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Reduced risks and improved economic operation of ancillary services

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Abstract. Present arrangements and regulation for ancillary services for power balance in power systems cannot cope with future developments in power systems as the participants do not receive proper incentives for required behaviour. This paper analyzes the consequences of current arrangements for system operation and stability when all participants make their own trade-off between risks and economic operation. Two-sided markets for ancillary services are proposed to replace the single-sided market of present secondary control arrangements and a price-based control strategy for power imbalances is described which can replace primary control. In contrast with present arrangements for primary control, all participants receive proper incentives such that economically rational behavior supports the global requirements on stability, reliability and minimal costs. Both new proposals guarantee a reliable and efficient operation of power systems in a market environment with responsive, reliable and accountable but also competing prosumers, a large penetration of renewables and continent spanning transmission networks.

KEY WORDS: Ancillary services; power balance; control of power systems; risks and economic operation; primary control; secondary control; price-based control; two-sided market

1. INTRODUCTION

We assume that there are transparent and open markets for day-ahead trading of energy based on predictions of available power sources and demand. These markets are based on Balance Responsible Parties (BRP) which are the only entities that are allowed and capable to trade on these markets. Based on their bids on these (future) energy markets, they decide about the amount of energy they will sell/buy on these markets to create an energy balance among their own production, demand and net energy bought/sold from the markets, in all time periods of some future time interval (e.g. the next day). The System Operator (TSO) provides them with incentives which ensure that BRPs will maximize their profits by reducing their risks for having an energy imbalance. The market will decide about how much net energy has to be delivered/received from other BRPs and for which price. These considerations are based on predicted amounts of energy and prices. Uncertainty and disturbances are explicitly

not taken into account. Bilateral contracts, although maybe less optimal than selling or buying on the Power eXchange (PX) market, are still attractive to keep risks due to volatile prices at the PX within acceptable limits.

Paper [1] discusses what has to be done, from a systems point of view, to guarantee a reliable and an economic operation of the power system. It focuses on arrangements, markets and required incentives to deal with Ancillary Services (AS) for power imbalance which are intended for and can cope with uncertainties and unexpected disturbances [2-6]. It was shown that the present way of dealing with uncertainty and disturbances is neither consistent, nor optimal and not well suited for the challenges of the future [2,8]. In [1] a proposal has been made about market-based solutions to achieve that goal, namely a two-sided ahead market and price-based control for ancillary services. This paper continues that discussion with a focus on the trade-offs of the participants (BRPs and TSO) in such a market environment between risks and economic operation. It proposes consistent and incentives-driven alternatives for the presently used primary and secondary control arrangements.

Notation: We assume that *power [MW]* and *energy [MWh]* can be both positive (production) and negative (consumption), *prosumer*: end-user who can produce (producer) or consume (consumer) electric energy, *prosumption*: production or consumption.

2. PRESENT ARRANGEMENTS

A BRP is a reliable, accountable partner in the daily operation of power markets. It has to and is able to represent its own production capacities and demands but also the prosumption of its prosumers (producers/consumers) which are represented by their BRP on the markets. In the Netherlands there is an open market for energy with a market share > 20%. At the APX (Amsterdam Power eXchange) all BRPs can trade and take care of their own energy balance (production + demand + net import = 0). Together with long-lasting and short bilateral contracts and traded energy at the APX (and associated prices) they shape the E-program for the next day. All BRPs have to satisfy their *energy commitments in each PTU*, else the unknown real-time price of imbalance power has to be paid. As stated earlier, this trade is based on the amount of energy in a PTU of T [h], e.g. 0.25 or 1 [h]. The power is measured each 4 seconds and integrated over T [h]. This outcome yields the energy. A BRP has no responsibility to keep a *power balance*.

In real-time the predicted values will deviate from their real values. In a grid without control at system level any load imbalance ΔP [MW] will introduce a constant frequency deviation $\Delta P/c_{nw}$ [Hz] from the nominal frequency f_0 (50

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[Hz]), with c_{nw} [MW/Hz] the network constant owing to frequency-dependent prosumption. The larger the equivalent inertia J [kgm²] and the network constant c_{nw} in the network, the better the disturbance is counteracted. Control is the ultimate tool to cope with unpredictability. Control requires signals of which both a reference and a measured value are known. Inside a synchronous (AC) power system, the global available frequency f and the local power flows are relevant signals to track the power balance. Primary (PC) and Secondary control (SC) are based on these signals. Each BRP and most likely several of its controllable power sources (+/-) will locally measure the frequency f [Hz], detect any deviation Δf [Hz] from the nominal frequency f_0 [Hz] and adjusts its power accordingly with a proportional control law: $\Delta P = c_{pci} \Delta f$ [MW]. The power grid is divided into several control areas, coinciding with individual countries. The TSO in a control area measures the cross-border power and energy exchange. Based on this error in the power exchange (ΔP) and possible frequency deviation (Δf) the control area error e is calculated: $e = \Delta P + c_{sc} \Delta f$ [MW], where c_{sc} is the system constant of the area. SC has to reduce this error to zero. The TSO utilizes an I-controller, which output P_{sc} [MW] indicates how the power set points in the control area have to be changed.

In [1] drawbacks of these present arrangements are discussed, with the following conclusions:

- BRPs have to satisfy their negotiated energy within a PTU. This requirement is not sufficiently to guarantee the power balance of the grid.
- Although PC is a necessary service for guaranteeing a proper power balance of the power network, it has only negative incentives for the BRP.
- SC concerns the energy imbalance, not immediately the power balance.
- At the transition between PTUs there are too many, often conflicting, control signals active that will influence the power balance: the necessity to control the demanded energy in a PTU, and the actions from the PC en SC. The net effect is that up to 70% of the PC reserve capacity is used for this purpose, reducing the precious PC capacity for emergency situations to 30% of its intended value [10]. The amount of available PC will reduce even more in the near future.
- The effects of these drawbacks on the present power balancing can introduce unwanted oscillations and even instability

In the future more destabilizing trends are to be expected. For example:

- The dynamics of technical devices, control loops and market are starting to overlap [2], introducing unexpected and unintended “stability” problems, as elucidated at the end of a PTU with large frequency deviations of up to 150 mHz within a time frame of 10 minutes [10].
- The grid will be used ever more for economic operation making some (cross-border) tie-lines to be loaded up to their maximum, which restricts the use of AS from far away. By sacrificing some economic profits, sufficient spare capacity must be allocated on the relevant (cross-

border) connections. The spatial dimension of the grid really matters for AS [3-5].

- Many units become connected by power-electronic converters to the grid. These units become purposely insensitive for the actual frequency and voltages of the network, reducing the network constant c_{nw} and the equivalent inertia of the network, resulting in less passive stability.

3. NEW ARRANGEMENTS FOR ANCILLARY SERVICES

Incentives and rules are required to guarantee both a reliable and a stable grid in spite of technological, economic and societal changes, competing BRPs, and cross-border trade. They have to guarantee low prices, high reliability, low sensitivity to the large uncertainties of renewables, low sensitivity to large, unexpected disturbances and sufficient incentives for upgrading the grid and the production capacity for future operations. This generic goal is not the natural aim of prosumers, neither of BRPs. It is important to note that, although the TSO could have better estimates of uncertainties in the system (and therefore for the AS needs) as it benefits more from the aggregation effects, the BRPs have more knowledge and more incentives for this estimation. These incentives include their desire for improving its time-varying uncertainty estimates as well as finding the optimal trade-offs between risks and economic benefits. The TSO, as the only ‘consumer’ of AS, has a monopoly and its only incentive is to be on ‘the secure side’, even if this security implies utilization of over conservative and less optimal solutions.

Therefore, in [1] a new ancillary services market which is open, transparent with sufficient liquidity, with proper regulation and with sufficient incentives for a reliable and economic power system. The ancillary services market is an *ahead* market to cope with expected uncertainties before operation. The quantities traded are options in energy [MWh] to receive or deliver within a PTU when needed. They can be called into operation when needed. BRPs assess their own uncertainties and liabilities. They define their own reserve needs for SC for the expected uncertainties in their production or demand. Any excess or deficit can be traded on an AS market. If the AS markets yields a cheaper solution compared with its own adjustment of power (e.g. switchable or adjustable loads), the BRP can select the market. *This ahead AS market-based approach* is being proposed as an attractive alternative of present SC.

Adequate modeling and thorough mathematical analysis [12] presents firm theoretical justification for the policy to install “smart meters” and so price-based control, which helps consumers control their demand for power in response to evolving prices. Price-based control has been proposed earlier, e.g. in [14]. Past years we have generalized these approaches to distributed and real-time implementations which can cope with only local information and hard transmission constraints and so yield local or nodal prices [4,8]. *This real-time, imbalance market approach* is being proposed as an attractive alternative of PC.

4. NEW ARRANGEMENTS FOR SECONDARY CONTROL

With AS markets [1,2,6,8], each BRP has to define its own expected production P_k [MWh] and consumption D_k [MWh] of energy for each considered PTU k . The expected difference E_k [MWh] ($P_k + D_k + E_k = 0$) has to be assured by trading on the energy market (PX). However, both quantities P_k and D_k are associated with uncertainties. This uncertainty can, for example, be expressed by using so-called probability density functions (PDF) of both P_k and D_k , which express the probability that P_k/D_k has a certain value. The mean values will be partly a function of the price λ [€/MWh]: the higher the price, the higher the estimated production and the lower the expected demand. By combining the PDF's of both P_k and D_k , the PDF of E_k can be constructed or estimated. In Fig. 1 an example of such a PDF is elucidated.

Figure 1, PDF of E_k , and selection R_k^+ and R_k^- .

Given such a PDF the BRP has to decide which deterministic bid curve for $E_k(\lambda)$ he has to offer to the power exchange and to which risks the BRP will be exposed when the agreed value E_k^{PX} at the PX market will not coincide with the value of E_k . Not satisfying the agreed energy E_k^{PX} will result in costs incurred by the TSO. We distinguish between costs as a consequence of an agreed maximum size of the imbalance on the AS market, billed with the AS price, and the non predicted imbalance, billed with the imbalance price.

As an open and transparent market will offer the required amount of energy at at least the same, but in general a better price than employing own facilities, participating in the AS market is beneficial, compared with own arrangements for ancillary services. We propose two AS markets (+, -). In each market a BRP is requesting (R) ancillary services, is supplying (S) them or is passive. A request R is expressed as a maximum amount of energy [MWh]: R_k^+ [MWh] is the maximum amount of surplus energy and R_k^- [MWh] the maximum amount of shortage energy that a BRP will try to compensate by trading on the ahead AS markets. The decision about these values R_k^+ and R_k^- can be taken based on the PDF of E_k and the expected prices at the AS market $\lambda^{AS+/-}_k$ and the expected imbalance price $\lambda^{imb+/-}_k$, as elucidated in Fig. 1. The area in Fig.1 indicated with R^- and R^+ represent the probability p that $\Delta E_k = E_k - E_k^{PX}$ satisfies: $-R_k^- < \Delta E_k < R_k^+$, so the probability to be in imbalance is $1-p$. In selecting $R_k^+ = R_k^- = 0$, so being passive at the AS markets, all deviations $\Delta E_k = E_k - E_k^{PX}$ from the agreed E_k^{PX} have to be paid based on the price at the imbalance market. With non-zero values of both R_k^+ and R_k^- , deviations $-R_k^- < \Delta E_k < R_k^+$ have to be paid based on the AS market prices $\lambda^{AS+/-}_k$ and outside this interval based on the

imbalance market price $\lambda^{imb+/-}_k$. The price λ^{AS+}_k is used when there is a request to absorb too much energy, and λ^{AS-}_k when there is a request to deliver energy. The price λ^{imb+}_k is used when the TSO detect a surplus of power in its control area, and λ^{imb-}_k when the TSO detects a shortage of power. Using the PDF of ΔE_k , the expected costs can be calculated. A proper choice of both R_k^+ and/or R_k^- reduces or even minimizes these expected costs. Based on these insights the BRP can make a proper selection for his bid curves $\lambda^{AS+}(R)$ and $\lambda^{AS-}(R)$ and the amounts R_k^+ and R_k^- . Fig. 1 illustrates that the selection of an appropriate value for R_k^+ or R_k^- is a trade-off between probabilities. By asking a fee from BRPs requesting AS and giving (part of) that amount to BRPs prepared to supply AS when asked by the TSO, transparent behavior is being supported. Just requesting large amounts of AS to avoid high cost when imbalance energy is needed, is therefore financially not a recommended strategy. The costs for requesting AS can be formulated, for example, as $c_0 + c_1 \lambda^{AS+}_k R_k^+$ [€] with c_0 [€] and $c_1 [-] > 0$. These bid curves are decreasing function $\lambda^{AS+}(R)$ and $\lambda^{AS-}(R)$. Each BRP can have for each PTU k two bid curves $\lambda^{AS+}_k(R)$ and $\lambda^{AS-}_k(R)$. The prices reflect the maximum affordable price for buying AS when needed. If the market price $\lambda^{AS+/-}(R)$ is higher, own alternatives have to be found, as the market is not willing to supply the required services for the stated maximum price. If the market price $\lambda^{AS+/-}(R)$ is lower, the market offers a cheaper solution than own alternatives.

A market not only needs demand (request) for AS, but also BRPs offering AS (supply). BRPs which have easily controllable or price-sensitive power and/or loads, can offer their excess capacity at the AS markets. They can make a profit from their ability to quickly supply (S) energy when needed by unexpected requests (R) from the TSO when an imbalance occurs in a control area. The AS supplying BRPs can offer in each PTU their bid curves $\lambda^{AS+}(S)$ and $\lambda^{AS-}(S)$ [€/MWh] and the maximum amounts S^+ and S^- [MWh]. The bid curve will be increasing functions of S . The prices reflect the minimum price $\lambda^{AS+}(S)$ [€/MWh] for which the required option S [MWh] will be made available when demanded. When the market price $\lambda^{AS+}(S)$ is lower, the BRP is not willing to supply the desired quantity of ancillary service. At the AS market the aggregated bid curves are added, both for the +market (request for absorbing energy: R too much energy, S : offers to absorb this energy when needed) and for the -market (request for additional energy: R shortage of energy, S : offers to deliver this energy when needed). For each PTU k , separately for the + and - market, prices λ^{AS+}_k and λ^{AS-}_k are determined and maxima for each BRP i ($R_{i,k}^+$, $R_{i,k}^-$, $S_{i,k}^+$, $S_{i,k}^-$) such that there is a balance between the requested ($R_{i,k}$) and supplied ($S_{i,k}$) ancillary services of all BRPs i :

$$\sum_i \{R_{i,k}^+ (\lambda_k^{AS+}) + S_{i,k}^- (\lambda_k^{AS+})\} = 0$$

$$\sum_i \{R_{i,k}^- (\lambda_k^{AS-}) + S_{i,k}^+ (\lambda_k^{AS-})\} = 0$$

Ultimately the buyer/seller of the ancillary service has to pay/will receive the agreed price (λ^{AS+}_k or λ^{AS-}_k) when AS is requested by the TSO. A unique market solution necessitates that the aggregated monotonously non-increasing curve $\lambda^{AS+}_k(R/S)$ crosses the monotonously non-decreasing

aggregated curve $\lambda^{AS-}_k(R/S)$. With the market clearing prices there are unique combinations of BRPs which agree to prosume their offered bid when needed. When the deviations of R and/or S are outside the agreed values of the AS-markets, the TSO will ask for imbalance power with price $\lambda^{imb+/-}_k$ [€/MWh]. A necessary requirement will be $\lambda^{PX}_k < \lambda^{AS+/-}_k < \lambda^{imb+/-}_k$ with, within a BRP, the marginal production costs λ^p_k [€/MWh] $< \lambda^{PX}_k$ and the marginal consumption costs λ^c_k [€/MWh] $> \lambda^{PX}_k$. These price dependencies are illustrated in Fig. 2.

Figure 2, Dependencies among prices: $\lambda^p_k < \lambda^{PX}_k < \lambda^c_k < \lambda^{AS+/-}_k < \lambda^{imb+/-}_k$

Now, the costs and profits of a BRP can be calculated. If a BRP consumes too much ($E_k < E_k^{PX} - R_k^-$) in a time period k, the following costs can be distinguished:

- fixed costs at the power exchange: $E_k^{PX} \lambda^{PX}_k$
- fixed costs owing to the ancillary service market, reserving energy: $(c_0 + c_1 R_k^- \lambda^{AS-}_k) + (c_0 + c_1 R_k^+ \lambda^{AS+}_k)$
- costs owing to the ancillary service market, using the maximum reserved energy: $R_k^- \lambda^{AS-}_k$ and
- costs owing to having imbalance: $(E_k^{PX} - R_k^- - E_k) \lambda^{imb-}_k$

The first amount is being paid at the PX, the second part to the TSO for reserving AS energy, the third part to the TSO for utilizing contracted AS energy in PTU k outside the agreed amount E_k^{PX} to a maximum R_k^- . The fourth contribution is owing to utilizing non-negotiated imbalance energy. As the BRP also earns money by selling the contracted power D_k with price λ^c_k to its internal consumers, and by paying for the energy P_k with price λ^p_k bought from its internal producers, its profit f^{profit}_k [€] becomes

$$f^{profit}_k = D_k \lambda^c_k - P_k \lambda^p_k - E_k^{PX} \lambda^{PX}_k - (c_0 + c_1 R_k^+ \lambda^{AS+}_k) - (c_0 + c_1 R_k^- \lambda^{AS-}_k) - R_k^- \lambda^{AS-}_k - (E_k - E_k^{PX} - R_k^-) \lambda^{imb-}_k$$

The maximum profit is achieved when $E_k = E_k^{PX}$, some less profit when the deviations are agreed on in the AS-markets ($-R_k^- \leq E_k - E_k^{PX} \leq R_k^+$) and considerable less when the deviations are exceeding the estimated and agreed values of R_k^+ and R_k^- , as illustrated in Fig. 3, for a net-producing BRP with too much energy (Request for AS). The maximum profit is obtained when $E_k = E_k^{PX}$. Any deviation has to be paid, for smaller deviations with the price of the AS markets and for larger deviations with the price of real-time imbalance price. In Fig. 4 a net-consuming BRP with can supply (S) AS is illustrated. Without request from the TSO, its maximum profit is achieved when $E_k = E_k^{PX}$. When the TSO asks this BRP to supply AS or when requested imbalance power is being produced, its profits will increase.

Both Fig. 3 and Fig. 4 elucidate that the proposed market arrangements yield true financial incentives for maintaining the agreed presumption of both the PX- and AS-markets. Yet, there are also incentives to request and supply AS when prices are appropriate.

Figure 3, BRP net-producer, requests AS: selling (PX), paying production costs and ancillary services (AS markets and imbalance to TSO) when deviating from appointments at PX- and AS-markets. Bottom: net profit, maximum when $E_k = E_k^{PX}$.

Figure 4, BRP net consumer, supplying AS when asked by TSO: selling to internal consumers, buying at (PX) and selling ancillary services (AS markets and imbalance to TSO) when deviating from appointments at PX- and AS-markets. Bottom: net profit can increase when selected by TSO to supply extra power/energy.

Summary secondary control: With the proposed AS market and sufficient BRPs participating, this market mechanism can replace the present arrangements for SC. Each BRP can assess its own needs and options for AS. The TSO still has to operate at the AS markets for guaranteeing the control areas requirements on frequency, cross-border power deviations and emergency situations, but the majority of AS is traded among

the BRPs. Network constraints introduce one-sided restrictions for AS. So, the AS are not homogenously distributed among the network, but discretely different. Also nodal pricing is needed when network restrictions occur [4-6]. The theory presented in [9,11] has the capability for devising novel distributed control schemes for optimal secondary control of the future European power network, even among countries.

Comparison: The BRPs will become responsible for their own estimation of AS. BRPs can reduce their risks by buying AS at the AS market. There are consistent incentives for correctly estimating and trading the needs for AS. Both too high and too low estimates introduce additional costs. Owing to the two-sided market lower costs are to be expected, yet there are sufficient incentives to guarantee a required energy and power balance.

5. NEW ARRANGEMENTS FOR PRIMARY CONTROL

As already discussed, the primary control action is of crucial importance for the power balance and for the proper operation of a power system. Provision of PC is now enforced by regulations and as such it is not in line with an economically driven behavior of a BRP. As a consequence, inconsistencies arise in the system wide control actions, which could not only result in suboptimal use of energy sources, but also raise questions concerning feasibility and stability of the future, dynamically more stressed power systems. A solution to these problems can technically be obtained by utilizing a real-time price-based control scheme [8], as briefly described next and as illustrated in the example below. So, the assumed fixed imbalance price $\lambda^{\text{imb}+/-}_k$ per PTU k of section 4 is now replaced by a time-varying imbalance price $\lambda^i(t)$.

Virtually all global network constraints, such as global power balance and transmission network power flow limits, can be adequately translated in real-time varying prices which, loosely speaking, quantitatively correctly reflect the economical value for satisfying each constraint at each time instant. Mathematically, this can be obtained through a suitable *dynamic* extension [9] of the so-called Karuch-Khun-Tucker (KKT) optimality conditions [16] related to the power flow equations and constraints in the transmission network. At any location in the network, an *imbalance price* is defined as a suitable combination of the Lagrange multipliers [16] from the KKT optimality conditions. These Lagrange multipliers are in turn updated in *real-time* based on the network frequency deviation measurements and on power flow measurements in the critical lines of a transmission system. The imbalance prices therefore reflect the current state of the physical system and give real-time incentives for prosumers to adopt their prosumption in such a way that integrity and stability of the system are protected. It is proven that such KKT price-based controllers yield economically optimal power balancing solution, while the stability of the system can be assessed using suitable techniques from robust control theory [4]. An indication of the real-time price $\lambda^i(t)$ [€/MWh] is shown in Table 1. The costs f_k [€] incurred by the TSO depend on the sign of the area control error (ACE) and the relative value of the actual power $P(t)$ of a BRP exchanged with the grid with

respect to the "average power levels" defined by $(E^{\text{PX}}_k + R^+_k)/T$, E^{PX}_k/T and $E^{\text{PX}}_k - R^-_k/T$, with T [h] the length of a PTU. The costs incurred by the TSO are calculated, for example, as follows. First the region $\{\text{Imb}^+, \text{AS}^+, \text{AS}^-, \text{Imb}^-\}$ is being calculated depending on the value of $P(t)$ with $P_{\min} \leq P(t) \leq P_{\max}$. Then, the time-continuous integral of the product of actual power $P(t)$ and actual price $\lambda^i(t)$ is calculated for the PTU k . With the BRP in Imb^+ , the costs are:

$$f_k = \int_0^T \{P(t) - \frac{E^{\text{PX}}_k + R^+_k}{T}\} \lambda^i(t) dt$$

There are many reasonable alternatives, e.g. by stating that all BRPs which contribute to decreasing the power imbalance get a reward, even if they are in an AS or an Imb region.

Table 1. Price $\lambda^i(t)$ [€/MWh] for energy incurred on a BRP by TSO depending on the area control error (ACE) and the value $P_{\min} \leq P(t) \leq P_{\max}$. Length of a PTU is T [h].

ACE<0	ACE≈0	ACE>0	$P_{\min}$	$P_{\max}$
$f < 50$ Hz	$f \approx 50$ Hz	$f > 50$ Hz		
$\lambda^{\text{imb}+}_k$	0	$-\lambda^{\text{imb}+}_k$	$(E^{\text{PX}}_k + R^+_k)/T$	$>(E^{\text{PX}}_k + R^+_k)/T$
$\lambda^{\text{AS}+}_k$	0	$-\lambda^{\text{AS}+}_k$	E^{PX}_k/T	$E^{\text{PX}}_k + R^+_k)/T$
$-\lambda^{\text{AS}-}_k$	0	$\lambda^{\text{AS}-}_k$	$E^{\text{PX}}_k - R^-_k/T$	E^{PX}_k/T
$-\lambda^{\text{imb}-}_k$	0	$\lambda^{\text{imb}-}_k$	$<(E^{\text{PX}}_k - R^-_k)/T$	$E^{\text{PX}}_k - R^-_k)/T$

To illustrate the potential of the price-based control methodology in real-time control, we consider the widely used IEEE 39-bus New England test network [13]. All generators in the system are modeled using the standard third order model used in automatic generation control studies [15], while quadratic functions are used to represent the variable production costs of the generators. The loads in the system are taken to be price inelastic, i.e. their value does not depend on the price.

Figure 5. Trajectories of real-time updated nodal prices for generator buses, i.e., for busses 30-39.

The simulation results of this example with a price-based control scheme [4] for real-time congestion management of the transmission network are presented in Fig. 5. A unique price of 39.16 [€/MWh] for all busses in the system is calculated without network constraints. At $t=5$ s, a constraint is imposed on transmission line 25-26. The solid lines are the trajectories of nodal prices for several generator buses where the generators are connected. The dotted lines indicate the off-line calculated values of the corresponding steady-state economically optimal nodal prices. All 39 trajectories

converge to the corresponding optimal values of nodal prices as well. The obtained simulation results illustrate the efficiency of the proposed price-based control scheme in solving a *real-time* congestion management problem, which is considered to be one of the toughest problems in electricity market design [14]. Within seconds after a disturbance, a new equilibrium is achieved.

Present situation: PC is enforced, can even introduce imbalance costs and is not paid for. Still, PC is necessary and can react autonomously without interaction by the TSO.

Proposed situation: In [2-4] it is shown that when the market dynamics are comparable with the power system dynamics, real-time, price-based control is a realistic option and can replace PC. BRPs have proper and consistent financial incentives to make economic viable decisions about power and ancillary services. A real-time price signal, calculated by the TSO, invite them to adjust their presumption. The proposed AS markets guarantee the most cost-effective and reliable solution for the ancillary services [2,6,9,11].

6. CONCLUSIONS

The present arrangements for ancillary services for power and energy balance show insufficient and inconsistent incentives for BRPs and TSOs to deal with risks and economic operation. The introduction of an *ahead market* for ancillary services guarantees an *energy balance* and enforces that the estimation of the size and the character of these services are determined by the BRPs themselves. The BRP takes the decision to distribute its resources among the energy and the AS market. These AS settlements can improve the existing secondary control arrangements. Primary control can be replaced by a *real-time, price-based control strategy* operated by the TSO with imbalance prices changing real-time depending on the area control error. This new, consistent primary control strategy ensures a *proper power balance* in the control area of a TSO. The proposed ahead AS market and the real-time, price-based control strategy guarantee a cost-effective and reliable solution for ancillary services to achieve a proper power balance and a proper energy balance in the power network. Such a power system is consistent in its incentives, is transparent, is reliable and is well prepared for the many challenging new developments in the near future.

7. LIST OF SYMBOLS AND ABBREVIATIONS

7.1. Symbols

λ	Price [€/MWh]	f	Frequency [Hz]
c_{nw}	Network constant [MW/Hz]	P	Power [MW]
c_{pc}	PC constant [MW/Hz]	R	AS request [MWh]
c_{sc}	SC constant [MW/Hz]	S	AS supply [MWh]
f	costs/profits [€]	p	probability

7.2. Abbreviations

AS	Ancillary Service	PC	Primary Control
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BRP	Balance Responsible Partner	SC	Secondary Control
PTU	Program Time Unit	PX	Power eXchange
TSO	The System Operator		

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