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# Price-based control of ancillary services for power balancing

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## SUMMARY

A reliable and an efficient power system is a necessity for any industrialized society. Governments have to enforce regulations to guarantee that such a power system, in spite of many competing stakeholders, participants, companies, and regulating agencies can be operational. This paper analyzes the present arrangements and the future requirements to be posed on incentives and regulation for ancillary services (AS) for power balancing. The paper proposes companies to assess their own needs for AS. A two-sided market for AS is being described to replace the existing arrangements for secondary control. The proposed solution guarantees 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 less-predictable renewables and continent-spanning transmission networks. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: ancillary services; control of power systems; primary control; secondary control; price-based control; two-sided market

## 1. INTRODUCTION

The European electric power system experiences a fundamental change in the quasi-monopolistic, top-down oriented, stable, and reasonably well-predictable arrangements of the past. It now spans continents, has hundreds of millions consumers and hundreds of thousands of producers, from nuclear power plants to privately owned and operated badly predictable renewables such as solar cells, wind and microturbines, and operates in an increasingly liberalized market. These developments pose huge challenges to ensure reliable and economic operation. This paper focuses on the real-time power imbalance in the power net, which arises as a consequence of errors in the prediction of both production and demand. As these fluctuations in power imbalance will increase both in size and in frequency, present arrangements to cope with this imbalance are inadequate. This paper proposes a two-sided market and a price-based control framework for ancillary services (AS) (reserve capacity) which allows a more intelligent solution by giving consumers and producers clear, real-time financial incentives to adapt their consumption/production according to the actual needs of the power system.

We assume that there are sufficient incentives and proper arrangements for creating and extending the infrastructure, 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. As such they are reliable and accountable for their operations, so trustworthy partners. These BRPs make predictions of both their own available production capacity and their own demand and their costs (costs and/or benefits) associated with producing and supplying energy. For achieving a better economic and/or technical solution, energy can be sold/bought bilaterally or on day-ahead markets. Based on their

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bids on these (future) energy markets, they can decide how much energy they will sell/buy on these markets to create an energy balance among their production, demand, and net energy bought/sold from the markets, in all time periods of some future time interval (e.g., the next day). Their main incentive is to maximize profits by bidding energy contracts defined by time period, size, and price. The market will decide about how much net energy has to be delivered/received from other BRPs and against which price. These considerations are based on predicted amounts of energy and prices. Uncertainty and disturbances are explicitly not taken into account.

This paper discusses what has to be done, from a systems point of view, to guarantee reliable and economic operation of the power system in case of uncertainties and disturbances. We will focus on the arrangements, market, and required incentives to deal with the AS that are intended for and can cope with uncertainties in the power supply/demand and unexpected disturbances [1–6]. Although partly different implementations exist in other countries [7], the present arrangements in The Netherlands will be used as an example, discussed, analyzed, and commented. It will be 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]. A proposal is being made about market-based solutions to achieve that goal, namely a two-sided ahead market and price-based control for AS. The paper concludes with a consistent description of how these markets and their regulation could be organized with some final concluding remarks about the differences compared with present-day solutions.

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

## 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 production and consumption 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 Amsterdam Power eXchange (APX) all BRPs can trade and take care of their expected energy balance (production + demand + net import). 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. The prices at APX elucidate quite impressive dynamics with, for example, prices as low as 0.01 €/MWh and up to 500 €/MWh in 1 year (2007). The Dutch TSO (TenneT) validates this E-program with respect to constraints in the network. If any undesired overloading is being detected, this E-program is adjusted. The costs associated with this change owing to congestion management are initially paid by the TSO and are included in the transport tariff. The final program clearly describes the expected energy contributions (+/−) of each BRP in each PTU (Program Time Unit of 15 minutes) for the coming day. Besides this day-ahead market a new, intraday market has been established. It allows additions to the appointments of the APX market up to a few hours before execution. The closer to the moment of execution, the less uncertainty and the better the prediction will be. All BRPs have to satisfy their commitments according to the E-program. Not satisfying their commitments will introduce imbalance costs incurred by the TSO. These imbalance costs are clear price-based incentives to comply with the E-program as good as possible. The acquired imbalance costs are transferred to the BRPs which contribute to the request from the TSO for support, so actively supply the needed AS.

The ahead trade is based on the amount of energy in a PTU of 15 minutes. The power is measured each 4 seconds and integrated over 15 minutes. This outcome yields the energy. There are no restrictions on the power. Any power profile is allowed as long as the contracted amount of energy, the time integral of the power over 15 minutes, is satisfied. In Figure 1 two different power profiles are illustrated that both satisfy the required amount of energy in a PTU.

During operation, the predicted values will deviate from their real values. This is clearly true for renewables like solar and wind, but also for loads. In a grid without control at system level any load imbalance $\Delta P$ (MW) will introduce a constant frequency deviation $\Delta f = \Delta P / c_{nw}$ (Hz) with respect to the nominal frequency $f_0$ (50 (Hz)), where $c_{nw}$ denotes the network constant owing to frequency-dependent loads. The larger the equivalent inertia $J$ (kg m$^2$) in the network, the better the disturbance is

 
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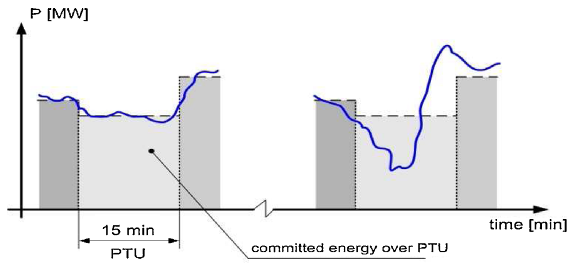


Figure 1. Power profiles satisfying the same energy requirement of a PTU.

counteracted, which follows from

$$f(t) = \frac{\Delta P - c_{\text{nw}} \Delta f(t)}{4\pi^2 J f_0} \tag{1}$$

with $c_{\text{nw}} \approx 6 \times 10^3$ (MW/Hz) and $J \approx 1.5 \times 10^2$ (M kg m$^2$) in the interconnected European grid (ENTSO-E interconnection). Control is the ultimate tool to cope with unpredictability and requires signals of which both a reference and a measured value are known. Inside a synchronous (AC) power system, the globally available frequency $f$ and the local and interarea/cross-border power flows are relevant signals to track the power balance.

- The frequency is an indication of the power balance in the interconnected European grid. When the frequency drifts away from its nominal value of 50 (Hz) it indicates a clear power imbalance.
- The (local) power flows yield a clear indication of power imbalance between a BRP and the grid. The BRP will try to adjust, within the PTU, its power to re-establish its negotiated E-program.
- The cross-border power flows can be compared with their required values. Any deviation is an indication for the TSO of a (national) imbalance.

Basically, there are four different control actions active to deal with deviations and uncertainties (http://www.etso-net.org).

### 2.1. Primary control (PC)

Each BRP and most likely several of its controllable power sources (+/−) can locally measure the frequency $f$ (Hz), detect any deviation $\Delta f$ (Hz) from the nominal frequency $f_0$ (Hz) and adjusts their power accordingly with control law: $\Delta P = c_{\text{pci}}.\Delta f$ (MW). The controller constants $c_{\text{pci}}$ (MW/Hz) are negotiated values agreed upon between the TSO and the BRP. This arrangement necessitates that the units participating in the primary control (PC) loop have to operate a certain amount from their limits. Else, in emergency situations, the requested power is not guaranteed to be delivered in time. Owing to the enforced PC-regulation and the uniform implementation in the interconnected grid, the sensitivity of the grid for disturbances reduces considerably. The network constant is increased from about 6 (no control) to about 30 (GW/Hz) (between 18 and 45). This value changes depending on the actual participation of units and the value of their controller constants $c_{\text{pci}}$ (MW/Hz). As PC requirements are not equally distributed among the BRPs, a BRP has only negative incentives to participate in PC: PC introduces lost opportunities for earning in the energy markets; PC makes production less predictable, more hectic and so introduces wear and less efficient operations as these units have to react quickly to changes in the frequency; PC can enforce that the agreed energy production in a PTU will not meet its target such that the BRP will be penalized for deviations of its agreed E-program.

*Conclusion PC*: As the passive stability (no control) of a grid is too low, PC is an essential ingredient to preserve stability in case of large power imbalances. However, in the Netherlands, a BRP has no incentive and, consequently, has to be enforced to participate in PC. The enforced participation introduced financial losses. There is a monopoly in determining the size of the power needed for PC. The values of $c_{\text{pci}}$ are not adjusted to the actual network topology, which could introduce not-intended overflow. A nice property of PC is that no human interaction or global communication is necessary to activate PC. It is fully locally measured and autonomously executed as frequency is a global property for the whole network.



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### 2.2. *Secondary control (SC)*

The power grid is divided into several control areas, in general being defined by the national borders. The TSO in a control area measures the cross-border power exchange. Based on this error in the interarea power exchange ($\Delta P$) and possible frequency deviation ($\Delta f$), the area control error (ACE) e is calculated: $e = \Delta P + c_{sc}\,\Delta f$ (MW), where $c_{sc}$ is a system constant of the area. Secondary control (SC) is designed to reduce this error to zero. The TSO utilizes a controller, which output $P_{sc}$ (MW) indicates how the power set points of the BRPs in the control area have to be changed. The TSO utilizes a list of BRPs who have shown interest to participate in SC. They are permanently available or offer bids for an amount of power (MW) with a price (€/MWh). As soon as a deviation is detected the TSO selects the cheapest bids until the required $P_{sc}$ is satisfied. The last accepted bid determines the price $\lambda_{SC}$ (€/MWh) for all. This pricing mechanism is called "Marginal Pricing". Other European countries use a different mechanism, for example, "Pay as Bid". All selected BRPs have to produce the requested power rewarded with price $\lambda_{SC}$. As the agreed E-program is also adjusted, participating in the SC does not introduce a penalty. If a BRP does not satisfy the demanded power/energy consistently, the contract will be reduced and/or the TSO will neglect him next time for SC.

In general, SC requires a minimum power rate of 7% of the maximum power per minute, so in about 15 minutes (one PTU) the commanded power change has to be realized. When the TSO demands an increase of the power in the pending PTU, the BRP has only the requirement to increase its energy output, with no statements about the power profile. So, the demanded power can be delivered more than 10 minutes later than (urgently) needed.

*Conclusions SC*: The ENTSO-E and the TSO determine, unilaterally, the coefficient $c_{sc}$ in the control area error calculation and the requirements (7%/minutes), respectively. There is a single-sided open market for BRPs to participate in the SC. The TSO has to guarantee that sufficient BRPs participate in the SC market to guarantee sufficient liquidity. The BRPs have an incentive to participate in the SC as participation yields financial rewards.

### 2.3. *Tertiary control*

About 15 minutes after an incident, bilateral contracts can replace the effects of the SC. These contracts are not the responsibility of the TSO. If the ACE still exists after 15 minutes, the TSO will continue to demand support from the selected BRPs. A TSO has to reduce the control area error zero, using the SC as feedback to selected BRPs. However, this does not imply that the net energy exchange over a certain time period across the border has satisfied its agreed values. To avoid bills for deviations, the TSO takes care that when such a net energy error has occurred it will be compensated in a next day according to ENTSO-E policies. As prices will not be equal, this action introduces some disturbance in the system.

### 2.4. *Time control*

At ENTSO-E level the integral of the frequency is monitored and controlled to keep grid frequency dependent clocks synchronized. If, as a consequence of imbalances the frequency changes from 50 (Hz), these frequency deviations are integrated into a frequency error. Next, the set point of the nominal frequency is being adjusted to reduce the average frequency error to zero. TSOs receive the frequency reference $f_0$ and send its value to the large BRPs. Time control is implemented in SC but the local PC with not-adjusted values of the reference value, will always counteract this.

Emergency situations will rarely occur but if they occur it may hamper a BRP considerably. It has to do with a trip of a large unit or parts of the grid. To cope with these disturbances is too difficult for a BRP. For this type of situations, the grid (TSOs) may give the best solution, as it shares the risks of an event with very low probability, but large consequences.

## 3. CONTROL CONSIDERATIONS

In Figure 2, the effects of a load disturbance $\Delta P$ (MW) is elucidated for five situations: $J = 0, c_{nw} = 0$; $J > 0$ $c_{nw} = 0$; $J, c_{nw} > 0$ and no control; $J, c_{nw} > 0$ with PC and $J, c_{nw} > 0$ with PC and SC. Initially the inertia $J$



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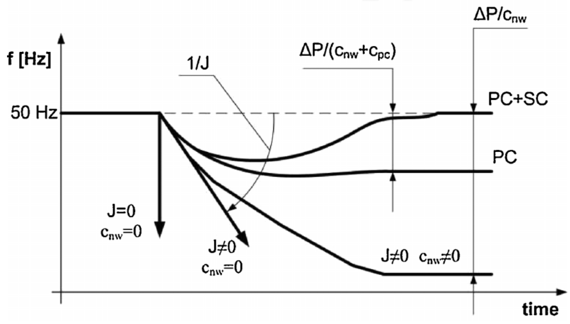


Figure 2. Effect of load disturbance $\Delta P$ (MW) on frequency $f$ depending on values $J$, $c_{\mathrm{nw}}$ and without/with PC and/or SC control active.

constraints the rate of change of the frequency deviation, the network constant $c_{\mathrm{nw}}$ and PC restrict the size of the constant frequency deviation and, finally, SC reduces the frequency deviation back to zero.

Drawbacks of the present arrangements of AS for power imbalance are:

- PC is a necessary service for guaranteeing the stability of the power network. Still, it has to be enforced and yields only negative incentives and unreasonable costs for the BRP. Only strict enforcement by the TSO makes the PC available.
- The gains in PC and SC have to be dependent on the grid topology ($J$, $c_{\mathrm{nw}}$), the size of expected uncertainties and the rate of load change, but they are not adjusted.
- SC allows the TSO to adjust the E-programs in the actual PTU of the selected BRPs. However, the power needs not become available immediately as the BRP has only to satisfy its adjusted E-program in the PTU.
- The rule that BRPs have to satisfy their negotiated energy within a period of 15 minutes is too coarse. It will not help to stabilize the grid as the power can fluctuate considerably without violating any regulation.
- At the transition between PTUs, there are too many, often conflicting, control signals active that influence the power balance: the necessity to control the demanded E-program in the PTU, and the actions arising from the PC and SC. The net effect is that up to 70% of the PC reserve capacity is used for this purpose, reducing this precious PC capacity for emergency situations to 30% of its intended value [9].

The effects of these drawbacks on the stability of the power balance cannot be predicted. It can introduce unwanted oscillations and even instability.

## 4. NEW CHALLENGES

The power system and energy markets will change in the future and so regulation has to adapt to new technological, societal and economic developments:

- The synchronous grid will increase in size and complexity. With more generators and rotating loads the network constant $c_{\mathrm{nw}}$ and $J$ will increase. This is a positive development. Power-controlled DC-lines do contribute neither to $c_{\mathrm{nw}}$ nor to $J$.
- The grid will be used ever more for economic operation. That implies that quite some cross-border tie-lines are loaded up to their maximum. When they are at their maximum capacity, no control (emergency) power can be used from far away. Consequently, only that part of the grid connected with the area of the disturbance by unconstrained lines can contribute to deliver the needed power shortage [4,5]. By sacrificing some economic profits, sufficient spare capacity must be allocated on the relevant cross-border connections.
- Although the grid size increases, the physical connections (tie-line system) still pose a constraint on the allowed power flows. As a consequence, there will always be an upper limit for the amount



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of locally available emergency power and AS. The spatial dimension of the grid really matters for AS [3–5].

- A considerable penetration of renewables is to be expected. Present policy is to increase to 30% wind and solar energy, which will introduce larger uncertainties and more demanding arrangements for AS.
- Many units become connected by power-electronic converters to the grid. As a consequence these generators and loads become purposely insensitive for the actual frequency and voltages of the network. The demanded or supplied power is realized, in spite of changing variables in the grid. That decreases the network constant $c_{nw}$ and the equivalent inertia of the network, resulting in less passive stability. When all loads and producers are connected by a power-controlled converter to the grid, so the network $J$ and $c_{nw}$ disappear, any passive safety margin is being removed, making the network extremely susceptible for disturbances, as elucidated in Figure 3.
- The dynamics of technical devices, control loops and market are starting to overlap, 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 [9].

All, except the first, arguments will increase the sensitivity of the frequency $f(t)$ for uncertainties and disturbances.

## 5. NEW ARRANGEMENTS FOR ANCILLARY SERVICES

Required are incentives and rules to guarantee both a reliable and a stable power system 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 and even not of a TSO with respect to future situations. Nobody cares directly about the integrity of the power system on the long run. Still that goal has to be achieved to the benefit of all.

It is important to note that, although the TSO could have better estimates of uncertainties in the system (and therefore for the global 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 reliability and direct economic benefits. Therefore, we propose, as additions to the already existing ahead markets (PX) for energy, a new AS market which is open, transparent with sufficient

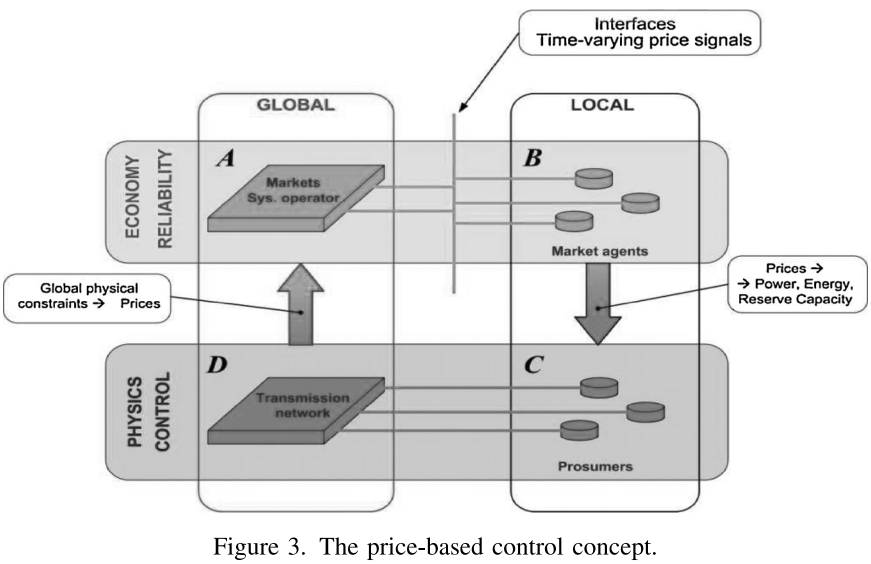


Figure 3. The price-based control concept.

liquidity and with proper regulation which can give sufficient incentives for an economic and reliable power system. The AS market is an ahead market to cope with expected uncertainties before operation. The quantities traded are options (MWh) to deliver energy within some time interval when needed. They can, but in general will not, be called into operation. With an AS market BRPs assess their own uncertainties and liabilities. They define their own reserve needs for the expected uncertainties in their production or demand. Any expected/predicted excess or deficit can be traded on the AS market. If the AS market yields a cheaper solution compared with its own solution (e.g., switchable or adjustable loads), the BRP can select the market. It is a necessity that the price at the power exchange is lower than the price at the AS market, which, in turn, has to be lower than the expected price incurred by the TSO for detected imbalances. Consequently, the BRPs have a clear incentive to take care of their own uncertainties instead of relying on the more expensive imbalance arrangements.

Our approach is enabled by ICT technologies and by utilizing decentralized and distributed control systems theory and modern optimization techniques. It deals with the increasing overlap between the dynamics of the interconnected physical power system (Figure 3C,D), with time varying power requirements as prominent signals and the economical layer (Figure 3A,B) with time varying price signals as the prominent information carriers.

Our goal is to design efficient control schemes for coordination and time synchronization of BRPs actions. These schemes have to guarantee that the overall system benefits are maximized while the crucial global constraints on efficiency and reliability, for example power balance, transmission system power flow constraints, stability, and reliability related constraints, are satisfied. The overall system objective is to maximize its economical benefit: the sum of benefits of all involved BRPs in the system. Satisfaction of global constraints is not a natural goal of BRPs. By introducing the prices for global constraints, the overall system optimization problem is decomposed into set of problems, each assigned to one BRP. Using prices to coordinate local objectives, crucial global constraints can be optimally satisfied. Solving the global optimization problem through decomposition and price-based coordination of BRPs is schematically illustrated in Figure 3.

It is widely recognized that the price inelasticity of the demand is one of the biggest flaws of current electrical energy markets [1]. For example, adequate modeling and thorough mathematical analysis presents firm theoretical justification for the policy to install "smart meters" enabling demand-side matching by price-based control, which helps consumers control their demand for power in response to evolving prices [10]. Price-based control has been proposed earlier, e.g., in Ref. [11,15]. 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 zonal prices [12,13].

Based on this global concept, this paper focuses on an ahead AS market [1,2,6,8] for reliably and efficiently making available and supplying energy when demanded by the TSO.

### 5.1. AS market

Each BRP has to define its own expected production $E_k^p$ (MWh) (including negotiated imports) and consumption $E_k^c$ (MWh) (including negotiated export) of energy for each considered $PTU_k$. The expected difference $E_k$ (MWh) ($E_k^p + E_k^c + E_k = 0$) has to be assured by trading on the energy market (PX). However, both quantities $E_k^p$ and $E_k^c$ are associated with uncertainties. This uncertainty can, for example, be expressed by using so-called probability density functions (pdf) of both $E_k^p$ and $E_k^c$, which express the probability that $E_k^p$ and $E_k^c$ have a certain value. The mean values will be partly a function of the price $\lambda$ (€/MWh): the higher the price, the higher the estimated production and the lower the expected demand. By combining the pdfs of both $E_k^p$ and $E_k^c$, the pdf of $E_k$ can be constructed or estimated. In Figure 4 an example of such a pdf is elucidated. 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 as, in general, the value of $E_k$ will not coincide with the agreed value $E_k^{PX}$. 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. A BRP has several possibilities to avoid imbalance costs:

 
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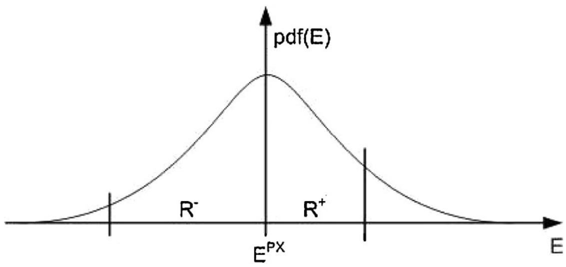


Figure 4. pdf of $E_k$, and selection $R_k^+$ and $R_k^-$.

- actively controlling its own production $E_k^p$ and/or consumption $E_k^c$ to keep $E_k^{PX} + E_k^p + E_k^c = 0$
- better predictions of $E_k(\lambda_k^{PX})$, depending on the expected price $\lambda_k^{PX}$ at the power exchange
- buying options on the AS market for a maximum energy imbalance in a PTU at lower expected prices than the imbalance price.

As an open and transparent market will offer the required amount of energy at at least the same, but in general at a better price, participating in the AS market is beneficial, compared with own arrangements for AS. We distinguish two situations ($AS^+$, $AS^-$). In each situation a BRP is requesting (*R*) AS, 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 market. The decision about these values $R_k^+$ and $R_k^-$ can be taken based on the pdf of $E_k$, the expected prices at the AS market $\lambda_k^{AS+/-}$ and the expected imbalance price $\lambda_k^{imb}$, as elucidated in Figure 4. In selecting $R_k^+ = R_k^- = 0$, so being passive at the AS market, 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 finite values of both $R_k^+$ and $R_k^-$, deviations $\Delta E_k$ within the interval $-R_k^- < \Delta E_k < R_k^+$ have to be paid based on the AS market prices $\lambda_k^{AS+/-}$ and for $\Delta E_k$ outside this interval the imbalance market price $\lambda_k^{imb}$ will be incurred. The price $\lambda_k^{AS+}$ is used when there is a request to absorb too much energy, and $\lambda_k^{AS-}$ when there is a request to deliver energy. Using the pdf of $\Delta E_k$, 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, for each $PTU_k$, proper selections for his bid curve $\lambda_k^{PX}(E)$ and, based on the clearing of the PX $\{\lambda_k^{PX}, E_k^{PX}\}$, the two bid curves $\lambda_k^{AS+}(R)$ and $\lambda_k^{AS-}(R)$ and the amounts $R_k^+$ and $R_k^-$. These bid curves are decreasing function $\lambda_k^{AS+}(R)$ and $\lambda_k^{AS-}(R)$. The prices reflect the maximum affordable price for buying AS when needed. If the market price $\lambda_k^{AS+/-}(R)$ 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 $\lambda_k^{AS+/-}(R)$ is lower, the market offers a cheaper solution than own alternatives. The selection of appropriate values for $E_k^{PX}$, $R_k^+$ or $R_k^-$ is a trade-off between probabilities. By asking a fee from BRPs requesting AS and paying 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 just requesting AS can be formulated, for example, as $c_r R_K^{+/-}$ [] with $c_r$ (€/MWh) > 0.

A market not only needs demand (request) for AS, but also BRPs offering (supplying) AS. BRPs which have easily controllable or price-sensitive power and/or loads, can offer their excess capacity at the AS market. 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 $\lambda_k^{AS+}(S)$ and $\lambda_k^{AS+}(S)$ $[/MWh]$ 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 AS. At the AS market the aggregated bid curves are added, both for the $AS^+$-market (request for absorbing energy: *R* too much energy, *S*: offers to absorb this energy when needed) and for the $AS^-$-market (request for additional energy: *R* shortage of energy, *S*: offers to deliver this energy when needed). For each $PTU_k$, separately for the $AS^+$ and $AS^-$-market, prices $\lambda_k^{AS+}$ and $\lambda_k^{AS-}$ are



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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 ($S_{i,k}$) AS of all BRP$_i$ for all PTU$_k$:

$$\lambda_k^{AS+} = \arg_\lambda\left\{\sum_i [R^+_{i,k}(\lambda) - S^-_{i,k}(\lambda)] = 0\right\} \tag{2}$$

$$\lambda_k^{AS-} = \arg_\lambda\left\{\sum_i [R^-_{i,k}(\lambda) - S^+_{i,k}(\lambda)] = 0\right\} \tag{3}$$

### 5.2. *AS market financial incentives*

The buyer of the AS has to pay the agreed price ($\lambda_k^{AS+}$ or $\lambda_k^{AS-}$) and the seller will receive when AS is requested by the TSO. A unique market solution necessitates that the aggregated monotonously non-increasing curve $\lambda_k^{AS+}$ (R/S) crosses the monotonously non-decreasing aggregated curve $\lambda_k^{AS-}$ (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-market, the TSO will ask for imbalance power with price $\lambda_k^{imb}$ [$/MWh$]. A necessary requirement for the expected prices will be: $\lambda_k^{PX} < \lambda_k^{AS+/-} < \lambda_k^{imb}$ with, within a BRP, the marginal production costs $\lambda_k^p$ [$/MWh$] $< \lambda_k^{PX}$ and the marginal consumption costs $\lambda_k^c$ [$/MWh$] $< \lambda_k^{PX}$. These price dependencies are illustrated in Figure 5. Just like BRPs requesting AS have to pay fixed costs, BRPs supplying AS will receive a financial reward for making AS available when needed, for example, as $c_s S_K^{+/-}$ [] with $c_s$ (€/MWh) $> 0$.

Now, the financial consequences for a BRP can be calculated. For example, if a BRP consumes too much ($E_k < E_k^{PX} - R_k^-$) in PTU$_k$, the following items can be distinguished:

- PX: commitment at the power exchange: $E_k^{PX}\lambda_k^{PX}$
- AS-market: fixed costs in the AS market, $c_r(R_k^- + R_k^+) - c_s(S_k^- + S_k^+)$
- TSO: costs owing to the AS market, using the maximum reserved AS energy $R_k^-$: $R_k^-\lambda_k^{AS-}$
- TSO: costs owing to having imbalance: $((E_k^{PX} - R_k^- - E_k)\lambda_k^{imb}$

The first amount is being paid at the PX, the second part at the AS-market for reserving when needed/supplying when asked for of 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 energy $E_k^c$ with price $\lambda_k^c$ to its consumers, and by paying for the energy $E_k^p$ with price $\lambda_k^p$ bought from its producers, its profit $f_k^{profit}$ [] becomes ($E$ can be positive and negative)

$$f_k^{profit} = E_k^c\lambda_k^c + E_k^p\lambda_k^p + E_k^{PX}\lambda_k^{PX} - c_r(R_k^- + R_k^+) + c_s(S_k^- + S_k^+) - R_k^-\lambda_k^{AS-} - (E_k - E_k^{PX} - R_k^-)\lambda_k^{imb}$$

The maximum profit is achieved when $E_k = E_k^{PX}$, some less profit when the deviations are agreed on in the AS-market ($-R_k^- \leq E_k - E_k^{PX} \leq R_k^+$) and considerable less when the deviations are exceeding the estimated and agreed values of $R_k^+$ and $R_k^-$, as illustrated in Figure 6, for a net-producing BRP with too

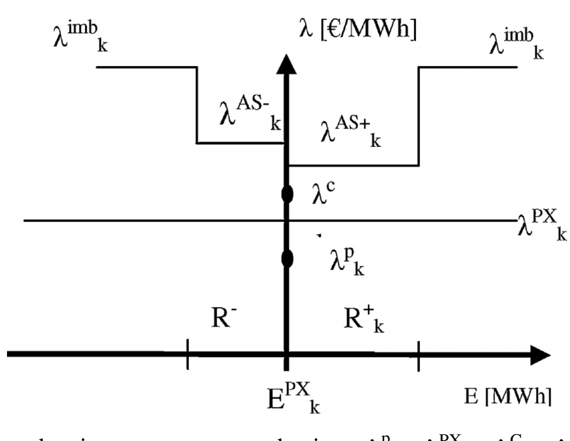


Figure 5. Dependencies among expected prices: $\lambda_k^p < \lambda_k^{PX} < \lambda_k^C < \lambda_k^{AS+/-} < \lambda_k^{imb}$.



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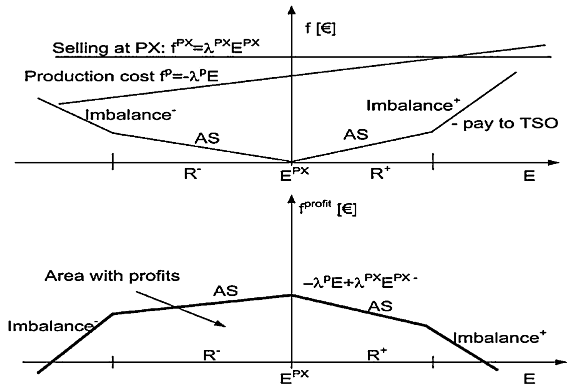


Figure 6. BRP net-producer, costs f if AS needed, $f_{\mathrm{k}}^{\mathrm{profit}}$ maximum if $E_{\mathrm{k}} = E_{\mathrm{k}}^{\mathrm{PX}}$.

much energy (request for AS). In Figure 7 a net-consuming BRP which can supply (*S*) AS is illustrated. Without request from the TSO, its maximum profit is achieved when $E_k = E_{\mathrm{k}}^{\mathrm{PX}}$. When the TSO asks this BRP to supply AS and/or imbalance energy, its profits will increase.

### 5.3. AS market reliability

Both Figure 6 and Figure 7 elucidate that the proposed market arrangements yield true financial incentives for maintaining the agreed prosumption of both the PX- and AS-markets. Yet, there are also incentives to request AS to avoid the higher and yet unknown prices for imbalance and to supply imbalance power when requested by the TSO. The AS market solutions (2) and (3) imply that the reliability, guaranteeing sufficient AS when needed, is assured in each $\mathrm{PTU_k}$ by the inequality $-\sum_i S_{i,\mathrm{k}}^{+}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}-}\right) \leq \sum_i R_{i,\mathrm{k}}^{+}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}+}\right) - \sum_i R_{i,\mathrm{k}}^{-}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}-}\right) \leq \sum_i S_{i,\mathrm{k}}^{-}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}+}\right)$. Only when all AS requests are fully correlated (either $\sum_i R_{i,\mathrm{k}}^{+}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}+}\right) = 0$ or $\sum_i R_{i,\mathrm{k}}^{-}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}-}\right) = 0$), the equal signs are active. In all other situations, the inequalities are valid. When the uncertainties of the BRPs are uncorrelated, so $\sum_i \mathrm{R}_{i,\mathrm{k}}^{+}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}+}\right) - \sum_i \mathrm{R}_{i,\mathrm{k}}^{-}\left(\lambda_{\mathrm{k}}^{\mathrm{AS}-}\right) \approx 0$, almost no power imbalance will be visible in the power net with few demands for AS. Consequently, in daily operation, the amount of available AS for supply (*S*) is almost always larger and only sometimes equal than the amount of requested AS (*R*). When the TSO

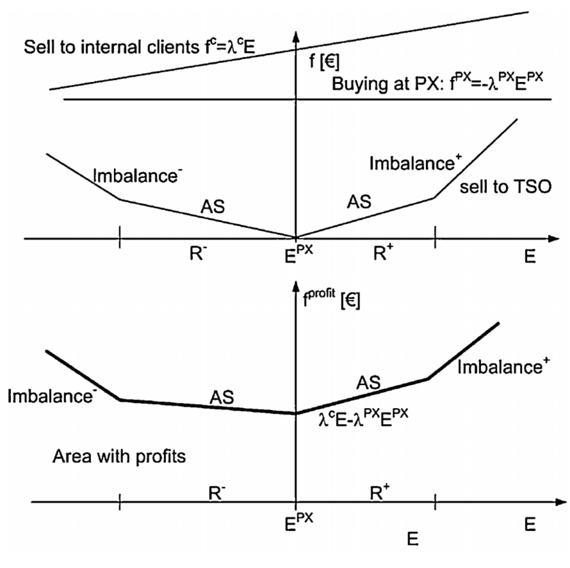


Figure 7. BRP net consumer, supplying AS and imbalance energy when asked by TSO.



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needs AS energy in $PTU_k$, all BRPs that have been prepared to supply AS energy in that PTU for agreed price $\lambda_k^{AS+/-}$, are requested to adjust their E-programs proportional to their agreed maximum $S^{+/-}\left(\lambda_k^{AS+/-}\right)$. Consequently, the contribution of the demanded AS is distributed among all participating BRPs, and not, like now, the BRP with the lowest bid on a bid ladder. All BRPs can benefit according to their agreed share in the AS market.

### *5.4. AS market tuning by TSO*

By selecting an appropriate value for both $c_r$ and $c_s$ the TSO can influence the AS market. Low values for $c_r$ will invite many BRPs to request more than to supply AS, with high values $c_s$ less AS will be requested and more offered to supply, so influencing both the liquidity and the price $\lambda^{AS}$ at the AS market. If appropriate, these coefficients $c_r/c_s$ can be made $PTU_k$ (k−) dependent and/or price-dependent. To further improve responsible behavior of BRPs the fixed amount $c_s\,S_k$ (€) is only being (partially) paid when a BRP (partially) satisfies the demand for AS by the TSO. For example, when $S_k^d$ extra energy in $PTU_k$ is being demanded and only $S_k$ delivered, the profits of offering and supplying AS will be $S_k(\lambda_k^{AS}-\lambda_k^p)-|S_k\text{-}S_k^d|\lambda_k^{imb}+\text{minute}((S_k/S_k^d,1)c_sS_k^+\,[]$.

The reliability can be further improved, without more involvement of the TSO, when the TSO decides to require only imbalance costs when a BRP is operating outside its agreed region $(-R_k^- < \Delta E_k < R_k^+)$ and contributes to the imbalance. Other BRPs outside their agreed region contribute in counteracting the imbalance, so did not need a negative incentive. As both the sign of the imbalance and the value of the imbalance price (which can be large [too few power] or small [too much power]) are not known in advance, BRPs have strong incentives to keep their own imbalance within the agreed region $(-R_k^- < \Delta E_k < R_k^+)$, reducing the need for imbalance energy.

### *5.5. AS market replacing secundary control (SC)*

With the proposed AS market and sufficient BRPs participating, this market mechanism can replace the present arrangements for SC. Each BRP has to assess its own needs and options for AS. A BRP can profitably reduce its risks and costs by buying AS at the AS market. Then the power net is used to supply the needed AS cheaper than by own prosumption and the uncertain, higher imbalance costs are avoided. There are consistent financial 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. The TSO is also active at the AS market requesting AS ($R$) 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. The TSO can consider the AS market to reserve or contract (part) of its needed emergency power for rare incidents with a high impact, although separate arrangements for these rare situations can be considered.

Network constraints introduce one-sided restrictions for AS. So, the AS are not uniformly distributed among the network, but discretely different. Also nodal or zonal pricing is needed when network restrictions occur [4–6].

### *5.6. Outlook for primary control (PC)*

SC is demanded by the TSO to make energy available within a PTU. Consequently, it can take a maximum of 15 minutes before the required energy has been produced. For faster adjustments, PC is required. PC is a necessary commodity that can react autonomously without interaction by the TSO. The paper elucidates that PC has to be enforced, can even introduce imbalance costs and is not paid for. So, only negative incentives for BRPs. In Ref. [2–4] it is shown that 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 AS. A real-time price signal $\lambda^{imb}(t)$, determined by the TSO each point in time t and not known in advance, gives BRPs financial incentives to adjust their prosumption immediately. Together with the proposed ahead AS market they guarantee a cost-effective and reliable solution for the AS [2,4,8]. The theory presented in Ref. [8,14] has the capability for



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devising novel distributed control schemes for optimal PC of the future European power network, even among countries.

It can even be argued, that with an appropriate, reliable and fast ICT infrastructure and real-time price sensitive BRPs, an arrangement with only real-time, price-based control, both the ahead PX and AS markets can be avoided. The TSO-determined price will fluctuate instantaneously and unpredictably according to the actual power and energy balance of the power net, relying on the price-sensitivity of the majority of prosumers. Still, price-sensitivity is not yet achieved, neither commercially, nor technically. We consider such an arrangement, at this moment in time, not yet feasible. The PX and AS markets give predictability, reliability, and transparent prices, reducing risks. These prices are proper guidelines for all participants in the power net. Cross-border trade and constraints in the power network are easier to predict and corrected now by the TSOs.

## 6. CONCLUSION

It is shown that the present arrangements for maintaining a power and energy balance in power networks are based on insufficient and inconsistent incentives for BRPs and TSOs to behave in such a way that a reliable and economic future power system is guaranteed. The introduction of a market for AS enforces that the estimation of the size of these services is determined by the BRPs themselves. The BRP itself takes the decision to distribute optimally its resources among the ahead energy and the proposed ahead AS market. Price mechanisms for AS have been designed in such a way that the collective action of all BRPs in maximizing their own profits will realize the global goals of power balance, efficiency, and reliability of the power system. The proposed AS market guarantees a cost-effective and reliable solution for AS for SC. A power system equipped with this AS market is well prepared for the many challenging new developments in the near future.

## 7. LIST OF SYMBOLS AND ABBREVIATIONS

### 7.1. *Symbols*

| | |
|---|---|
| $\lambda$ | Price (€/MWh) |
| $c_{\mathrm{nw}}$ | Network constant (MW/Hz) |
| $c_{\mathrm{pc}}$ | PC constant (MW/Hz) |
| $c_{\mathrm{sc}}$ | SC constant (MW/Hz) |
| $f$ | Frequency (Hz) |
| $P$ | Power (MW) |
| $R$ | AS request (MWh) |
| $S$ | AS supply (MWh) |

### 7.2. *Abbreviations*

| | |
|---|---|
| AS | ancillary service |
| BRP | balance responsible partner |
| PTU | program time unit |
| PC | primary control |
| PX | power exchange |
| SC | secondary control |

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