Deterministic frequency deviations – root causes and proposals for potential solutions

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A joint EURELECTRIC – ENTSO-E response paper

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Deterministic frequency deviations – root causes and proposals for potential solutions

EURELECTRIC – ENTSO-E Joint Investigation Team

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ABBREVIATION LIST

AGC	Automatic Generation Control
ACE	Area Control Error ($ACE=P_m - P_s + K_{ri} * (f_m-f_r)$)
BRP	Balance Responsible Party
CET	Central European Time
FC	Frequency Control
FQI	Frequency Quality Investigation
HPP	Hydro Power Plant
NPP	Nuclear Power Plant
TPP	Thermal Power Plant
RWE	Rheinisch-Westfälische Elektrizitätswerk
AhT	Ad hoc Team
Kri	Network Characteristic *Kri* is constant (MW/Hz) set on the secondary controller proportional with the control area's power system frequency characteristic
RMS	Root Mean Square
LFC	Load Frequency Control
CE system	Continental Europe system
IPS	Interconnected Power System
UPS	Unified Power System
EDF	Electricité de France
EFET	European Federation of Energy Traders
ENTSO-E	European Network of Transmission System Operators for Electricity
REE	Red Eléctrica de España
RTE	Réseau de Transport d'Electricité
TEL	Transelectrica
TSO	Transmission System Operator
UCTE	Union for the Coordination of Transmission of Electricity

0. EXECUTIVE SUMMARY

Frequency is the sole parameter in the interconnected power system common to all TSOs and system users in the synchronous area. The quality of frequency[1] is of special concern to Transmission System Operators (TSOs) who are responsible for the reliable operation of the electricity system, and generating companies whose generators have to react to frequency deviations.

In the last few years practically all synchronous areas of ENTSO-E (similar to a number of other synchronous systems in the world) have been experiencing increasing frequency variations, amplitude and duration, at hour boundaries multiple times per day mainly during the ramping periods in the morning and the evening. The variations with peak-to peak values up to 150 mHz are observed mainly within a time window of ten minutes centred on the change of the hour, corresponding with the standardised time interval for cross border (international) schedule changes.

This joint study from ENTSO-E and Eurelectric examined the causes of this increasing frequency deviation, and threats to the quality of frequency in Europe this may imply. The study suggests areas for improvements to be further analysed and direct implementation and adoption via European electricity network codes.

The causes of the deterministic frequency deviations were identified to be:

I. Weakening in the strong link between power consumption and power generation information, the existing market rules require development. The current market rules between generation and consumption are based on energy blocks of fixed time periods.

II. The hourly transit period for generation schedule is currently not explicitly defined between all market participants. The resulting imbalances are reflected in the frequency deviations.

Increasing control reserves does not seem to substantially improve the situation; rather it increases system operation costs considerably.

This report proposes guidelines for market rules to cope with this challenge. It includes proposals and technical observations to be further assessed and developed as input to the ENTSO-E drafting teams working on grid codes and operational guidelines; as market rules for TSOs, traders and generators under the supervision of European regulators and the EC.

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[1] The system frequency of an interconnected power system reflects the balance between load and generation. Deviations from the setpoint value of 50 Hz (ENTSO-E power system) signal either a generation surplus or a generation deficit within the whole system. Normal operational practice within the European power systems is to keep frequency, deviations less than +/- 1% of the nominal value.

1. INTRODUCTION

The system frequency corresponds to the heartbeat of an interconnected power system, as it permanently reflects the balance between load and generation. Deviations from the setpoint value of 50 Hz (ENTSO-E power system) signalise either a generation surplus or a generation deficit within the whole system. Based on this fact the most important automatic control schemes use the system frequency as a main input variable.

Normal operational practice within the European power systems is to keep frequency deviations less than +/- 1% of the nominal value.

In the last few years practically all synchronous areas of ENTSO-E (similarly like a few other synchronous systems in the world) have been experiencing increasing frequency variations at hour boundaries, multiple times per day mainly during the ramping periods in the morning and the evening. Statistics show an increase of these system frequency variations, in respect to number and size. These frequency deviations are not caused by critical events such as forced power plant or load outages. The variations with peak-to-peak values up to 150 mHz and even more are observed mainly within a time window of ten minutes centred on the change of the hour, corresponding with the standardised time interval for cross border (international) schedule changes.

These frequency deviations activate a significant integral share of the primary reserve in the systems which is initially intended and dimensioned for large generation and load outages and consequently endanger the secure system operation by limiting the required control reserves for longer time periods. A further increase in size of the frequency deviations will result in the activation of the whole available primary reserves without any critical incidents having occurred.

Within the continental European synchronous area a dedicated working group composed of experts from TSOs has already analysed this phenomenon and prepared a corresponding report /1/.

Generating companies have also started to investigate the phenomenon of deterministic frequency deviations and the impact on their generating units. The investigation should lead to the development of possible solutions to improve the situation.

Based on bilateral contacts between the associations of the TSOs and Generation Companies (ENTSO-E and EURELECTRIC respectively) a joint pan-European Ad-hoc Team (AhT) was set up in December 2009 in order to perform with an in-depth analysis of the phenomena and to define potential solutions for the improvement of the frequency quality.

This report reflects the results of the joint AhT activities.

Presently a pan-European harmonisation for naming of different types of reserve is in progress within ENTSO-E in the frame of drafting the new network codes. As the corresponding codes have not yet been approved, the report is based on the terminology currently in use. However, please find below a reference list for the new naming conventions:

Primary control reserve	frequency containment reserve (FCR)
Secondary control reserve	frequency restoration reserve (FRR)
Tertiary control reserve	frequency replacement reserve (RR)

2. APPROACH

The main objective of the work was to analyse in depth the origins of system frequency deviations as well as their consequences for power system security and generating units, and to suggest possible actions to be taken in order to mitigate these phenomena based on the assumption that the actions have to take into account both - the interests of TSOs as well as of generators. Therefore, the advantages and disadvantages of each solution as well as their influence on the market have been evaluated carefully.

The AhT consists of ten members – five TSO experts from different synchronous areas and five experts from EURELECTRIC including the experts from VGB PowerTech. The Secretariats of both associations provides both organisational and technical support for the AhT.

Following the description of work described in the Terms of References the first step was the in-depth analysis of the problem. This includes analysis of load behaviour, generating unit control aspects, and their impact on TSO operation. The influence of the different operational market models on frequency deviations have also been taken into consideration. The consequences of the experienced frequency variations on generating unit operation and on the overall power system security have been analysed as well.

As a result of its work the AhT in this report proposes possible solutions for reducing the critical frequency deviations during schedule ramping. Concepts for the introduction of new ramp products, such as ramp-based billing, half-hour ramping, four quarter-hour steps, smoothing scheduled variations of large hydro-power plants and respective financial incentives are presented and assessed in the report.

This report is a platform for common understanding of issues and solutions, but it is not intended to reach a binding joint position since this is the subject of decision of relevant bodies and committees of both organisations.

If necessary, the report, under the explicit agreement, can be used in the dialogue with the stakeholders, such as Regulators at both European and national level, the European Commission, EFET, etc. If approved by the respective bodies in both associations the results will be a contribution to the European Operational Standards as well as the related Market Standards.

Chapter 3 briefly outlines what deterministic system frequency deviations are, as well as their causes. It then describes the impacts that large system frequency deviations have on both generating units and the operation of the overall power system.

Chapter 4 digs into previous analyses related to frequency deviations as performed by relevant stakeholders. It features the analysis undertaken by the former UCTE Frequency Quality Investigation Working Group, as well as the frequency behaviour analyses made in the framework of the VGB-research project "Origins of the Occurrence of Large Frequency Deviations within the UCTE Power System and Improvement Measures". It also sheds lights and draws knowledge from the experiences and planned actions of certain power systems, namely the Nordic, the Turkish and the Baltic systems. Finally, the sixth part of this chapter summarizes the conclusions based on the distributed questionnaire.

Chapter 5 goes to the core of the present paper. It provides the reader with the result from the investigation of root causes of system frequency deviations and offers proposals for improving the management of the power system.

Chapter 6, finally, provides conclusions and recommendations to tackle the issue of system frequency deviations.

3. IMPACT OF FREQUENCY DEVIATIONS ON POWER PLANT AND ON POWER SYSTEM OPERATION

3.1 IMPACT OF FREQUENCY DEVIATIONS ON POWER SYSTEM OPERATION

3.1.1. PARTICULARITY OF THE PHENOMENA

Based on observations over the last few years we can define the inter-hour frequency deviations as a typical phenomenon for all systems, independently of their total power or geographic dimensions, but having one common characteristic: the development of a market mechanism with corresponding market rules and according to the system unbundling strategy separation between generation, transmission and distribution. The frequency deviations occur in the same manner, for the same time period of year and day. These observations lead to the conclusion that this phenomenon is deterministic and has a determinant cause.

The main characteristics of deterministic frequency deviations are: typical moment of occurrence, duration and value.

From the point of view of time behaviour, the frequency deviations observed in the last few years occur in a deterministic way at a fixed hour, i.e. on the hour. Occasional but less significant variations were registered quarterly and half hourly. The most significant times of occurrence are noticed at the fixed hours: 6:00, 7:00, 8:00, 21:00, 22:00, and 23:00 CET and coincide with the large changes within the system load.

The duration of the behaviour observed is usually: t ± 10 minutes centred on fixed hour (total 20 min),

The dynamic behaviour of frequency is systematically monitored in Continental Europe. These statistical results confirm a continuous increase of gradient values df/dt and its occurrence. Values greater than 1.5 mHz/s are more and more present. Comparing with the usual frequency gradient df/dt occurring in the case of more than 1,000 MW unit tripping, 6-8 mHz/s it can be concluded that the dynamic evolution of frequency around the change of the hour should be also taken into account in dynamic studies of generation (classical and renewable).

Regarding the magnitude of phenomena, the frequency deviations have amplitudes more than 100 mHz peak to peak, usually centred on the 50 Hz system frequency setpoint. The amplitude increases in winter months, and a part of them remains unnoticed due to fact that in absolute terms the normal frequency variations are in the range of ± 50 mHz within the Continental Europe system. Even then the frequency amplitude variations at change of the hour are higher than frequency drops occurred when outages of large power plants happen (approx. 40 mHz).

In the long term (e.g. with respect to daily average), frequency behaviour is quite normal, due to the fact that the event starts and ends in a stable process: in 50 Hz ±20 mHz range.

The shape of frequency deviations follows the load evolution. When the load increases (morning) the frequency deviation starts with an increase; conversely in the evening, when the load evolution decreases, the frequency deviation starts with a decrease, see **Figure 3.1**.

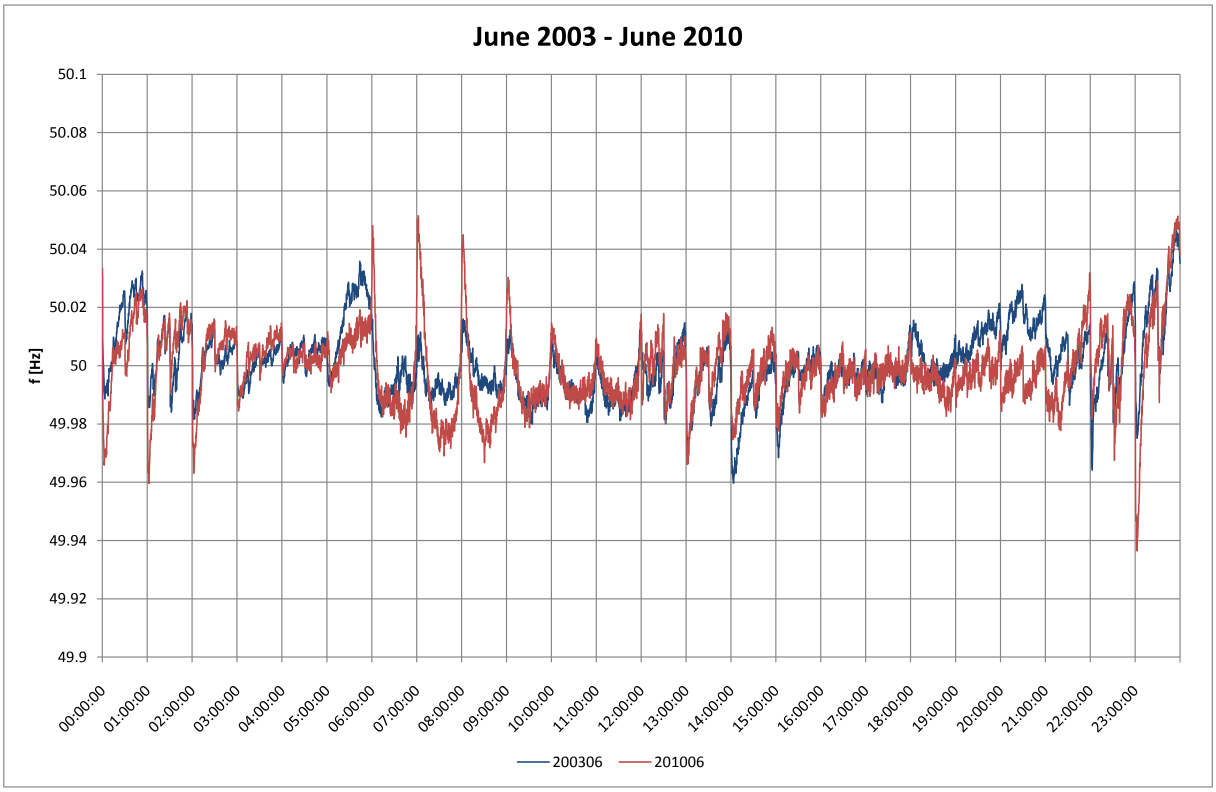

Fig. 3.1: Average frequency values in Continental Europe, June 2003 and June 2010, Source: Swissgrid

The frequency shape reveals a short-time mismatch between load and generation in the sense that generation anticipates load demand. The phenomenon could appear because generation follows market rules which anticipate the necessary energy and does not consider the real time load demand. This frequency behaviour has consequences for: generators, system stability, exchange flows and finally for energy prices to end-consumer. These systematic frequency deviations endanger the capability of the system to curtail and restore system frequency if a loss of a generator or a big consumer occurs during these time periods.

Figure 3.2 shows **t**he result of permanent monitoring and analysis on a monthly basis of the Continental system frequency based on the simple criterion of exceeding +/- 75 mHz around the 50 Hz setpoint.

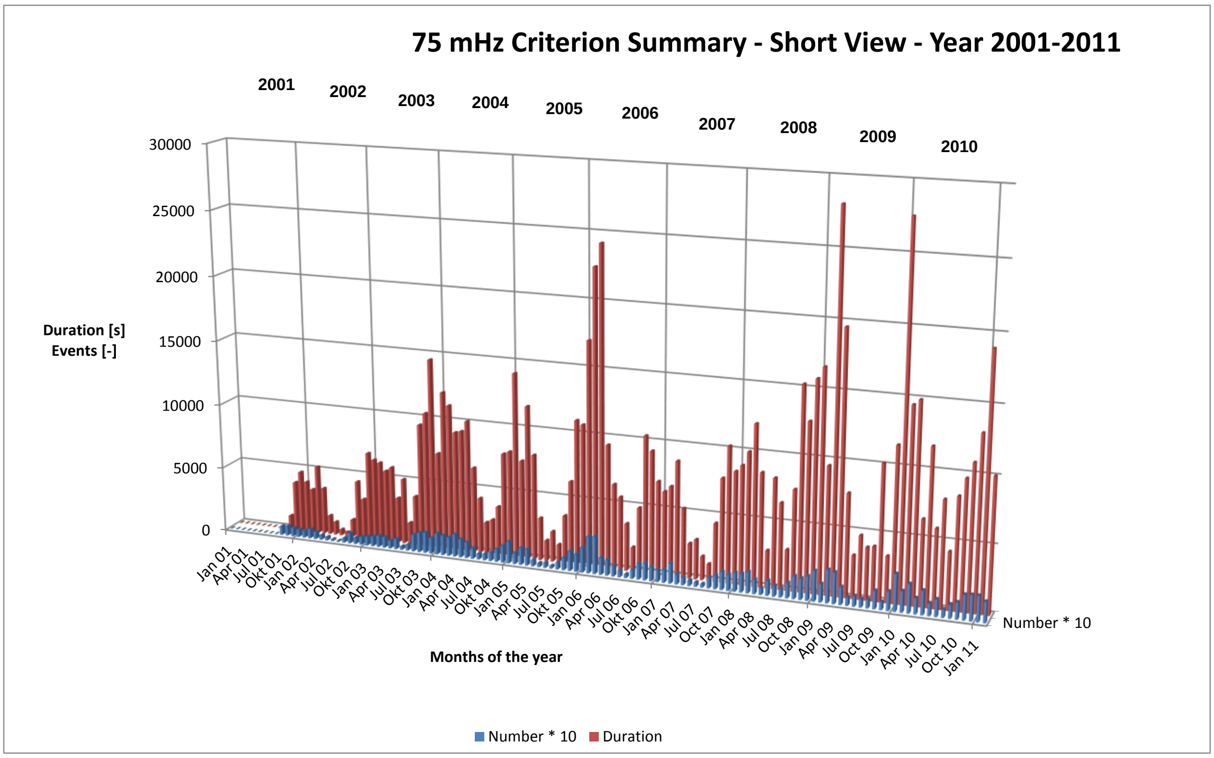

Fig. 3.2: Frequency quality behaviour in Continental Europe during the last ten years. Source: Swissgrid

It can clearly be observed how the accumulated time continuously increases with higher frequency deviations as well as the number of corresponding events.

3.1.2. CAUSES

The unbundling process has separated power generation from TSO, imposing new commercial rules in the system operating process. Generation units are considered as simple balance responsible parties without taking dynamic behaviour into account: slow or fast units. Following the principle of equality, the market has created unique rules for settlement: energy supplied in a time frame versus energy calculated from schedule in the same time frame. Energy is traded as constant power in time frame.

The market, being orientated on energy, has not developed rules for real time operation as power. In consequence we are faced with the following unit behaviour (**Figure 3.3**):

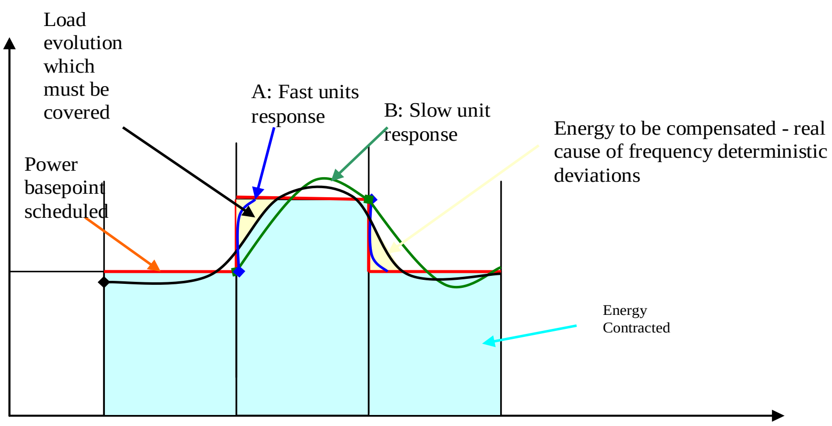

Fig. 3.3 a: Unit behaviour in scheduled time frames. Source: Transelectrica

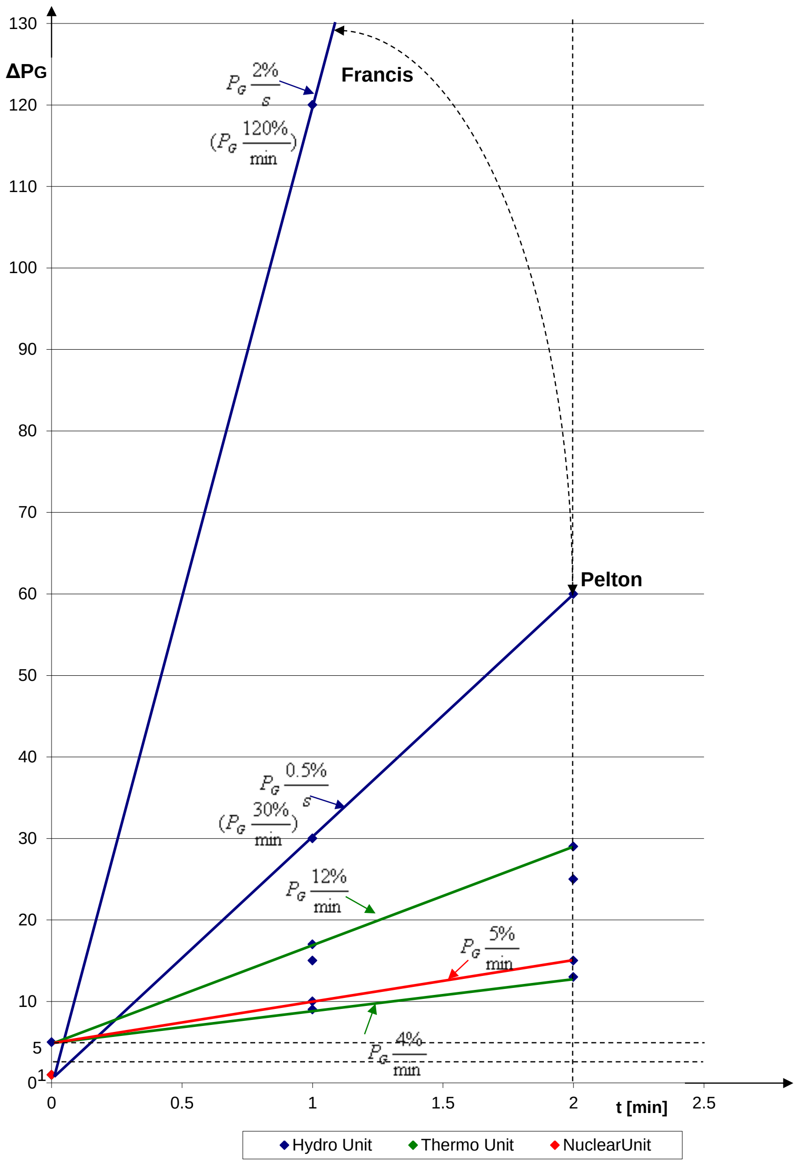

Fig. 3.3 b: Range of maximum power gradients for different generating units. Source: University of Stuttgart

A: Fast units behaviour is near a power step without correspondence in real load. In this manner the hourly behaviour of fast units is quite similar to an incident. The impact on system frequency is in relation to schedule steps leading to frequency deviation in the whole system.

B: Slow units are faced with opposite requirements: technical requirements which impose the natural ramp and the commercial ones which impose to deliver scheduled energy in the time frame. Usually two mechanisms are adopted:

- Energy compensation (c) from fast units – other BRP
- Ramp compensation by the unit itself, with power modification in the time frame

Both behaviours contribute to frequency deviations. The solution could be to find a set of market rules capable of adapting the market model to the behaviour and needs of real load.

3.1.3. IMPACT ON SYSTEM OPERATION

The frequency deviations diminish the capability of TSOs to assure the system reliability due to a decrease of the operational reserve for frequency stabilisation (primary reserve), decrease of stability in case of simultaneous outage, and decrease of secondary reserve which is used for mitigating the frequency deviation instead.

Independently of the structure of frequency control in different synchronous areas, in order to mitigate frequency deviations, generating units automatically deliver active power reserves and the system subsequently activates additional reserves, too. In system areas having automatic frequency restoration control this control activate frequency restoring reserve proportional to the deviation. The reserve is activated in both directions, as opposition on frequency evolution, by all interconnected TSOs highest contribution having the greatest control blocks. The deterministic frequency deviations have a major influence on reserves in systems which control area error (ACE) as sum of interchanges power and frequency contribution as: ACE= ΔP + Kri*Δf. In CE for control blocks having the constant of power frequency characteristic (Kri) bigger than 1000 MW/Hz a frequency deviation as $\Delta f = \pm 0.075$ Hz implies a reserve activation of -/+ 75 MW. In the case of present phenomenal reserves activations have usefulness aspect (the activated reserve is deactivated in a few minutes) but imply supplementary cost in market.

For the same deviation of 0.075 Hz, which is often observed, the primary reserve used fruitlessly is 3/8 of total reserve (for a medium TSO with 100 MW primary reserve, 37.5 MW are used for mitigation of inter-hour frequency deviations).

At the level of continental Europe, for a calculated power-frequency characteristic of 26434 MW/Hz, a frequency deviation of ±0.075 Hz leads to a total primary reserve activation of 1125 MW (related to primary reserve 3/8 of 3000 MW), and to a total ACE deviation made up of Kr*Δf of 1982 MW in case of a determined power-frequency characteristic λu = 26434 MW/Hz.

Abusive reserve activation: No consequence on phenomena mitigation, because it is not a phenomenon to which reserves are dedicated and dimensioning.

3.1.4. CONSEQUENCES ON THE ELECTRICITY MARKET

These continuous system frequency deviations involve the activation of ancillary services such as e.g. primary and secondary reserve, and increase end-users final electricity prices. Additionally, the ramp compensation outside a specific mechanism, leads to a cost increase or determines the procurement from different BRP or by the introduction of new imbalances in case of power compensation during the corresponding time frame. This leads to a significant cost increase for generating parties due to higher maintenance and lifetime reduction of the power plant equipment and make generating energy more expensive. Aiming at assuring the reliability of the system, TSO are forced to procure supplementary ancillary services for compensating events induced by market rules which do not correlate with system physics.

The principal market consequence of frequency deviations is the increase of the activated power and energy required for frequency control, their costs leading to an increase of the electricity final price for end-users, i.e. it affects all consumers.

3.2. Impact of Frequency Deviations on Power Plants Operation

In the Continental European system, there have been frequency control principles for more than 50 years. They have demonstrated their efficiency in controlling the frequency and comprehensive experiences with control systems have spread in the past across Europe. Philosophy, principles, performances and values are set by ENTSO-E Policy 1 and Appendix A, defining global rules prescriptions in terms of dynamic performance and power volume. The main frequency control rules prescriptions (power volume and dynamic performances) are detailed and enforced in national grid codes.

Power volumes are dispatched by TSOs on generators. Some TSOs allow dispatching power reserve on the power plant fleet of the generator company, others require dispatching on each generator.

From a technical point of view the dynamic performances of frequency response are firstly chosen depending on generation mix and power plant technology (hard coal, lignite, water etc.). The way primary control power demand is covered by the different European TSOs differs according to the corresponding national grid codes' requirements. In principle the individual reserve power is shared over generating units based on local ancillary market rules or grid code requirement regulations.

Frequency deviations mainly solicit plant components because of the sudden variation and the short response time of primary frequency control specifications (response proportional to frequency deviation up to 200 mHz, in less than 30 s, prevalent fast load changes etc.).

Even if frequency deviations remain within their normal range [-200 mHz; +200 mHz], if they are large, frequent and predictable, it should be recognized that power plant components are operated outside their design specifications for normal conditions. Moreover, there is no international industrial standard which defines and specifies the characteristic of power plants which are able to cope during the plant lifetime with large, frequent and deterministic frequency deviations covering more than 2/3rd of the designed frequency control range.

Figure 3.4 shows typical frequency behaviour during the morning time period while system load is gradually increasing. As the power plants increase their feed in almost step-wise according to current applied rules, but the load demand increase remains much slower, positive frequency steps can be observed.

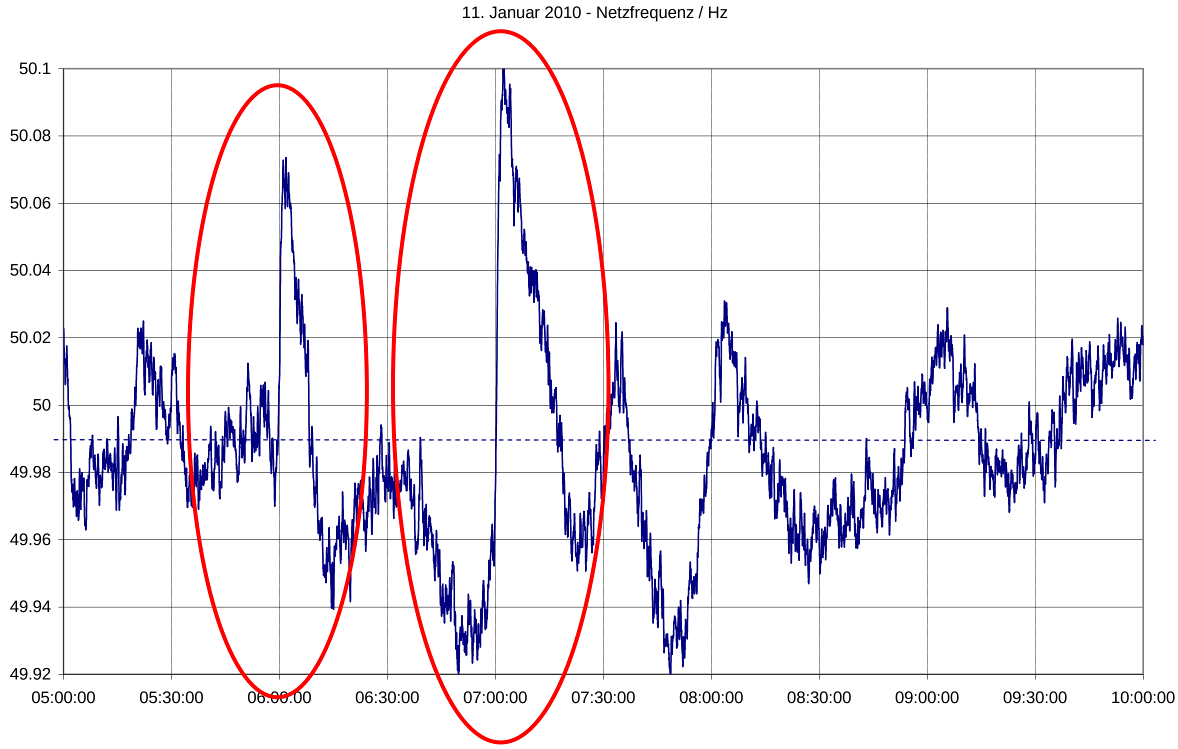

Fig. 3.4: CE System frequency during morning hours of January 11th 2010. Source: Swissgrid

The individual contribution depends on the available technology. The more the plant is sensitive to frequency response by design and tuning, the higher the plant is affected and disturbed.

Consequences:

Power plants are designed to contribute to frequency control for frequency perturbations, based on a normal distribution due to normal system operation. ENTSO-E states observable activation of primary control for a frequency variation greater than 20 mHz. The average frequency RMS observed is about 20 mHz too. When frequency deviates largely and often above (or below) the "standard" fluctuations (less than about 75 mHz), plants are solicited in non-normal ways.

According to the different frequency response well founded by technical construction and sensitivity of power plants, the same large frequency deviation generates many different impacts on plants. Plants are not affected in the same way by frequency deviations. Due to the significant influence of aging and tuning in dynamic performances, plants belonging to the same family (example, 600 MW coal fired units) behave in significantly different manner, with impacts on different equipment.

Due to the excessive use of the primary control, most of the primary reserve is used in less than the first minute. In order to keep enough safety margins, this predictable situation forces TSOs to largely offset the secondary level signal, thus requiring after the large frequency deviation from the setpoint a larger contribution for secondary control. A few minutes after the large frequency deviation, the distribution of the available reserve capacities is significantly disturbed and the defence against a sudden large generation loss is weakened.

3.2.1. CONSEQUENCES ON TECHNOLOGY

Wind power plants

As wind turbines do not yet participate in primary control, no corresponding impact is observable. However, outside of the frequency range of ± 200 mHz around 50 Hz the risk of uncoordinated disconnection or re-connection of all kind of renewable generation mainly feeding in lower voltages levels can be considered to be quite significant. Generally, wind farms are quite sensitive to frequency deviations and have a higher probability to get temporarily disconnected.

- Turbines equipped with induction generators have their gear box highly used.
- Variable speed machines and doubly-fed induction are less used.
- Full converter turbines are not used, because they do not provide inertia.

Hydro:

- Francis turbines – no major consequences observed so far.
- Pelton turbines: - in case of power loop with primary response operation, if the frequency deviations occur in power points where the nozzles' configuration is changing. This type of phenomena leads to double nozzles movement which can use their hydraulic system.
- Kaplan turbines: are the most affected in runner mechanism. The cause is the double movement in Winkles Gates due to frequency deviation and through the combinatory coupling, the reference transmitted to runners involves instabilities. Also in case of larger units with considerable inertia, the ± 75 mHz variations at 5-8% drop lead to double action of a hydraulic system with consequences in axle bearing
- Run-of-river (RoR) power plants might have problems with the water flow control. Generally RoR power plants are equipped with Kaplan turbines. Due to this fact, all technical consequences concerning the Kaplan turbines noted above have an impact on the operation of these power plants.

Thermal:

Conventional thermal power plants participating in primary control on a contractual basis are highly affected during significant deviations of the system frequency from the setpoint.

Generator and turbine thermal and mechanical stresses, mills speed deviations, high risk of combustion self-extinction, security and high frequently valve opening (noise pollution) lead to higher maintenance and reduction of the lifetime of the power plant equipment. In case of a small drop, the whole boiler control process reaches its stability limits.

Another effect of the frequency deviations phenomena is that power plants are not operated efficiently, hence causing higher emissions which impact the natural environment.

The following figures illustrate the impact of high frequency variations on the operation of a typical conventional thermal power plant with a rated power of 250 MW.

By having the system frequency as one main control input variable the generator active power output of a conventional coal-fired power plant deviates as shown in **Figure 3.5**:

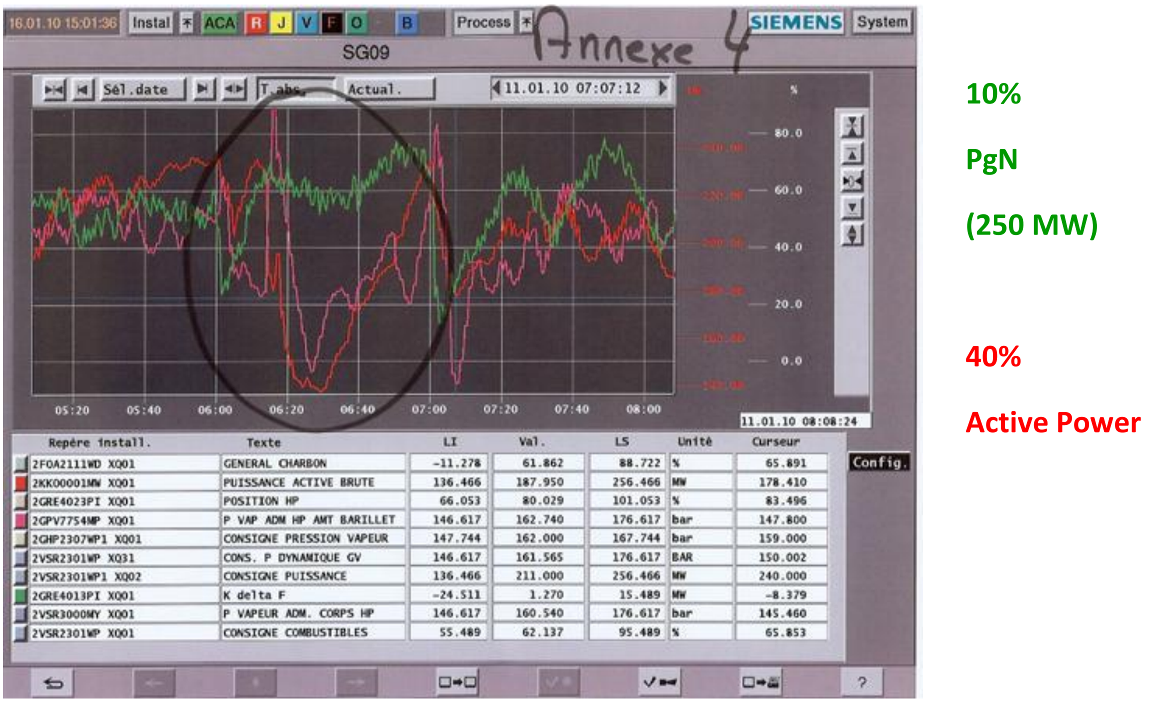

Fig. 3.5: Active power deviations due to frequency variations. Source: Electricité de France (EDF)

Figure 3.6 and **Figure 3.7** illustrate how internal power plant control loops responsible for fuel flow or temperature control are affected and operate close to their stability limits:

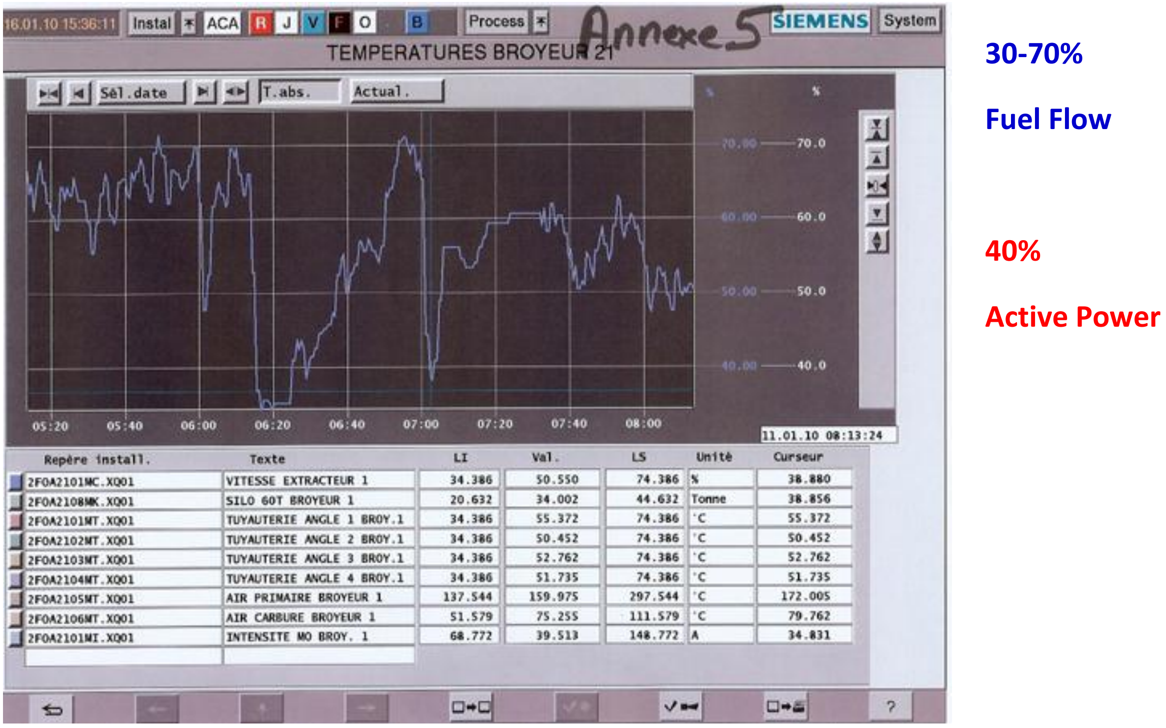

Fig. 3.6: Coal mill operating point variations. Source: Electricité de France (EDF)

0-40 t/h

Steam within

Reheater

+/- 20 °C

Temperature

Difference

40%

Active Power

Fig. 3.7: Mass flow and temperature control variations. Source: Electricité de France (EDF)

Nuclear : Nuclear power plants participating in primary control are highly used by delivering the full primary response for frequency deviations lower than 50 mHz, hitting power limiter and extracting power control rod up to the maximum.

Figure 3.8 shows a primary frequency response of a 1300 MW plant (in green the mechanical power of the turbine, red and blue are control rod positions). At 00:13 on June 23rd 2010, the primary response (90.7% to 96%) is followed by a short stabilisation, then secondary response, pushing the plant to almost full throttle (98.3%). 10 minutes after, initial conditions are still not recovered, even with a decreasing demand (50278 MW @ midnight and 47372 MW @ 00:30 am; 30 min after).

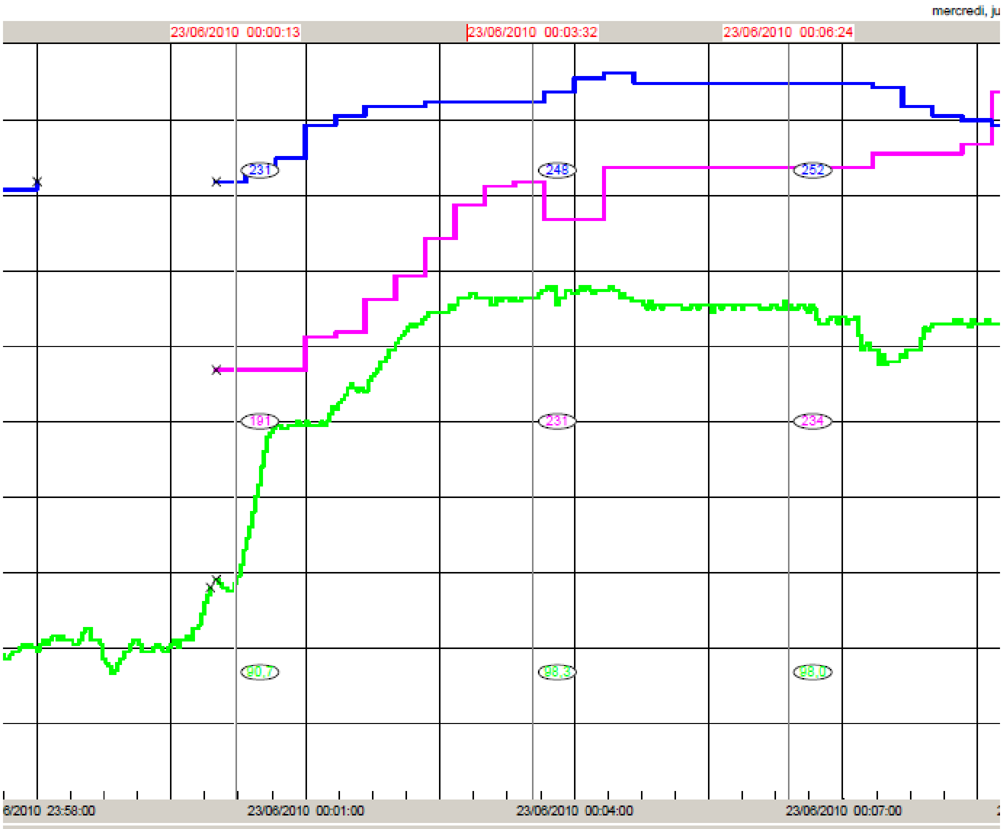

Fig. 3.8: 1,350 MW nuclear plant primary frequency responses on June, 23rd, 00h00. Source: Electricité de France (EDF)

Figure 3.9 shows a 140 MW step in 9 minutes for a 1350 MW unit. The normal operation procedures limit the frequency response to 2.5% for the primary and 4.5% for the secondary controls. The plant is not allowed to operate when power steps are over 10%.

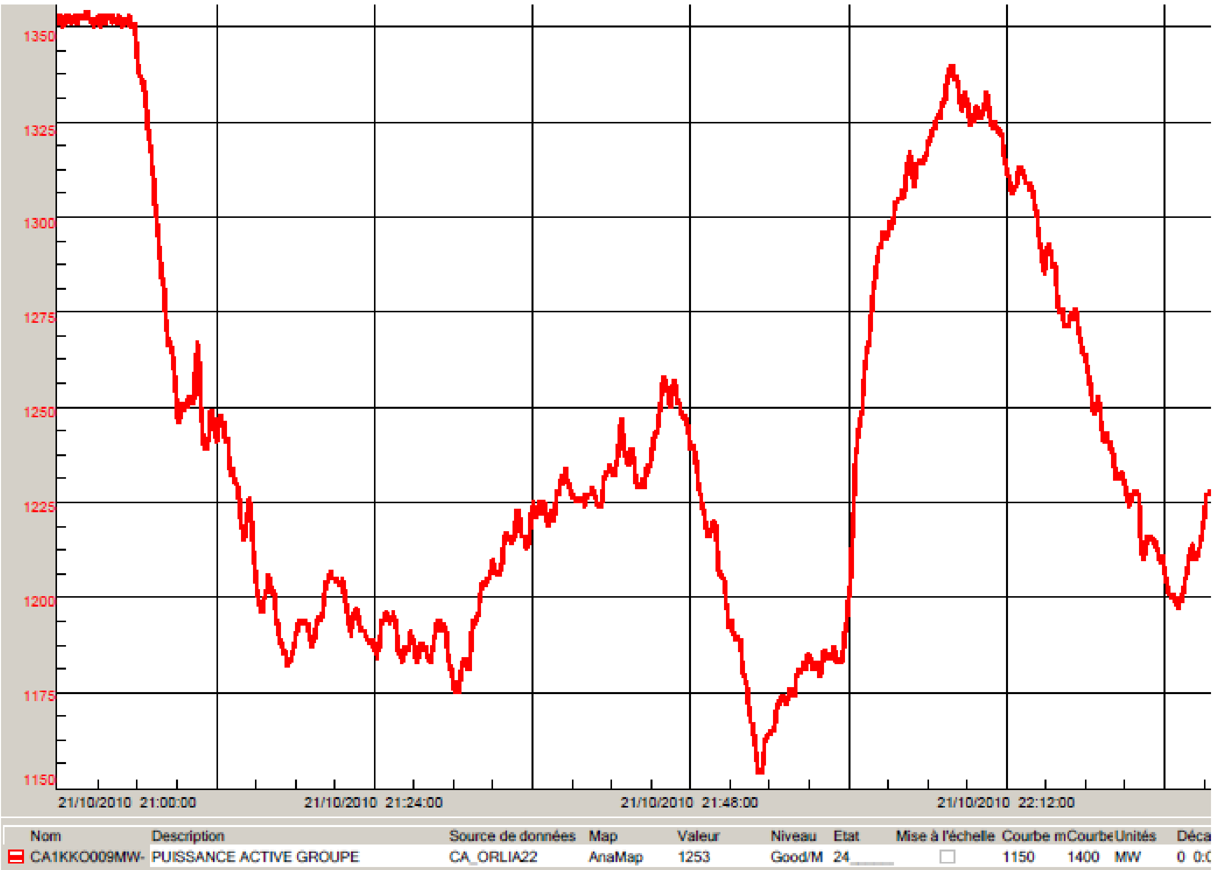

Fig. 3.9: 1,350 MW nuclear unit electrical power on October, 21st, 2010, 22h00. Source: Electricité de France (EDF)

4. PREVIOUS STUDIES RESULTS AND OTHER SYSTEMS EXPERIENCES

4.1. FREQUENCY QUALITY INVESTIGATION WORK GROUP

The work of the former UCTE ad-hoc group called Frequency Quality Investigation group (FQI) included the assessment of the risk level for the electric system due to deterministic frequency deviations, the analysis of the system behaviour using data collections, and searching for the causes and possible solutions of the frequency excursions in the electric system /1/. A system simulator was developed in order to reproduce the frequency excursions and to evaluate possible improvements in the system behaviour. The simulator was adjusted using real data from frequency excursions that took place in the synchronous network.

4.1.1. OPERATIONAL RISKS AND CONSEQUENCES

The study showed the following operational risks and consequences associated with increasing frequency deviations:

- Higher and repetitive use of primary reserves, and risk of insufficient primary reserve, particularly if grid outage or power plant disturbance occurs during frequency excursions. In addition to the repetitive use of primary reserve in a structural way, a technical and economic problem exists from the point of view of generation companies.

- Decreased damping of frequency oscillations due to low availability of primary reserve, causing the damping of inter-area oscillations to be also reduced.

- Power flow variations: The deep frequency excursions result in unscheduled power flows due to primary reserve activation. The effect of these unscheduled flows over the lines can last for periods of up to 15 minutes, leading, in certain cases, to temporary overloading of network elements.

- Risk named above (in 3.2.1.1 consequences on technology)

4.1.2. ANALYSIS OF THE FREQUENCY INFLUENCES

For the study of the root causes that lead to frequency excursions, the following phenomena were studied:

- Seasonal and time influence: The study of the mean values of daily frequency curves per month proved a seasonal effect and a strong hourly effect depending mostly on the consumption curve shape in each season. In general, the higher the gradient of demand, the higher the frequency deviation.

- Inter-area schedule changes: The possible correlation between inter-area schedule changes and frequency variations was studied. However, the studies didn’t always show a clear correlation. The cause is that not only the inter-area schedules affect the frequency deviations, but also and mainly the schedule changes inside each area.

- Control of hydraulic units: The impact of the control of hydraulic units on frequency deviations was analysed in detail, based on the collected information from measurement campaigns, individual measurements and simulating the behaviour of the system. The variation in the hydro energy was found to be a very important cause of frequency deviations. The gradient of power output that can be achieved with hydro power may lead to very fast power output variations. These ramp rates cannot be counteracted immediately by the Load Frequency Control, thus the effect on the frequency is approximately similar to an outage of a generator.

- BRP and producer control strategy: Schedule changes between market parties inside areas are one of the main causes for frequency variations. The change in the schedules of different Balance Responsible Parties (BRPs) in an uncoordinated way increases the problem. The root cause for this is that the control target for BRPs is the energy delivery, whereas the operational real-time control is centred on the power balance at each moment.

4.1.3. Considered Measures and Recommendations

Several suitable measures were taken into account in order to improve the system balancing and reduce the inter-hour frequency excursions. The measures studied were the following:

Increase of reserves (primary and secondary)

The option to increase primary reserve in UCTE in order to stabilise the frequency is discarded since it would be a very uneconomical solution. In order to efficiently counter the observed variations at least the double amount of primary reserve would be needed compared to the current reserve. Besides, there are technical reasons that discourage increasing primary reserve as a solution for deterministic frequency deviations: the target of primary control reserves is to ensure power balance during forecasted load deviations or unexpected generation or load outages. The target of primary control reserves is not to cope with deterministic frequency deviations which should be mitigated avoiding their known cause.

The increase of the secondary reserves does not mitigate the problem either, since the deployment time is too large in comparison to the speed of the observed frequency deviation. This was confirmed by simulation results. Increasing the amount of secondary reserves only brings a slightly faster recovery of scheduled frequency value, as can be seen in **Figure 4.1** which presents the simulated frequency deviations for different amounts of secondary reserve.

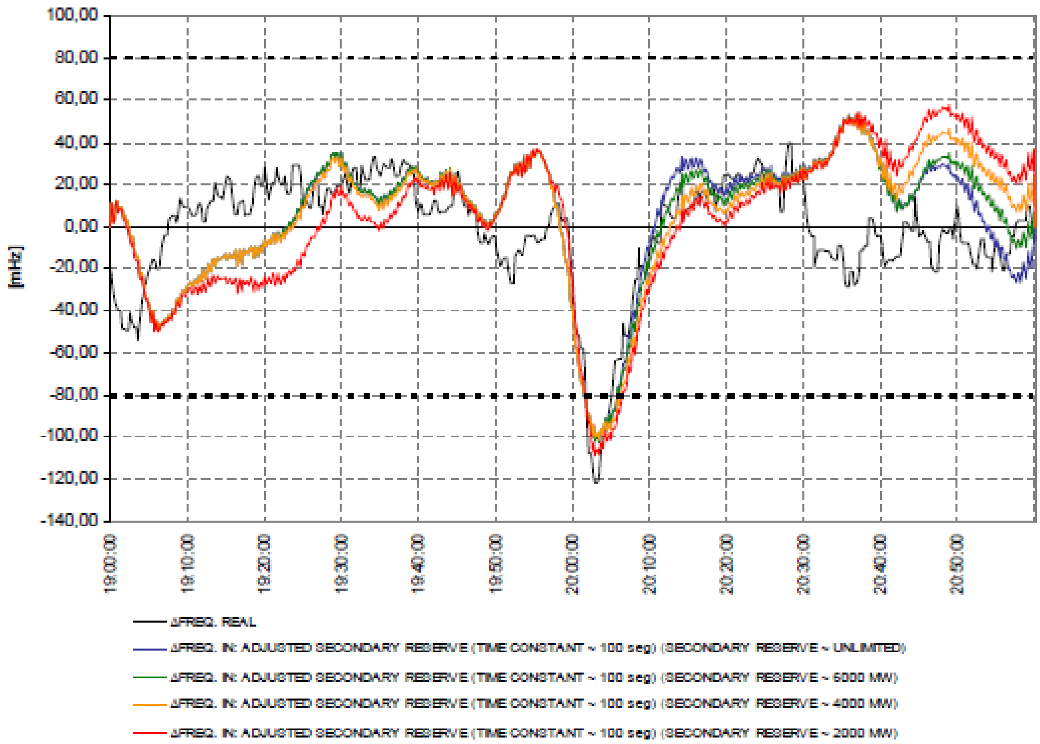

Fig. 4.1: Simulated frequency deviations for different amounts of secondary reserve. Source: Red Eléctrica de España (REE)

Increasing the speed (i.e. reducing the activation time) of secondary response does not solve the problem. Even with a fast secondary response, the activation time of secondary reserve is not comparable to the frequency variation speed. As can be seen in the simulation results shown in **Figure 4.2**, increasing the speed of secondary response only brings a slightly faster recovery of scheduled frequency value.

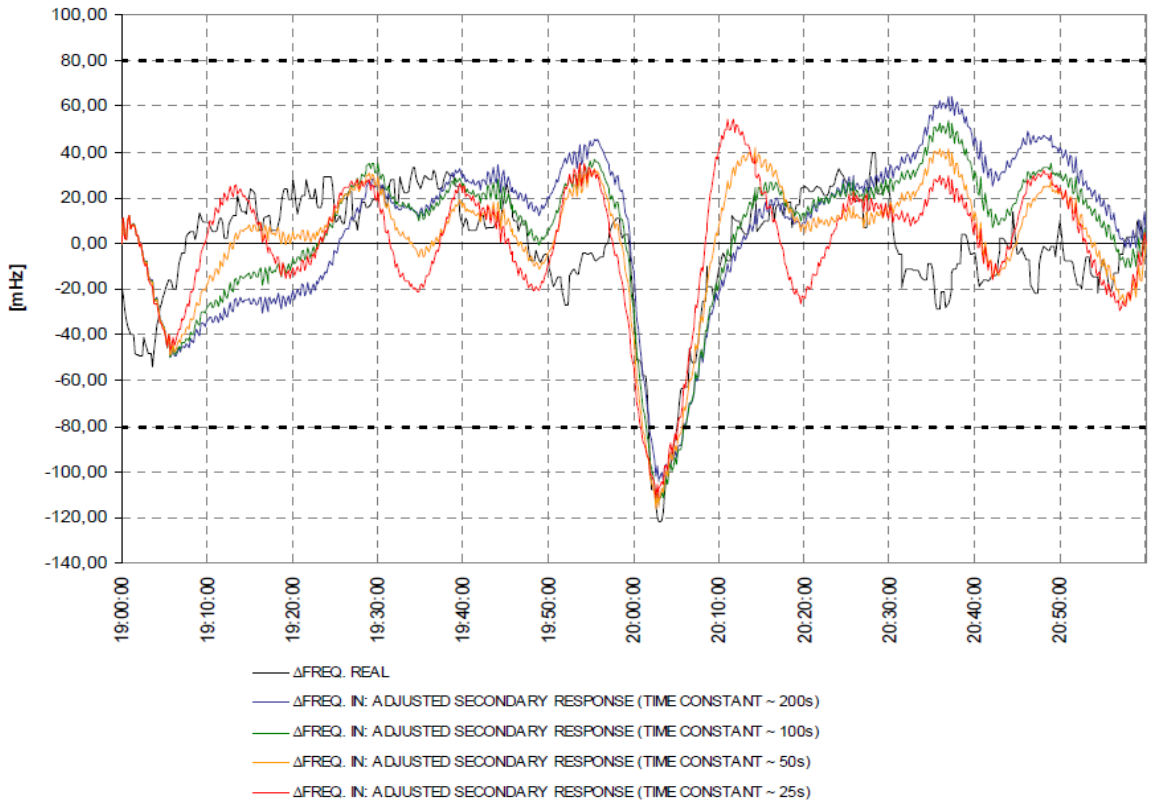

Fig. 4.2: Simulated frequency deviations for different speed of secondary response. Limit generator and demand gradients. Source: Red Eléctrica de España (REE)

Defining a maximum gradient for each TSO for all global generation changes was considered as a useful way to improve system performance. This global gradient should be linked with the capacity of the secondary control reserve of each TSO. If the schedule change is higher than that value, TSO should ask power generating companies to stagger the groups connection or disconnection in order to smooth the variation.

In order to achieve an efficient application of this rule, the TSOs should have the ability to monitor the system power output with a time frame no longer than 10 seconds. The TSOs should also have the scheduled programs of each important generation group. The limits for gradients should be applied during +/-5 minutes of the TSO ramping periods. Besides, the implementation of this rule should be taken into account for imbalance accounting, in order to not penalise, but incentivise the ramping efforts made in order to respect the gradient limits.

The simulations proved that limiting the gradient for global generation changes would considerably reduce the frequency deviations. **Figure 4.3** shows the simulated frequency deviations that result when the gradients in schedules are limited. As can be seen, the frequency excursions are notably reduced.

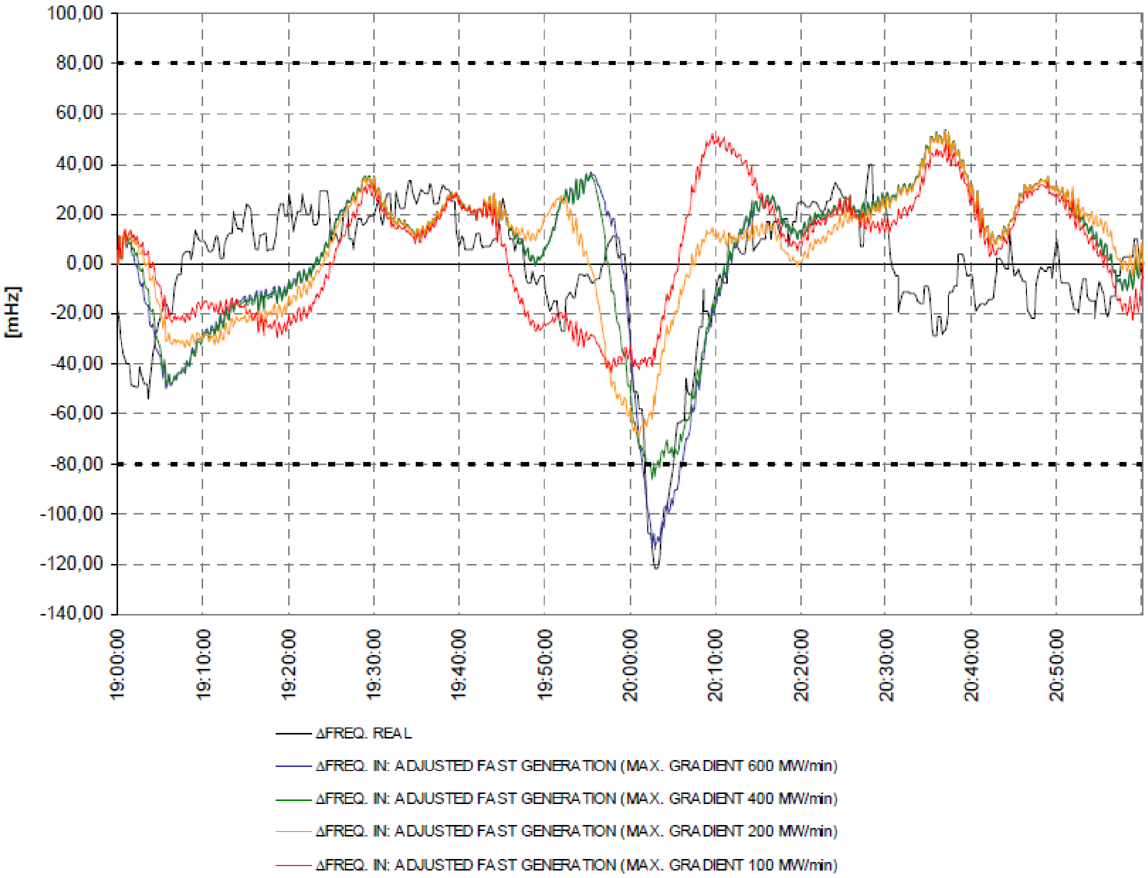

Fig. 4.3: Simulated frequency deviations for different gradients of fast generation. Source: Red Eléctrica de España (REE)

Other possible measures were studied, but finally discarded in the FQI work group. Defining a limit in schedule changes for the market activity was considered as a measure that, despite improving the frequency performance, would be unacceptable under the present market regulations. Changing settlement periods to shorter intervals was considered as a useful solution, since it would imply a better “load following” behaviour of the system.

4.2. VGB PROJECT REDUCTION OF POWER STATION LOADS FROM GRID CONTROL

In the framework of the VGB-research project 306 "Origins of the Occurrence of Large Frequency Deviations within the UCTE Power System and Improvement Measures" several analyses of the frequency behaviour were made /2/. A short abstract of the main reasons for the deterministic deviations is given in the following chapters[2].

4.2.1. DETERMINISTIC PART OF THE FREQUENCY

Figure 4.4 shows the ensemble-average values of the frequency in December 2009. Because of the averaging over this long time period, only the deterministic values of the frequency are visible. There are two characteristic patterns: On the one hand, the large deviations at the full hour in the morning and the evening, on the other hand, the characteristic rise/drop of the frequency over the hour.

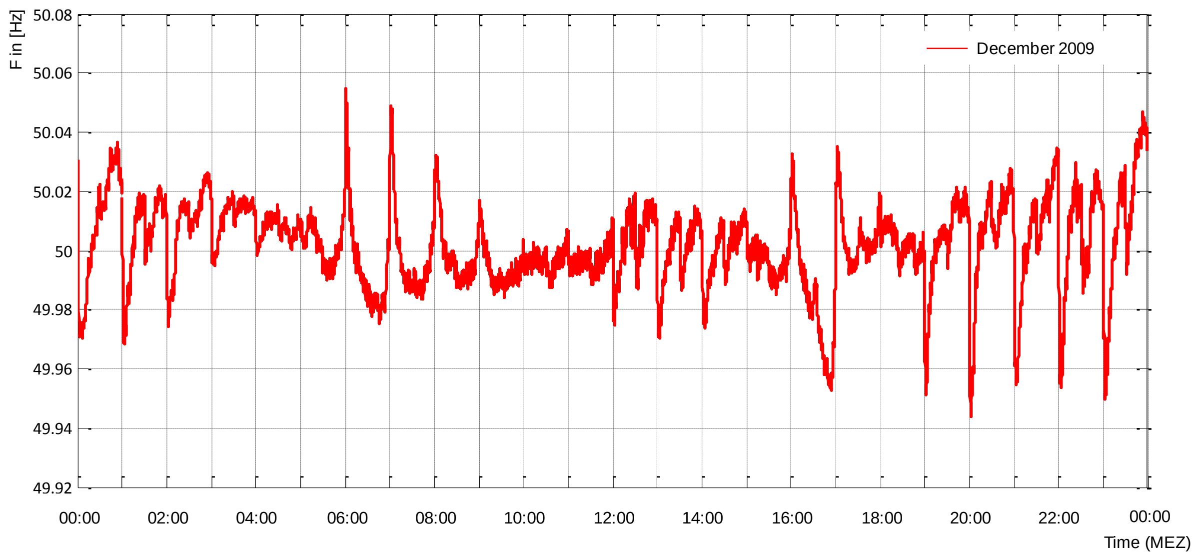

Fig. 4.4: Ensemble- average values of the frequency in December 2009. Source: University of Stuttgart.

4.2.2. CONNECTION TO THE LOAD BEHAVIOUR

Regarding the behaviour of the load and the frequency deviations, a distinct correlation between both is visible. Further investigations will show that the correlation is due to the connection between market based generation and physical load behaviour. If the load increases, the frequency rises above 50 Hz, if the load decreases, the frequency drops below 50 Hz. This market-induced behaviour of frequency and load is completely opposite to the real physical dependences between them.

Figure 4.5 shows this behaviour. The green curve shows the behaviour in summer, the grey curve in winter.

2 Weißbach T., Welfonder E.: High Frequency Deviations within the European Power System – Origins and Proposals for Improvement, VGB PowerTech 6/2009 page. 26 – 34

The time interval between 16:30 and 18:30 offers a very good clue as to the origins of the frequency deviations. Within this time frame there is an increase of power demand during the winter months leading to frequency deviations. In contrast, there are no big changes of the power demand during summer within the respective time interval, and no frequency deviations are observable. Obviously, the load behaviour and the frequency deviations are correlated.

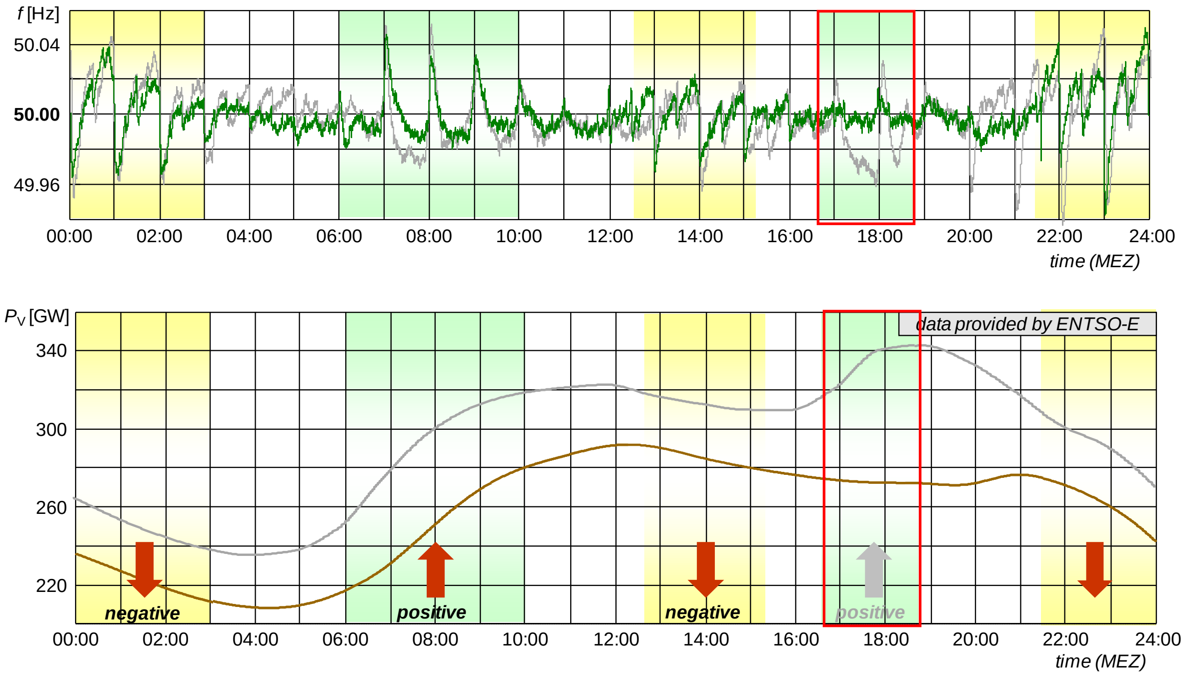

Fig. 4.5: Connection between load and frequency; summer month in green, winter month in gray. Source: University of Stuttgart

4.2.3. REASONS FOR THIS CORRELATION

The reason for this correlation lies in the electric power market and corresponding market rules. **Figure 4.7** clearly describes the situation in the German power market; however, similarities can also be found in many other European power markets.

Looking at the morning hours of the day, the demand side shows a forecasted increasing behaviour of the load. Due to the market rules, the demand side needs to order 1-h block based products to cover this load. The generator side generates the ordered amount of energy following the 1-h-schedules as tight as possible to reduce imbalance energy costs. Between the continuously increasing load and the stepwise increasing generation a power imbalance occurs. After the change of the hour, there is a large power surplus turning into a power deficit as the load increases continuously. This "stepwise" imbalance cannot be balanced by control energy at any reasonable cost; in consequence the frequency rises instantly and drops again below 50 Hz over the hour.

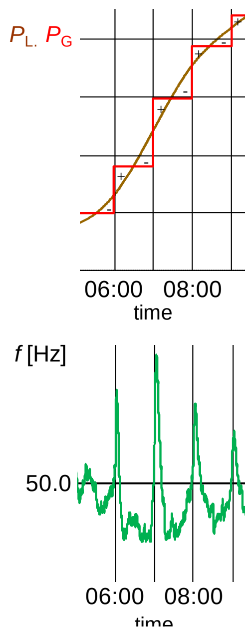

Fig: 4.6: Behaviour at change of the hour. Source: University of Stuttgart

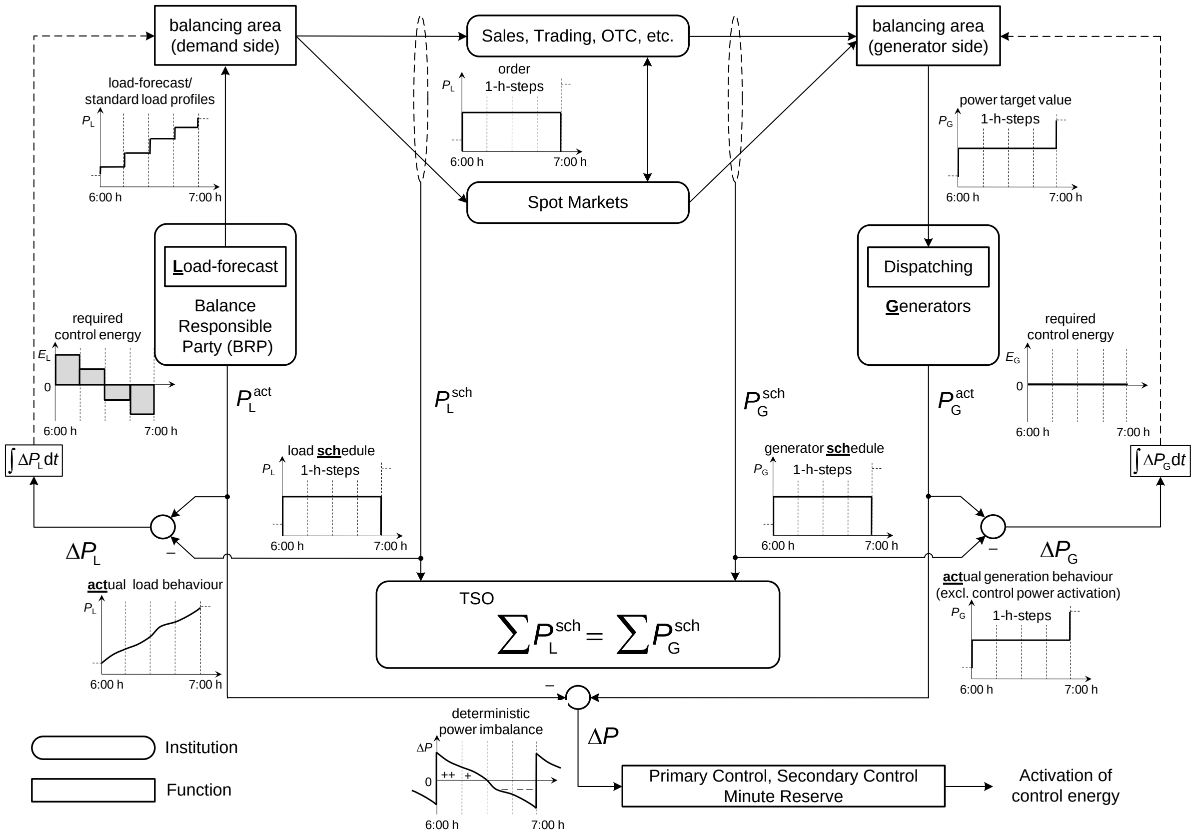

Fig. 4.7: Power-system market, situation in Germany. Source: University of Stuttgart

To sum up it can be said that the large power imbalances between generation and consumption mainly arise from the power difference between the continuous ramp-wise physical load behaviour and schedule/market-rule-based step-wise power generation. The changes are inherent in the system according to actual market rules and market boundaries and entail the observed frequency deviation despite the correct impact of the load-frequency control mechanisms. In particular, the main origins of the power imbalances are not related to any “misconduct” of market participants.

There are several other potential origins for the frequency deviations that have been investigated as well, including:

- Mismatch between fast and slow generation
- Stepwise load behaviour on the demand-side
- Use of a possible arbitrage between spot market prices and control energy prices by individual BRPs

All evaluations, surveys, measurements and simulations performed during the corresponding VGB project show that these origins are clearly subordinate.

4.3. EXPERIENCE AND PLANNED ACTIONS WITHIN THE NORDIC SYSTEM

4.3.1. BACKGROUND: THE NORDIC BALANCING MODEL

The Nordic frequency quality has shown a weakened tendency over the last ten years, see (**Figure.4.8**) and /3/. To remedy this, to improve the conditions for system operation in general and to prepare for expected future development with more HVDC-connection to other synchronous systems and more fluctuating production (wind), the Nordic Transmission System Operators (TSOs) agreed to implement a ”package” of actions (see below).

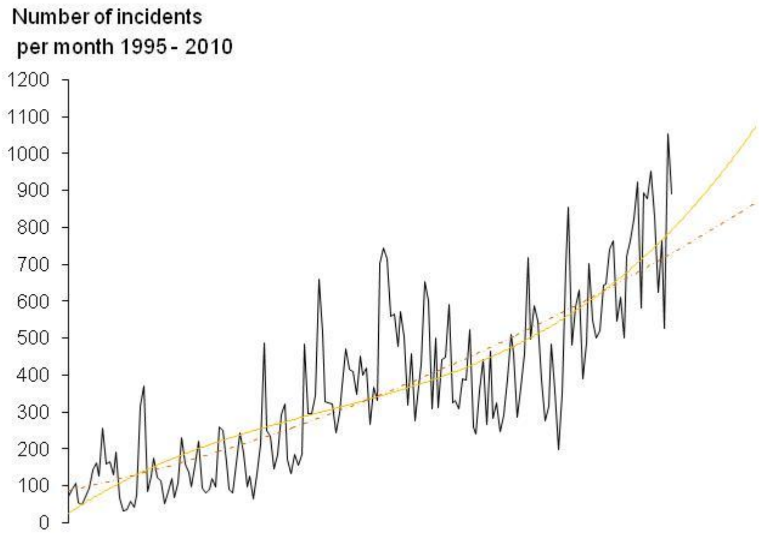

Fig. 4.8: Number of incidents pr. month where the frequency has been outside of the normal operation band (49.90 Hz < f < 50.10 Hz). Source: Statnett.

The power system is dependent upon a continuous and momentary balance between production, consumption and exchanges. The energy market is supposed to secure the balance on an hourly basis. In the Nordic area 70% (2009) of the consumption is traded through the day-ahead market, 12-36 hours ahead of delivery.

In the Nordic market there is an obligation according to regulations/rules and agreements for the BRPs to balance their positions in the day-ahead market (Elspot). Finally the BRPs send in firm hourly power notifications (notification plans) to the TSOs currently no later than 45 minutes before each operational hour. These plans are used for operational planning and also as input to the settlement with hourly resolution.

After the intraday market has closed, the system balancing is centralized and performed in cooperation with the Nordic Transmissions System Operators (TSOs) by means of common arrangements such as e.g. the Nordic bid ladder for tertiary regulation. The actions that the TSOs do to balance the system is partly planned actions (4 hours to 30 minutes before operational hour) and partly real time actions.

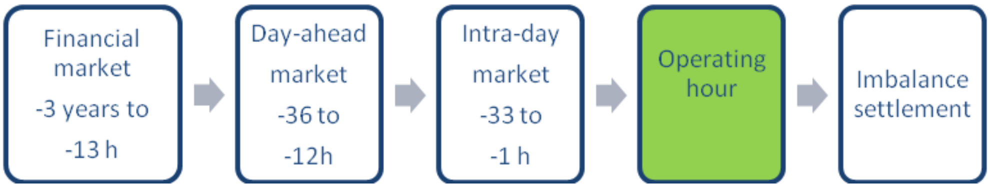

Fig. 4.9: The different market segments before and after operating hour. Source: Statnett

4.3.2. THE AGREED ACTIONS

The agreed action can be divided into two groups: i. better operational planning (presented in chapter 4.3.2.1); and ii. new and improved operational tools to handle the real time balancing (see chapter 4.3.2.2).

4.3.2.1. BETTER OPERATIONAL PLANNING

The main idea behind these actions is that the better operational planning and the more adequate system balancing actions taken before the real time system balancing, the less expensive reserves are needed for the real time balancing. Some of the most relevant actions are listed below.

RAMPING RESTRICTIONS ON HVDC-CONNECTIONS BETWEEN SYNCHRONOUS SYSTEMS

The current capacity on HVDC-connections between the Nordic synchronous system and the Continental European synchronous system is 4,000 MW. The Nordic system is about 1/5 as large as the Continental system. This – together with the fact that the flow pattern on the connections behaves like consumption seen from the Nordic system (more export in the morning and opposite in the evening) – leads to HVDC connections having a much larger impact on the Nordic system than the Continental system. The variation in exchange on those connections is more and more synchronized resulting in price variations in the two systems in the day-ahead markets. Due to this there are potential risks for up to 8,000 MW change in flow on those cables at one hour shift. To avoid this threat to system security, the Nordic TSOs agreed to restrict possible changes in the exchange on each cable connection to maximum 600 MW from one hour to the next. Currently this allows for up to 3,000 MW changes in exchange at any one hour shift. The TSOs are monitoring the economic consequences of this restriction and compare with other alternative actions like extra reserves, counter trade in the market, etc. The goal is to find the best socioeconomic solution. There is also a restriction on the gradient for changed flow on the individual connection (max 30 MW/min giving a total of about 200 MW/min for the synchronous system).

COMMON NORDIC GATE CLOSURE FOR PRODUCTION PLANS

A consequence of the Nordic balancing model is that the TSOs must have the possibility to know the size of the imbalances to expect, which must be taken care of. To have as accurate information as possible, a lot of effort is made to improve forecasting tools for consumption and wind production. All production units must deliver production plans to the TSOs before the operating hour. In order to have sufficient time to plan the system balancing and execute needed actions before real time, the TSOs agreed on a common

Nordic gate closure for production plans 45 minutes before the operating hour. The estimations for expected imbalances are calculated with quarterly resolution in a common Nordic IT-system.

Quarterly resolution for production Schedules

As mentioned earlier, the Nordic market has hourly resolution. This tends to result in flat hourly production plans which are not in correlation with variations in consumption and exchange with other synchronous systems. To achieve a better system balance within the hour, the Nordic TSOs agreed that large producers must deliver production plans with quarterly resolution and different quarterly values according to specifications especially addressing the physical system balance 15 minutes before and after each hourly shift. The specifications are yet to be detailed and full implementation is expected in 2013. (Norway which is nearly 100% hydro-based has had such plans for a decade).

A possible future option is to change to quarterly based settlement.

Ramping product

The size of the synchronous system is rather small (90 000 MW installed capacity, 70 000 MW peak load) compared to the HVDC-cable capacity to other synchronous systems. This implies that ramping on the cables has a large impact on the system balance. To be able to follow the planned ramping on the HVDC-cables, a new ancillary service product is planned to be implemented where production units with large variations in their production will receive minute-based adjustments of their physical plans before real time (15-30 minutes before real time). Expected Nordic imbalances are the input for the adjustment signal. The plan is to use the future under construction AGC infrastructure for the secondary control for this purpose.

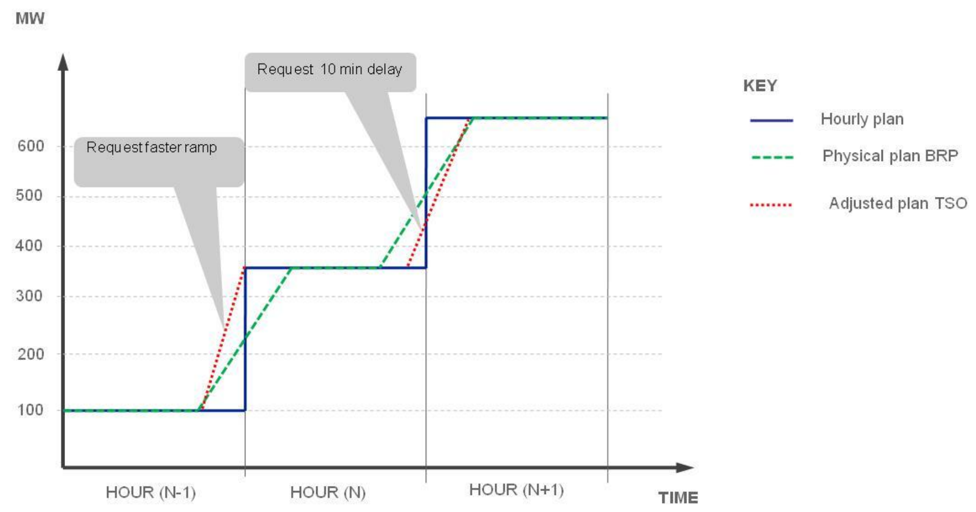

Fig. 4.10: Examples of consequences of planned ramping product. Source: Statnett

4.3.2.2. *IMPLEMENTATION OF AUTOMATIC SECONDARY CONTROL FOR REAL TIME BALANCING*

So far there has been no automatic secondary control in the Nordic system. The integration of markets over larger areas and the increased grid capacity has meant that previous balancing tools (primary and tertiary control) are no longer sufficient to cope with the need for system balancing of the remaining imbalance after the actions in 3.1. Consequently the Nordic TSOs are now planning to implement a common single system for secondary control of the whole synchronous system. The secondary control will have frequency as the main input and is therefore a Frequency Control (FC) different to the LFC which is common on the continent. The main functionalities of the FC are shown in the figure below.

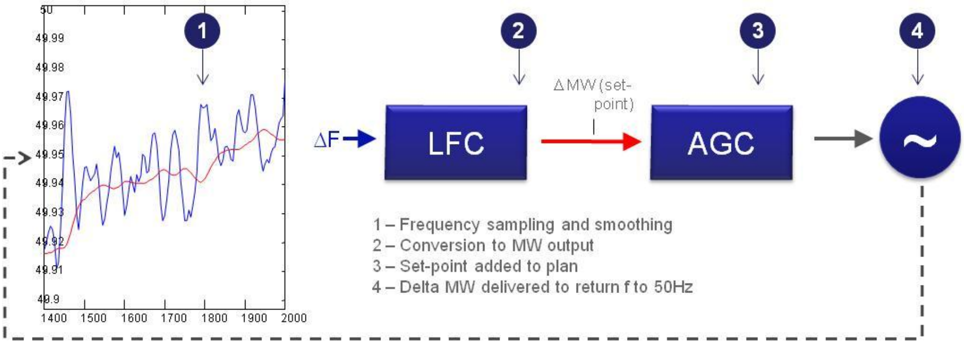

Fig. 4.11: Principles for Nordic secondary control. Source: Statnett

4.4. FREQUENCY OF TURKISH POWER SYSTEM AFTER MARKET OPENING

Before connection of the Turkish power system on Sept. 18th 2010 to the CE system Turkey operated within an electric island with a peak power of about 30 GW.

Market opening started in Turkey at the end of 2009. **Figure 4.12** and **Figure 4.13** show how the schedule changes synchronously with change of the hour had the same impact as observed in our systems too. The frequency measurements represent the average frequency over all the days of one respective month /4/.

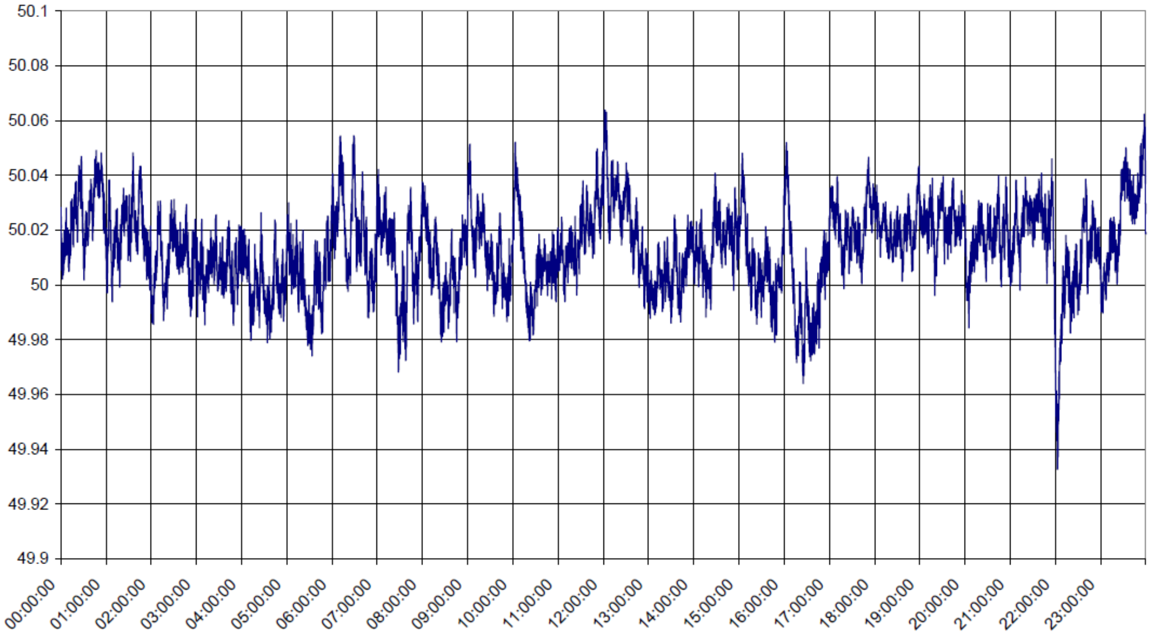

Fig. 4.12: Frequency Turkey Electric Island, November 2008. Source: Swissgrid

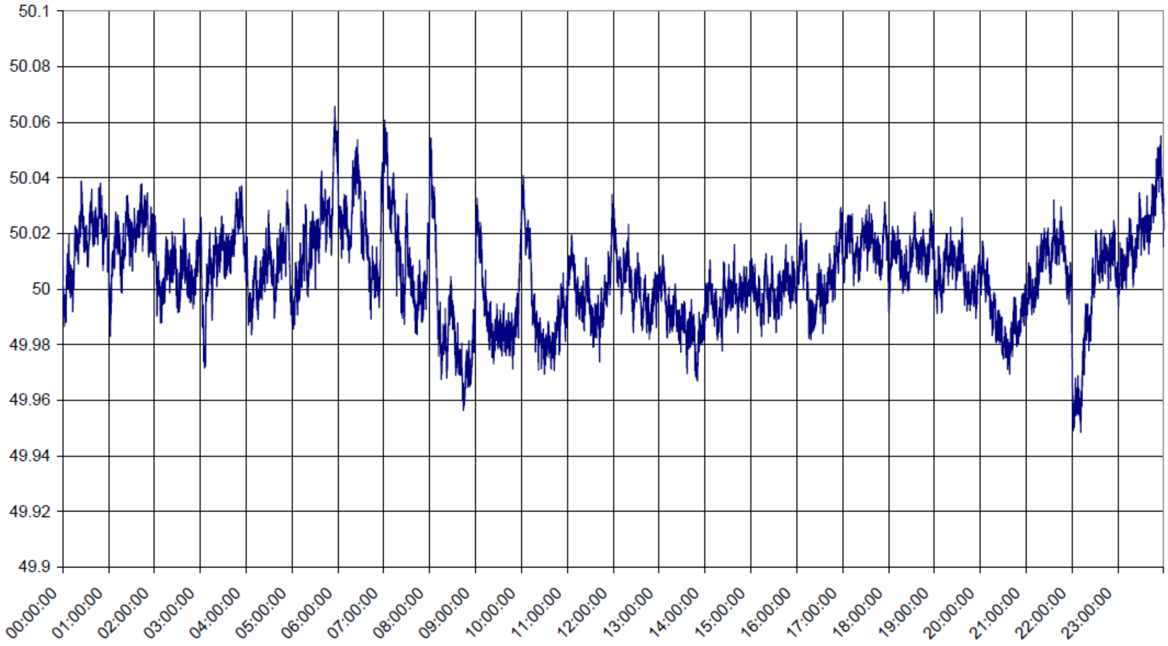

Fig. 4.13: Frequency Turkey Electric Island, August 2009. Source: Swissgrid

4.5. BALTIC STATES FREQUENCY BEHAVIOUR

Baltic power systems are part of IPS/UPS and secondary control within IPS/UPS is performed in such a way that every interconnected power system IPS (control area) controls its own account balance and unified power system UPS (control block) controller controls frequency. The UPS dispatching centre maintains the frequency of the entire IPS/UPS. There are agreements between interconnected power systems for maximum permissible power and energy deviations for limiting time frame also during hourly schedule changes.

Some correlation between hourly schedule changes and frequency deviations can be observed in IPS/UPS, although the frequency changes are not that big and usually are from 30 to 40 mHz (**Figure 4.14**, **Figure 4.15 and Figure 4.16)** /5/.

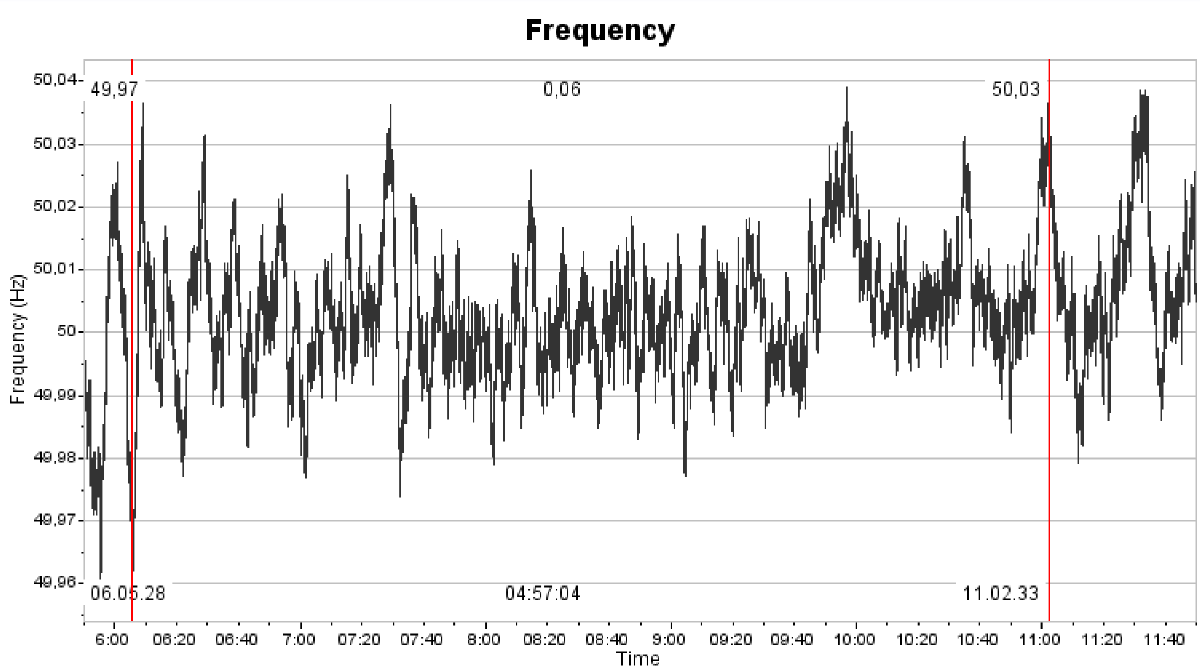

Fig. 4.14: Baltic System Frequency, January, 27th 2011, Source: Litgrid

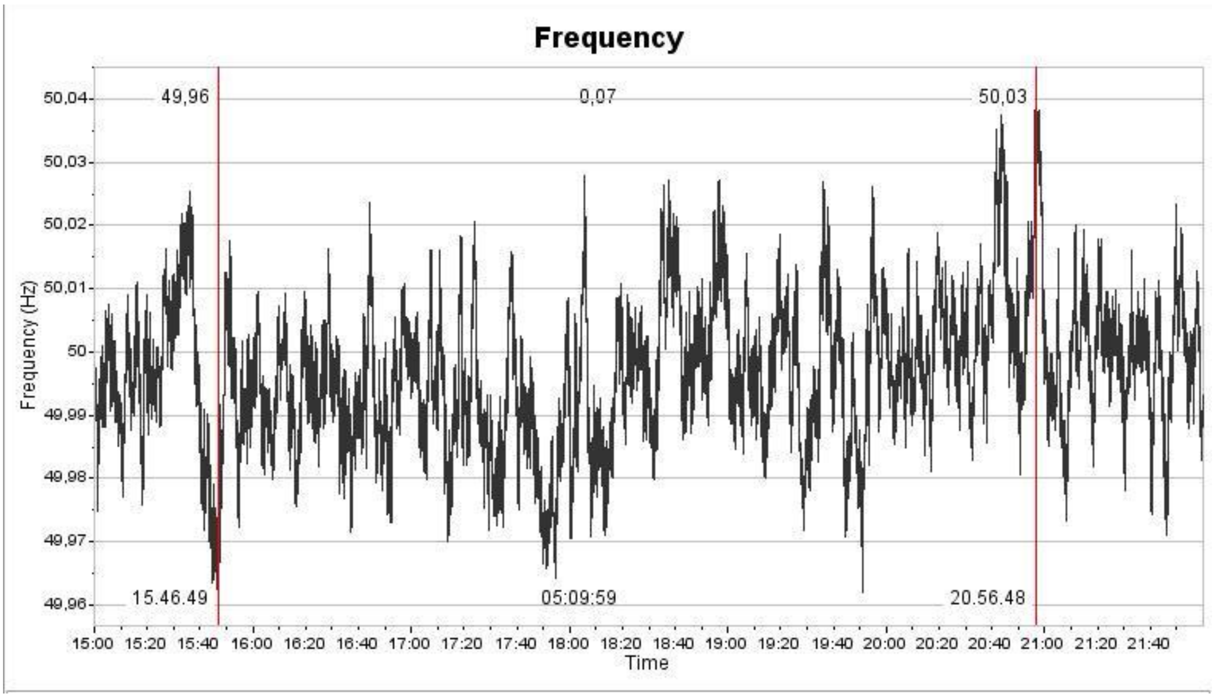

Fig. 4.15: Baltic System Frequency, January, 30th 2011. Source: Litgrid

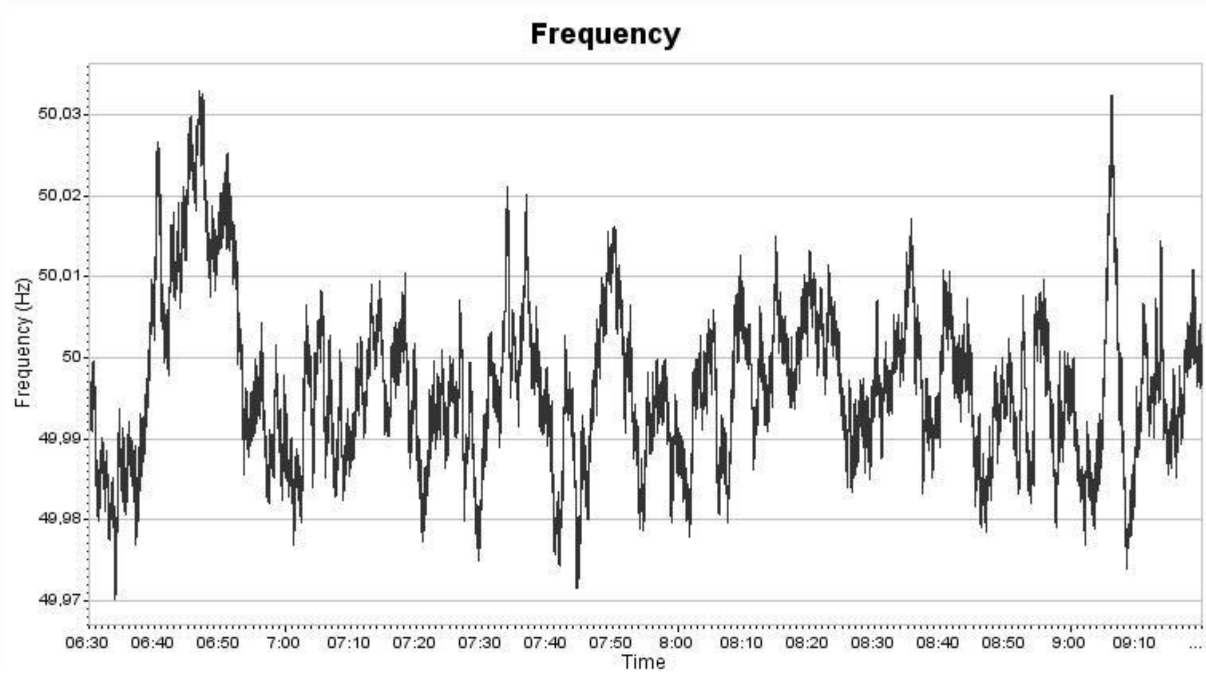

Fig. 4.16: Baltic System Frequency, January, 30th 2011. Source: Litgrid

During 2010 99.7% of time frequency was in range of ±50 mHz and deviations over ±200 mHz were not observed at all.

This perception clearly shows the difference between another market system and other control principles, and ultimately confirms the market mechanism influences on the frequency deviations within the ENTSO-E system.

It should be noted that similar observations related to deterministic frequency deviations around the change of the hour were made in the North American system too /6/.

4.6. CONCLUSIONS BASED ON QUESTIONNAIRE EVALUATION

The aim of the questionnaire was to have a global image of market and generation. It was divided into two sections: the first section asking for the generation behaviour: type of schedule, type of settlement, recognition of natural ramps and type of compensations, the harmonization market possibilities, and the second section asking for the TSO behaviour related to the frequency deviations.

We have analysed the collected questionnaire answers from 12 companies including TSOs and generation companies.

The main conclusions are:

1. The majority of electricity markets are based on generation hourly energy schedules/blocks without special requirements regarding steps value or requirements on ramping.

2. The majority of TSOs intend to diminish the interval schedule (e.g ¼ h) and implement intraday market. This natural tendency should mitigate the deterministic frequency deviations. It is not strictly required to harmonise the interval schedule, a different time frame (15 min, 10 min) could have a positive impact on the phenomena.

3. Within the majority of TSOs there are no special rules (in market or operation/codes) concerning power evolution within the time frame (1/4 or 1 h.) schedule. Respecting technical possibilities of generating units (TPP) or in order to avoid high generating steps (HPP) at change of the schedule, some TSOs ask for unit ramps centred on schedule changing time.

4. The ramping energy is more or less considered in the settlement process. All TPP are required to follow a ramp centred on schedule frame. The time ramping usually lasts 10 minutes. In the majority of cases this process is not clearly described in market rules as schedule and settlement.

5. In the main and largest control blocks the ramp rates are compensated by a few generators in order to respect the declared schedule step. This solution leads to frequency deviation and creates an artificial generation which is not asked by consumption. A few TSOs try to compensate the high impact of fast generation schedule change (stop/start) creating generation ramps from different moment of activations of hydro units. Therefore e.g. the Rumanian TSO Transelectrica has recently introduced a new settlement process which takes ramping periods into consideration. Being singular examples, they can have an impact on frequency mitigation.

6. At TSO level, the increasing interchange step schedules are not restricted in terms of maximum amplitude. The time ramp is +/- 5 min.

7. The system load change in the most cases is approximated partly from generation online measurements and partly from post-mortem calculation (from generation).

On-line measurements of consumption behaviour do not exist, the control being done by exchange power-frequency control.

8. Depending on the country, BRP (balance responsible parties) are usually responsible for next and intraday schedule/balancing and have no responsibilities for their own real-time consumption-generation balance.

As a general conclusion it can be stated that the schedule frame diminishing is in process but the settlement process does not encourage a ramp schedule transition.

SOLUTIONS AND PROPOSALS SUGGESTED BY QUESTIONNAIRE RESPONDENTS

- Take into consideration for slow units (e.g. thermal PP) scheduling process only a schedule step which respects the real ramp rate e.g. [MW/min]* 30 min for hourly time frame or [MW/min]* 7.5 min for 15 min time frame
- Impose adequate ramp rates for fast units using sequential star/stop to/from minimum load and after the ramps sets in power loop controller. Is necessary to adopt a linear ramp similar with the interchange ±5 min.
- Try to define BRP with slow and fast units capable of “load follow” (own load) and coming in market balanced;
- Use ramp rates in the settlement process;
- Use a shorter time schedule frame (1/2 hour or 10/15 min) and a common approach for interchange schedules in same frame. Different approach on time frame length could be an advantage on frequency evolution.
- Create a monitoring process of “load follow” not only at TSO level but also at BRP level. This process must focus on inter schedule frame unit behaviour. Deliver on-line load measurement to BRP.

  Based on these proposals the working group has developed corresponding potential solutions, see report chapter 5.

5. ANALYSIS OF ROOT CAUSES AND DEVELOPMENT OF PROPOSALS FOR IMPROVEMENTS

The previous analyses highlight a few considerations:

- The duration and the importance of the frequency deviations observed in CE have been increasing since market unbundling in 2001.
- The system operation costs are not determined exactly but must be gradually increasing.
- The ability of the system to cope with an unexpected large generation loss during market hour changes (7am, 10pm, noon, ..) is reduced.
- Up to now, no technical or market arrangement has been to counter large deterministic frequency deviations. There is no specific tool used by most of the market players in order to counteract to the deterministic frequency deviations.
- The toolbox used by TSOs (UCTE policies, anticipated reserve management) to limit the consequences of deterministic frequency deviations, might not be effective if these deviations worsen. Such a situation will probably be discovered when a large generation trip occurs.
- The development of the EU power market might contribute to the worsening of frequency deviations over the next few years

A first conclusion emerges from all previous studies and it is that hourly step generation scheduling, as it has been common practice since market liberalisation, seems to be the main cause for systematic frequency deviations. However, energy trading does not necessarily mean that generators have to be scheduled in hourly steps. This chapter focuses on how to smooth these schedules respecting the current trading agreements.

Interconnection scheduling happens in hourly steps with a 10-minute ramp while in most countries generation schedules are pure steps. From the point of view of frequency excursions, all schedules have a similar weight, but generation scheduling practices are easier to change, as it can be done on a country-by-country basis, changing just domestic regulation. Further smoothing of the interconnection schedules is advisable, but the priority has to be given to smoothing the generation schedules.

Load following vs. Scheduling

Traditionally, in vertically integrated energy systems, system operators scheduled generation in ramps according to their best estimate of the demand. This represents the most efficient way to schedule generation as it reduces the regulating needs to a minimum. However, since the end of the mandatory pool e.g. in UK, demand-side bidding has been the rule and generation is scheduled to fit the demand purchases. Imbalance settlement provides the right incentives for suppliers to purchase their best forecast of the demand but it should still be noted that the total demand purchase will not replicate the best estimates of the demand.

The following proposals aim at producing smooth schedules to fit the demand purchases. On top of these schedules, system operators should activate reserves to cope with deviations not scheduled by the markets.

Hourly vs. Quarter-hourly imbalance settlement

Energy trading happens in hourly blocks. This is common practice for the majority of European countries and it would require great efforts to change it, so the proposals in this chapter respect hourly trading blocks.

Schedules are binding to the extent that imbalances are measured and settled, placing penalties on the generators that do not comply with the schedule. Imbalance settlement has a granularity varying from 10 minutes to 1 full hour depending on the country. Units providing spinning reserve may have a direct incentive to comply with a smooth schedule depending on the ancillary services arrangements in place by each TSO. Any proposed scheduling procedure should take into account that generators will try to minimise penalties.

Changing the granularity of imbalances settlement means that metering equipment has to be upgraded, or in the best of cases, be re-programmed. This can be too expensive for individual consumers and households. Even though imbalances settlement on a period equal to or shorter than 15 minutes is a recommendable solution, proposals in this chapter will be restricted to TSOs and generators, and will not involve changing customers' metering equipment.

TSO side vs. generation side implementation

An important issue when designing a method to smooth schedules is the question as to who will be in charge of converting the energy schedules resulting from the market in power schedules to be followed by individual generators. It has to be either the generator itself or the TSO.

The problem arises because there is no general procedure to convert an energy schedule into a smooth power schedule fully respecting the market output. There will be small differences in energy for each imbalance settlement period.

If the TSO is to prepare the power schedules, these energy imbalances will have to be settled and paid to the generators, according to predefined rules to compute the prices. On the other hand, if the generators are to prepare the schedules subject to some predefined rules (TSOs should define what schedules are acceptable), no settlement is needed but trading will have to take into account these limitations. These limitations to trading should not be relevant for generators, as smooth schedules tend to reflect the actual behaviour of power plants more accurately.

5.1. RAMP-BASED BILLING OF BALANCE ENERGY

5.1.1. DESCRIPTION

A schedule is a trading item with discrete changes. But following the Operation Handbook and some national grid codes the physical implementation of schedule changes must take place in a linear fashion over a period of 10 minutes (ramp). Subsequently, every TSO whose billing of balance energy is based on (discrete) schedules provides an incentive for an improper operational implementation:

On the one hand market participants are obliged to deviate from the trading schedule in favour of the ramp, on the other hand balancing energy is determined on the basis of trading schedules. Hence, ramping does not take place.

However, in order to compensate for the ramp the TSO has to provide control power, which originally was not designated for this very purpose, i.e. inappropriate use of control power (spinning reserve).

Swissgrid's step to eliminate the above mentioned opposed incentives: Consider the ramp for the billing of balance energy[3].

For balance energy settlement, swissgrid takes into account the ramps resulting from physical implementation of financial transactions. Consequently, schedules remain the same, but the billing basis for balancing energy changed.

5.1.2. *Implementation*

Until mid 2010 the calculation of the balance energy was based on the discrete (in steps) schedule balance of the balance responsible parties (BRP). Since mid 2010 the new ramp-based energy calculation has been introduced for balance energy settlement.

Swissgrid calculates the imbalance data of each BRP billing unit on a 15 minute basis taking into account the corresponding schedule information and by applying the ramps as they are requested at inter-TSO level.

However, while calculating ramps, secondary and tertiary control energy deliveries are not considered, as these control energy schedules already represent the desired delivery profile. Balance responsible parties in which no physical feed-ins or feed-outs have occurred during the billing month always have a zero schedule balance. A non-zero schedule balance can occur in the event of scheduling errors. In such cases the calculation of ramps does not apply.

5.1.3. *Experiences*

Up to now Swissgrid has received a good feedback from the applied change, see **Figure 5.1**. The change of the Swiss schedule of about 1900 MW during morning hours does not request any substantial secondary control reserve.

[3] http://www.swissgrid.ch/power_market/legal_system/balance_group/

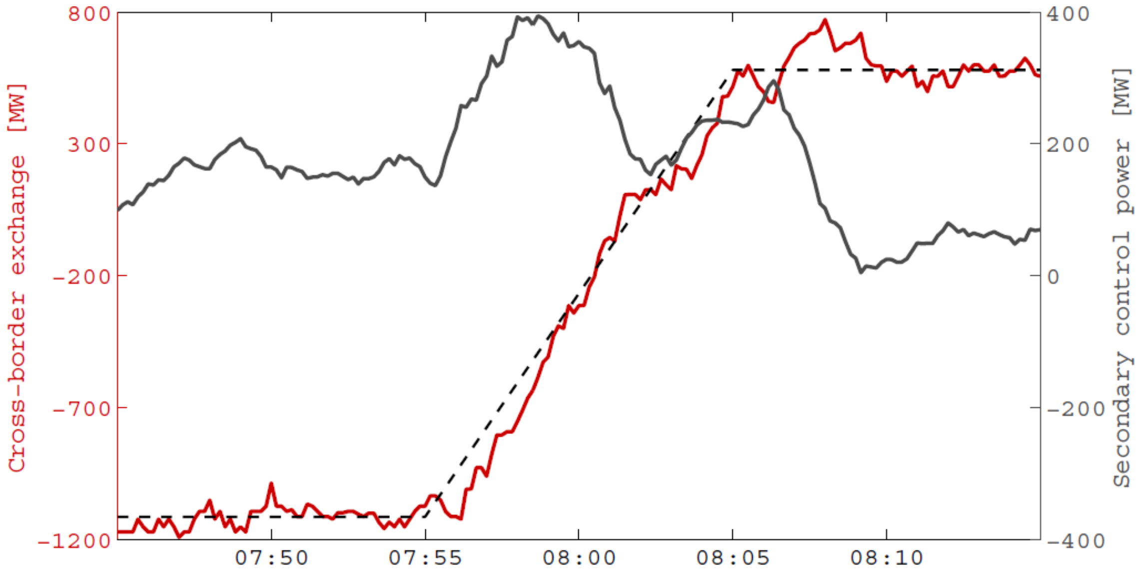

Fig. 5.1/ Swiss Ramp change during morning hours, September 2010. Source: Swissgrid

5.1.4. Advantages/Disadvantages

The change does not affect the scheduling of BRPs. The schedules are prepared and submitted as before. There must be no amendment or inclusion of the ramps within the schedules submitted to the TSO. The change referred to only affects the rule for calculating the balance energy. The ramp calculation and inclusion is done by the TSO on the basis of the available schedules and considered respectively for the billing process for the balance energy itself.

5.2. Methods that are Changing the Schedules

5.2.1. Continuous Half-hour ramping Method

This proposal is a procedure to prepare generation schedules using 30-minute ramps, instead of the current "hourly step" schedules, compatible with the current trading and operation practices. The procedure can be adapted to 1-hour or 15-minute ramps if needed.

Trading at the forward and spot markets takes place in 1 hour blocks. Generation schedules are usually prepared as "steps": the power output remains constant for the whole hour and shifts instantaneously to a new level at the change of the hour. This procedure aims at producing smooth, linear continuous schedules for power plants, so that their output changes gradually along time instead of shifting at the change of the hour.

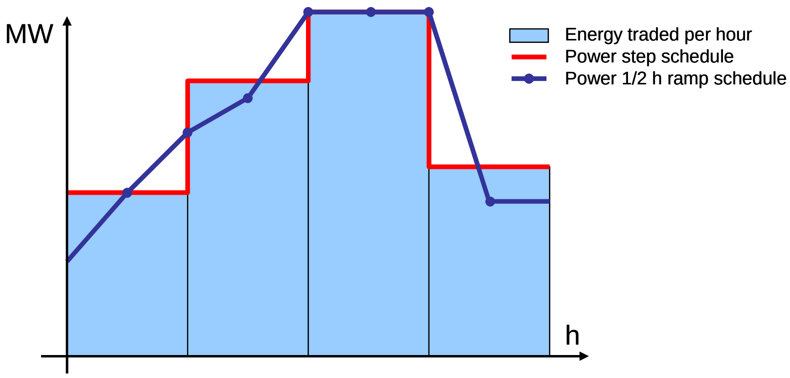

Fig. 5.2: Hourly step vs. half-hour ramp schedules. Source: Red Eléctrica de España (REE)

5.2.1.1. Description

The proposal focuses on how to build up power (not energy) schedules for generating units at the gate closure time.

After gate closure time, generators will submit linear power schedules to the TSO, which are prepared according to the following rules:

- A power schedule for each hourly block consists of 2 power values to be reached at the 30th minute and at the change of the hour, the latest being the starting point for the next hour. Between these points, the power output of the generating units must change linearly.

- Unnecessary peaks should be forbidden imposing some additional constraints, in order to avoid an excessive use of reserves. E.g. the sign of the ramp (positive or negative) cannot change its sign twice in two consecutive blocks.

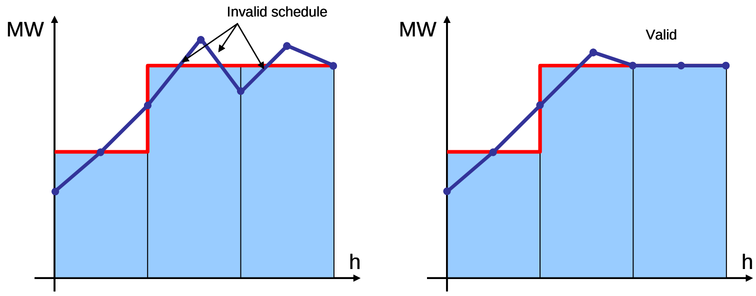

Fig. 5.3: Additional rules to further smoothing schedules. Source: Red Eléctrica de España (REE)

Linearised schedules may not exactly match the energy sold in each and every settlement period. The difference between energy schedule value and energy resulting from linear power schedule when accepted by the TSO will be adjusted to avoid imbalances to the generating unit. The difference has to be accepted by the TSO and settled before the imbalances settlement. So the linearised schedule becomes the basis for the settlement of imbalances[4]. Settlement of these differences can follow the same rules of imbalance settlement, but compensation with the true imbalance should not be allowed. Otherwise, the incentive would still be to produce the traded energy, instead of following the linearised schedule. Given the fact that not every energy schedule can be converted into a linear schedule fully respecting the traded energy, it becomes traders' responsibility to sell an energy profile compatible with some linear power schedule. In the spot markets, as it comes close to real time, energy sales have to adapt to what the power plants in the portfolio can perform.

International exchanges can be scheduled in 30-minute ramps, but the way to linearise 24 energy blocks has to be agreed bilaterally between the TSOs in each border, because, in a general case, it will not be possible to compute linear schedules matching exactly the interconnection energy profile. Any imbalance between the linearised schedule and the energy schedule will be traded by both TSOs and supplied by the operating reserves.

5.2.1.2. *Experiences*

This kind of linearisation has not yet been put into practice. It is a theoretical design based on a proposal by REE dated 2006.

5.2.1.3. *Advantages/disadvantages*

5.2.1.3.1. Advantages

- Step schedules at the change of the hour disappear.
- The procedure does not involve any intra-hour trading of energy. Only in the case that the schedules do not match the energy traded, the difference has to be settled ex-post following the imbalances settlement rules.
- The procedure does not need any change in the current trading practices, nor harmonisation of the imbalances settlement period. No money will be spent for changing meters.
- The procedure does not need European regulation, just domestic (operating procedures and the settlement of imbalances). Standardisation of the main guidelines in the European network code would be advisable.

5.2.1.3.2. Disadvantages

- Linearisation of the energy sold is not as efficient as pure demand following, as it used to be the rule before liberalization. This happens because the energy sold in the market does not necessarily add up to the total demand, just to the energy bought by other market participants. TSOs will have to use reserves on top of the power schedules and final schedules may not be fully linear.

[4] E.g. A unit sells 300 MWh and submits a linear schedule starting at 290 MW and ending at 330 MW, which adds to 310 MWh. If accepted, the 10 MWh difference would be paid by the TSO at some price between the market price and the downwards imbalance price. Imbalances should then be computed as the meter reading minus 310 MWh. If settlement of imbalances is quarter-hourly, the schedule would be 295, 305, 315 and 325 MWh for each period.

- Not all units can follow a linear schedule (e.g. pumping units at start-up). However, a portfolio of power plants may perform close to a ramp. Therefore, schedules may be defined for each portfolio, not for the individual units.

- Settlement of imbalances by itself does not provide an incentive to closely follow a linear schedule, defined in terms of power, not energy. Units that are not observable will try to generate in each settlement period exactly the energy sold in the market. Deviations from the linear schedule will tend to be "compensated" within the settlement period and further deviate from the schedule, as it is shown in the figure below. For those units the four quarter method could be more appropriate.

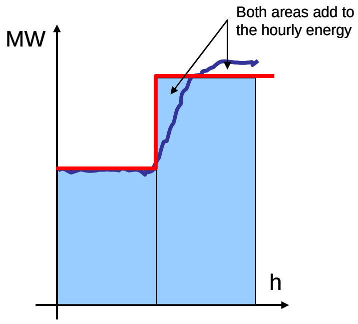

Fig. 5.4: Actual output matching energy. Source: Red Eléctrica de España (REE)

Linear schedules, however, minimize this effect compared to energy step schedules, as ramps are easier to follow by the generating units. Only AGC monitoring can compute penalties associated to non-compliance with linear power schedules.

5.2.2. 4-Quarter-Step-Method

5.2.2.1. Description

The "4-quarter-step-Method" aims at keeping the 1-h-time period, but distributing the power target value during increasing load into four equally climbing 15-minutes-steps within each 1-h-time period. In **Fig 5.5** curve 1 shows this behaviour.

Therefore, only the two power set point values at the beginning ($P_{L,1}$) and end ($P_{L,2}$) of the 1-h-time period are required. The resulting four different power target values are closer to the physical ramp wise changing load than constant 1-h-products, see **Figure 5.5** curve 0.

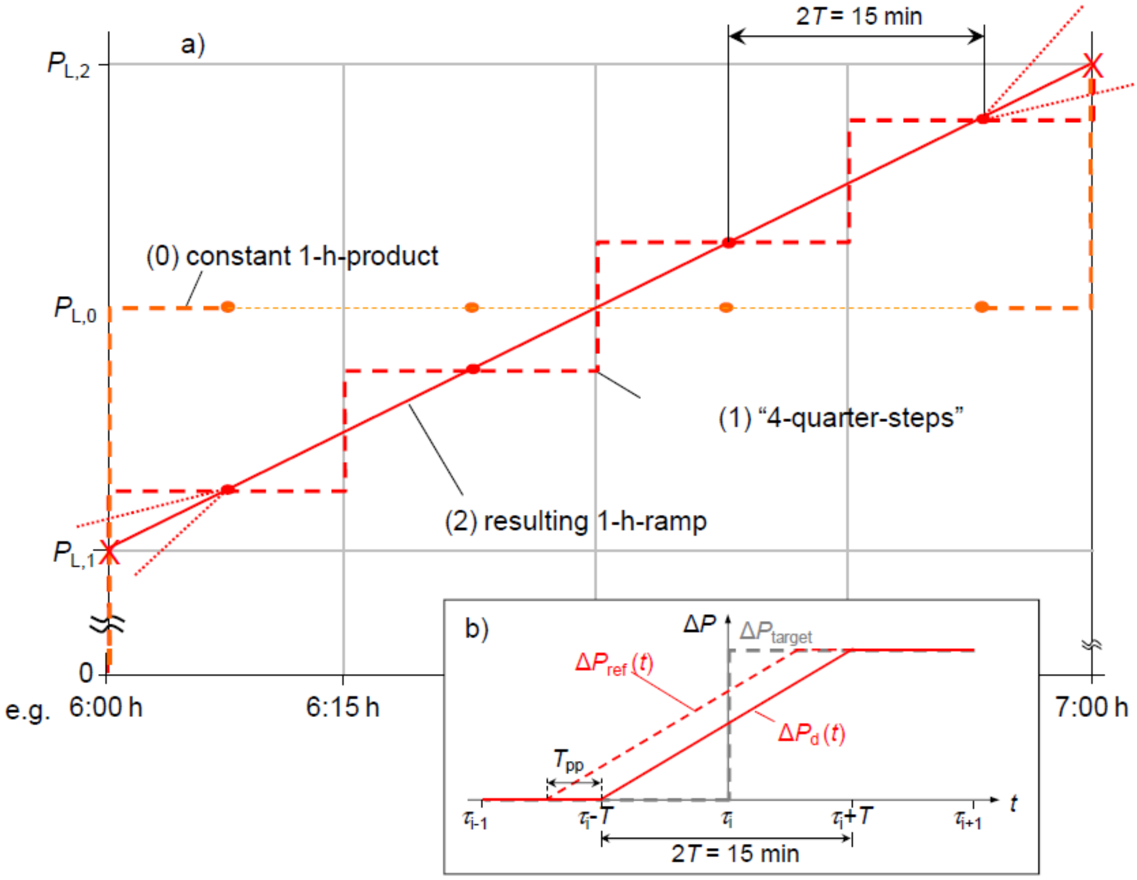

Fig 5.5: 1-h-ramp, based on the concept of "4-quarter-steps". Source: University of Stuttgart

Subsequently, the "4-quarter-steps" can be realised ramp-wise according to the method for converting 15-minutes power steps into ramps, starting 7.5 minutes before the step and ending 7.5 minutes after the step. This method is already used by Swissgrid, transferring stepwise scheduled changes of power exchange programme to ramps. This method is described in **Figure 5.5** b). If this method is used together with the four quarter steps, the resulting 1-h-ramp is shown in **Figure 5.5** curve 2. This curve is now equivalent to the generation behaviour of the classical load-following operation, but it is still schedule-based and hence capable of being integrated within the framework of a deregulated energy market.

5.2.2.2. Experience

There are no practical experiences for this method. Simulations have shown that this method is suitable and has a positive impact on the system.

5.2.2.3. Implementation

5.2.2.3.1. Possible realisation on the "BRP-side"

Since BRPs on the customer side normally carry out the load forecast, they know "their" expected individual load behaviour. Based on this knowledge, they currently determine the corresponding 1-h-schedule to cover the load. This knowledge may also be used to smooth the actual 1-h-schedule by ordering corresponding 15 minutes steps, i.e. to order

1-h-products with variable start and end power values. Such 1-h-products can already be ordered today in the OTC-market (**Figure 5.6)**. As the end of one ramp does not have to be equal to the start of the subsequent ramp, schedule steps remain further possible for consumers having large load steps.

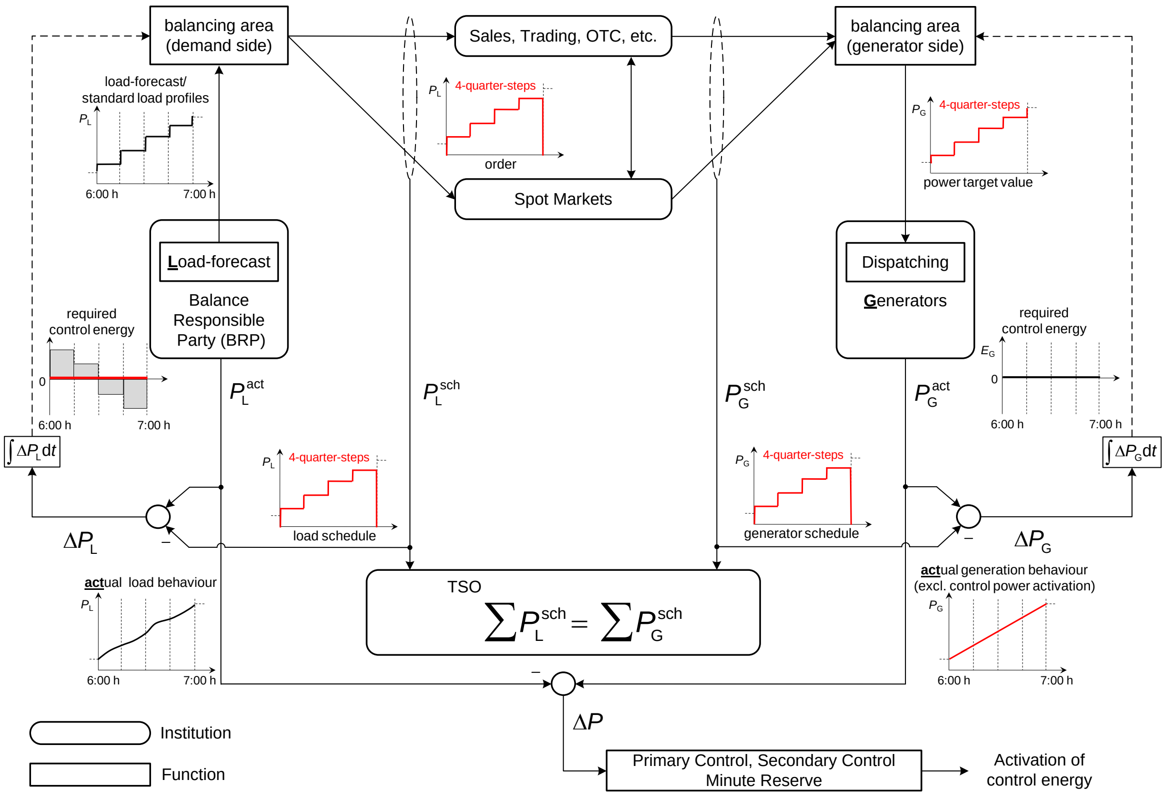

Fig. 5.6: Current Status and Possible Implantation at "BRP-Side". Source: University of Stuttgart

5.2.2.3.2. Possible Realisation on the "TSO-side"

Instead of smoothing on the customer side, the 1-h-ramps could also be ordered by the TSOs. The desired 15-minutes steps could be achieved by pre-scheduling.

As a further possibility the TSO could smooth the stepwise 1-h-schedules into 15-minutes-schedules by applying pre-defined algorithms and return the resulting smoother 15-minutes schedules to the BRP.

5.2.2.4. Advantages and Disadvantages

5.2.2.4.1. Advantages

- The behaviour of the generation side gets closer to the behaviour of the load. Deterministic deviations will disappear. If load and generation gets closer to each other, the differences between both will decrease. Smaller imbalances in the load will cause smaller deterministic deviations in the frequency.
- Trading is still based on 1-h-step products.

- Principles and rules of a liberalized energy market remain the same, the only effort for implementation occurs in planning and realizing the schedule.
- Compared to other methods, the maximum of primary control load can be earmarked for disturbances and outages

5.2.2.4.2. Disadvantages

- Smoothing the schedules on TSO-side could be a problem of time, due to the delivering of the "real" schedule 45 minutes before the hour. To avoid these problems, the realization of the schedule could be adapted.
- Not all units can follow a linear schedule (e.g. pumping units at start-up). However, a portfolio of power plants may perform close to a ramp. Therefore, schedules may be defined for each portfolio, not for the individual units. Another possibility could be a switching of pumping units in steps.

5.3. Smoothing scheduled variations of large hydro power stations

The variation in the hydro power with high ramp rates was found to be an important cause for frequency deviations (see section 4.1.2).

This section proposes various specific measures for large hydro power stations in order to smooth their scheduled variations during normal operation: the implementation of a time shift for their schedule changes or of a ramping restriction. This method could also be performed by any other power plant.

These solutions have to be compatible with the possibility for the TSOs, to ask for a fast delivery or reduction of the power in emergency situation (without any restriction).

5.3.1. Description

5.3.1.1. Time shift of schedule changes

This solution consists in anticipating or delaying for some minutes the changes in the station power output compared to what is planned with the schedule.

The simplest solution consists in using a fixed time shift for each power station. Each power station has a different time shift (for example between ± 10 minutes around the hour or the ½ hour shift). so that the changes in power output are spread over a period of some minutes, making it possible to avoid their synchronization at the moment of the change from one schedule step to another.

A more complex and flexible solution consists in using an adjustable time shift, adapted to the network situation. In that case, the time shift could be modified or controlled by the TSO.

According to the pattern of frequency variations, the starting up of the hydro generation could be delayed in the morning (positive frequency deviations) and their stop could also be delayed in the evening (negative frequency variations). From this observation, we can suggest that the implementation of fixed delays on power stations could be enough to reach the main part of the intended advantages.

The difference of energy between the schedule and the actual energy delivered (with the time shift) could be integrated to the settlement of imbalances. In that case, a pricing mechanism and a cost recovery scheme have to be designed in order to guarantee the financial balance of the system.

5.3.1.2. Ramping restriction

The previous solutions (time shift of scheduled changes) cannot avoid big output variations in a single power station (in the range of 1,000 MW for the largest ones).

As large hydro power stations generally consist of several generating units, it is possible to spread out the starting up or the stop of the various units in order to respect a ramping constraint. Using this possibility, the variation of power could be easily limited to approximately 200-250 MW/minute for each power station depending on local conditions. Due to the water hammer phenomena within long penstocks a gradient reduction is however recommended in order to reduce negative effects and damages within the hydraulic components.

As previously mentioned, the TSO shall have the possibility, in emergency situations, to ask for a fast delivery or reduction of power.

The difference of energy between the schedule and the actual energy delivered (with ramping restrictions) could also be integrated to the settlement of imbalances with an appropriate pricing mechanism and cost recovery scheme.

5.3.2. EXPERIENCES

In France, most of the large EDF hydro power stations are equipped with a timer (about 25 power stations > 100 MW) shifting systematically the changes in power output from some minutes before or after the expected time, according to the schedule. The time shift is fixed for one power station and each of them has a different time shift (between ± 10 minutes).

This spreading out is implemented at the level of power stations and not for generating units.

This spreading out is not taken into account in the settlement process.

5.3.3. IMPLEMENTATION

These measures need the implementation of timers in hydro units or power stations, making it possible to spread out the starting up or the stop of the various units or stations based on the information given by the standard schedules. These timers shall be inhibited in case of emergency orders sent by the TSO in order to have the fastest possible power delivery or reduction.

The process for the settlement of imbalances has to be adapted.

5.3.4. ADVANTAGES/DISADVANTAGES

5.3.4.1. ADVANTAGES

- These measures allow for the reduction of the sharp variations in hydro generation which were found to be an important cause for frequency deviations
- The implementation of such measures in the existing hydro power stations seems to be relatively easy, requiring minor technical adaptations.
- Low impact on market design and rules.

5.3.4.2. DISADVANTAGES

- These measures are probably insufficient to solve the whole problem of the deterministic frequency deviations, but are expected to realize a significant improvement.

5.4. CONCLUSION AND EVALUATION

Several methods were introduced and described in the previous chapters. The evaluation of these methods is done by simulations, using a simplified model of the European Transmission system.

Simplified Model of the dynamic behavior[5]

The model used is shown in **Fig.** 5.7. There are two main working areas. On the left side of the picture, the load covering is simulated. In every simulation there are two ways to cover the load. On the one side this could be done by load-following, and on the other side this could be done by one of the suggested methods. The combination results in a power value, that is generated by all units. This generated power is compared with the actual load value. The difference between these two values is the actual power imbalance.

The right side of the model represents the summarized electric system, with the different control systems (primary and secondary control), the inertia and the self regulation effect of the system. With this part of the model, a certain power imbalance could be transformed to a frequency deviation.

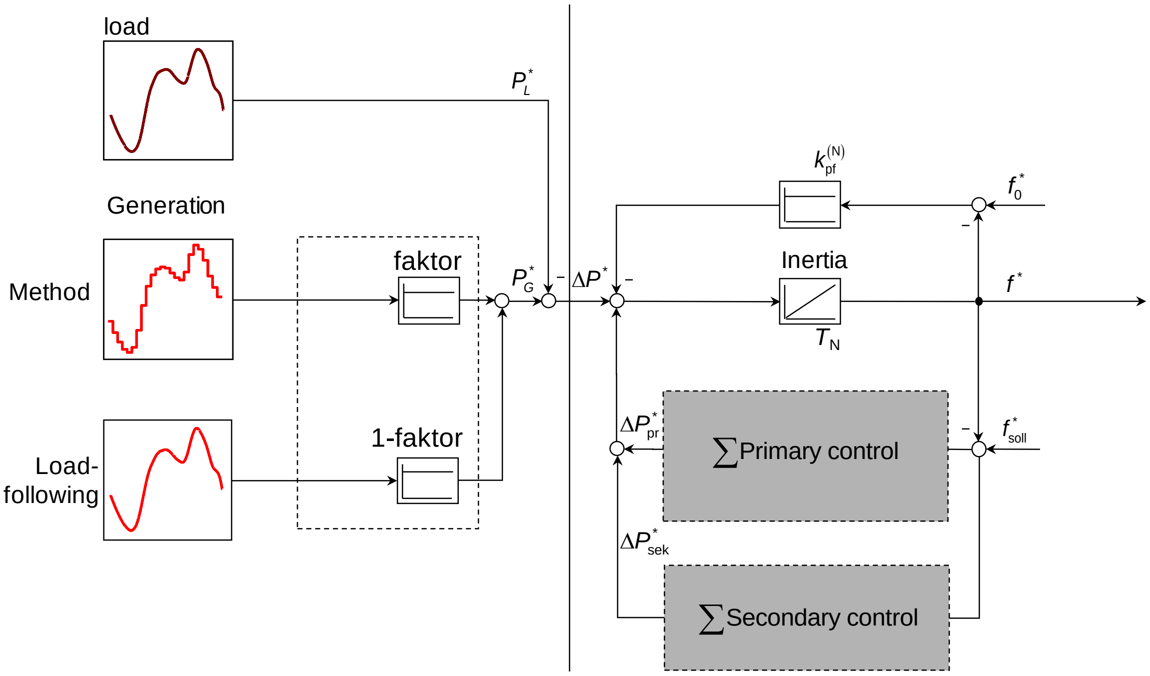

Fig. 5.7: Setup of the simplified model. Source: University of Stuttgart

For the following simulations, the averaged load behavior of the winter month 2007 for the former UCTE-area is used.

[5] Weißbach, Tobias: Verbesserung des Kraftwerks- und Netzregelverhaltens bezüglich handelsseitiger Fahrplanänderungen, VDI- Fortschrittsbericht 586, vdi-Verlag 2009

Evaluation of the suggested methods

As initial case, the actual behavior is reproduced. This was realized with 70% of the load covered by generation units doing "load following" and 30% of the load covered by generation units following an hourly step-wise schedule. The resulting behavior of the frequency is shown in **Figure 5.8**. This simulated frequency behavior could be observed in reality too.

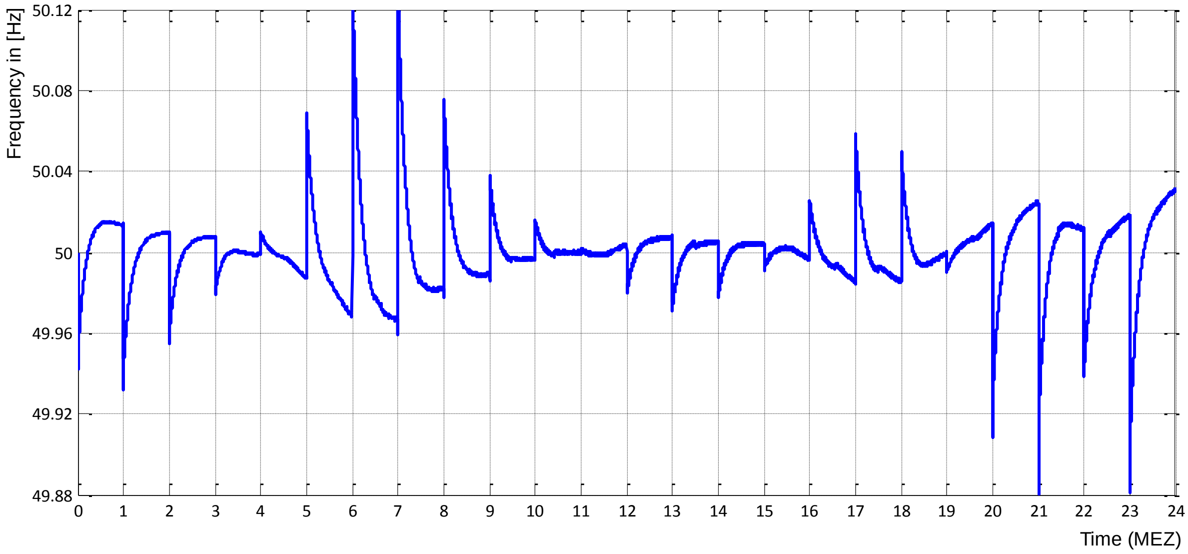

Fig. 5.8: Behaviour of the simulated Frequency, initial Case. Source: University of Stuttgart

Consistent with the initial case, 70 % of the load is covered by generation units using load following in all following simulations. The remaining 30% of the load is covered by generation units following one of the suggested alternative methods. The resulting behavior of the frequency for these simulations is shown in **Figure 5.9.**

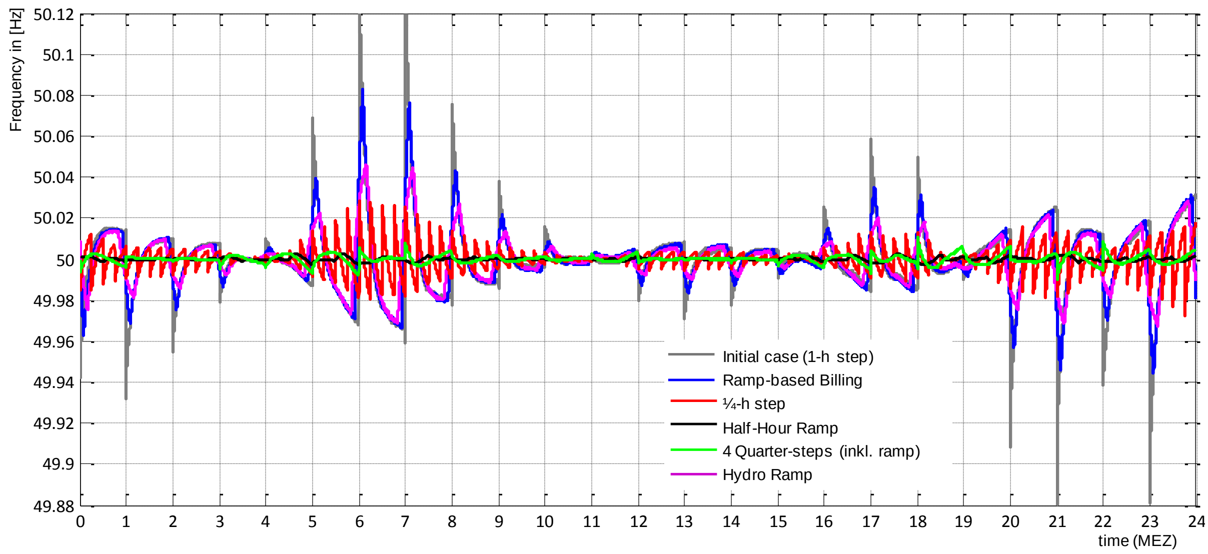

Fig. 5.9: Behaviour of the simulated Frequency, suggested Methods. Source: University of Stuttgart

The results in **Table 5.1** below show that every method has a positive impact on the size of the frequency deviation.

Method	1- hour schedule (initial case)	Ramp-Based Billing (5.1)	Half-Hour Ramping (5.2.1)	4-Quarter Steps (5.2.2)	Hydro PP Ramping Speed (5.3)
Positive Frequency deviations	134 mHz	82 mHz	3 mHz	10 mHz	46 mHz
Negative Frequency deviations	-120 mHz	-55 mHz	-3 mHz	-5 mHz	-32 mHz

Table 5.1: Comparison of Methods / Frequency

Another important value in this evaluation is the amount of balancing energy that is caused by the power imbalances between generated power and the actual load value.

Table 5.2 presents the values for the activated balancing energy. The amount of balancing energy of each method is compared with the activated amount from the initial case. Also for this variable all simulated methods resulted in improvements compared to the initial case.

Method	1- hour schedule (initial case)	Ramp-Based Billing (5.1)	Half-Hour Ramping (5.2.1)	4-Quarter Steps (5.2.2)	Hydro PP Ramping Speed (5.3)
Balancing energy compared to initial case	100 %	83 %	9 %	10 %	67 %

Table 5.2: Comparison of Methods / Energy

6. CONCLUSIONS AND RECOMMANDATIONS

It can clearly be stated that by increasing control reserves the frequency quality cannot be improved substantially. The most effective and efficient way is to eliminate the cause of deterministic frequency deviations at the roots. The rules for generation scheduling and the related market rules have to be adapted to the current operational needs to control the frequency. The way the schedules are applied have to be adapted to the way in which the load behaves and change on a daily basis.

Due to the fact that the European power system operation is based on highly meshed interconnection lines, all changes required will have to be synchronised at European level. However, as a result of different market rules in different system areas as well as different generator pooling strategies, the report presents different proposals which have been elaborated. Consequently even a mix of the different proposals is possible and will result in important frequency quality improvements. Corresponding adaptions or changes within the current grid codes might ensure the right signals for all market participants.

The proposals that have been studied include incentives for the power generators to follow ramps at the settlement process (ramp base billing), methods that change the schedule handling (i.e. replace 1 hour power step by 2 half an hour ramping schedule), methods that replace the current schedule by quarter hour steps or quarter hour ramps and methods that smooth the scheduled variations of large hydro power plants.

Simulations show that all of these solutions have a positive impact (reduction of the frequency variation amplitude as well as reduction of control energy). The schemes which “follow” the load behaviour better will be the most successful ones.

The existing ten minutes inter-TSO ramping period may also be questioned and should be correlated with the time frame of generator schedule periods. Incentives which encourage a better coordination between power plants and TSO schedules following the natural load behaviour might result in a better system frequency quality and therefore a more secure and less cost-intensive system operation.

An in-depth assessment of the proposed solutions concerning economical aspects, market implications, impact on generation companies operation and balance responsible parties as well as the technical implications for the secondary control will have to be considered, as the solutions proposed are based on technical considerations alone.

An additional solution to implement the proposals might be a market mechanism which creates incentives for Balance Responsible Parties (BRP) to support system balancing. This would mean creating the right incentives for BRPs to submit and follow more detailed schedules than hourly schedules. The right time resolution for schedules and settlement will have to be designed. The goal is to ensure an adequate load following behaviour. Incentives for allowance of ramping between settlement periods should be considered as well.

A settlement time period with a time resolution less than 1 hour (current main practice) will result in an increase of frequency quality. However, changes will have to be coordinated on the level of trading activities, scheduling process, metering and cross border schedules.

It should be evaluated which market changes are necessary and efficient and which changes are not adequate, e.g. spot markets, balancing market, intra-day market.

The findings of the current report should be analysed in detail by the market divisions of ENTSO-E and EURELECTRIC in order to evaluate the related solutions with respect to their feasibility from the point of view of market rules and market products. Afterwards both associations will have to decide on the next steps in a well-coordinated way.

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