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Improvement of the Performance of Scheduled Stepwise Power Programme Changes within the European Power System

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Abstract: Since the deregulation of the electrical energy market, the technical realisation of power transactions based on energy market contracts often effects large stepwise power programme changes – especially at the change of the hour. Originating from mainly economic reasons, these stepwise power programme changes lead to remarkable power imbalances within the European Power System causing large unintended frequency deviations with a negative impact on the control performance of power plants and power system. Within the framework of this paper, possible causes for the resulting poor control performance are analysed. Subsequently, measures for an improvement of the performance of scheduled stepwise power programme changes are proposed.

1. INTRODUCTION

The deregulation of the electrical energy market has deliberately led to the separation of energy market, transmission system operation and power plant operation. The interaction between power plants and power system as well as between power system and energy market is regulated by the UCTE Operation Handbook (UCTE, 2004) and several national grid codes, e.g. the German TransmissionCode 2007 (VDN, 2007). However, no technical regulations currently exist concerning the interaction between power plant operation and energy market.

As a direct consequence, large unintended frequency deviations occur, mainly at the change of the hour, see Fig. 1. Among other aspects, the occurrence of large frequency drops in the evenings and large frequency rises in the mornings is remarkable. Within the scope of this paper, the origins of this poor control performance of the power system on the operational side are analysed on the basis of model cases and, on this basis, counter measures presented.

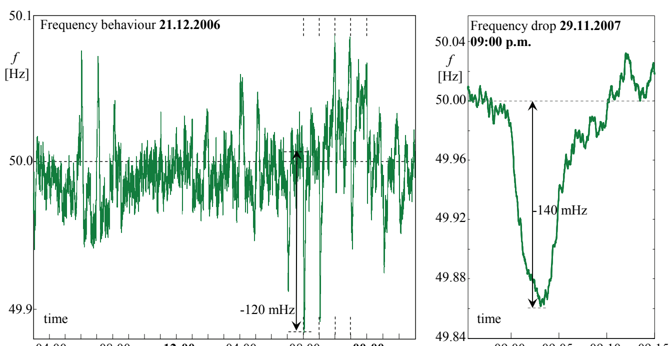

Fig. 1. Current operational frequency behaviour, almost similarly every day

2. ANALYSIS OF THE SYSTEM FREQUENCY BEHAVIOUR

Since frequency deviations generally represent only the summarised power balance within the entire power system, the exact behaviour of individual power generation units and consumers cannot be re-constructed from the course of the frequency deviation itself. Measurement campaigns aiming to record the total power exchange between all control areas have also not yet been successful. Therefore, in the following chapters three successive model cases of power deficits caused by scheduled power programme changes leading to large frequency drops are evolved, supported by corresponding measurements of actual cases. Self-evidently, the same applies also for frequency rises caused by power excesses.

2.1 Gradient of the Frequency drop

Disturbances of the power system resulting from a sudden drop of power generation, possibly caused by an outage of a large-scale power plant unit, lead to an instantaneous frequency drop and subsequently to the activation of primary control power within the time period of 0 to 30 s. In most cases, the absolute value of the corresponding power drop is smaller than 1000 MW, inducing frequency drops of less than $\Delta f_{\min} \leq |-50 \text{ mHz}|$. Such outages of power plant units occur twice weekly on average. The concurrent outage of 3000 MW in total, which corresponds to the UCTE reference incident for the calculation of the total primary control reserve (UCTE, 2004) is extremely rare, about once a year during normal power system operation.

The technical realisation of scheduled power transactions based on energy market contracts at the time instances τ_i = 0:00, 0:15,…, 23:45 h defined by the energy market leads

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to much slower frequency deviations, often with large amplitudes of $\Delta f \geq |-100 \text{ mHz}|$, see Fig. 1. The subsequent re-adjustment process takes approximately $10 \div 15$ min, see Fig. 2 and Fig. 3.

2.2 *Model Case 1: Uncoordinated Preset of Reference Variables during Power Programme Changes*

The first model case is based on a frequency drop having occurred on December 21st 2006, see Fig. 2a. As shown in Fig. 2b, power transactions based on energy market contracts entail stepwise power programme changes of approximately 4 GW between two power generation areas I and II at $\tau_i = 9{:}00$ pm. The term *power generation area* (PGA) substitutes representatively

- one single power plant unit,
- a group of power plant units, potentially organised within a balancing group, or
- all power plant units within the power system,

which have to react on the required positive or negative power programme changes scheduled for $t = \tau_i$.

Since the currently unavoidable power deviations between stepwise target value changes of the power output, provided by the energy market, and actual power output, are accounted on a quarterly hour basis, the power plant operators have to aim for keeping the power deviations as small as possible, i.e. for actual power output changes as fast as possible. In the regarded model case, pumps with a scheduled power consumption $\Delta P_{\text{pump}} = -\Delta P_{\text{G,I}}$ are run up within PGA I at the change of the hour $t - \tau_i = 0$ min, evoking a rampwise increase of power consumption with a high gradient, see Fig. 2b2. Due to the fast dynamics of pumped storage power plants, i.e. a very small delay and high possible power gradient, the final desired power set point value of PGA I is already reached after 3 min. The fast decrease of the summarised power output within PGA I can also be evoked by hydro power plants in turbine operation or by quick gas turbines respectively, see Fig. 2b1.

Equivalently, slower power plant units within PGA II rise their summarised power output, like thermal power plants with a maximum power output gradient of e.g. $\dot{P}^*_{\max} = 2\,\%/\text{min}$, and therefore do not reach their final desired power output value before $t - \tau_i = 13$ min. The outlined scenario leads to the triangular power deficit area shown in Fig. 2b, taking into account the influence of primary control and the self-regulating effect of the power system. The maximum absolute value of the power deficit can be estimated as follows:

$$\boldsymbol{\Delta P}_{\text{G,max}} = \lambda\,\Delta f = 26{,}1\,\frac{\text{GW}}{\text{Hz}}\cdot 0{,}12\,\text{Hz} = \mathbf{3{,}1\ GW} \qquad (1)$$

Equation (1) takes into account the quasi-stationary state of the primary control due to the slow frequency gradient, as well as a network frequency characteristic of $\lambda = 26.1$ GW/Hz (UCTE, 2004; Bachmann, Grebe *et. al*, 2000) corresponding to a total system load of $P_{\text{L0}} = 370$ GW (UCTE, 2007) and a system self-regulating effect of $k^{\text{S}}_{\text{pf}} = 1{,}5\,\%/\%$ (Welfonder et. al, 2006).

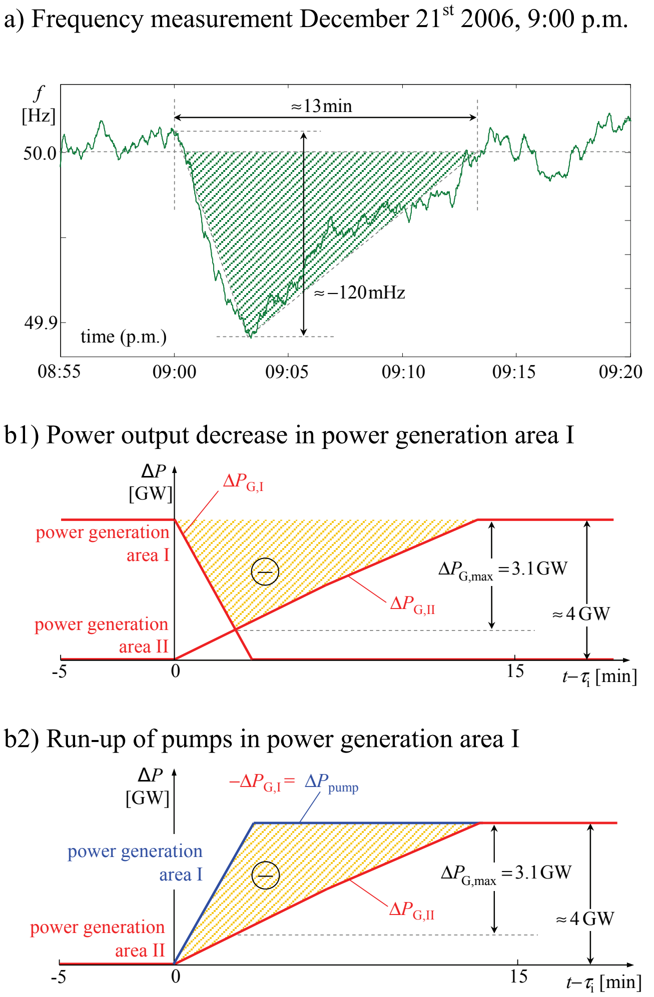


Fig. 2. Model Case 1: Uncoordinated preset of reference variables during power programme changes

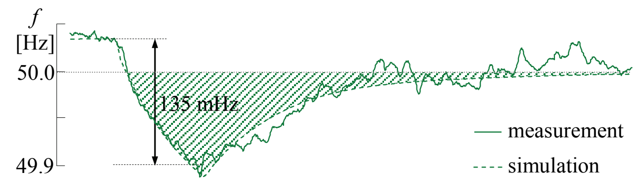
2.3 *Model Case 2: Balancing of the Power Deficit by Secondary Control*

The second model case considers a scenario where the power plant units within PGA II, which are committed to provide active power according to respective energy market contracts, do not perform their set point change reference-variable-controlled as assumed in model case 1, but utilising the automatic increase of the power output by the participating secondary controlled power plant units.

This scenario is substantiated by simulation results based on a frequency drop having occurred on May 10th 2006 at 10:00 pm, see Fig. 3a. Is the summarised power generation and consumption behaviour presumed according to Fig. 3b, a good agreement of the measured and simulated frequency curve is yielded, see Fig. 3a. The described second model case again induces the temporary activation of all energy storages within the power system, i.e. primary control reserve and system self-regulating effect. The remaining power deficit is finally balanced by secondary control power activated inside PGA II within a time period of approximately 15 min.

As an additional remark it should be mentioned that the high frequency start value of $f = 50.04$ Hz for $t \leq 10{:}00$ p.m. in the considered case was also taken into account during the simulation. The higher initial value can partly be assigned to a power excess within PGA II before the scheduled power programme change at $t = \tau_i$. This in reality often applied strategy aims towards a reduction of the initial power deficit within PGA II after $t = \tau_i$ when the summarised power output can only increase inertly.

a) Measured and simulated frequency drop, May 5th 2006, 10:00 pm



b) Simulated summarised power generation and consumption behaviour

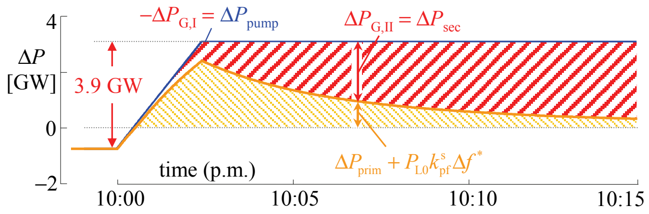


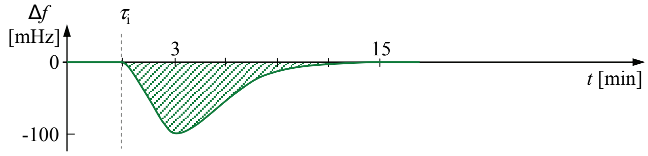
Fig. 3. Model Case 2: Balancing of the power deficit by secondary control

2.4 *Model Case 3: Medium-term balancing of the Power Deficit by Beneficial System Load Behaviour*

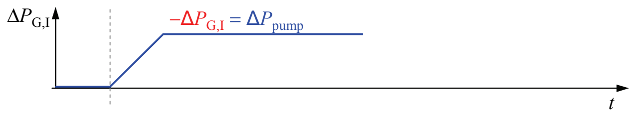
The third model case additionally incorporates the fact that power deficits $-\Delta P_{G,I} = \Delta P_{pump}$ caused by scheduled power programme changes in the evenings are finally balanced by a gradual decrease of the total system load $\Delta P_L(t)$ in the medium-term, see Fig. 4. It must be noted that the described effect is possibly interconnected to the modality of a potentially applied load following strategy within the regarded control area or balancing group respectively. However, also in this – from a transmission system operation's point of view – positive constellation, the balancing of the remaining power deficit $\Delta P_L(t)$–$\Delta P_{pump}(t)$ only via secondary control is not possible, since due to the resulting frequency drop $\Delta f(t)$ again all primary controlled power plant units are unintentionally stimulated. Concurrently, also the system self-regulating effect is utilised.

Finally it should be marked that the described model cases may occur at any place within the power system. Furthermore, several of relatively small power deficits occurring synchronously at prominent schedule times $t = \tau_i$ may accumulate and finally lead to high frequency deviations as well.

a) Network frequency



b) Run-up of pumps in pumped storage power plants



c) Balancing by secondary control and negative load trend

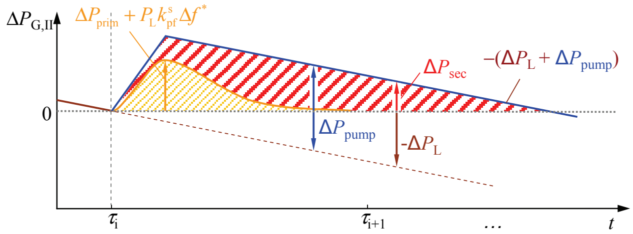


Fig. 4. Model Case 3: Medium-term balancing of the power deficit by beneficial system load behaviour
→ Schematic representation based on Model Case 2

3. NEGATIVE IMPACT ON POWER PLANT AND POWER SYSTEM OPERATION

3.1 Impact on Primary Controlled Power Plant Units

The unintended participation of the primary controlled power plant units in compensating imbalances between power generation and consumption, provoked by the regularly appearing frequency deviations, leads to highly negative impacts on the power plant units themselves. These impacts are exemplarily shown in Fig. 5 by measurement curves for the turbine valve aperture $y^*_T(t)$, condensate mass flow $\dot{m}^*_C(t)$ and generator output $P^*_G(t)$ during the frequency drop on May 10th 2006 (Weissbach, *et. al*, 2006), compare Fig. 3. From these measurement curves it can be seen that the stresses for the different actuators within the primary controlled power plant units are much higher than necessary to maintain a good control performance of power system operation.

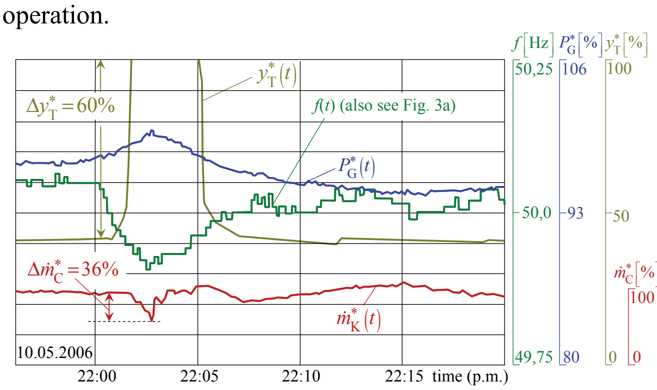


Fig. 5. Impact of the frequency deviations on a primary controlled steam power plant unit

A long-term evaluation of these power plant variables shows that the stresses caused by the regular occurring frequency deviations have been increasing significantly, concerning the magnitude as well as the commonness of their occurrence (Weissbach, *et. al*, 2006). Caused by these frequency deviations, all primary controlled power plant units within the UCTE power system carry out unnecessary control work, which leads to stresses and a higher fuel consumption.

3.2 Impact on Power System Operation

Additionally, the power system is operated nearer its security limits, since especially during the scheduled power programme changes in the mornings and evenings a large part of the primary and secondary control reserve power is activated unnecessarily. Thus:

$$\Delta f = \begin{cases} -100\text{ mHz} \\ -120\text{ mHz} \\ -150\text{ mHz} \end{cases} \Rightarrow \Delta P^{*}_{\text{pr}} = \begin{cases} {}^{100\text{ mHz}}\!/_{200\text{ mHz}} \cdot 100\% = 50\% \\ {}^{120\text{ mHz}}\!/_{200\text{ mHz}} \cdot 100\% = 60\% \\ {}^{150\text{ mHz}}\!/_{200\text{ mHz}} \cdot 100\% = 75\% \end{cases} \quad (2)$$

4. MEASURES TO IMPROVE THE POWER SYSTEM CONTROL PERFORMANCE

The different operational causes for power deficits and frequency drops illustrated by means of the Model Cases 1 to 3 can be diminished or even avoided applying the following proposed measures.

4.1 Realisation by the power plant operators or dispatchers

The scheduled stepwise power programme changes ΔP_{target} resulting from transactions based on energy market contracts for $t = \tau_i$ are required to be realised by means of uniformly defined rampwise changes of the respective power outputs ΔP by the power plant operators or dispatchers accordingly. For this purpose, all rampwise changes of the desired power output ΔP_d have to start at $t = \tau_i - T$ before the scheduled stepwise power programme change and end at $t = \tau_i + T$, see Fig. 6a and b.

From the generators' point of view, the ramp duration $2T$ is to be defined as long as possible, i.e. $2T^{(G)} = 15$ min taking into account the 15 minutes accounting intervals T_A. This ramp duration enables power output set point changes of conventional steam power plant units up to $\dot{P}^{*}_{\max} \cdot 2T = 2\%/\min \cdot 15\min = 30\%$. The respective stepwise target value changes ΔP_{target} can be converted into rampwise changes ΔP_d with variable gradients without difficulties (Weissbach, *et.al* 2006) using standard setpoint control modules already provided by automation suppliers, either decentralised inside the power plant units or upstream inside the respective dispatching systems. The reference variable curve for the power output ΔP_{ref} which has to start already at $t = \tau_i - T - T_I$ due to the inertance of the power plant units, see Fig. 6b, can also be prearranged without problems, since the scheduled power programme changes are available for the power plant operators or dispatchers respectively in time.

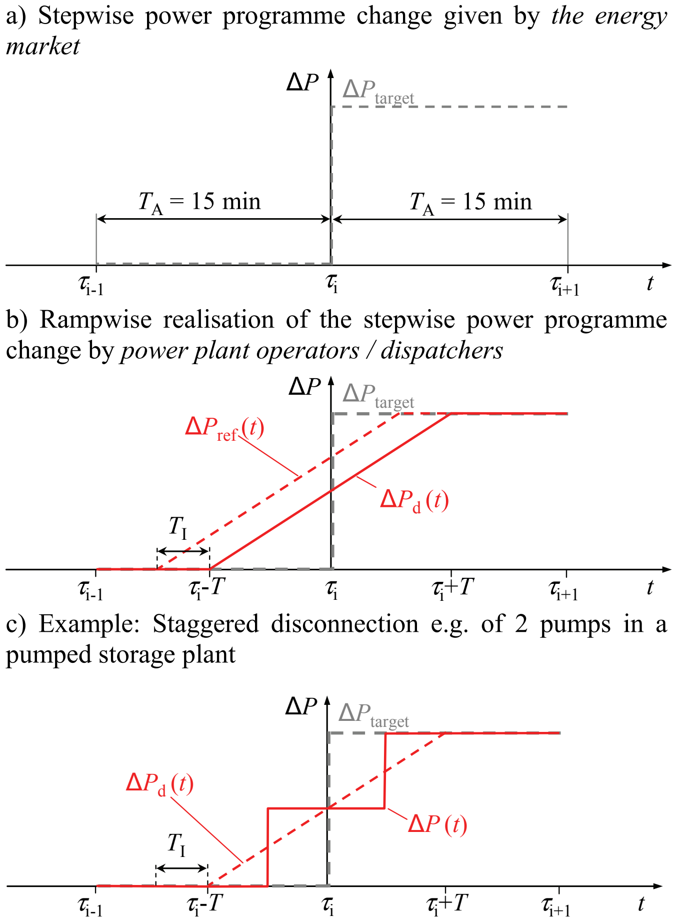


Fig. 6. Uniform rampwise changes of the reference variable and desired value of the power output

If the actuators of some particular power plant units do not allow rampwise reference variable curves, as often the case with pumps in pumped storage power plants, a staggered connection or disconnection of several units within the time period $2T$ is also possible, see Fig. 6c. Obviously, no energy deviation occurs within the accounting interval, when the power programme change is realised by the staggered run-up of an even number of pumps. The same strategy can be applied to the connection or disconnection of off-peak storage heating, which often induces large power programme changes at $t = $ 10:00 p.m. In cases where an operating mode in hydraulic short-circuit is possible, i.e. the concurrent run-up of pump and turbine to obtain a continuously controllable pump operation (Pürer, 2007), this operating mode is also possible.

4.2 Realisation by the transmission system operators:

Transmission system operators (TSOs) convert the stepwise changes of the power exchange values between different control areas into rampwise changes already today, using a ramp period of $2T = 10$ min (UCTE, 2004). Such adaptations of the power exchange values are necessary in case of scheduled power programme changes between different control areas or control blocks respectively. Additionally, the UCTE Operation Handbook (UCTE, 2004) postulates that '*in* *particular, care must be taken to ensure that generating capacity is brought on line or disconnected on a staggered basis, particularly for tariff changes at 6 a.m. and 10 p.m.'*

4.3 Modification of the Accounting Procedure for Activated Control Energy

The accounting of the control energy W_C within the i-th accounting interval $T_A = \tau_{i+1} - \tau_i = 15$ min is performed using the difference area between the stepwise scheduled power programme change P^i_{target} and actual power output $P(t)$ as follows:

$$W^i_C = \int_{\tau_i}^{\tau_{i+1}} P^i_{\text{target}} - P(t)\,\mathrm{d}t = T_A \cdot P^i_{\text{target}} - \int_{\tau_i}^{\tau_{i+1}} P(t)\,\mathrm{d}t \tag{3}$$

Applying the new concept of rampwise changes of the power output, the control energy is calculated using the difference area between the rampwise desired power output change $P_d(t)$ and actual power output $P(t)$, as shown in Fig. 7. Since $P_d(t)$ is exactly specified according to the uniformly defined ramp duration, coming from Fig. 7 every accounting interval i can be allocated a modified difference area given by:

$$T_A \tilde{P}^i_{\text{target}} = \left(T_A - \frac{T}{2}\right) P^i_{\text{target}} + \frac{T}{4}\left(P^{i-1}_{\text{target}} + P^{i+1}_{\text{target}}\right) \tag{4}$$

Using the modified difference area given in (4), which is applied exclusively to the accounting of control energy, the conventional proceeding of accounting based on (3) can be kept. Therefore, regarding (3), the target value P^i_{target} has to be replaced by the modified target value $\tilde{P}^i_{\text{target}}$. Regardless of the described modifications, the accounting of the power transactions themselves on part of the power generation, energy market and energy provider continues on basis of the scheduled stepwise set point values P^i_{target}.

5. CONCLUSIONS

To improve the performance of stepwise scheduled power programme changes and avoid large frequency deviations with unnecessary activations of primary control reserve power, the following measures are proposed:

- The stepwise change of the target value for the power output scheduled for $t = \tau_i$ is performed as rampwise change of the desired power output in such way, that the ramps already begin at $t = \tau_i - T$, have reached half of the power change at $t = \tau_i$ and reach their final set point value at $t = \tau_i + T$. The ramp duration T has to be uniformly defined. A ramp duration of $2T = 15$ min, which corresponds to the length of accounting intervals for the power programme changes, leads to the least actuator movements within the power plant units and hence minimises stresses.

- To achieve such power output curves, the ramp of the corresponding reference variable curve has to begin already in advance at $t = \tau_i - T - T_I$, with T_I being the inertia of the respective power plant unit. The rampwise reference variable curves lead additionally to a smoother operational mode of the power plant units.

- The rampwise realisation of scheduled stepwise power programme changes implies uniformly defined ramp durations on the power generation as well as on the power transmission side.

- On part of the TSOs, the conventional accounting procedure of the control energy can be kept. Only the set point value for the power output within every accounting interval has to be modified to allow for the rampwise change of the desired power output around the power programme change time τ_i.

The results of the carried out research project are currently discussed by power plant operators and TSOs. The aim is a uniform realisation of the proposed measures.

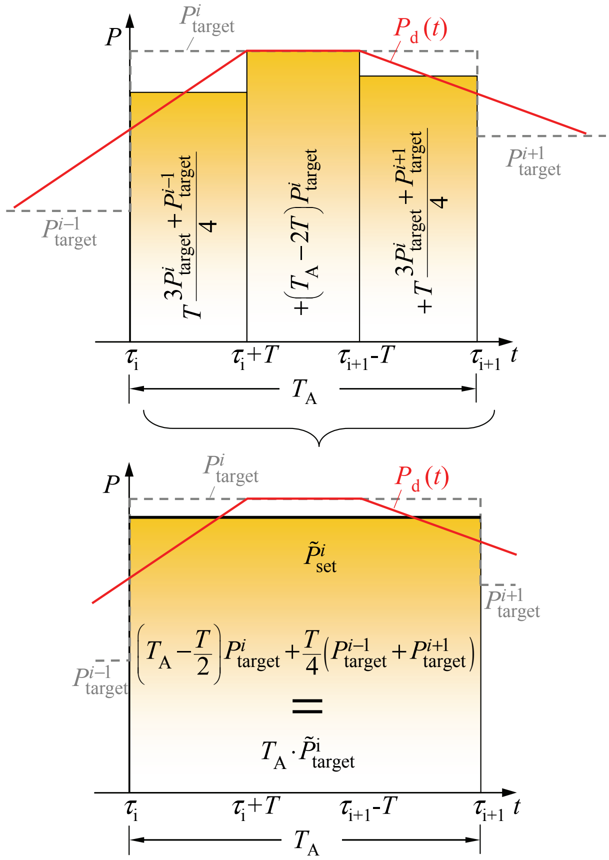


Fig. 7. Modification of the desired power output value for the accounting of control energy

6. OUTLOOK

In this paper only operational aspects for the improvement of the dynamic system behaviour have been considered. Additionally, purely economic aspects may also play a role, as e.g. has been stated for other power systems like the Eastern Interconnection in the USA (NERC, 2002). It has been clearly observed, that energy market aspects and cost optimisations influence the physical realisation of power schedules just as well, which is not sufficiently monitored. Other proposed measures include the definition of rampwise 1-h-products to reduce the gap between scheduled power programmes and physical load behaviour (NERC, 2002), or establishing ¼-h-products on the energy exchange market.

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