A Control Loop Approach for Integrating the Future Decentralized Power Markets and Grids

Yong Ding, Martin Alexander Neumann, Matthias Budde and Michael Beigl
TECO, Institute of Telematics
Karlsruhe Institute of Technology (KIT)
Karlsruhe, Germany
Email: {firstname.surname}@kit.edu

Per Goncalves Da Silva
SAP Research
Karlsruhe, Germany
per.goncalves.da.silva@sap.com

Lin Zhang
Department of Electronic Engineering
Tsinghua University
Beijing, China
linzhang@tsinghua.edu.cn

***Abstract*—We are facing a restructuring of the power industry towards a smart grid. The vision of the smart grid represents not only the creation of intelligent power supply networks to allow efficient and reliable use of energy resources, but also the redesign of the market structure coupled with it. In order to develop a smart grid-ready power market, the integration of the physical reality of the power grid into the economic market model has been set as the first requirement. To address this problem, we present a feedback control model to interconnect the physical grid and the economic market in a decoupled control loop. Our proposed control loop consists of two subsystems, namely an Optimal Power Flow based physical system and a Continuous Double Auction based economic system. A dynamic coefficient matrix generated by the Locational Marginal Pricing algorithm is adopted for the market clearing mechanism to account for the real-time power flow and transmission constraints. Finally, we demonstrate some initial experiments for a feasibility test of the interaction between the proposed physical power system and economic power market.**

I. Introduction

The restructuring of the power industry towards a smart grid has already begun and will be fully implemented in the Pan-European Grid Network [1]. In the course of smart grid development, the European Union has defined its own objectives for 2020. One of the 2020's goals is that the energy share of renewables is expected to increase by at least 20%. However, the increasing share of decentralized power generation systems from renewables poses challenges: the limited predictability and controllability of the power generation capacity [2]. Consequently, the power market will often be affected by spontaneous and short-term fluctuations in dynamics, uncertainties and operational constraints of the physical grid.

Real-time monitoring of power flow, which reflects the physical reality of the power system, plays a crucial role in the power market, since the market behavior often deviates from the long-term market forecasts. For instance, market participants' behavior has become more and more unpredictable, which contributes as one of the crucial factors to electricity price volatility in some power markets [3]. The real-time market results have in turn a major impact on the stabilization of the power system (on generation, transmission, distribution and consumption).

In our work, we aim at a feedback control model coupling the economic power market and physical power system in real time. In contrast to other power markets, such as the derivatives market (long-term), the spot market (short-term) and the balancing market (quasi-real-time-capable), the power market model in the proposed system emphasizes the interaction with the power grid in real time. The physical system presents power flow aspects about dynamics, uncertainties and transmission constraints. The power market steers the power flow in terms of trades (forecast power demand). Based on the forecast power demand, our control loop determines configurations of generation units and transmission capacities that all preserve OPF. Using LMP [4] the individual dispatch prices for each configuration can be determined.

The rest of the paper is organized as follows: a review of the state of the art in power system modeling and power market modeling is provided in Sect. II. In Sect. III, we present our system design for integrating the economic power market and physical power grid. We, then, demonstrate the feasibility of the proposed interactive system and outline the future evaluation plan in Sect. IV. Finally, Sect. V concludes the paper.

II. Related Work

The deregulation of the power markets, which has been progressing since the early 90's, has led to a tightening of the competition for electrical energy generation, transmission and distribution [5]. Despite country-specific characteristics in the scale and method of the deregulation, two phenomena can be observed in every deregulated power market:

- Electricity is by its nature difficult to store and has to be available on demand.
- Demand is price-insensitive, which means the electricity demand remains the same or continues to increase even if the electricity price goes up by a large amount.

These two phenomena lead to the typical problem of high volatility and increase on short notice with respect to demand and price in the most current power markets. These properties are specific to the power markets and can not be readily changed without integration of the physical system. Therein lies the reason for the extension need of modeling the power market with an accurate representation of the underlying technical characteristics and limitations of the power production and transmission facilities [6].

The particular nature of power systems makes the introduction of the market competition a challenging task [7]. From a grid point of view, the optimum value of reliability in power supply is an instantaneous power balance based on the deregulated power market, which implies the balance between customers' marginal increase and power flow transmission cost [8]. From a market point of view, the power transmission system should be simplified to a system to inject and withdraw the traded power [7]. Furthermore, economic dispatch of the power flow [9] brings the physical power system and economic power market in interaction.

A. Power System Modeling

Power system modeling is the base of power system calculation, analysis and control. The purpose of the physical power system is to generate and transport electric energy to consumers through the physical interconnection of generators, transformers, transmission lines and loads [10]. In order to study the power grid dynamics of a physical power system, the first step is to define the model, which requires hypotheses and simplifications [11].

The core of almost all power system representations is a set of equilibrium equations known as the power flow model [12]. This set of nonlinear differential algebraic equations (DAEs) is utilized to describe the power system status and the entire power flow dynamics. Based on the equilibrium model of power flow, an optimal power flow model [11], [12] can be utilized to determine the minimum generation cost and loss, as well as the balance of the entire power flow at the same time. This optimization model is subject not only to the above mentioned power flow DAEs, but also to physical grid constraints, such as transmission limits, active and reactive power limits, as well as bus voltage limits.

B. Power Market Modeling

Fundamental power market models are used to derive competitive marginal generation cost estimations which are compared with observed electricity prices [13]. Marginal costs can be calculated based on e.g. plant capacities, fuel prices as well as supply and demand structures. The rationale behind them is to express explicitly the dependence between the parameters of the model and a certain random variable underlying the price process [14].

The key task in the power market modeling is to continuously maintain the equilibrium between production and consumption, so that the demand can be balanced with the supply offer in each considered period of time. Therefore, Ventosa et al. [15] highlighted the trend of market competition modeling in terms of equilibrium models. In general, equilibrium models have been used to represent the common market behavior, taking into account the competition among all market participants. The market equilibrium problems that are modeled in those equilibrium models, distinguish from each other in terms of the strategic variable (amount vs. supply curve) from the classical Bertrand and Cournot Oligopoly [16], [17] to the complex supply function equilibrium (SFE) [18], [17]. Kahn [19] noticed that the Cournot competition framework has been most commonly used for the competition of the electricity amount offer. In contrast, the SFE approach allows additionally the competition modeling based on the price.

Due to the multiplicity of market designs, both Hogan [20] and Ma et al. [21] suggested a standard market design (SMD) for power market modeling. In recent decades, market design and power market modeling has drifted towards two directions: reliability-driven and price-driven. In the course of this co-existence, an optimal SMD for a coordinated spot market for energy trade and ancillary services has always been proposed. For this, Hogan [22] and Joskow [23] explained the necessity that the pure economic models of the power market should be extended by the complexity of the electrical marginal conditions of the physical power system. Therefore, Leuthold et al. [24] developed a spatial optimization model in terms of SMD for the European power market, which as a bottom-up model considered both the technical and economic aspects.

III. System Design

Our proposed control loop models a local power market and a local power grid, and is extensible by composing hierarchies of control loops, such as the two-tier architecture in Fig. 1. In the proposed distributed architecture, an individual system consists of these components - *power market*, *power system*, *predictor* and *controller*.

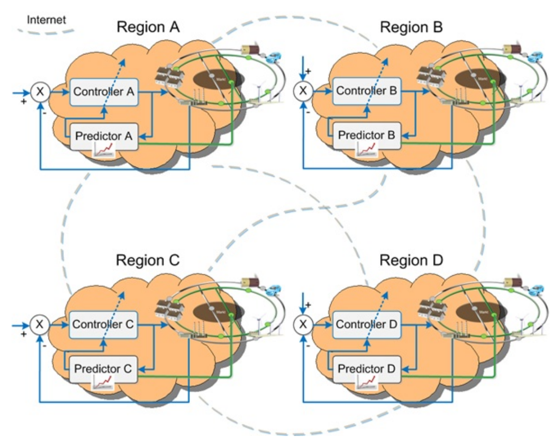

Fig. 1. Distributed control architecture for decentralized power markets

In the power market, the power system (e.g. optimal power flow, locational marginal cost, etc.) and market variables (e.g. price level, pending offers and demands, trading results, etc.) are captured. The predictor forecasts power demand based on information in its local market and remotely connected ones. The controller reconfigures the power grid to execute trades while preserving OPF, and afterwards triggers LMP to update the market. The components foster a dynamic equilibrium between the power system and the power market. A global system based on the above distributed architecture is future work.

A. Modeling the Physical Power System

In a competitive environment of a decentralized power market, the objective function is typically the maximization of the social benefit and system security. In order to reach this maximization under the physical reality of the power system, an optimization problem of power system operation must be formulated. The optimal power flow model, which has been introduced in the 60's as a generalized, non-linear economic dispatch problem in power system analysis, will be applied for modeling the operation problem of the proposed power system.

1) Optimal Power Flow Formulation: The OPF problem is used to optimize the steady state performance of a power system in terms of minimizing generation cost, loss, etc., while satisfying several equality and inequality constraints of power flow, bus voltage, etc.:

$$\begin{aligned} \underbrace{min}_{x} \quad & \varphi(x) \\ \text{subject to} \quad & g(x) = 0 \\ & h(x) \leq 0 \\ x^{min} \leq & \; x \leq x^{max} \end{aligned} \tag{1}$$

where the optimization variable $x \in \mathbb{R}^{n_x}$ is defined in terms of a $n_x \times 1$ vector of bus voltage angles Θ and magnitudes V as well as real and reactive powers P and Q of buses. x^{min} and x^{max} are the variable limits of each optimization variable. $\varphi(x)$ is the objective function ($\varphi(x) : \mathbb{R}^{n_x} \mapsto \mathbb{R}$), $g(x)$ are equality constraints ($g(x) : \mathbb{R}^{n_x} \mapsto \mathbb{R}^{n_g}$), and $h(x)$ are the inequality constraints ($h(x) : \mathbb{R}^{n_x} \mapsto \mathbb{R}^{n_h}$), both $n_g, n_h < n_x$.

$$\underbrace{min}_{x;u} \quad \varphi(x;u) = \sum_{G \in \mathbb{G}} f_G(P_G) + \sum_{C \in \mathbb{C}} f_C(P_C) + \sum_{P \in \mathbb{P}} f_P(P_P) \tag{2}$$

$$\begin{aligned} \text{subject to} \quad g_P(\Theta, V, P_G, Q_G, P_P, Q_P, P_C; u) &= 0 \\ g_Q(\Theta, V, P_G, Q_G, P_P, Q_P, P_C; u) &= 0 \\ |\phi_{ij}(\Theta, V)| &\leq \phi_{ij}^{max} \\ |\phi_{ji}(\Theta, V)| &\leq \phi_{ji}^{max} \\ P_G^{min} \leq P_G &\leq P_G^{max} \\ Q_G^{min} \leq Q_G &\leq Q_G^{max} \\ P_C^{min} \leq P_C &\leq P_C^{max} \\ P_P^{min} \leq P_P &\leq P_P^{max} \\ Q_P^{min} \leq Q_P &\leq Q_P^{max} \\ V^{min} \leq V &\leq V^{max} \\ \Theta^{min} \leq \Theta &\leq \Theta^{max} \\ u^{min} \leq u &\leq u^{max} \end{aligned}$$

For simplicity we define a power system consisting of N buses, indexed by $1, 2, \ldots, N$, each of them is considered as *generator node* (denoted as $g \in \mathbb{G}^{N_G}$), *consumer node* (denoted as $c \in \mathbb{C}^{N_C}$) or *prosumer node* (denoted as $p \in \mathbb{P}^{N_P}$), where $N = N_G + N_C + N_P$. Besides, we assume M transmission lines to transport power from node to node. In our power system model, the three types of nodes refer to big power plants (e.g. wind farm), power consumers without and with PVs, respectively. Then, we extend the optimization variable for the proposed power system with $x = [\Theta, V, P_G, Q_G, P_P, Q_P, P_C]^\top$. In order to consider the controllability of the power system, we introduce u as a vector of additional independent variables, which represent the controllable quantities in the system, such as transformer tap settings, shunt VAR compensations, etc. Considering the power flow equations and transmission limits among the above nodes, our power system model based on the OPF problem description can be represented as above formula 2: where the objective function $\varphi(x;u)$ is a summation of individual cost functions of the generator powers ($f_G(P_G)$), consumer powers ($f_C(P_C)$) and prosumer powers ($f_P(P_P)$), respectively. The details of the individual cost functions are based on the welfare function defined in [6]. The equality constraints consist of two sets of N non-linear nodal power balance equations (generator powers = load powers + injected powers), one for real powers g_P and the other one for reactive powers g_Q, in which P_G, Q_G, P_P, Q_P, P_C stand for the generator real and reactive powers, the prosumer real and reactive powers, and the consumer load powers, respectively. The inequality constraints ϕ_{ij} and ϕ_{ji} represent M flow limits of the active powers flowing through the transmission lines in both directions. The variable limits include upper and lower bounds of generation outputs (P_G and Q_G; possibly P_P and Q_P), power loads (P_C; possibly P_P), stability or security limits (V and Θ) and controllability (u, such as transformer constraints, etc.).

$$\begin{aligned} \mathcal{L} = \sum_{g \in \mathbb{G}} f_G(P_G) + \sum_{c \in \mathbb{C}} f_C(P_C) + \sum_{p \in \mathbb{P}} f_P(P_P) \\ -\rho_P^\top g_P(\Theta, V, P_G, Q_G, P_P, Q_P, P_C; u) \\ -\rho_Q^\top g_Q(\Theta, V, P_G, Q_G, P_P, Q_P, P_C; u) \\ -\lambda_{\phi_{ij}^{max}}^\top (\phi_{ij}^{max} - \phi_{ij}(\Theta, V) - s_{\phi_{ij}^{max}}) \\ -\lambda_{\phi_{ji}^{max}}^\top (\phi_{ji}^{max} - \phi_{ji}(\Theta, V) - s_{\phi_{ji}^{max}}) \\ -\lambda_{P_G^{max}}^\top (P_G^{max} - P_G - s_{P_G^{max}}) \\ -\lambda_{P_G^{min}}^\top (P_G - P_G^{min} - s_{P_G^{min}}) \\ -\lambda_{Q_G^{max}}^\top (Q_G^{max} - Q_G - s_{Q_G^{max}}) \\ -\lambda_{Q_G^{min}}^\top (Q_G - Q_G^{min} - s_{Q_G^{min}}) \\ -\lambda_{P_C^{max}}^\top (P_C^{max} - P_C - s_{P_C^{max}}) \\ -\lambda_{P_C^{min}}^\top (P_C - P_C^{min} - s_{P_C^{min}}) \\ -\lambda_{P_P^{max}}^\top (P_P^{max} - P_P - s_{P_P^{max}}) \\ -\lambda_{P_P^{min}}^\top (P_P - P_P^{min} - s_{P_P^{min}}) \\ -\lambda_{Q_P^{max}}^\top (Q_P^{max} - Q_P - s_{Q_P^{max}}) \\ -\lambda_{Q_P^{min}}^\top (Q_P - Q_P^{min} - s_{Q_P^{min}}) \\ -\lambda_{V^{max}}^\top (V^{max} - V - s_{V^{max}}) \\ -\lambda_{V^{min}}^\top (V - V^{min} - s_{V^{min}}) \\ -\lambda_{\Theta^{max}}^\top (\Theta^{max} - \Theta - s_{\Theta^{max}}) \\ -\lambda_{\Theta^{min}}^\top (\Theta - \Theta^{min} - s_{\Theta^{min}}) \\ -\lambda_{u^{max}}^\top (u^{max} - u - s_{u^{max}}) \\ -\lambda_{u^{min}}^\top (u - u^{min} - s_{u^{min}}) \\ -\mu_{min} \sum_i \ln s_{i^{min}} - \mu_{max} \sum_i \ln s_{i^{max}} \end{aligned} \tag{3}$$

In order to transform inequality constraints into equalities, we consider the Lagrangian function $\mathbb{L}$ associated to problem 2 by employing a vector of slack variables s: where ρ_P and $\rho_Q \in \mathbb{R}^N$, and all the $\lambda > 0$ are the Lagrangian multipliers. The s variables are the individual non-negative slack variables used to transform the inequality constraints to equalities. Both μ_{min}

and μ_{max} are barrier parameters for the logarithmic barrier function of the slack variables.

2) Nodal Price for Power Transaction: The nodal price, which refers to the theoretical price of electricity at each node in the power grid, can be calculated through locational marginal pricing (LMP) within an OPF framework. The LMP at each node is defined as the marginal cost to supply an additional unit of load at that node while satisfying all the required constraints.

According to the LMP decomposition into marginal energy price, marginal congestion price and marginal loss price [25], [26], the LMP at node $i \in 1, 2, \ldots, N$ can be calculated based on the Lagrangian multipliers of the function 3 as follows:

$$LMP_i = LMP_i^e + LMP_i^l + LMP_i^c \tag{4}$$

$$LMP_i^e = \begin{bmatrix} \rho_{Pr} \\ \rho_{Qr} \end{bmatrix} \tag{5}$$

$$LMP_i^l = -\left(1 - [\mathcal{J}_m]^{-1}\,\mathcal{J} \begin{bmatrix} 1 - \frac{\partial P_L}{\partial P_i} & -\frac{\partial Q_L}{\partial P_i} \\ -\frac{\partial P_L}{\partial Q_i} & 1 - \frac{\partial Q_L}{\partial Q_i} \end{bmatrix}\right) \begin{bmatrix} \rho_{Pr} \\ \rho_{Qr} \end{bmatrix} \tag{6}$$

$$LMP_i^c = [\mathcal{J}_m]^{-1}\,\mathcal{J} \sum \begin{bmatrix} \frac{\partial h(x)}{\partial P_i} \\ \frac{\partial h(x)}{\partial Q_i} \end{bmatrix} \left(\lambda^{max} - \lambda^{min}\right) \tag{7}$$

where ρ_{Pr} and ρ_{Qr} correspond to the Lagrangian multipliers of the real and reactive power balance equation at the reference node (slack bus). P_L and Q_L are system real and reactive power loss, while P_i and Q_i represent nodal injection real and reactive powers at node i. $h(x)$ stands for a vector of all the inequality transmission constraints and λ^{max}, λ^{min} are correspondent Lagrangian multipliers of the transmission constraints. Both Jacobian matrices $\mathcal{J}$ and $\mathcal{J}_m$ can be calculated as follows:

$$\mathcal{J} = -\begin{bmatrix} \frac{\partial P_i}{\partial V_i} & \frac{\partial Q_i}{\partial V_i} \\ \frac{\partial P_i}{\partial \Theta_i} & \frac{\partial Q_i}{\partial \Theta_i} \end{bmatrix} \tag{8}$$

$$\mathcal{J}_m = -\begin{bmatrix} \frac{\partial P_i}{\partial V_i} + \frac{\partial P_{Di}}{\partial V_i} & \frac{\partial Q_i}{\partial V_i} + \frac{\partial Q_{Di}}{\partial V_i} \\ \frac{\partial P_i}{\partial \Theta_i} + \frac{\partial P_{Di}}{\partial \Theta_i} & \frac{\partial Q_i}{\partial \Theta_i} + \frac{\partial Q_{Di}}{\partial \Theta_i} \end{bmatrix} \tag{9}$$

where V_i and Θ_i are the voltage magnitude and angle at node i. Since we consider dynamic power demand transactions (just active load powers), $P_{Di} = P_{Ci} \vee P_{P_i}$ and $Q_{Di} = 0$ represent the real and reactive power demands at consumer or prosumer node i.

Finally, we calculate $LMP_i^P - LMP_j^P$ as the real power transaction charges from node j to node i and generate a dynamic coefficient matrix C for a real-time update of the power market:

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1N} \\ c_{21} & c_{22} & \cdots & c_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ c_{N1} & c_{N2} & \cdots & c_{NN} \end{bmatrix} = \begin{bmatrix} 0 & \cdots & \frac{\left|LMP_1^P - LMP_N^P\right|}{LMP_N^P} \\ \vdots & \vdots & \vdots \\ \frac{\left|LMP_N^P - LMP_1^P\right|}{LMP_1^P} & \cdots & 0 \end{bmatrix}$$

B. Modeling the Economic Power Market

The market component of our model is based on the energy market model described in [27], called the NOBEL market. The NOBEL market model is composed of a series of overlapping "timeslots". Each timeslot corresponds to a time interval (e.g. 15 minutes) in the future that dictates when the traded electricity should be produced or consumed. Thus, participants trade based on their forecast levels of consumption and/or production. The time of the first timeslot (i.e. how close the market is to real-time trading), and the number of timeslots in the sequence (i.e. the maximum time horizon for the participants' forecasts) is configurable. Furthermore, the sequence is continuously updated on a rolling horizon by closing the nearest timeslot and opening a new one at the end of the sequence. Once a timeslot is closed, no further trading is allowed. Thus, the NOBEL market provides a common platform to enable electricity trading between smart grid stakeholders, such as, consumer or prosumer households and businesses, electric vehicles, district generators, wind farms, etc.

The underlying trading mechanism in each timeslot is the continuous-double-auction (CDA). In a CDA, the market clears continuously. That is, each time a new order is submitted, the market tries to match with the outstanding orders stored in a publicly viewable order book. This is in contrast with call auctions (CAs) that collect orders for a predetermined amount of time and clear at discrete time intervals. While in CAs the allocation is optimally computed by an auctioneer, in CDAs the allocation emerges from the continuous interaction between the participants. While CDAs can lead to suboptimal outcomes, continuous allocation does provide an avenue for participants to adapt to dynamically changing market conditions. An important aspect when considering, for instance, the intermittent nature of mainstream renewable generation technologies, such as, wind and solar, the dynamic behavior of household's demand, and how forecasts might change given exogenous information. As each timeslot is open for a considerable amount of time (e.g. 24 hours), the participants have ample opportunity to update their standing on a timeslot as more information becomes available, or as market conditions change.

Generally, an order is composed of four values: timeslot, type (buy or sell), price and quantity. A transaction will occur whenever a buy and sell order agree in price, that is, the buy order price is greater or equal to a sell order price. If an order is unmatched, or only partially matched (it still has quantity left), the order is stored in the order book of the respective timeslot. The model also includes other order constraints that are accounted for by the matching process. For instance, an order can stipulate that its entire quantity must be met (i.e. no partial matching), or that any price will be accepted. For each timeslot, each participant will forecast consumption or production, determine its marginal cost (benefit) for selling (buying) electricity, and employ different strategies to maximize its economical outcomes. This model has been shown to be both efficient [27] and scalable [28]. As an example, Fig. 2 depicts the trading outcomes for one day of market operation with 1897 participants, mainly households, of which 80% have solar production. The participants have a limit price for buying of $14\,c/kWh$, defined by their retailer contract (i.e. they will not pay more than what they already pay the retailer), and an assumed limit price of $5\,c/kWh$ for selling. This figure is based on results from [28].

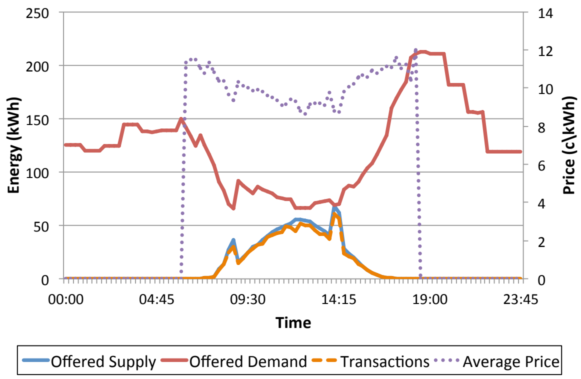

Fig. 2. The average traded price, transaction volume, and offered supply/demand of one day of trading between 1897 households of which 80% have solar production.

In this work, we extend the NOBEL market's clearing mechanism to account for the power flow information encoded in the previously described coefficient matrix. This is done by augmenting the order prices with the coefficient matrix C to include the power transmission costs between nodes. As any two nodes have individual transmission cost, each node effectively has its own view on the market. This is achieved by extending the sorting function that gives the merit order of the orders in the order book (i.e. the orders against which incoming orders will be matched). Whereas previously this function only considered the order prices, it will now also consider the physical transmission costs from the node of the order to be matched.

C. A Dynamic Equilibrium

The supply-demand equilibrium point of the most current power market models is an end point in an economic analysis of standard economic models. In order to extend the usual competitive equilibrium (supplier and consumer only), we employ control theory as a feedback modeling approach to extend the power market with real-time transmission constraints information of the power grid, in order to achieve a dynamic competitive equilibrium among supplier, consumer and transmission/distribution network.

As shown in Fig. 3, the feedback control loop for integrating the power market and grid is simplified as a basic control loop, including a plant, a controller and an additional transducer. The plant is the final object under control and refers to the proposed OPF-based power system. Thus, the state space, which describes the plant, consists of real and reactive power state variables as well as nodal voltage magnitude and angle variables. The transducer is used to monitor the state variables of the plant. In this control loop, the transducer performs the dynamic locational marginal pricing (DLMP) algorithm to produce observed relative transaction charges between each two nodes in terms of a coefficient matrix C. The reference transaction charges are compared to the calculated C matrix (feedback signal) to generate an error signal, which implies at this point the possibility of an update of the market orders sorting. This error signal is fed into the controller block, which employs the NOBEL market platform to determine the market clearing. The extended NOBEL market clearing algorithm augments the order prices with the power transmission costs between nodes, and updates the actual production/consumption for each node in terms of time series, which are then fed back into the plant for the next run of optimal power flow.

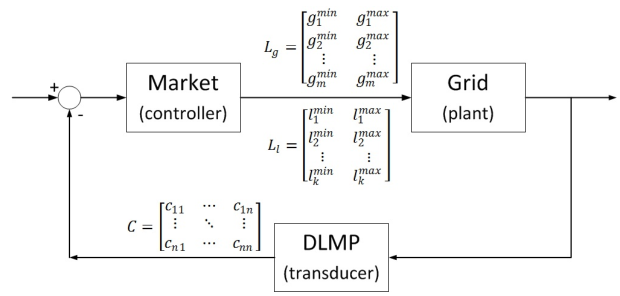

Fig. 3. A control loop for real-time interaction between the power market and grid

IV. Discussion

Currently, we have performed some initial experiments with the augmented NOBEL market to verify the clearing algorithm. We have simulated the market operating on a power system based on the IEEE 14-bus system with 14 prosumer households. Market operation was simulated during one timeslot (15 minutes) in which half of the prosumers acted as buyers, and the other half as sellers. We have compared the transactions generated by the market with the power system constraints incorporated and without them. The coefficient matrix was set up such that it would be cost prohibitive to have electricity transfers between certain nodes. When the power transmission constraints were not incorporated, 100% of the available power on the market was traded. With constraints in the coefficient matrix, the traded energy dropped to 89%, as some generators were unable to trade due to power flow restrictions. Moreover, we simulated the grid output as objective function value of OPF, which was iteratively triggered by the market transaction result of every timeslot, see Fig. 4. In the figure, we noticed that the objective function value of OPF is proportional to the total market trades (Aggregate Demand) of every timeslot, which shows the adaptation of the market clearing mechanism that takes the real-time power flow and transmission constraints into account.

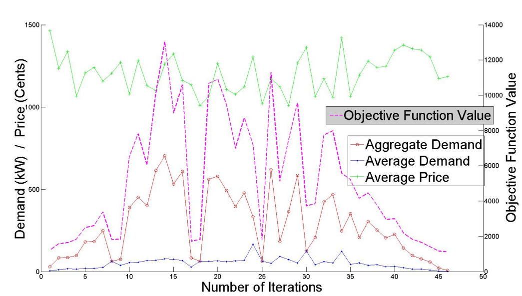

Fig. 4. Output of the power grid model with market integration

In the future, we will evaluate our power system model by utilizing the IEEE 14-bus system and extending it with

1 generation node (wind farm), 6 consumer nodes (loads) and 6 prosumer nodes (loads + PVs). We will utilize real-world smart meter data collected from the NOBEL project to simulate the loads, and weather data (from the same location) to simulate the wind and PV generation. To establish a baseline for comparison, the Zero-Intelligence trading strategy [29] will be adopted. In this strategy, the traders place orders on the market at random prices. In order to evaluate the market, we will compare the power flows created through the market transactions with the optimal power flow in the system given perfect knowledge about each node's production and consumption behavior. We will also seek to investigate the impact of the power system on the market, by comparing the market performance (e.g. prices, transaction volume and resource usage efficiency) with and without the power system flow constraints.

V. Conclusion

In this paper, a control loop approach for integrating the future decentralized power markets and grids was proposed. We presented an OPF-based power system model and the NOBEL market platform for describing each local physical power grid and local economic power market. A dynamic LMP algorithm was employed to generate a coefficient matrix, which reflects the real-time transaction charge between each two nodes considering the physical transmission constraints. Through initial experiments, we shown that a real-time adaptation of the power market order clearing based on the coefficient matrix is feasible.

In future, we will first evaluate the proposed control loop in terms of its stability with real world data on both, the power system and the power market, and then demonstrate by simulation that the physical reality of the power system and the market results can be coupled and controlled.

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