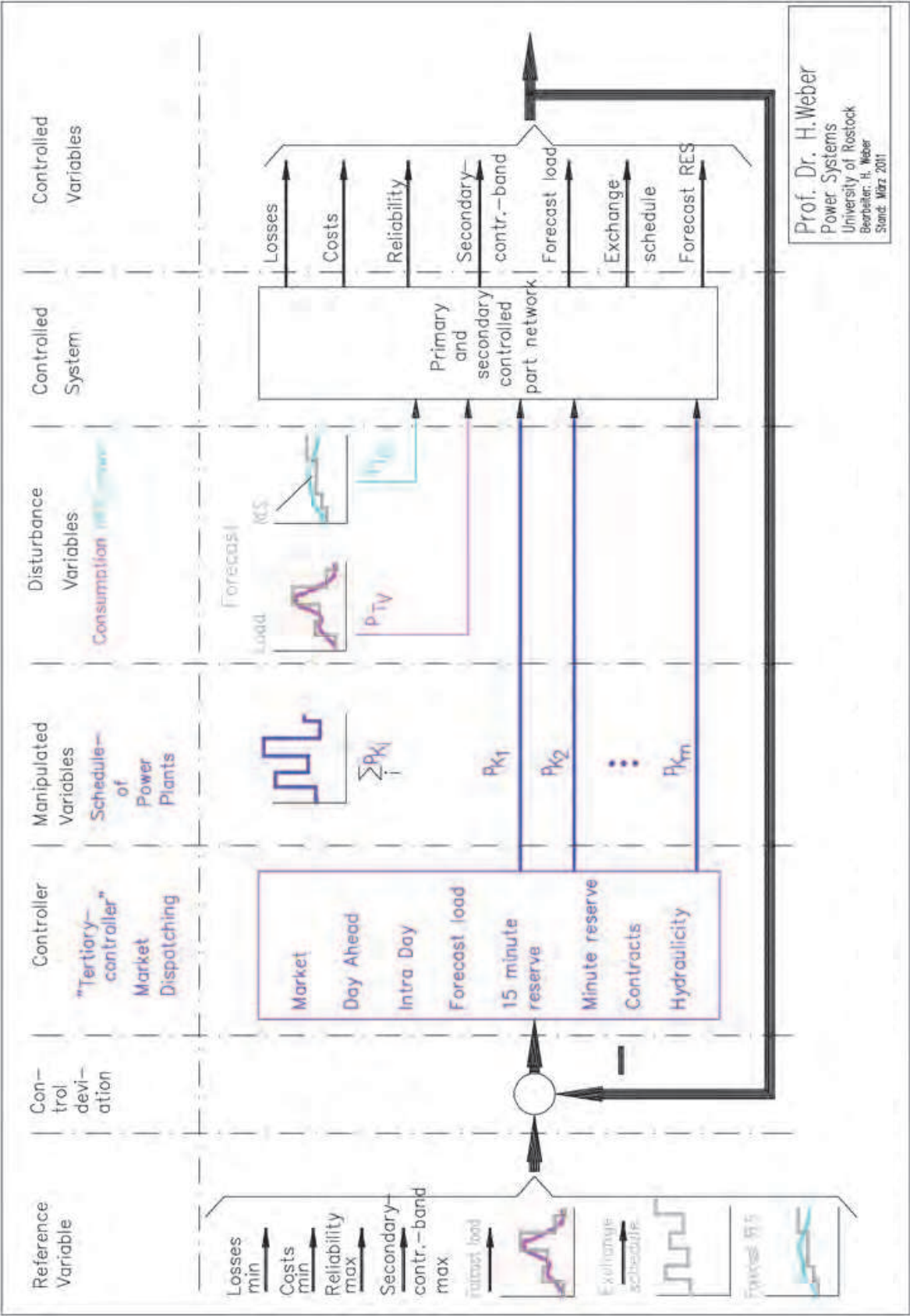
Fig. 8. Control oriented scheme of the tertiary control

4. Power plant scheduling and technical limitations of conventional power plants

To analyze the intermitting power sources and to simulate the influence onto the conventional Thermal Power Plants (TPP) several simulation models are necessary. The network control was described in detail in the previous sections. In this section particularly the power plant scheduling model will be described with some more details. To have a more precisely formulation of the associated equations please take look at the references mentioned in the text.

The so called unit commitment models can be used to simulate the power plant scheduling, e.g. the tertiary control, to take care of general technical parameters of thermal power plants like minimum up- and downtimes, minimum power output and ramping rates, reserve capacities and time dependant start-up costs. Today often these models have a Mixed-Integer Linear Programmed (MILP) optimization structure that uses commercial solver engines like IBM CPLEX to calculate the schedules of the fossil and nuclear power plants using variable time resolutions usually set to a one or a quarter-hour. In these models the spinning reserves for primary and secondary control and the non-spinning reserves for the tertiary control have to be considered. Fig. 10 gives an overview of the different types of power reserves.

To give an example for such a scheduling process for an existing thermal generation system the power plant parameters for the following scenarios were set to realistic values that hold for most of the German power plants. These values were determined with the help of the five biggest power plant operators in Germany and Dong Energy from Denmark as well as the combined cycle power plant (CCPP) operator "Kraftwerke Mainz-Wiesbaden (KWM)" in Mainz (Germany) within the research project "Power plant operation during wind power generation" – the "VGB Powertech" research project No. 333. The "VGB Powertech" is the holding organization for more than 460 companies from the power plant industry in 33 countries especially in Europe.
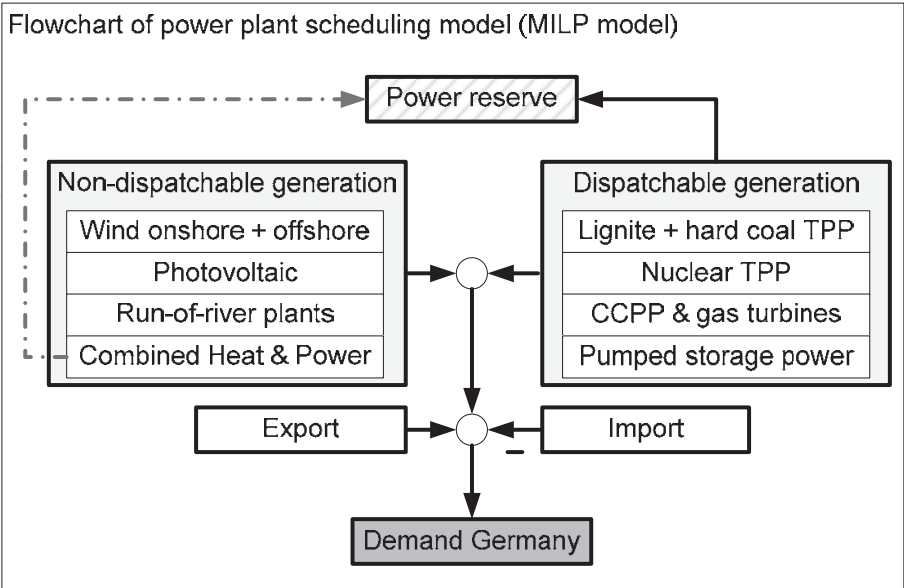

Fig. 9. Overview of the different types of generation sources for the scheduling simulations shown in this section

For the following scenarios the simulations include estimation models for the wind and photovoltaic time series as well as time series to take care of the Combined Heat and Power (CHP) stations whose electrical output power normally depends on the outside temperature and therefore the heat demand and which will have heavy influence onto the remaining must-run power and inertia as well as the resulting residual load that has to be covered by dispatchable power stations.

Therefore Fig. 9 gives a general overview of the different types of power plants and energy sources within the simulations. In this diagram two main boundary conditions must be observed at any time. The first is the active power balance stated in equation (13) between dispatchable generation and the residual load, the second one is the observation of the availability for the different types of reserve power as stated in equation (14).

Constants		**Variables**	
$R^{rt}(t)$	Total reserve of type rt in period t	$c_u^{fu}(t)$	Production cost of unit u in period t
$RL(t)$	Residual load demand in period t	$c_u^{su}(t)$	Start-up cost of unit u in period t
Sets		$c_u^{sd}(t)$	Shut-down cost of unit u in period t
U	Set of indexes of the generating units	$p_u(t)$	Power output of unit u in period t
T	Set of indexes of the time periods		
RT	Set of indexes of the different reserve types		

$$\sum_{u \in U} p_u(t) = RL(t), \quad \forall t \in T \tag{13}$$

$$\sum_{u \in U} p_u^{rt}(t) = R^{rt}(t), \quad \forall t \in T, \forall rt \in RT \tag{14}$$

Due to the huge number of flexible units in such models, here more than 150 units, and a time horizon of one or more days with a an hourly resolution (here 36 hours), the number of overall binary variables can be reduced by using an efficient formulation of the different boundary conditions as stated in Carrión *et al.* (2006) under consideration of equations from Arroyo *et al.*, (2000). A detailed description of all equations used for the simulations shown here can be found in these two references to describe all aforementioned technical constraints of the conventional power plants. The equations were slightly adjusted to the assumption described in this section but the basic structure was not changed at all.

For similar approaches where MILP structures are used to solve the unit commitment problem even under consideration of security constraints and simplified transmission line capacities see Streiffert *et al.* (2005), Delarue *et al.* (2007) and Frangioni *et al.* (2009).

4.1 Consideration of the different types of reserve power

As mentioned before the reserve power is considered as well within the scheduling process. Therefore there are different classes and types of reserves for different purposes with different response times.

The reserves can be divided into two classes – the spinning and the non-spinning reserves as shown in Fig. 10. Spinning reserves are available in the aforementioned inertia of the rotors of the directly synchronized generators. The reserve provided by the accelerating power of the directly synchronized inertia responds immediately to any active power disturbances.

The second class of reserves – the non-spinning reserve – is provided by generators that can be online or offline but ready to start up within 15 minutes. Usually this tertiary or so called minute reserve is provided by gas turbines or Combined Cycle Power Plants (CCPP).

These different types of reserves are necessary to guaranty the stable operation of the generation system and to respond to outages of generation units or changes in the power demand.
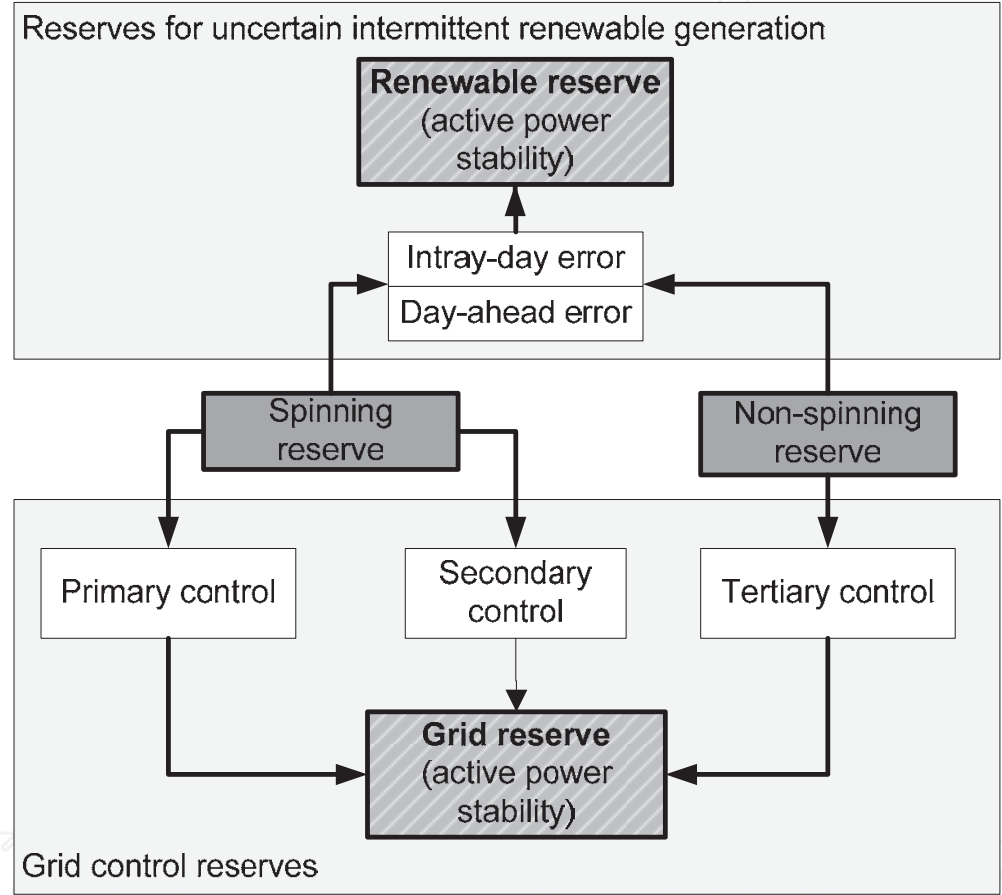
Fig. 10. Classes and types of different power reserves

Unfortunately due to the intermittent character of solar and wind power these energy sources are uncertain and so they are forecasted depending on meteorological measurements and forecasting models. These models always have forecast errors but they were enhanced intensively within the last years. These forecast errors can be divided into two types, the day-ahead or long-term errors and the intra-day or short-term errors. Normally the intra-day errors are noticeable smaller than the day-ahead errors because the forecast horizon is much smaller. The average forecast errors are usually characterized by the root-mean-squared-error (RMSE), which was between 3.7 and 5.8 % in 2010 for day-ahead and about 2.7 % for average intra-day forecasts in Germany according to information of the German Transmission System Operators (TSOs).

4.2 Objective function for the tertiary control optimization process

As shown in Fig. 9 the power plants are divided into dispatchable and non-dispatchable generation. Normally only the power plants that belong to the dispatchable generation are able to fulfil the network control requirements. This means their operation point as well as the amount of primary and secondary control reserves are optimized by an optimization process so that the total operational costs are minimized as stated in equation (15). These operational variable costs split into fuel costs on the one hand and start-up and shut-down costs on the other hand.

$$Minimize \sum_{t \in T} \sum_{u \in U} c_u^{fu}(t) + c_u^{su}(t) + c_u^{sd}(t) \tag{15}$$
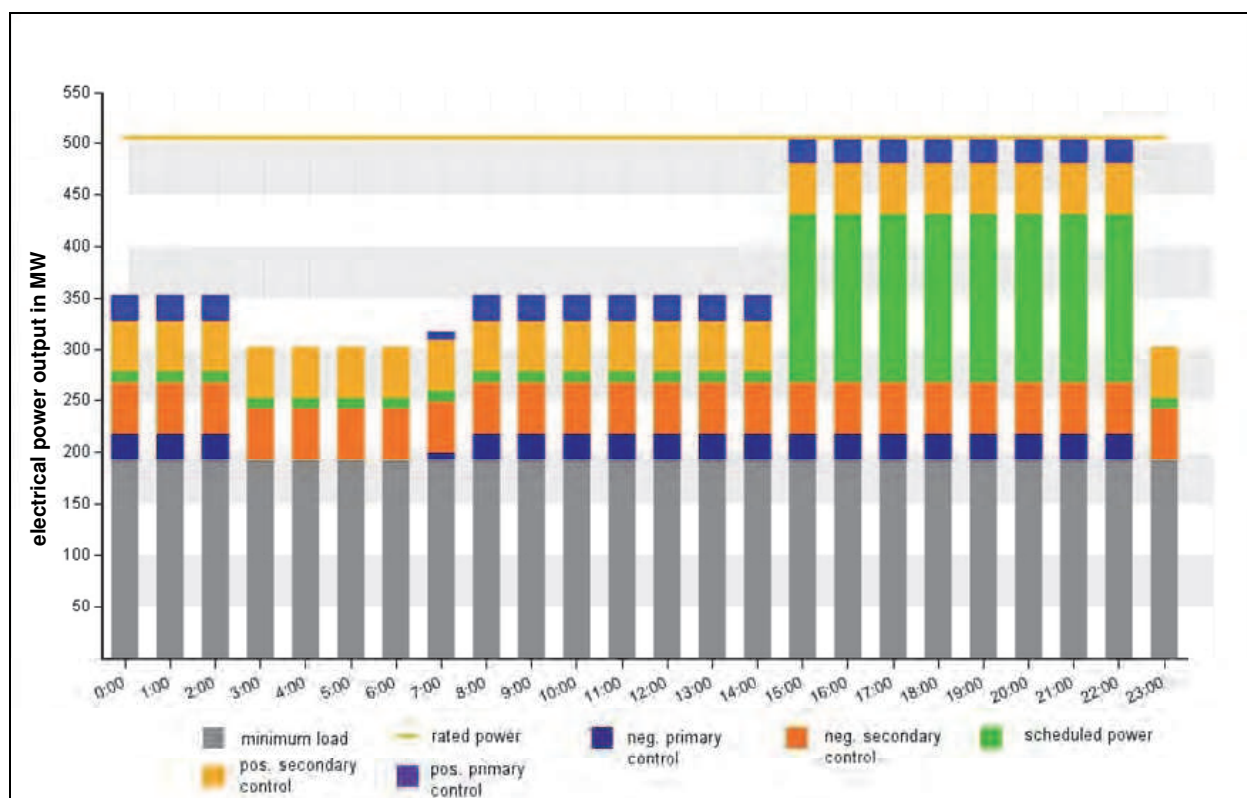
Fig. 11. Simulated schedule with reserved control areas for primary and secondary control for a single power plant

This kind of optimization problem is commonly known as the unit commitment problem. For simplification the fuel costs often are modelled by a step-wise linear production cost curve for partial loads of conventional power plants. For the scenarios shown here the partial production cost curve is divided into maximal three segments. The detailed equations used and adjusted for modelling such step-wise functions as well as equations for start-up and shut-down costs and ramping rates are stated in Carrión *et al.* (2006), but in addition to the reserve stated there, the scenarios here consider a detailed allocation of the different types of spinning and non-spinning power reserves, too. This means that the amount of reserve power for primary and secondary control as well as a dynamical reserve for forecast errors is determined for each station that is online. By considering these

spinning reserves in each station, the resulting must-run power that can't be undercut is determined by the optimization process.

Fig. 11 shows the result of such an optimization for a certain single power plant. Here the area with the reserved power for the primary and secondary control is illustrated for each hour. In this diagram the scheduled power output of the plant for each hour is the power value which belongs to the top of the green area. Therefore only the range of the green area can be used to correct the schedule in the negative direction without a change of the online state of the plant. In the positive direction the maximum possible correction is limited by the rated power output of the plant.

4.3 Exemplary scenarios for 2020 of the power plant scheduling process

To simulate a future power plant scheduling scenario it is necessary to generate some reasonable input time series for the different types of non-dispatchable generation. Therefore Fig. 12 shows an exemplary behavior of this non-dispatchable generation. Such time series are used in the following scenarios for different seasons of the year.
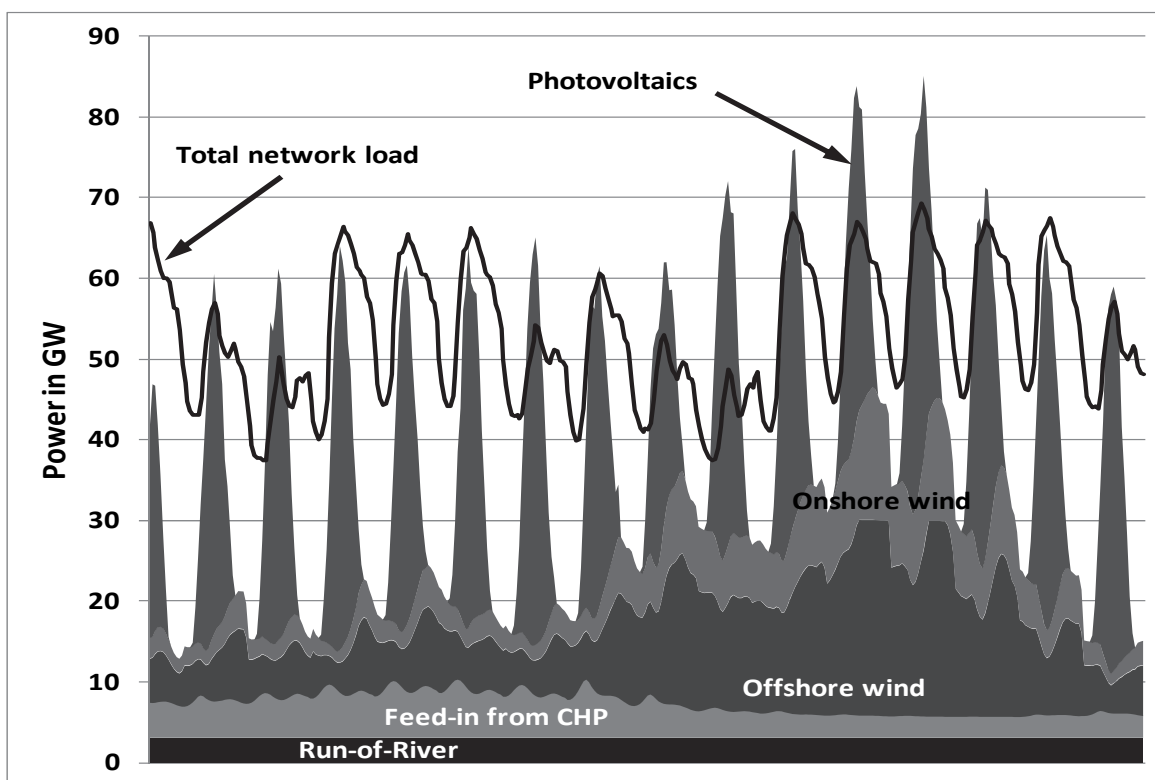
Fig. 12. Non-dispatchable power feed-in for a two weeks summer period in 2025

Fig. 13 and Fig. 14 show the accumulated results of the power plant scheduling for two different scenarios. The first scenario is a typical winter scenario showing the situation in Germany today. In Fig. 13 the typical types of operation modes for base, medium and peak load are clearly visible. Herein the nuclear and lignite power plants are almost operated as base load. The hard coal power plants provide the medium load and the gas and pumped storage capacities (PSPS) support the peak load. In this scenario no offshore wind capacities were defined. Due to the high district heating demand in a winter period the CHP-fraction in this scenario is relatively high.
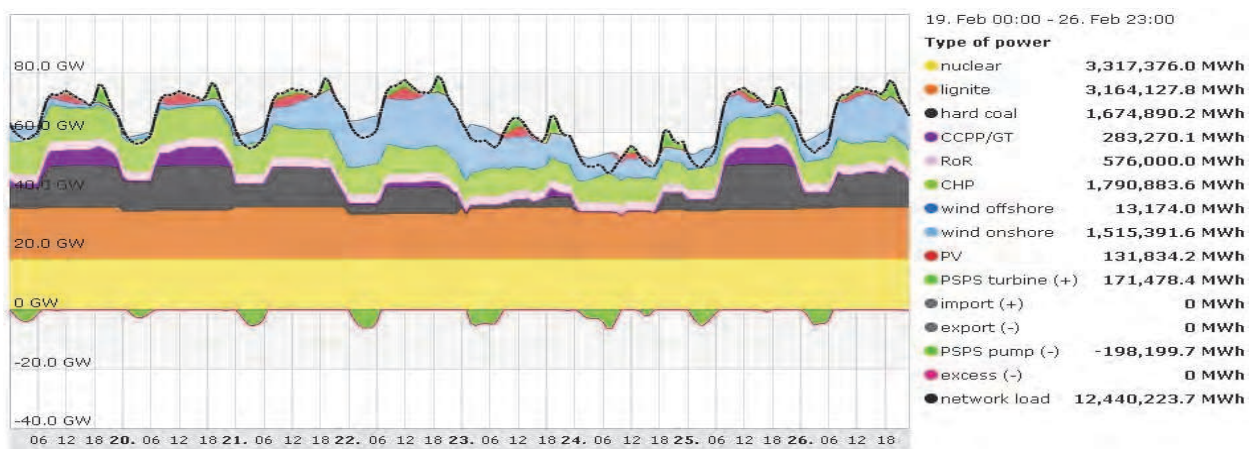
Fig. 13. 7 days period – winter scenario 2010 without import/export capability
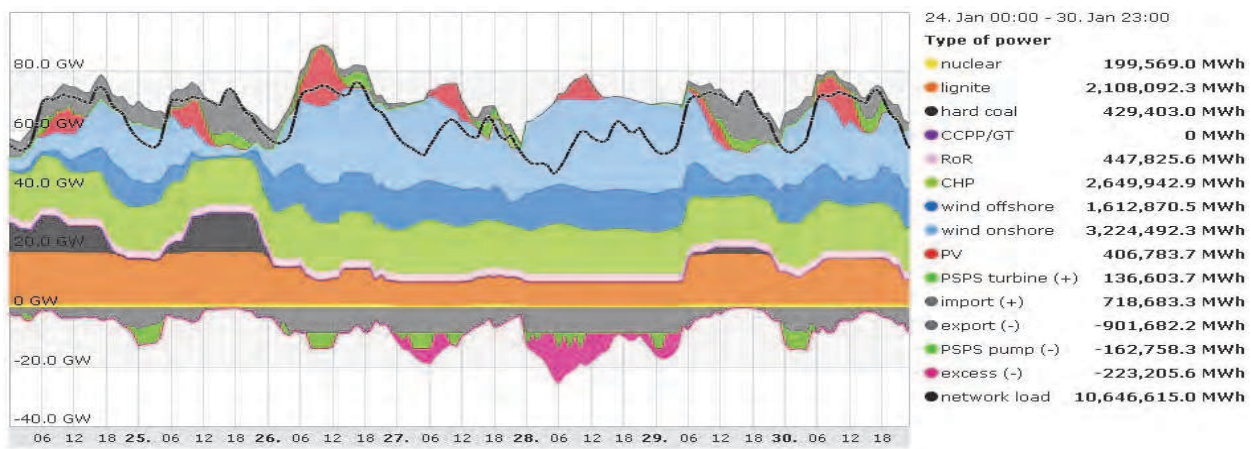

Fig. 14. 7 days period – winter scenario 2020 with import/export capability

In the second scenario, shown in Fig. 14, a 7 day period illustrates a typical high wind at load low load scenario for a winter weekend as expected for 2020. In this scenario the lignite power plants are operated on a very low partial load during the weekend. They ramp up to their nominal output at the end of Sunday (the 5th day) because the wind power feed-in decreases massively at the end of this weekend. At this time several power plants have to start-up as well.

The fraction of nuclear power was reduced due to the high probability of a nuclear phase-out in Germany. The CHP-fraction in this scenario is relatively high because of the high demand for district heating in the winter period.

Due to the limited storage capabilities of the pumped storage power plants and the limited power transmission line capacities to the German neighbour countries it could be possible that a certain amount of renewable energy could not be integrated into the system with today's storage capacities. This amount of energy respectively the excess power is identified

by the model as power surplus shown in Fig. 14. In reality today there are about 10 GW of transmission line capacities, but how much of these capacities will be available in such a high renewable feed-in scenario depends on the renewable power feed-in in the other countries. This problem has still to be investigated in furthermore studies.

By the use of such power plant schedules in addition to certain disturbance signals to simulate the non-predictable deviations of the forecasts for the consumer and the renewable energy generation it is possible to determine the life time consumption of different highly stressed components of single power plants. Therefore a detailed model of each power plant is necessary to simulate the exact thermodynamical behaviour. The methods for such investigations are discussed in the next sections.

5. Life time consumption and life time improvements of conventional fossil power plants

In a future power grid with high renewable power feed-in, especially from wind power, it becomes more important as well as economically beneficial for conventional power plants to be able to adjust the production in order to balance the renewable energies. But due to the long life time, the majority of current power plants have been designed decades ago mainly for steady state operation. Consequently, the focus was put more on reliability and preservative operation than on high dynamics.

The recent and ongoing changes in the energy market in Germany will lead to an increased number of start-ups and load changes, which cause additional life time consumption. Improvements of the existing technologies are required to enable higher dynamics at limited additional stress during transient operation.

This is especially true for coal fired power plants because of the fuel pulverization in coal mills. These mills have a slow and often unknown dynamic and limit the ramping rates of coal fired units. Additionally, the boiler itself shows a slow transient response due to its big metal and water masses as well as uncertainties like degradation of the heat transfer due to ash build up on the heating surfaces. To overcome this, the ramping rates are made sufficiently slow.

Improvements to this conservative approach could be achieved by the use of advanced control systems, e.g. state observers and model based control systems or additional sensors, like for example coal dust measurement (Dahl-Soerensen, M.J./Solberg, B., 2009).

For the evaluation of such optimizations of the process and the control system, computer aided simulation of the power plant process could be a powerful tool.

5.1 Methods for simulation

In order to judge the expected impacts of a more dynamic power plant operation a detailed, transient model consisting of one-dimensional or lumped interlinked sub models, based on thermodynamic fundamental equations, has been created. A 550 MW hard coal power plant, that started its operation in 1994, has been used as a reference. This power plant represents the state of the art and is due to its long rest life time heavily effected by future changes of the energy market.

The focus of the investigation has been put on the water-/steam circuit, the combustion chamber of the steam generator and the fresh air passage with the coal mills, as well as their

dynamics and the influence of different operation modes on distinct devices e.g. thick-walled headers and turbine shafts.

A simplified schematic of the model is shown in Fig. 15. Indicated are the feed water pumps, high pressure preheaters (HPP), the steam generator, the different turbine stages, as well as the forced draft and mill fan, the air preheater and the coal mills. The low pressure preheaters (LPP) are not part of the power plant model, since they are not highly stressed, due to their low temperature level.
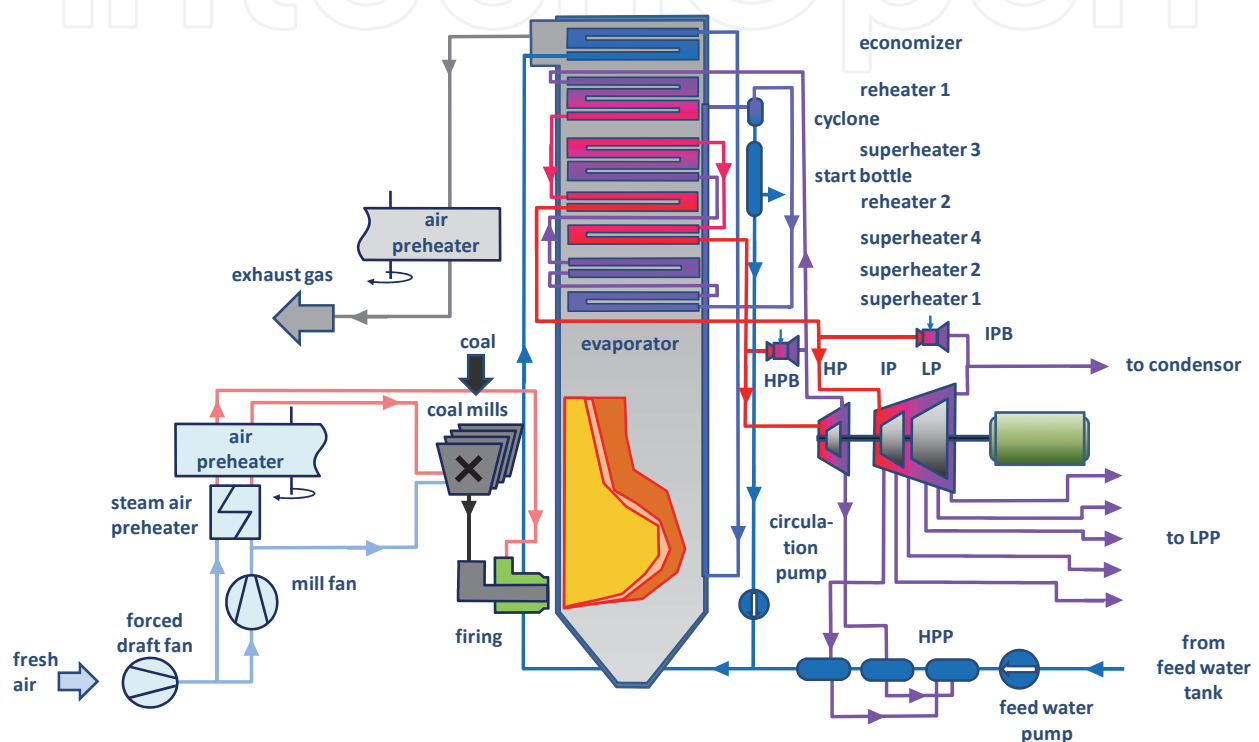
Fig. 15. Structure of the power plant model

For making simulation-based statements about the influence of different power plant operation modes the thermodynamical model is coupled to a reduced copy of the power plant control system.

The modeling is conducted in Modelica (Casella *et al.*, 2003, Casella *et al*, 2005, Fritzson, 2004) using the simulator Dymola®. The modeling with Modelica is characterized by its modular concept.

5.2 Methods for evaluation of life time consumption

With this model it is possible to predict temperatures and temperature gradients at points which are inaccessible to measurements like wall temperatures of highly stressed components.

For the first 90 minutes of a soft start the occurring wall temperatures of the superheater 2 outlet header are displayed in Fig. 16. Obviously the metal temperature at the outside of the wall follows the inner temperature with a certain delay and its amplitudes are considerably

smaller. This effect can be explained with time specifics of the heat conduction. The noticeable phase shift of the temperatures leads to relative high temperature differences between the inner and outer phase in case of sharp edged changes in evaporator heating or cooling.

The evaluation of metal temperatures offers the possibility to benchmark different controller parameter sets with a view to preserving operation at concurrently high load dynamics.

Quantification of the effects of thermal stress on the different components of a plant is a challenging task as the processes of fatigue are complex and highly statistical. For this reason the results of a fatigue prediction in this context can only be of qualitative nature and should be understood as a trend indicator that is capable of identifying the most stressed components and predict possible side effects of innovative control strategies on this complex system. For a detailed investigation of certain components a FEM-analysis considering the installation situation (and with it possible pretensions in the component) and the exact geometry should be taken into account.
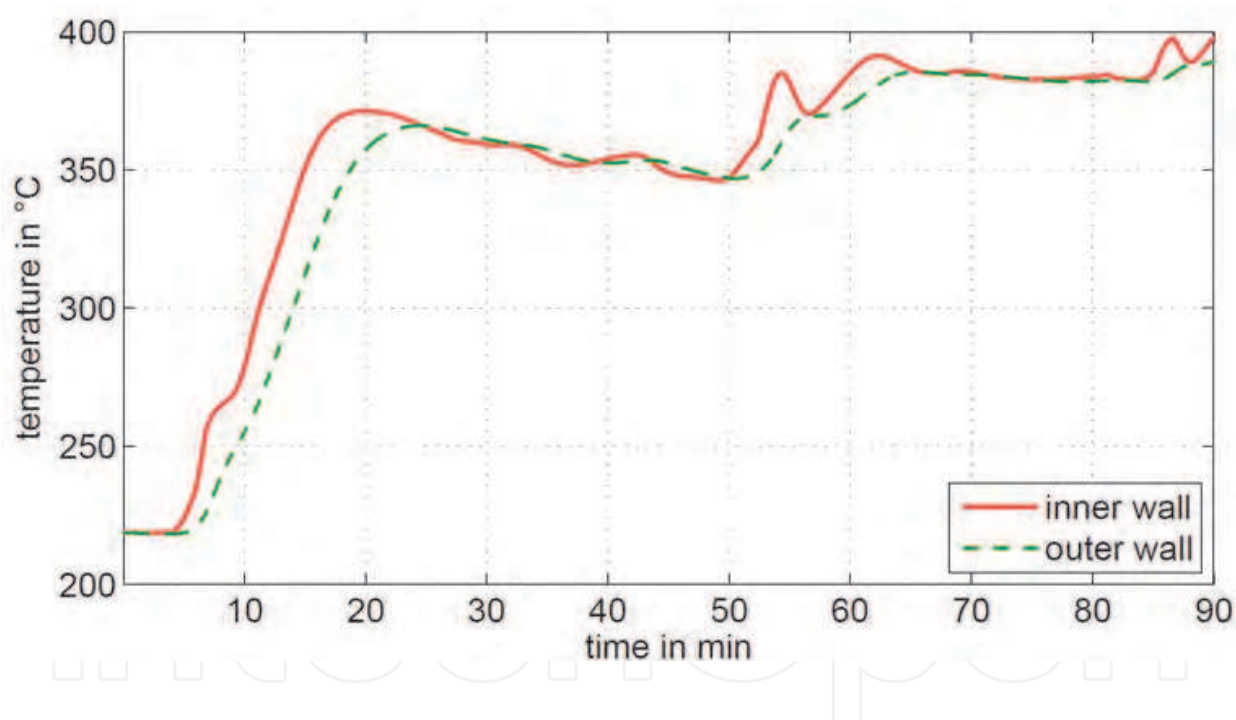

Fig. 16. Metal temperatures in the SH 2 outlet header

However, for a first estimation of the effects of future more dynamic plant operation two different approaches are used and should be discussed in the following:

The guidelines of the *Deutsche Dampfkesselausschuss (2000)* TRD 301 and 508 give directives for the estimation of fatigue of thick-walled boiler components under smoldering pressure and temperature due to start-up processes.

For this purpose an effective stress range is evaluated with a Wöhler-diagram for crack initiation. The following equation gives the law for calculating the stress range Δσ.

$$\Delta\sigma_i = \left(\alpha_m \frac{d_m}{2s_b}\right)\Delta p + \left(\alpha_\vartheta \frac{\beta_{L\vartheta}E_\vartheta}{1-v}\right)\Delta\theta \tag{16}$$

Herein $\alpha_m, \alpha_\vartheta, d_m, \beta_{L\vartheta}, E_\vartheta, v, \Delta p$ and $\Delta\theta$ denote for mechanical and thermal correction factors for stress super-elevation at branches, mean diameter, mean wall thickness, linear expansion coefficient, Young's modulus, Poisson's ratio and the range of pressure and temperature difference during load change, respectively. Fig. 17 shows qualitatively the evaluation of the working stress during load change. The maximum number of load changes comparable to the actual one is generated from the Wöhler-curve. The percentile fatigue of the actual load change is then:

$$e = \frac{1}{N}100 \tag{17}$$
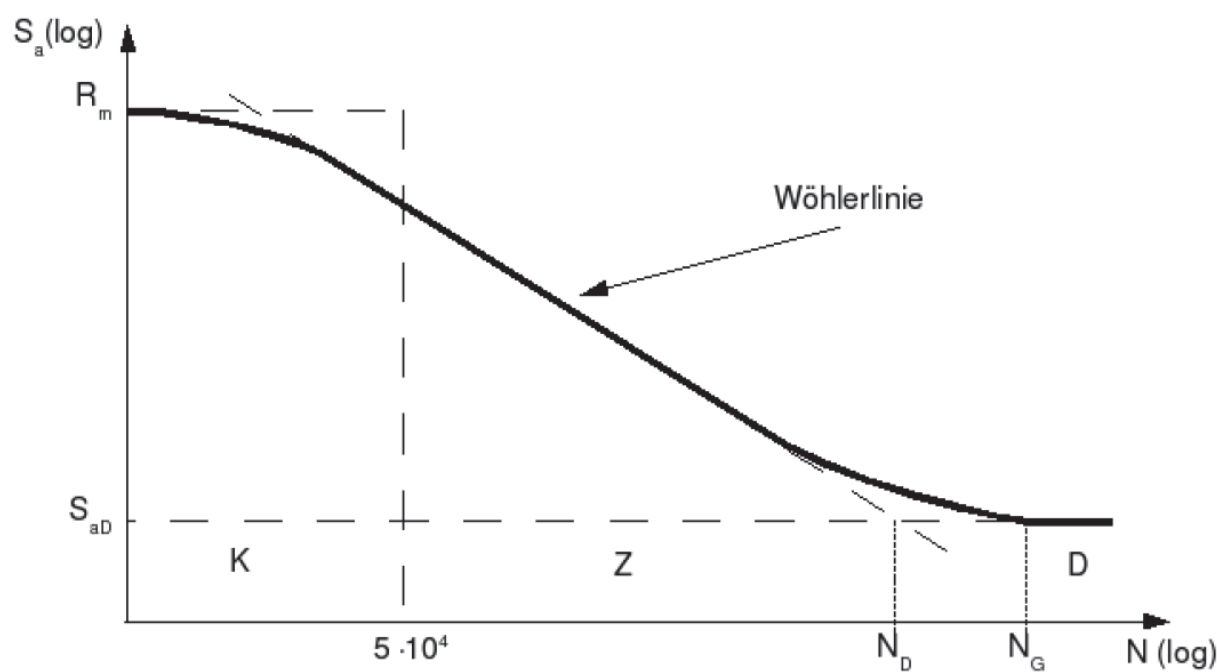
Fig. 17. Principle of evaluation of component stress for cyclic loading (Levin et. al, 1990).

This estimation leads to conservative results in order to handle the numerous uncertainties in calculation of working stresses at complex components and material properties.

This method allows to benchmark different and possible future operation modes in terms of their level of deterioration to different components. In Fig. 18 is the fatigue of a warm start and several load changes plotted for the in- and outlet headers of the super- and reheaters. It should be stated, that currently normal operation is between 50 % and 100 % load with a ramping rate of 2 % per minute, so the shown load change of higher then 60 % as well as the load gradients of 4 % per minute could be considered as an unconventional operation. These load changes corresponds to a possible future operation with a lowered minimum load of for instance 35 % and a doubled load gradient.
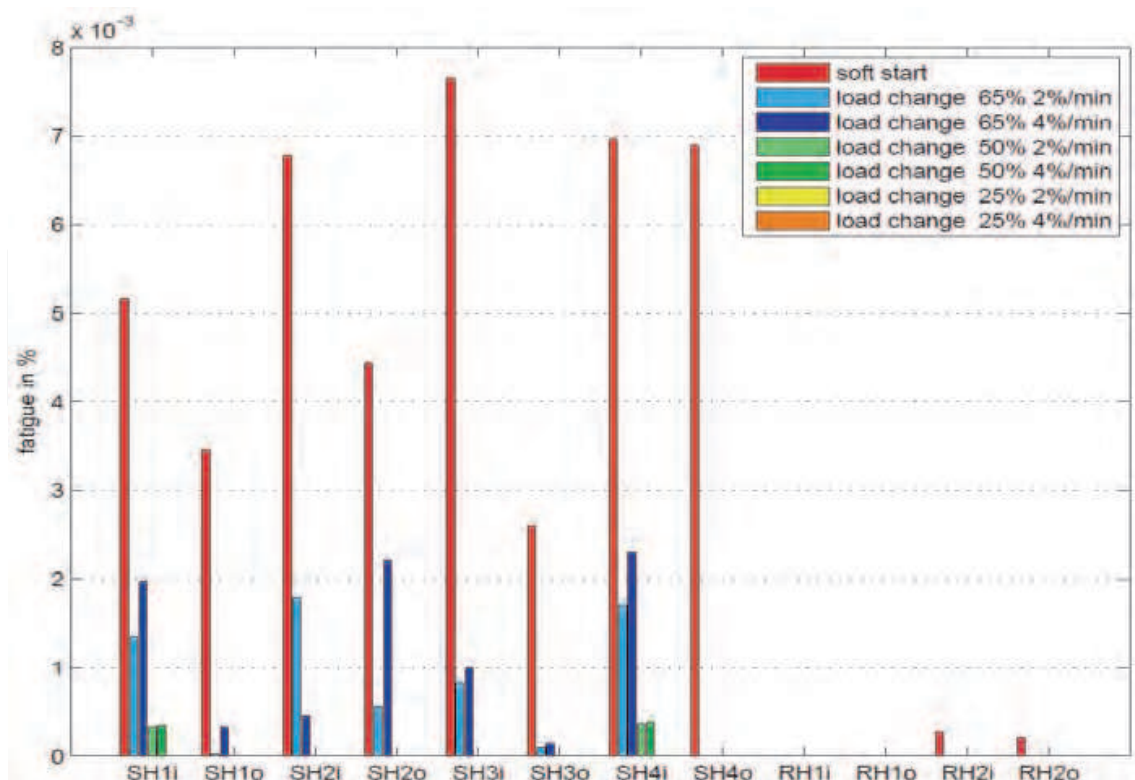
Fig. 18. Fatigue of heating surface in- and outlet headers for different base stress situations

It could be obtained, that the outlet header of super heater three and four are affected the most, whereas the headers of the reheaters are not or low stressed. Furthermore it could be derived, that conventional load changes less the 50 % barely cause any fatigue, because the stress levels are below the endurance strength.

Considering the flaw growth of pre-damaged component gives a far more sensitive view on the operation mode. The *Forschungskuratorium Maschinenbau* (FKM, 2001) gives guidelines for the calculation of crack progress. Fig. 19 gives a general overview on crack propagation rate as function of the range of stress intensity factor ΔK .

There is a certain load that does not lead to crack propagation $(\Delta K \leq \Delta K_{th})$. In region I to III there is a stable propagation to be expected $(\Delta K_{th} \leq \Delta K \leq \Delta K_c)$ which can be conservatively estimated by the law of Paris and Erdogan:

$$\frac{da}{dN} = C\Delta K^m \tag{18}$$

Where a, N, C, m denotes for crack length, number of cycles, a case-specific factor and a load specific exponent, respectively.

The stress intensity factor has to be calculated depending on the flaw's geometry and size and its position within the component. With this tool it is possible to detect the most strained components by comparing the crack growth over a certain reference time period.

In an analogue manner as in Fig. 18 the flaw propagation is shown for thick-walled headers in Fig. 20.

In contrast to the fatigue also low stress levels of small load changes cause impairment and consequently with this estimation a method is given to evaluate the deterioration potential of load changes during normal operation.
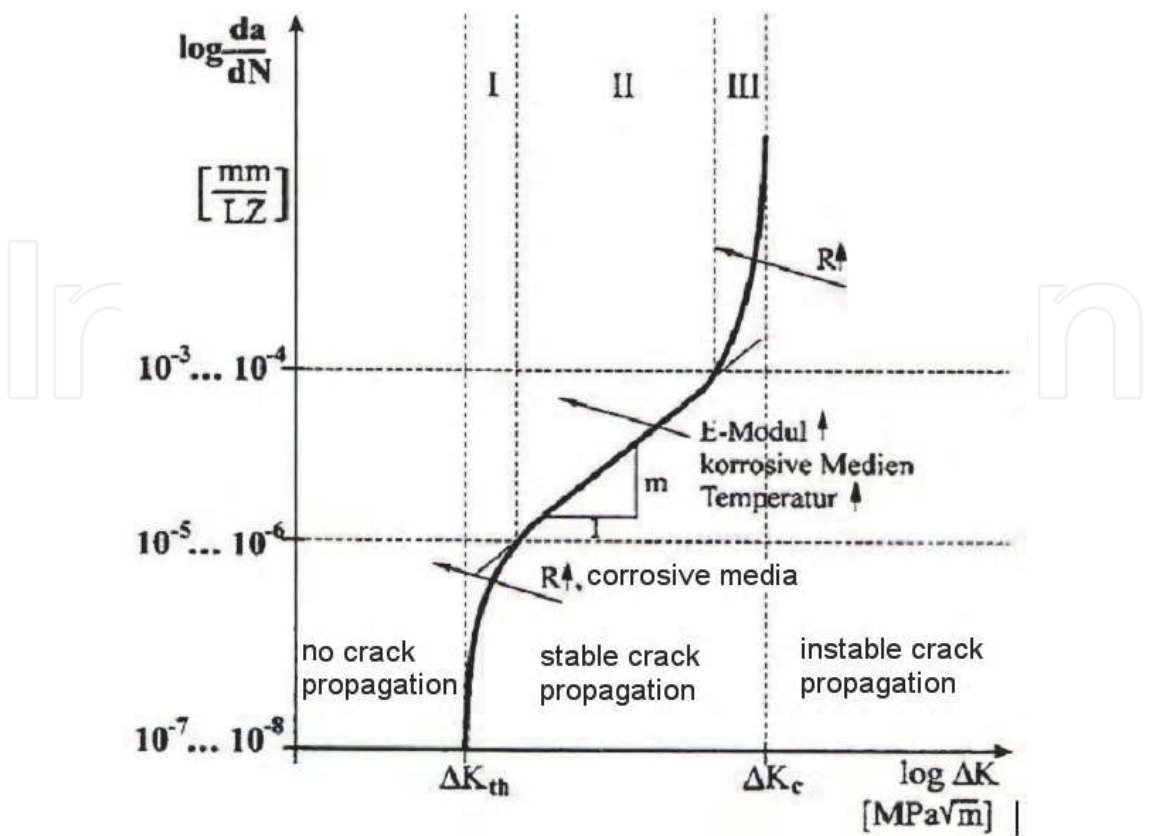
Fig. 19. Overview on crack propagation under cyclic load (FKM, 2001)
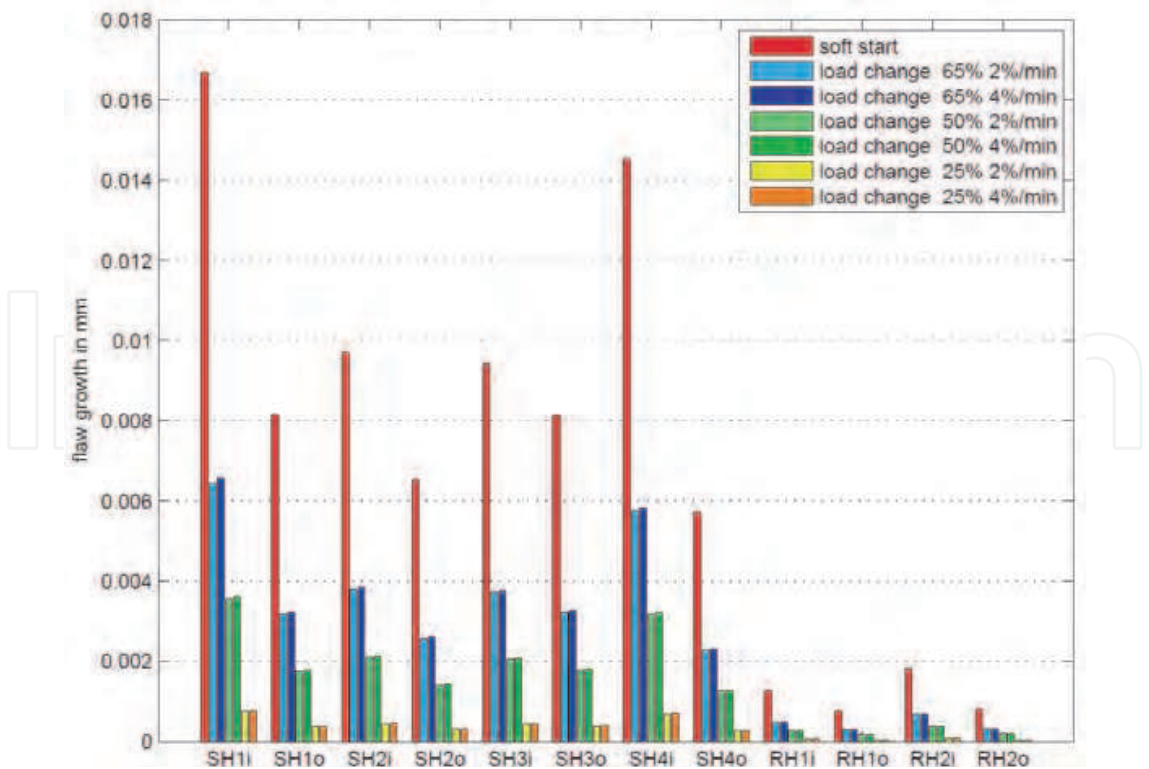

Fig. 20. Flaw growth in potentially pre-damaged thick-walled in- and outlet headers for different base stress situations

In this way, future demands on power plants which might become necessary in order to realize wind integration successfully at controllable costs can be benchmarked. Since the detailed manner of the plant model does not allow long term simulation over years or even weeks due to high computing time, the fatigue has to be extrapolated by decomposing long term load schedules to base operation scenarios and adding the individual fatigues and crack growths under the assumption of linear damage accumulation. In cooperation with the power plant scheduling model it is possible to evaluate such long term load profiles for e.g. a heavy wind month.

This aspect of power plant operation management will probably become more important due to highly increasing wind power production and its fluctuating characteristic.

Furthermore the modular structure of the model allows the easy replacement of single components, e.g. life steam temperature control, which enables for example the benchmark of advanced control systems or the implementation of different or additional hardware for different operation scenarios.

6. Conclusion

In Germany the existing electrical power production and distribution systems are going to be essentially influenced due to the continuously increasing relevance of renewable energy sources.

To analyze these intermittent power sources and to simulate the influence onto thermal power plants, several simulation models can be used. These models can be used to simulate the power plant scheduling that is necessary to consider technical restrictions of thermal power plants like operation states, minimum up- and downtimes, minimum power output, ramping rates, storage capacities etc. Today such models are often formulated as a Mixed-Integer Linear Programmed (MILP) optimization problem, commonly known as the unit commitment problem.

With the calculated schedules for each station within the model, the number of load changes and start-up cycles for the different types of power plants can be determined. These schedules can be rated in terms of mechanical wear due to thermal stress by a thermodynamical model that simulates the life time consumption of the different components used within a hard coal fired power plant with a complex model of the water steam cycle as well as the mill and boiler components. This model of the thermodynamical process is controlled by a detailed simulation of the power plant control system.

The renewable energy generation will be the future solution for the global energy consumption problem. Therefore it is very important to consider all technical restrictions of the network control and the thermal power plants that are necessary to ensure the safety of supply.

To investigate the effects of the increasing fraction of renewable energy produced by intermittent generators like wind turbines and photovoltaic systems within the existing generation system several models with different time domains are necessary as described in this chapter. These models can help to evaluate new concepts for power plants in regard to economical issues and they can help to determine the limitations of a stable system operation in regard to reduced system inertia.

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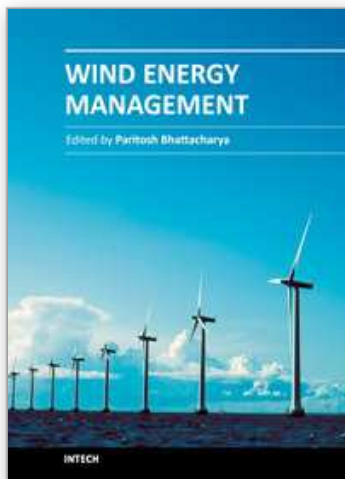
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Edited by Dr Paritosh Bhattacharya

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