Incentivizing Market and Control for Ancillary Services in Dynamic Power Grids

Kenko Uchida, Kenji Hirata and Yasuaki Wasa

Abstract We discuss an incentivizing market and model-based approach to design the energy management and control systems, which realize high-quality ancillary services in dynamic power grids. Under the electricity liberalization, such incentivizing market should secure a high-speed market-clearing by using the market players' private information well. Inspired by contract theory in microeconomics field, we propose a novel design method of such incentivizing market on the basis of integration of the economic model and the dynamic grid model. We first outline our contract and model-based method to design the incentivizing market and clarify the basic properties of the designed market. We then discuss possibilities, limitation, and fundamental challenges in the direction of our approach and general market-based approaches.

1 Introduction

Achieving a quality assurance of electric energy, called the ancillary service, is a key target of next-generation energy management and control systems for dynamic electric smart grids where electricity liberalization is fully enforced and renewable energy is highly penetrated [1]. Frequency, voltage, and power controls, which are typical contents of the ancillary service, have been technical requirements for the electric energy supplier (e.g., see [2, 3]). Since the electricity liberalization starts, such ancillary control services have been investigated and realized in competitive

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electricity markets; early market designs consider ancillary services as constraint conditions of the optimal energy dispatch and provide simultaneously the energy dispatch and the ancillary services in a single market [4–8]; the subsequent developments [9–11], focusing on the differences not only in the transaction process of energy and ancillary services but also in the required transaction response time, have proposed ancillary service markets, which are closely interacted with energy markets but external to energy markets, in order to implement ancillary services by transacting typically spinning reserves and regulation reserves; the more recent works [12, 13] have proposed a market model implementing the frequency response ancillary service in the primary control level and pointed out the importance of incentives in ancillary market designs. In view these, future energy management and control systems should include the ancillary service markets with some incentive mechanisms, as core elements, which provide high-quality and fast-response control services to the extent of the primary level. Moreover, if we need ancillary control services of transient state, ancillary service markets should include physical models of dynamic power grids. In this article, we propose an incentivizing model and market-based approach to design the energy management and control systems which realize high-quality ancillary services in such dynamic power grids; especially, we develop a design method of such incentivizing market based on the contract-based integration of the economic model and the dynamic grid model. Commenting on the possibilities and limitation of our approach, we discuss some challenges and significant research issues in the direction of our approach and general market-based approaches.

Our approach is developed under the assumption that an energy dispatch scheduling on a future time interval has been finished in a spot energy market at the tertiary control level [14, 15], e.g., for one-hour future interval and each agent has a linearized model of his/her own system along the scheduled trajectory over the future time interval. For this linear time-varying model, we formulate a design problem of real-time regulation markets, i.e., ancillary service markets, at the secondary and primary control levels [14, 15]. Participants in the dynamic electric grid are consumers, suppliers, or prosumers, called agents, who control their own physical systems selfishly according to their own criteria, and independent public commission, called utility, who integrates economically all the controls of agents into a high-quality power demand and supply. In the integration, a market mechanism is adopted inevitably in order to secure selfish behaviors of agents in the electricity liberalization; that is, each agent bids his/her certain quantity in response to a market-clearing price, while utility (auctioneer) clears the market based on the bidding and decides the price with the high speed for regulation at the secondary and primary levels.

The market model in our approach is characterized by two terminologies: “private information” and “incentivizing market”. A conventional market-clearing process based on an iterative exchange of price and quantity (private information) between utility and agents, called the tâtonnement model, does not need rigorous agents’ models, but does not generally converges to an equilibrium. Moreover, even if it converges, the tâtonnement model takes generally a long time to converge to the equilibrium without agents’ model information [16]. To overcome these issues, we propose a novel noniterative/one-shot market model, in which a market planner first designs contract-based incentives for the agents to report their private information (including their own model information) spontaneously to the utility so that the utility can make a high-speed market-clearing in the incentivizing market. This model needs incentivizing rewards, and the optimization process based on the rewards can be recognized as an intermediate model (the second best model) between two extremal models, namely the tâtonnement model and the so-called supply/demand function equilibrium model (the first best model) which uses for free all agents' rigorous models, i.e., agents' private information. On the basis of our incentivizing market, we discuss the relationships of our incentivizing mechanism with the Lagrange multiplier based integration/decomposition mechanism and the mechanism design.

This article has been organized as follows: In Sect. 2, we introduce a dynamic power grid model and a model-based incentivizing market model. We then outline a contract-based approach to the design of incentivizing markets. In Sect. 3, focusing on the relationship between the private information and the incentives, we discuss possibilities and limitation of our approach through some typical scenarios. From a systems and control perspective, we also provide some research directions on model-based and market-based approaches while taking into account the results of the proposed models and scenarios. In Sect. 4, we conclude our discussion.

2 Grid Model and Incentivizing Market Model

Two Layers Market In this paper, we consider the two-level architecture with the two layers market, spot energy market, and real-time regulation market (see Fig. 1). The well-known temporally separated architecture [14, 15] motivated by the conventional power system control is divided into the primary control level (voltage and frequency stabilization), the secondary control level (quasi-stationary power imbalance control), and the tertiary control level (economic dispatch). The two layers market reorganizes the conventional three-level architecture according to the functions of the markets. Our approach is developed under the assumption that an energy dispatch scheduling on a future time interval (shaded blue in Fig. 1) has been finished in a spot energy market (at the tertiary control level), and each agent has a linearized model of his/her own system along the scheduled trajectory over the future time interval (shaded red in Fig. 1). For this linear time-varying model, we formulate a design problem of energy management and control systems to realize ancillary services based on a real-time regulation market (at the secondary and primary control levels). The combination of the physical models is essentially the same as [14].

Linearized Grid Model Let us first consider the linearized time-varying model used in the ancillary market. This paper considers one of the standard grid models, e.g., the average system frequency model [17], as a generic model of high-speed response for ancillary service control problems with two area power networks and with two kinds of players: Utility and Agents. Here, we present a linearized model of each player's own system along the scheduled trajectory over a future time interval during

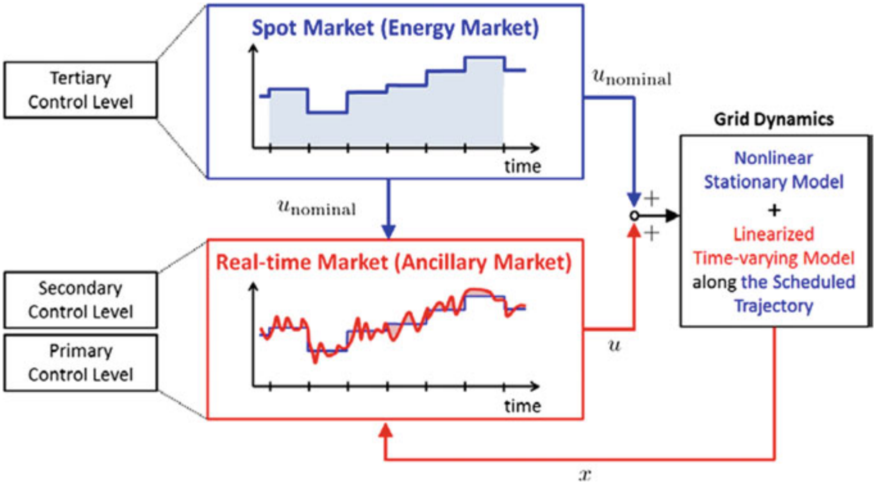

Fig. 1 Two layers market

when an energy dispatch scheduling has been finished in a spot energy market (at the tertiary control level). Of course, it is straightforward to extend the problem to the arbitrary number of agents.

The utility dynamics, which describes the deviation of the power and/or frequency balance and other deviations from physical constraints as well, obeys the following equation:

$$\frac{dx_{0t}}{dt} = f_0(t, x_{1t}, x_{2t}, \omega_t) = A_{01}(t)x_{1t} + A_{02}(t)x_{2t} + D_0(t)\omega_t, \quad t_0 \leq t \leq t_f, \quad (1)$$

and is evaluated by the utility's revenue functional:

$$J_0(t, x; u) = \mathbf{E}_{t,x}\left[\varphi_0(t_f, x_{t_f}) + \int_t^{t_f} l_0(\tau, x_\tau, u_\tau)d\tau\right], \quad (2)$$

where $x = (x_0^\top, x_1^\top, x_2^\top)^\top$ is the collection of the states of the utility dynamics and the two agents' dynamics and $u = (u_1^\top, u_2^\top)^\top$ is the local control inputs, respectively; ω_t is the disturbance modeled by a white Gaussian random process with zero-mean and unity-variance defined on $[t_0, t_f]$; $\mathbf{E}_{t,x}$ indicates an expectation given initial data (t, x); we use an abbreviation like $x_{0t} = x_0(t)$, $x_t = x(t)$. The agent's dynamics obeys the following equation:

$$\frac{dx_{it}}{dt} = f_i(t, x_{it}, u_{it}, \omega_t) = A_i(t)x_{it} + B_i(t)u_{it} + D_i(t)\omega_t, \quad t_0 \leq t \leq t_f, \ i = 1, 2, \quad (3)$$

and is evaluated by the agent's revenue functional:

$$J_i(t, x; u) = \mathbf{E}_{t,x}\left[\varphi_i(t_f, x_{it_f}) + \int_t^{t_f} l_i(\tau, x_{i\tau}, u_{i\tau})d\tau\right], \quad i = 1, 2, \tag{4}$$

where x_i is the state of agent i indicating typically the deviation of power generation or consumption from the scheduled trajectory; u_i is the control input of agent i compensating the deviation. An admissible control of agent i is a state feedback $u_{it} = u_i(t, x)$, which assures the existence of the unique state trajectory $x_t = (x_{0t}^\top, x_{1t}^\top, x_{2t}^\top)^\top$, $t_0 \le t \le t_f$ of the grid model defined by the Eqs. (1) and (3). We formulated the dynamic grid model with the evaluation functionals (2) and (4) defined on the future time interval from the current time t to the final time t_f, which follows from the time-consistency property of dynamic programming; in other words, our evaluation functionals are of model-predictive type.

We will develop our discussion under the assumption that the standard regularity conditions hold on the mathematical formulas, e.g., (1)–(4), and will not refer to such technical conditions on each formula, since the objective of this section is just to outline the incentivizing market and its contract-based design by using these formulas. For readers who are interested in a mathematically rigorous treatment, please see our companion paper [18].

Incentivizing Market Model Now, we present a contract-based approach to the incentivizing market design, which reformulates the conventional contract problems [19–24] adapted to the market mechanism from the systems and control perspective. To describe our market model, we need to specify the participant's private information. The private information of agent i consists of the model information $\Xi_i = (f_i, \varphi_i, l_i)$ and the online information $Z_{it} \subset \{x_{it}^{t_f}, u_{it}^{t_f}\}$, $i = 1, 2$, where $x_{it}^{t_f}$ and $u_{it}^{t_f}$ denote the histories of the state $x_{i\tau}$, $t \le \tau \le t_f$ and the control $u_{i\tau}$, $t \le \tau \le t_f$, respectively.

To incentivize agent's behavior in market model, we (or a market planner) use a reward (salary) functional of the following form. The reward functional:

$$\begin{aligned} W_i^w(t, x_t^{t_f}; u) = w_{if}(t_f, x_{t_f}) + w_{i0}(t, x) + \int_t^{t_f} w_{i1}(\tau, x_\tau)d\tau \\ + \int_t^{t_f} w_{i2}(\tau, x_\tau)\frac{dx_\tau}{d\tau}d\tau, t_0 \le t \le t_f, \quad i = 1, 2, \end{aligned} \tag{5}$$

are defined along with the trajectory $x_\tau = (x_{0\tau}^\top, x_{1\tau}^\top, x_{2\tau}^\top)^\top$, $t \le \tau \le t_f$ given by a control $u = (u_1^\top, u_2^\top)^\top$, where $w = (w_1, w_2)$ and $w_i = (w_{if}, w_{i0}, w_{i1}, w_{i2})$, $i = 1, 2$. An admissible parameter of the reward functional w, called the reward parameter, is in the same class as for the revenue functionals (2) and (4). We use the notation W_i^w so as to emphasize the dependence of W_i on the choice of the parameter w. In order to make these reward functionals play a role in the market model, we express the reward parameter w with another parameter h, called the price, such that $w = w(h)$. The price h will be decided by the utility in the market.

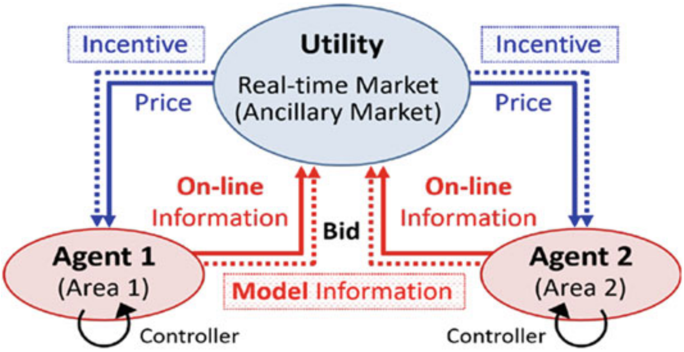

Fig. 2 Incentivizing market

The reward functionals together with the utility's revenue functional and the agent's revenue functional define the social welfare functional as

$$I^{w(h)}(t,x;u) = J_0(t,x;u) - \mathbf{E}_{t,x}\left[\sum_{i=1}^{2} W_i^{w(h)}(t, x_t^{t_f}; u)\right], \tag{6}$$

and the agent's profit functional as

$$I_i^{w(h)}(t,x;u) = J_i(t,x;u) + \mathbf{E}_{t,x}\left[W_i^{w(h)}(t, x_t^{t_f}; u)\right], \quad i = 1, 2. \tag{7}$$

A market planner designs a market mechanism with incentivizing structures (Fig. 2) and makes auction rules as well, based on the evaluation functionals and the grid model information introduced so far; the auction is performed in the following five steps:

Step 1 Utility announces the auction system, and agents decide participation.
Step 2 Agent offers his/her bid based on his/her own private information.
Step 3 Based on agents' bids, price is determined so as to maximize social welfare.
Step 4 Agent decides his/her control to maximize his/her own profit based on price.
Step 5 Utility pay rewards to agents.

Note that Steps 2, 3, and 4 will be performed continuously over a finite time interval.

Reward Design and One-shot Pricing To complete our market model, we need to fix a concrete procedure of agents' bidding by specifying agents' private information to be bidden in the market model; that is, *each agent's model information* $\Xi_i = (f_i, \varphi_i, l_i)$ *is sent a priori to utility, and each agent's online information to be bidden is just the current state, i.e.,* $Z_{it} = x_{it}$*, which means that utility cannot access control input* u_i. Then, the design problem of our market is reduced to finding the reward parameter $w = (w_1, w_2)$, as a function of the price, i.e., $w = w(h)$, such that the social welfare functional is maximized by the reward parameter and the agents' control inputs each of which maximizes his/her own profit and guarantees a satisfactory level of the profit, at a market-clearing price. Such reward parameters, controls and market-clearing prices are given as solutions of the following dynamic optimization problem:

$$\max_{u,h} I^{w(h)}(t, x; u)$$

subject to
Constraint 1 (Incentive compatibility constraint):

$$I_i^{w(h)}(t, x; u) = \max_{v_i} I_i^{w(h)}(t, x; v_i, u_{-i}), \quad (i, -i) = (1, 2), (2, 1),$$

Constraint 2 (Individual rationality constraint):

$$I_i^{w(h)}(t, x; u) \geq k_{i0}(t, x), \quad i = 1, 2,$$

where k_{i0} is in the same class as for the parameter w_{i0} in the reward functional (5). Constraint 1 claims that the reward incentivizes each agent's behavior to adopt the optimal control that maximizes his/her own profit, so that the agents' controls constitute a Nash equilibrium. This implies that, even if the control profiles are not bidden, the utility can reconstruct them based on the bidden model information. On the other hand, Constraint 2 assures a prescribed level of each agent's profit that incentivizes the agent to participate in the market with his/her model information to be sent to the utility a priori. Now, if the agents' bidding is done, the utility can decide a market-clearing price immediately by carrying out the above optimization, and send it to each agent together with the reward payment in real-time. Thus, we obtain a non-iterative/one-shot incentivizing market model.

The above dynamic optimization for market-clearing has an overlapped structure of a dynamic game and an optimal control problem. We developed an approach to this optimization based on the dynamic programming (see [18] for details); first, we parameterize the reward parameter and the agents' controls with the price, and then convert our complex problem to the single optimal control problem in which the social welfare functional is maximized by the price; we also discuss the case that the optimal price is given as the gradient of the value function with respect to the current state, called the shadow price in economics literature.

3 Fundamental Challenges

On the basis of a genetic model suggested from the average system frequency model [17], we have shown an incentivizing market and model-based approach to design the energy management and control systems which realize ancillary services in dynamic power grids. The key issue of the approach is to incentivize the agents (areas) to open their private information that includes model information, which is essential to realize our model-based scheme. In this section, first, following our incentivizing mechanism briefly through two typical scenarios, we discuss the limitation of the mechanism in collecting the private information and possibilities of revisions/reformations as well. Next, toward realization of our approach, we discuss basic technical issues when the utility gathers the model information and also when the utility and the agents process online information. Finally, we provide an outline of several fundamental research directions to realize the designed markets in actual smart grids from the point of view of systems and control.

Incentive Design and Private Information The incentive design in our market model depends on the setting of the utility's and the agents' revenue functionals. Here, focusing on some special cases of the model, we discuss the roles of the revenues in incentivizing the agents to open or report their private information to the utility.

Consider the case that the utility's revenue functional is given as the sum of the original utility's revenue functional, which is assumed not to depend directly on the agents' control such that $l_0 = l_0(t, x)$, and the agents' revenue functionals. Assume further that the payment of the rewards for the agents is not liquidated in the social welfare, i.e., the utility's revenue is identical to the social welfare and each agent asks a zero level profit, i.e., $k_{i0}(t, x) \equiv 0$. In this case, the social welfare maximization is done by the so-called dual decomposition of optimal control problems and the market-clearing price is given as the shadow price, i.e., the value of the "Lagrange multiplier", of the social welfare maximization [18]. From the viewpoint of the incentive design, this design provides each agent with a zero level of the inventive to his/her participation in the market. If all the agents are not satisfied with the zero level, our model-based market mechanism does not work and requires additional incentives or legal forces for participations of strategic agents. Even in such a simple problem setting, we can see that it is not trivial issues to implement an optimal solution considering some economic constraints.

The reward design discussed so far incentivizes the agents to constitute a Nash equilibrium and to participate in the market if the profit level is over his/her expectation. However, these are assured under the tacit assumption that the agents' private information consisting of the model data and the online data is truthfully sent and bidden; if an agent fictitiously bids his/her private information, for example, the Nash equilibrium shifts or disappears; the "mechanism design" [25–28] provides a solution in such case by using additional incentives. Consider the same setting as above where the social welfare functional does not include the budget for the payment of the agents' rewards, and, on the other hand, let agent 1's (2's) profit functional have an additional reward functional of the form $J_0(t, x; u) + J_2(t, x; u)$ ($J_0(t, x; u) + J_1(t, x; u)$). Then, the additional reward provides the utility and all the agents with the same revenue, so that the optimal price from the viewpoint of the social welfare is optimal for all the agents. Therefore, if an agent sends or bids fictitiously his/her private information to the market, the agent obtains a price which is not optimal for his/her own profit. This incentivizing scheme corresponds to the

Groves mechanism [25, 26] in mechanism design literature. Finally, we should note that the additional rewards will be paid from the social welfare budget. More general incentivizing schemes of this type, especially, the schemes realizing the budget balance are sought [28].

Model Information The most significant issue of the model-based approach is to clearly identify not only the dynamic physical models but also the economics models, i.e., $\Xi_i = (f_i, \varphi_i, l_i)$ in sophisticated future smart girds installing diverse energy management systems (EMSs) and state-of-the-art grid control mechanisms. There are generally a variety of the market participants; large conventional generators, xEMSs, aggregators and prosumers combining loads and small-scale renewables, risk-sensitive utility and agents, and players with different market power. It is strongly required to enrich such reliable mathematical models in order to stabilize the grid systems and reduce financial risks. The dynamics consisting of mainly mechanical systems can be estimated by using system identification techniques developed in the system and control field. It is also important to improve the predicting accuracy of the dynamical behavior of consumers through behavioral economic analysis and data-based analysis with environmental information systems. In the model-based approach, specifically to our approach and generally, the compression of the model information is another important issue for the future, although there have been already the trials using randomized models [27, 29], a model reduction method [30].

On-line Information Reducing the online information helps privacy protection and reduction of communication loads. One of the options is to use the output feedback strategy with Kalman filter [31] and distributed/decentralized approaches based on dual decomposition and control methodologies in multi-agent systems. The most crucial issue of the approaches is that it is a very long time to converge at an appropriate equilibrium. Actually, it is necessary to appropriately determine the following items according to circumstances; the compression of the model information and the online information, the system performance, the controller complexity and the computation time to converge at an equilibrium. For instance, in case of LQG power networks, we can obtain an optimal solution analytically [27, 28, 31]. When we use the fast regulation market with nonlinear models and state constraints to require the guarantee of the computability in real time, it is valid to use the continuation and generalized minimum residual (C/GMRES) method presented in [32, 33]. If the revenue functional is approximately composed by the combination of specific basis functions, e.g., linear polynomials, step functions, and piecewise linear functions, it is expected to shorten the computation time by reporting the basis functions as the model information and only the coefficients of the basis functions as the online information. The learning in transition is one of the essential research topics and has been encouraged in systems and control field.

Market Structure, Performance, and Evaluation In the presence of the aforementioned varied participants, it is important to theoretically reveal the performance of the electricity markets such as budget loss and the efficiency (Price of Anarchy), and an influence for physical state constraints and financial limitations. To enhance the reliability of the markets in smart grids, it is also needed to prepare a legal framework promoting the truth-telling mechanism and the crackdown on a malicious report of not only the agents but also the utility. As illustrated in Fig. 1, there are not only the ancillary markets including the incentivizing markets but also energy markets. Ultimately, it is expected to organize a widespread timescale electricity-related market layer from seconds to decades, similarly to the financial markets. Development of software platform and benchmark models integrating the above complex and multiple time-layers models becomes powerful in order to make an opportunity to test and compare novel control mechanisms and to predict some trends in the near future. Such system integration based on mathematical models is to enable the quantitative evaluation of multidisciplinary cost based on system and control theory, engineering and micro-/macroeconomics required at each timescale without field experiments. Through the platform, it is also expected to fill the gap between the fundamental theory based on the systems and control approaches and the well-elaborated practice to make policy recommendations.

4 Conclusions

We have developed a model-based approach to the incentivizing market design for realizing the ancillary services in dynamic smart grids and discussed significant research challenges in the direction of our approach and general market-based approaches. The target of our market design is to provide all the participants with the transparent transactions that assure a satisfactory level from both economic and technical viewpoints for realizing ancillary services; as a promising approach, we have reformulated the conventional contract problems in economics literature and proposed a new contract problem adapted to the model-based market design on the dynamic grid; from the discussion so far, we can point out that the essential roles in this research direction should be played by systems and control, dynamic team/games, multi-agent/distributed decision-making, and so on. We can also see that many challenges are waiting for people from systems and control community to join the research on the topics discussed.

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