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Dynamic System Studies of new Requirements and Strategies for the Primary Control in the UCPTE/CENTREL Power System

by

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1. Summary

As a result of increased load and the expansion of the UCPTE[1] power system by the CENTREL[2] network, it was possible to reduce requirements concerning the reserve needed for primary control. An estimate made for a power plant portfolio of a typical 10.000 MW power system revealed annual savings of over ECU 5 million in fuel costs of power plants.

Additional savings are possible by using modern methods in the provision of control power. While maintaining the quality of frequency control and taking into consideration the statistics for power plant outages and the technical characteristics of condensate stopping, the latter is able to provide two-thirds of the entire control reserve. The integration of condensate stopping into primary control by means of frequency-dependent activation steps will be demonstrated.

Keywords

Quality of frequency control, primary control reserve, condensate stopping, savings.

2. Introduction

Maintaining sufficient frequency quality and complying with limit values after large-scale generation outages are among the tasks to be carried out jointly by all interconnected partners. This principle of solidarity is mainly based on technical reasons: Managing a large-scale power plant outage requires reserve power to be activated within just a few seconds. This can only be achieved by mutual support on the part of all interconnected partners.

The quality of frequency control is closely linked to the reliability of electricity supply. These ancillary services have a significance that can barely be quantified, however, they certainly have a tremendous national economic significance.

Since most of the relevant expenses, consisting of keeping a second reserve for primary control available, occur in power plants, the system operator must take a holistic approach to the overall system of power plants, power system and consumers with respect to technical and economic aspects when dealing with this task successfully.

Serious system disturbances may not only result in production failures and damage on the consumer side. The power plant side is also affected. Therefore, power plants have a vested interest in complying with power system requirements.

Based on continuous monitoring of frequency quality and system studies conducted [1], recommendations that used to be applicable in the UCPTE power system for primary control reserves [2] have been revised in

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[1] **UCPTE:** Union for the Coordination of Production and Transmission of Electricity
[2] **CENTREL:** Networks of the countries Poland, Czech and Slovak Republic and Hungary

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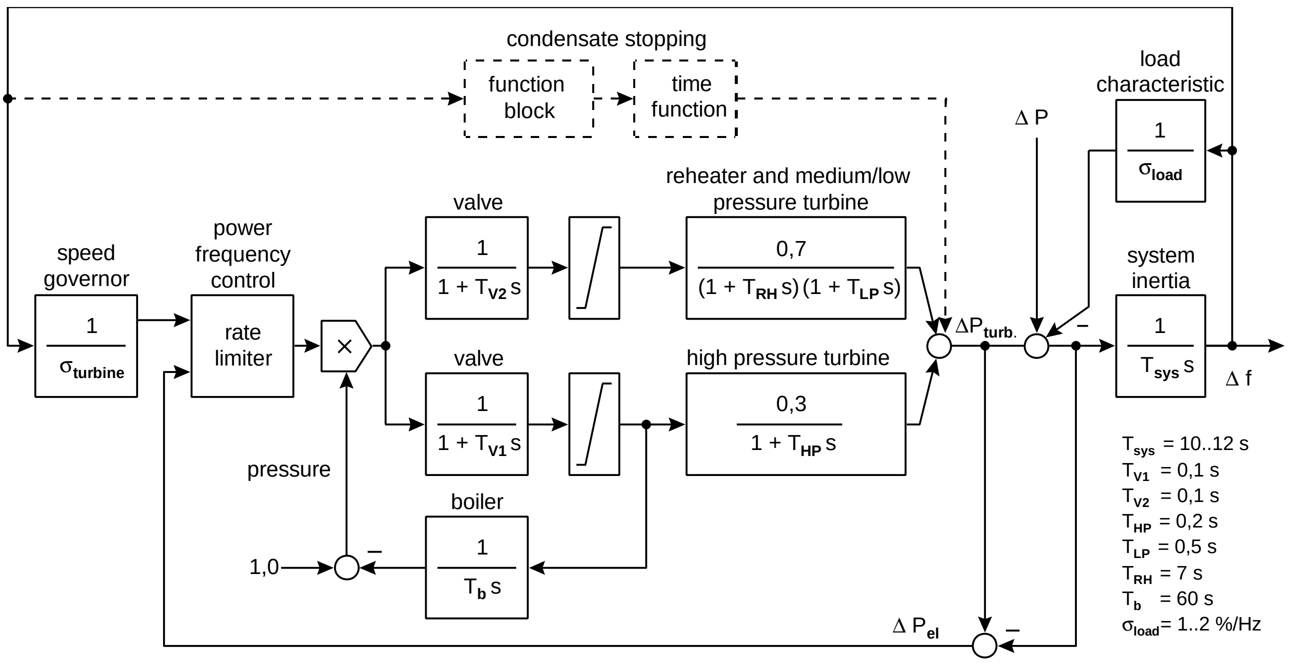


Fig. 1: Mid-term-model of power system

order to develop existing savings potentials under present conditions [3]. According to the principle of solidarity, individual system operators now have the obligation to use the technically and economically best possible way to provide the share of control power assigned to them within the interconnected system. The methods presently available for this task today must be assessed with regard to their economic effectiveness, and new methods must be integrated into a control strategy for the overall system, thereby taking their technical characteristics into account.

3. Mid-term dynamic model

The investigations for the power system were carried out using a single-node model according to Fig. 1 which enables the calculation of mid-term dynamics relevant to primary control [4, 5].

The model has a clear structure so that the influence of individual system parameters, such as power system size, dependence of load on frequency, controller types and parameters, as well as varying reserve approaches on the characteristics of system dynamics becomes transparent [6].

With respect to the processes that are of interest in the present context, the used model is able to reproduce with a high degree of congruence the results of earlier studies on power frequency control, based on much more complex models [7, 8] for the mid-term range, and the simulation results using the multi-machine model for the UCPTE power system which was set up for short-term dynamic problems including interarea oscillations [9, 10].

The reliability of the model used is additionally confirmed by the comparison with a number of existing measurements from the UCPTE power system. A measuring system called WAMS (Wide Area Measuring System) was set up Europe-wide for the monitoring of system behaviour after power plant outages. The system enables time-synchronous frequency recordings at several high-voltage nodes which are used for evaluating the quality of frequency control and power system stability. The simulation results correspond very well with the average frequency behaviour measured in the centre of the interconnected system (Germany) after a 900 MW unit outage, see Fig. 2. The present UCPTE recommendations for primary control (2.5 % of P_{sys}) [2] and P_{sys} = 200 GW, T_{sys}=12 s and σ_{load} = 2 %/Hz were taken as a basis for the simulation.

Frequency measurements at various places demonstrate that as a result of interarea oscillations which are uncritical in this case [9, 10], local frequency

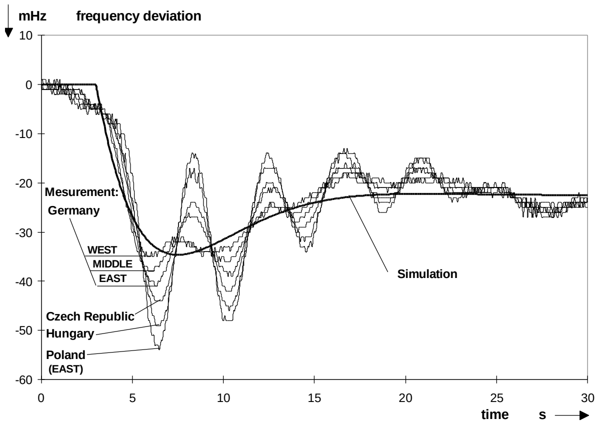


Fig. 2: Simulation and measurement of frequency after an outage of 900 MW

deviations from the average behaviour increase towards the periphery of the interconnected system. The deviations from the average frequency behaviour reflected in the model are considerably less than 50 mHz, which seems to be acceptable for a model fault, since it amounts to less than 5 % with respect to the relevant frequency range of 49 Hz to 50 Hz.

4. Statistics of power plant outages

Fig. 3 shows the generation outages recorded in the past five years in UCPTE power system [11] and classifies them according to categories of capacity. In the past five years, outages in the range from 600 MW to 1400 MW occurred approx. 440 times, whereas outages in the range between 1400 MW and 2000 MW only occurred 12 times.

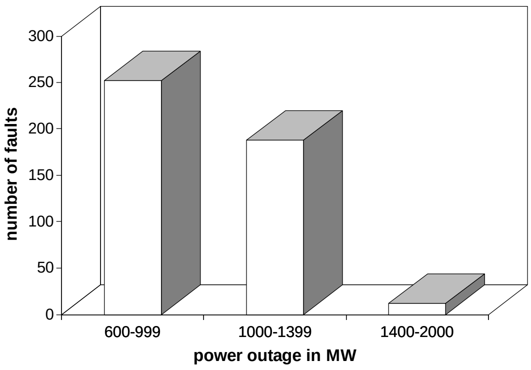


Fig. 3: Statistics of power plant outages

Based on the statistics, the following important conclusions may be drawn for the dimensioning of primary control:

- Single unit outages (up to approx. 1400 MW) must be settled by using methods for the provision of reserve capacity which may be utilized often, without practically any restrictions.
- For the dimensioning of primary control it is also necessary to consider a double unit outage or the outage of a busbar with several incoming supplies as a design case (ΔP = 3000 MW), although there is a considerably lower, but significant, probability of this case occurring.
- Deficits of more than 3000 MW occur very rarely and only in the event of serious network disturbances.

5. Dimensioning of control power

For the design case (ΔP = 3000 MW) the system parameters T_{sys} = 10s, P_{sys} = 150 GW, σ_{load} = 1%/Hz [12] were taken as a basis for the dimensioning of primary control. Often, system parameters are more advantageous in practice with respect to the behaviour of primary control so that the parameters used in the simulation are on the safe side. In summary, the studies came to the result that the control reserve with a fixed maximum of 3000 MW should be activated with a linear time characteristic within 30 seconds after the outage [3]. This characteristic is modelled by the rate limiter in Fig. 1.

The results of the simulation studies are listed in Fig. 4 and Table 1. Single, frequent unit outages (ΔP<1400 MW) are settled both dynamically and in steady state with minor frequency deviations ranging below 200 mHz.

In the design case (ΔP = 3000 MW) there is a dynamic frequency deviation of max. 800 mHz when using frequency-dependent load reduction in the short term. Thus, there exists a sufficient safety margin of 200 mHz up to the first step of a load shedding at 49 Hz. This also takes account of the deviations of the real system behaviour from the model. These deviations may occur when using the single-node model, in particular.

As far as the steady state is concerned in the event of outages up to 3000 MW, the frequency is returned to a level within a desired narrow frequency range (+/-200 mHz), thereby guaranteeing safe system operation.

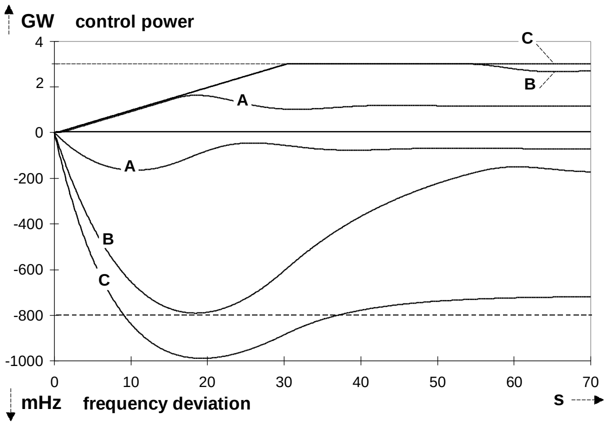


Fig. 4: Frequency behaviour and primary control power after generation outages

A: ΔP=1300 MW, P_{sys}=200 GW, σ_{load} = 1%/Hz

B: ΔP=3000 MW, P_{sys}=150 GW, σ_{load} = 1%/Hz

C: ΔP=6000 MW, P_{sys}=200 GW, σ_{load} = 2%/Hz

Even deficits going beyond the design case, may be settled to a certain extent (up to approx. 6000 MW) by taking advantage of frequency dependence of load. In this case, however, one must put up with a great steady-state frequency deviation which constitutes a danger to system and power plant operation and must be averted in the short term by dispatching the load accordingly.

Table 1: Consequences of power plant outages

$\Delta P \leq 3$ GW	$\Delta f_1 \leq 800$ mHz $\Delta f_2 \leq 200$ mHz	safe
3 GW $< \Delta P <$ 6 GW	800mHz $< \Delta f_1 <$ 1 Hz 200mHz $< \Delta f_2 <$ 1 Hz	endangered
$\Delta P \geq 6$ GW	$\Delta f_{1,2} \geq 1$ Hz	disturbed

(Δf_1 = max. frequency deviation, Δf_2 = steady-state frequency deviation)

In the event of even greater deficits or the separation of the interconnected system into subsystems, frequency-dependent load shedding is intended for the range between 48 Hz and 49 Hz for the following reasons:

- A continued dropping of frequency must be avoided because otherwise thermal units would have to be disconnected from the system in order to protect steam turbines against resonance damage at underfrequency. The consequence would be a blackout due to additional infeed loss.

- The transport of reserve power into an failure-stricken area should be limited in order to prevent an undefined opening of the interconnections due to line overloads and islanding of subsystems, since this would bear considerable risks due to possible follow-up disturbances.

Thus, this intended load shedding prevents the extension of a disturbance which would result in further noncontrollable supply interruptions.

6. Savings potentials

The following paragraphs will deal with an assessment of possible operating cost savings which are achievable if the requirements concerning primary control are reduced from 2.5 % of today's infeed [2] to 1 % of maximum infeed [3]. For this purpose, an economic efficiency calculation will be done for a fictitious energy utility by using a model.

Two shares of the costs must be stated for the provision of primary power by throttling turbine valves (at present, the most-widely used method in the UCPTE power system):

① *Generation shifting*: Due to the limitation of available power to the amount of control power provided, corresponding generation must be shifted to power plants with higher fuel costs.

② *Efficiency decrease*: As a result of valve throttling the efficiency of the thermodynamic process is reduced: per 1 % valve throttling with respect to electrical power, there is a specific increase in fuel consumption ranging from approx. 0.2 % in modern hard-coal-fired units to approx. 0.4 % in lignite-fired units [13, 14, 15]. Therefore, discontinuing the valve throttling process for 10 MW control power produces an additional capacity of 2 MW in a hard-coal-fired unit at equal fuel input.

The model utility has an installed capacity of 10.000 MW and typical power plant operating hours. The attribution of control power to the individual power plant types and the additional capacity resulting from reduced valve throttling are presented in Table 2:

Table 2: Characteristics of the model utility

power plant type	installed capacity [MW]	time of operation per year [h]	control reserve present / future 2,5% / 100 MW	throttle losses present / future	additional capacity future
1	4.000	7.500	100 MW/100 MW	20 MW/ 20 MW	0 MW
2	3.000	6.000	75 MW/0 MW	15 MW/0 MW	90 MW
3	2.000	4.000	50 MW/0 MW	10 MW/0 MW	60 MW
4	1.000	2.000	25 MW/0 MW	5 MW/0 MW	30 MW
S	10.000		250 MW/100 MW	50 MW/20 MW	180 MW

The additional capacity gained according to Table 2 generates the following annual savings:

① *Savings due to a generation shifting from power plant type n to power plant type m (type n is more expensive than type m)*

$\Delta C_{m\rightarrow n} = \Delta P_m \cdot t_n \cdot \Delta c_{n\rightarrow m}$

As an example, a cost difference of $\Delta c_{n\rightarrow m} = 10$ ECU/MWh is assumed between the power plant types. With respect to the generation structure assumed here, the shifting of generation resulted in savings amounting to

$\Delta C_{3\rightarrow 2} = \Delta P_2 \cdot t_3 \cdot \Delta c_{3\rightarrow 2} = 90\ \text{MW} \cdot 4000\ \text{h} \cdot 10\ \text{ECU/MWh} = 3{,}6$ Mio. ECU
$\Delta C_{4\rightarrow 3} = \Delta P_3 \cdot t_4 \cdot \Delta c_{4\rightarrow 3} = 60\ \text{MW} \cdot 2000\ \text{h} \cdot 10\ \text{ECU/MWh} = 1{,}2$ Mio. ECU

② *Fuel savings or resulting amount of energy.*

E_2 = 15 MW· 6.000 h = 90 GWh
E_3 = 10 MW· 6.000 h = 60 GWh
E_4 = 5 MW· 2.000 h = 10 GWh

Thus, annual savings due to generation shifting amount to some ECU 5 million, and the use of less fuel corresponds to additional savings of 160 GWh.

7. Use of condensate stopping for the provision of control reserve

Nowadays, valve throttling [13, 14, 15] is not the only method available to provide necessary control power. Other technically perfected state-of-the-art methods, such as condensate stopping or condensate flow reduction are widely used [16, 17, 18]. Economic efficiency analyses show that condensate stopping is less expensive for new power plant units than valve throttling.

Nevertheless, the varying technical characteristics of the methods available for the provision of reserves must be taken into consideration. This is the only way to achieve a coordinated integration of these methods into the control strategy for the overall system with a view to fully benefiting from the economic advantages and ensuring, at the same time, sufficient quality of control.

While the valve throttling method activates control power almost proportionally to frequency deviation, the condensate stopping method activates control power step by step according to predefined activation criteria. It takes approx. 30 seconds to activate total control power when using the latter method [17, 18], which is modelled by the time function in Fig 1.

It might be interesting to mention that load-variable condensate stopping is possible instead of step-by-step activation. This option has continuous control characteristics similar to valve throttling. However, this technically complex method does not allow continuous or very frequent use because of its adverse effect on power plant operation. Therefore, in practice, its control advantages can only be used to a certain extent.

Based on these disadvantages, the question arises concerning the share in total primary control power to be made available by condensate stopping and the share which valve throttling continues to provide in order to maintain sufficient control quality. Taking the above-mentioned technical characteristics and statistics of power plant outages into consideration, further simulation studies had the approach of not using condensate stopping in outages up to 1400 MW. These frequent demands should rather be met by turbine valve throttling alone due to the control technology advantages of this method.

Following considerations leads to the proposed share of control power, 1/3 of the total amount of control power provided by valve throttling and 2/3 provided by condensate stopping:

A network characteristic number of 18.000 MW/Hz will be required by the new UCPTE-rules [3]. With this network characteristic number an outage of ΔP = 1400 MW leads to a frequency deviation of about 80 mHz. According to a estimate (σ_{load} = 2 % / Hz, P_{sys} = 250 GW), this results in a load reducing of 400 MW so that 1000 MW control power provided by valve throttling is required. Since total control capacity for the UCPTE power system is fixed at 3000 MW, additional 2000 MW of required control power must be made available by activating condensate stopping.

Based on numerous simulation studies

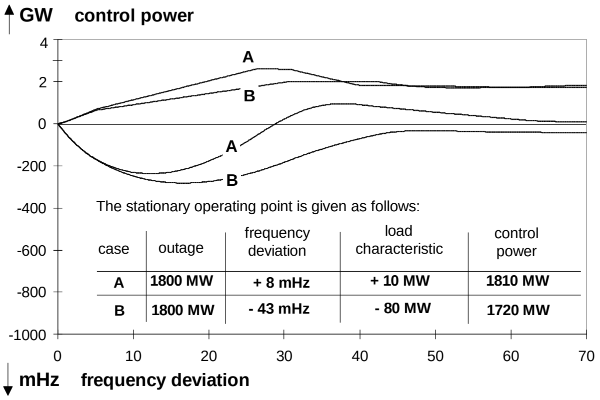
- the required number of activation steps for condensate stopping and
- the criteria for activating the individual steps

were fixed.

The simulation results reveal that a division of the control power provided by the condensate stopping method into only three steps may lead to the activation of excess power in some of the outage scenarios. This causes frequency overswing (see Fig. 5, case A).

Potential excess power which can be reduced without problems by closing the turbine control valves can also be reduced considerably by using four steps for the activation of condensate stopping (case B).

Reference curves were determined for frequency behaviour using valve throttling exclusively. Taking account of various types of generation outages, the range for Δf and df/dt depending on the size of the power outage was determined with respect to the possible range of system parameters (low load and peak



The stationary operating point is given as follows:

case	outage	frequency deviation	load characteristic	control power
A	**1800 MW**	**+ 8 mHz**	**+ 10 MW**	**1810 MW**
B	**1800 MW**	**- 43 mHz**	**- 80 MW**	**1720 MW**

Fig. 5: Frequency and primary control power after outage of 1800 MW, P_{sys} = 180 GW
A: Condensate stopping in 3 steps of 670 MW each
B: Condensate stopping in 4 steps of 500 MW each

load, variation of T_{sys} and σ_{load}) (see Fig. 6). Subsequently, these reference curves form the basis for determining the activation criteria for the four individual condensate stopping steps.

Based on numerous simulation calculations, the following criteria were determined for condensate stopping. The steps are to be activated consecutively from one to four as the power outage increases (function block in Fig.1):

1st step: ($df/dt \geq 30$ mHz/s **AND** $\Delta f \geq 200$ mHz)
OR Step 2 active

2nd step: ($df/dt \geq 45$ mHz/s **OR** $\Delta f \geq 250$ mHz **OR** Step 3 active)
AND $\Delta f \geq 50$mHz

3rd step: ($df/dt \geq 50$ mHz/s **OR** $\Delta f \geq 300$ mHz **OR** Step 4 active)
AND $\Delta f \geq 50$mHz

4th step: ($df/dt \geq 55$ mHz/s **OR** $\Delta f \geq 350$ mHz) **AND** $\Delta f \geq 50$ mHz

The logical links chosen serve the following aims:

- It is ensured that the activation of a certain step implies the activation of all preceding steps.
- The use of frequency transients improves the adjustment of the required activation of condensate stopping to the respective power outage.
- The logical connection with $\Delta f \geq 50$ mHz prevents an unnecessary activation of condensate stopping resulting from short-term local frequency transients.
- The logical OR-links with Δf in all steps guarantee that the necessary control power is activated even in the event of a slow frequency drop, e.g. when several power plants fail within a short period of time.

The frequency behaviour's characteristics resulting from the determined division of control power and the criteria defined for the activation of condensate stopping are presented in Fig. 6 and may be summarized as follows:

- In the event of unit outages of **up to approx. 1400 MW and greater 2800 MW** there is no great difference in system behaviour, when comparing this case to a case where primary control power is provided by valve throttling exclusively.
- Frequent unit outages **up to approx. 1400 MW** are settled by activating throttled power, thereby achieving high control quality, without making use of control reserve from condensate stopping. In addition, this approach meets the power plant's requirement to activate condensate stopping as seldom as possible.
- In unit outages **ranging from 1400 MW to 2800 MW**, step-by-step power activation by condensate stopping leads to deviations in the frequency behaviour in comparison with the reference cases (valve throttling exclusively), which may, however, be regarded as insignificant since the results are within the bandwidth of the reference cases. Essentially, the deviations may be traced back to the model's four frequency steps which, in practice, cannot be followed exactly due to the spreading of the steps' set values in power plants and the slight local frequency deviations, which eventually has a beneficial effect on the overall frequency behaviour.
- The settling of positive frequency deviations in the event of excess power is always possible by throttling turbine control valves – also for turbines equipped with condensate stopping.

This presents a solution that basically makes it possible to integrate control power provided by condensate stopping into the whole primary control strategy. These thoughts should be taken into account when today's small share of control power from condensate stopping should increase in future, which is to be expected for economic reasons.

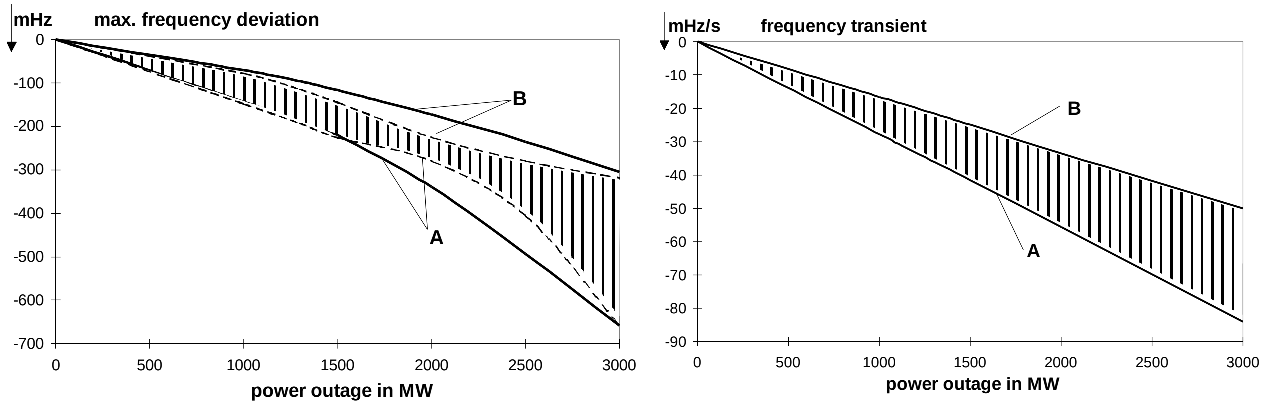


Fig. 6: Frequency behaviour with and without the use of condensate stopping

A: P_{sys}=180 GW, T_{sys}=10 s, σ_{load}=1% ☐ - using exclusively valve throttling for frequency control
B: P_{sys}=250 GW, T_{sys}=12 s, σ_{load}=2% ▥ - using 1/3 valve throttling and 2/3 condensate stopping for frequency control

8. Outlook

With respect to ancillary services, costs for maintaining frequency will continue to play an important role even after savings potentials have been used. In so far, intensive system monitoring and optimization will be of special importance in the future in order to tap further potentials for savings.

Acknowledgement

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10. List of symbols

$\sigma_{turbine}$	speed droop coefficient
T_b	boiler integration time constant
T_{sys}	system inertia constant
$P_{turb.}$	turbine power
$P_{el.}$	electric active power
f	frequency
P_{sys}	system power
σ_{load}	load characteristic
s	differential operator
$T_{V1,V2}$	time constants of turbine valves
T_{HP}	time constant of high pressure turbine
T_{LP}	time constant of low pressure turbine
T_{RH}	time constant of reheater
$\Delta C_{n\rightarrow m}$	absolut savings due to a generation shifting
$\Delta c_{n\rightarrow m}$	specific savings due to a generation shifting
E	amount of energy resulting from efficiency increase