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Limitations in the design of ancillary service markets imposed by communication network delays

R. M. Hermans *Student Member, IEEE*, A. Jokić, *Member, IEEE*, P. P. J. van den Bosch, *Member, IEEE*, J. Frunt, *Student Member, IEEE*, I. G. Kamphuis, and C. J. Warmer

Abstract—Real-time balancing of the European electricity grid will become increasingly dependent on market-based control mechanisms that are enabled by connecting millions of prosumers to an open communication network. The use of communication systems inevitably introduces delays in the energy balancing control loop, which could endanger market operation and stability of the electricity grid. By investigating the interaction between price-based control algorithms for real-time balancing and information and communication technology, we aim to provide systematic design rules for unrestricted ancillary service markets.

Index Terms—ancillary services, real-time balancing, price-based control, two-sided markets, decentralized solutions, smart-grid technologies

I. INTRODUCTION

AN important prerequisite for reliable and stable operation of the electrical power grid is that generation and load are balanced at all time, as efficient ways of storing electrical energy do not yet exist. Conventionally, real-time balancing (or load-frequency control) is implemented by directly adjusting centralized, large-scale supply to fluctuations in demand. Today however, the share of electricity generated by large power plants is decreasing significantly, as the electrical power network is subject to a growing penetration of distributed generation (DG). As a result, centralized control of the electricity grid is becoming increasingly difficult, which motivates the need for new, distributed balancing arrangements.

In the deregulated European electrical energy network, real-time balancing and noncentralized decision making is likely to be implemented via open markets for ancillary services (AS), see for instance [1], [2]. Effective operation of these markets, and hence a stable operation of the grid, requires every market player to be connected to an open communication infrastructure over which price signals and bids can be transmitted. However, the use of communication systems inherently introduces constant or time-varying delays in the control loop, which could endanger market operation and stability of the electricity grid. Although the effects of time delays on load-frequency control have been studied before (see e.g., [3]–[6] and the references therein), most of these

articles focus on direct, i.e., power-based, control of large-scale supply. To the best of our knowledge, the first steps in analyzing the consequences of communication delays on power system stability in the presence of market-based balancing arrangements were made only recently, in [6]. Therein an upper bound on the market clearing time and price signal delay is computed beyond which a time-discretized version of the single-supplier/single-consumer power-market model proposed in [7] becomes unstable. The results in [6] indicate that the impact of communication delays on the dynamic behavior of the power market can be significant and counter-intuitive, and should therefore be anticipated by proper design of balancing arrangements and market regulations.

In this paper we continue in the direction of [6], by investigating the limitations imposed by delays on large-scale ancillary service markets for real-time balancing. In contrast to the modeling employed in [6], we consider multiple (clusters of) generators that are subject to different communication delays originating from a hierarchical tree communication network. The choice for this particular model is motivated by the expectation that future information and communication technology (ICT) will enable every prosumer, i.e., hundreds of millions commercial or domestic parties fulfilling both the role of producer and consumer, to be connected to a near-real-time spot market by exploiting scalable network structures. Examples of these ICT architectures (or *multi-agent algorithms* for distributed optimization) that are being developed today, are the PowerMatcher concept (see e.g., [8], [9]), and the smart-meter platforms developed as part of the InovGrid (see e.g., [10]) and FENIX projects (see e.g., [11]), to name just a few.

A static bid mechanism is taken as starting point, to show that delays can destabilize the power-market feedback loop even in the presence of infinitely fast dynamics. The incentives for participating in ancillary service arrangements should be designed in such a way that rational behavior of prosumers and market agents reinforces the integrity of the future power grid as a whole, even in the presence of delays. Therefore, we attempt to deduce maximum-delay specifications that smart-meter communication platforms should comply with to contribute to robust power balancing and efficient market operation.

By investigating the interaction between price-based control algorithms for real-time balancing and ICT, we aim to provide systematic design rules for unrestricted smart-meter-based ancillary service markets. Efficiently designed ICT-driven market mechanisms could become a valuable tool for efficient real-time balancing and for ensuring stable operation of the future

R. M. Hermans, A. Jokić, P. P. J. van den Bosch and J. Frunt are with the Department of Electrical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, E-mails: {r.m.hermans, a.jokic, p.p.j.v.d.bosch, j.frun}@tue.nl.

I. G. Kamphuis and C. J. Warmer are with the Efficiency & Infrastructure Unit, Intelligent Energy Grids Research Program, Energy research Centre of the Netherlands, P.O. Box 1, 1755 ZG Petten, The Netherlands, E-mails: {kamphuis, warmer}@ecm.nl.

Fig. 1. General market-based power system balancing scheme that is subject to communication delays.

electrical grid as a whole. Moreover, they could alleviate the need for investments in transmission infrastructure, as well as in local sources for ancillary service, such as units for storing electricity.

II. MODEL AND ASSUMPTIONS

A schematic overview of a multi-prosumer (producer/consumer) market-based control loop for real-time imbalance management is shown in Fig. 1. The purpose of this feedback scheme is to maintain the balance between supplied and demanded energy by employing a time-varying spot price $\lambda(t)$ [€/MW] for electrical power. Most of the near-real-time markets establish this price through frequently updated auctions. In these markets, there is a natural tendency towards further increasing the frequency of price updates, in order to achieve greater economic efficiency and increased robustness with respect to unpredictable fluctuations originating from intermittent and uncontrollable, i.e., price-inelastic, sources such as sun and wind. To analyze some of the issues related to real-time delayed market response in future power systems, we approximate the periodically updated price by a continuous-time signal. The corresponding differential equations for imbalance power, energy and price, based on the model presented in [7], are given below.

Let $\mathcal{M}$ denote the set of generators $\{1, 2, \dots, M\}$ in the network and let $P_{G,m}(t)$, $P_L(t)$ [MW] be the power produced by generator $m \in \mathcal{M}$ and the total power demand at time t [s], respectively. The energy imbalance $E(t)$ [MWh] in the network at time t is defined as the time integral of the difference between the total generated and the total demanded power, i.e.,

$$\dot{E}(t) = \sum_{m \in \mathcal{M}} P_{G,m}(t) - P_L(t). \quad (1)$$

For simplicity and without losing generality, we assume that all generators are price sensitive, whereas the load is assumed to be completely price inelastic. Price-sensitive loads and price-insensitive generators (such as photovoltaic sources and wind turbines) can still be included in (1), by modeling them as negative generation or negative load, respectively. In interpreting (1), it is important to stress the difference between

consumption and demand. With demand we refer to the *desired* amount of power consumption, which is consumed if the network frequency and voltage equal their nominal values. The actual consumption however, i.e., the usage of power at the actual system frequency and voltage, is always balanced with generation as a result of the law of conservation of energy (if network losses are neglected). So, by considering demand instead of actual consumption, the notion of imbalance becomes well-defined, and balancing becomes a control problem.

The power required for balancing, i.e. $P_{AS}(t)$ [MW], is determined by an integral feedback control law on E , given by

$$\dot{P}_{AS}(t) = -k_C E(t), \quad (2)$$

where the time constant $\frac{1}{k_C}$, with $k_C > 0$, determines the controller's dynamics. Note that in real power systems, it is impossible to measure power and energy imbalance directly. In practice E can be assessed nonetheless, as it is proportionally related to the deviation of network frequency with respect to its nominal value, which is directly measurable at any location in the system.

In the deregulated electrical grid, power production units are owned and controlled by a large number of market players that compete for supply and demand of electrical energy under supervision of a transmission system operator (TSO). The TSO, who is responsible for ensuring reliable operation of the electricity grid, is unable to adapt production according to (2) directly. Instead, it should provide appropriate incentives for maintaining the network balance, in such a way that rational behavior of the market players leads to stable network operation. Many European TSOs have therefore established an intraday market for ancillary service, on which they act as single buyer of balancing power. On this market, requests for $P_{AS}(t)$ are translated into spot prices for balancing power $\lambda(t)$ [€/MW] through a predetermined aggregated bid/supply function $s(\cdot)$, i.e.,

$$\lambda(t) = s(P_{AS}(t)). \quad (3)$$

The aggregated market supply curve $s(\cdot)$ is constructed by "horizontally adding" the bid curves of individual market players. Hence, (3) can be rewritten as

$$P_{AS}(t) = s^{-1}(\lambda(t)) = \sum_{m \in \mathcal{M}} s_m^{-1}(\lambda(t)), \quad (4)$$

where the individual inverse bid curves that specify how much power a supplier $m \in \mathcal{M}$ wants to produce against market price λ , are represented by $s_m^{-1}(\lambda)$.

It is assumed that the supply functions are affine, increasing functions of the produced power, i.e., $s_m(P_{G,m}) = a_m P_{G,m} + b_m$, $m \in \mathcal{M}$, and hence $s(P_{AS}) = a P_{AS} + b$, where $a_m, a > 0$. Then, the differential equation describing the evolution of the ancillary service spot price is given by

$$\dot{\lambda}(t) = \frac{ds(P_{AS})}{dP_{AS}} \dot{P}_{AS} = -a k_C E =: -k_E E, \quad (5)$$

where the inverse time constant $k_E := a k_C > 0$ determines the dynamics of the price update. It can be shown that feedback law (5) is not sufficient to stabilize the closed-loop system

depicted in Fig. 1. Therefore, in [12] a modified, damped price-update relation is employed, i.e.,

$$\dot{\lambda}(t) = -k_E E - k_\lambda \lambda, \quad (6)$$

which, for appropriately chosen damping coefficient $k_\lambda > 0$, results in a stable balancing system.

Rational behavior of price-sensitive suppliers with time constant τ_G (that cannot exercise market power) is modeled as

$$\begin{aligned} \tau_G \dot{P}_{G,m}(t) &= \lambda(t) - s_m(P_{G,m}(t)) \\ &= \lambda(t) - a_m P_{G,m}(t) - b_m, \end{aligned} \quad (7)$$

for $m \in \mathcal{M}$. Thus, market parties increase their power output $P_{G,m}$ [MW] if λ (taken as an exogenous quantity) exceeds their marginal cost $s_m(P_{G,m})$. The corresponding market equilibrium is attained when the market price equals marginal costs.

For more information on the assumptions and limitations of the model presented above, the interested reader is referred to [7], [13].

A. Communication delays

Many of the smart-meter platforms for real-time price-driven balancing that are under development today, exploit communication over tree-structured networks such as the one shown in Fig. 2 (see e.g., [8], [9] for more details). These networks provide a scalable and distributed way of coordinating large numbers of dispersed generators and demand response units, whereas their ordered topology facilitates the integration into hierarchical market structures.

Tree-structured communication networks are characterized by a central *root* node (at the top of the hierarchy) that is connected to the nodes in the last-but-one highest level of the hierarchy. The nodes on this second level of the tree are connected to nodes on the third level, and so forth. Let the levels of the tree be denoted by $n \in \mathcal{N} := \{1, 2, \dots, N\}$, where the top root is the only node present in the 0-th level. Each node of the communication network corresponds to either a price-sensitive generator/load or a market aggregator (see [8], [9]), whereas the market-based feedback control law, i.e., the price-forming mechanism described by (6), is implemented in the root node. Assuming that the transmission of a message between two connected nodes in the n -th and $(n-1)$ -th level takes exactly T_c seconds, the time needed for price signals generated by the root node to reach a level- n node will be nT_c [s]. Hence, the delay-based clustering of generators shown in Fig. 1 directly coincides with the hierarchy defined by the communication network, i.e., all generators at the n -th level of the network are lumped in supply cluster n and receive a price signal that is delayed by $d_n := nT_c$ seconds. Introducing the price signal delay in (7) yields supply cluster dynamics

$$\tau_G \dot{P}_{S,n}(t) = \lambda(t - d_n) - \sigma_n(P_{S,n}), \quad (8)$$

where $P_{S,n}$ and $\sigma_n(P_{S,n}) := \alpha_n P_{S,n}(t) - \beta_n$ with $\alpha_n > 0$ represent the total power production and the aggregated supply function of all generators in supply cluster $n \in \mathcal{N}$, respectively.

Fig. 2. A hierarchical tree-based communication architecture for exchanging bids or price signals.

III. STABILITY ANALYSIS

As algebraic stability analysis of the delayed balancing scheme described in Section II can be tedious, we introduce a number of assumptions to obtain a simplified power-market model for which the closed-loop stability criteria can be assessed analytically.

A. Linear Feedback-Loop Model

Consider a power system in which the generators respond sufficiently fast to the delayed price signal $\lambda(t - d_n)$ (according to (8)), to be able to approximate their dynamics by the static equilibrium equation

$$\begin{aligned} \lambda(t - d_n) &= \sigma_n(P_{S,n}(t)) \\ \Rightarrow P_{S,n}(t) &= \sigma_n^{-1}(\lambda(t - d_n)) \end{aligned} \quad (9)$$

without changing the model significantly. This is the case if $\tau_G \ll \frac{1}{k_\lambda}$, and could be a realistic model of a network in which a large share of electrical energy is produced by fast distributed sources such as (car) batteries and combined heat and power generation (CHP). Moreover, let the supply functions of all clusters be linear, such that the simplified balancing model is given by (1), (6) and (9), where $\sigma_n(P_{S,n}) := a_n P_{S,n}$ for all $n \in \mathcal{N}$.

We start by analyzing the balancing scheme in the absence of delays, i.e., $d_n = 0$ for all $n \in \mathcal{N}$. The open-loop frequency response of the corresponding simplified balancing scheme is given by

$$L(j\omega) = \frac{\frac{\bar{a} k_E}{k_\lambda}}{j\omega(j\omega \frac{1}{k_\lambda} + 1)} =: \frac{K}{j\omega(j\omega\tau + 1)}, \quad (10)$$

where $K := \frac{\bar{a} k_E}{k_\lambda} > 0$, $\bar{a} := \sum_{n \in \mathcal{N}} \frac{1}{a_n} > 0$, $\tau := \frac{1}{k_\lambda} > 0$, and negative feedback is assumed. Stability of the closed-loop system with open-loop transfer function $L(j\omega)$ can be assessed using *Nyquist's stability theorem*, given below (see, e.g., [14] for details).

Theorem III.1 (Nyquist Stability) Consider a closed-loop system with negative open-loop transfer $L(j\omega)$ and P unstable open-loop poles, and let its Nyquist plot, i.e., the polar plot

Fig. 3. Gain (top left), phase (bottom left) and Nyquist characteristic (right) of open-loop transfer $L(j\omega)$.

of $|L(j\omega)|$ and $\angle L(j\omega)$, be given. This system is stable if a representative point s , moving along the Nyquist plot in clockwise direction, encircles the point $-1 + j0$ P times in the counterclockwise direction. ■

Since transfer function (10) has no unstable poles, i.e., poles with real parts that are larger than 0, by Theorem III.1 the balancing system with frequency response $\frac{L(j\omega)}{1+L(j\omega)}$ is stable if its Nyquist plot does not encircle the point $-1 + j0$ (in counterclockwise direction). In order to draw the Nyquist plot of (10), we require expressions for the open-loop gain $|L(j\omega)|$ and phase $\angle L(j\omega)$, given below.

$$|L(j\omega)| = \frac{K}{\omega\sqrt{\tau^2\omega^2 + 1}} \quad (11a)$$

$$\angle L(j\omega) = -180 + \arctan\left(\frac{1}{-\omega\tau}\right). \quad (11b)$$

Fig. 3 shows the open-loop gain, phase and Nyquist plots of (10). Note that the infinite-radius semicircle in the Nyquist plot is a direct consequence of $L(j\omega)$ having a pole on the imaginary axis, corresponding to the integrating action in (1). The Nyquist plot does not encircle $-1 + j0$, regardless of $K, \tau > 0$, which implies stability of the simplified balancing scheme in the absence of delays.

Next, we address the stability of the simplified balancing scheme when all price signals are delayed by T_c [s]. This is the case if the balancing scheme consists of one supply cluster only, or if the market outcome requires a single cluster to supply the total amount of requested balancing power. According to Theorem III.1, this system is stable if the Nyquist plot of $L(j\omega)e^{-j\omega T_c}$ does not encircle the -1 point. Since the delay term $e^{-j\omega T_c}$ has unity gain and phase $\angle e^{-j\omega T_c} = -\omega T_c$, the Nyquist plot of $L(j\omega)e^{-j\omega T_c}$ follows by rotating all points on the Nyquist curve in Fig. 3 clockwise around the origin by ωT_c [rad]. Consequently, the delayed closed-loop system is unstable if the delay T_c is large enough to rotate the cross-over point of $L(j\omega)$ (i.e. the point corresponding to frequency ω_0 such that $|L(j\omega_0)| = 1$) along the unit circle over the point $-1 + j0$. The cross-over frequency ω_0 of $L(j\omega)$ is given by

$$\omega_0 = \sqrt{\frac{1}{2\tau^2} \left(-1 + \sqrt{1 + 4K^2\tau^2} \right)}, \quad (12)$$

Fig. 4. Delay margin as function of feedback gain $K := \frac{\bar{\alpha}k_F}{k_\lambda}$ for $\tau = 1$.

and the corresponding open-loop phase is given by

$$\angle L(j\omega_0) = -180 + \arctan\left(\frac{\sqrt{2}}{\sqrt{-1 + \sqrt{1 + 4K^2\tau^2}}}\right). \quad (13)$$

Hence, the simplified balancing scheme has a phase margin $\phi_{PM} := \angle L(j\omega_0) - (-180)$, i.e., the amount by which the phase of $L(j\omega)$ exceeds -180° , of

$$\phi_{PM} = \arctan\left(\frac{\sqrt{2}}{\sqrt{-1 + \sqrt{1 + 4K^2\tau^2}}}\right). \quad (14)$$

Thus, the closed-loop delayed balancing scheme is unstable if the delay T_c exceeds the delay margin $\frac{\phi_{PM}}{\omega_0}$ [s], which is plotted in Fig. 4 as a function of K for $\tau = 1$. Fig. 4 shows that the delay margin converges asymptotically to 0 as feedback gain K is increased to infinity.

B. Multi-Delay Linear Feedback-Loop Model

Consider the simplified balancing scheme described by (1), (6) and (9), where $\sigma_n(P_{S,n}) := a_n P_{S,n}$, in closed-loop with the hierarchical-tree based delay network described in Section II-A. A schematic representation of the corresponding closed-loop model is shown in Fig. 5, where $H(j\omega)$ denotes the open-loop transfer of the integrator and market dynamics and where the transfer function of the delayed generator network is referred to as $D(j\omega) := \sum_{n \in \mathcal{N}} \frac{1}{a_n} e^{-j\omega T_c}$. By Theorem III.1, this closed-loop balancing scheme is stable if the Nyquist plot of $H(j\omega)D(j\omega)$ does not encircle the point -1 . In contrast to the approach described in the previous subsection, because $|D(j\omega)| \neq 1$ for all $\omega \in \mathbb{R}$ it is not possible to derive an upper bound on the maximum delay NT_c , and therefore also on the maximum depth of the communication tree, by evaluating the phase margin of $H(j\omega)$. Hence, algebraic stability analysis of the tree-based communication network balancing scheme can be tedious in general, although relatively simple expressions for the upper bounds on N or T_c can be found for specific cases of bid curves or delay structures. In this section, we focus on a network in which the aggregated bid curves of all supply clusters are equal and fixed, such that $P_{S,n}(t) := P_S(t) = \bar{\alpha}\lambda(t - d_n)$ for all $n \in \mathcal{N}$. By exploiting the linearity of the bid curves, the open-loop transfer function of the multi-delay scheme can be written as $G(j\omega) := D_\alpha(j\omega)H_\alpha(j\omega)$, with

$$H_\alpha(j\omega) = \frac{\frac{k_F}{\bar{\alpha}k_\lambda}}{j\omega(j\omega\frac{1}{k_\lambda} + 1)} =: \frac{K_\alpha}{j\omega(j\omega\tau + 1)}, \quad (15)$$

balancing arrangements and market regulations that take both economic and control-oriented objectives into account.

IV. CONCLUSIONS

Real-time balancing of the European electricity grid will become increasingly dependent on market-based control mechanisms that are enabled by connecting millions of prosumers to an open communication network. The use of communication systems inevitably introduces delays in the energy balancing control loop, which could endanger market operation and stability of the electricity grid. By investigating the interaction between price-based control algorithms for real-time balancing and information and communication technology, we proposed a number of systematic design rules for ensuring safe and stable operation of ancillary service markets in closed-loop with communication delays.

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