On the Economics of Power System Security in Multi-Settlement Electricity Markets

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Abstract— The tight coupling between system and market operations implies that there are strong inter-relationships between system security management and market performance. Therefore, the assurance by the regional transmission organization (*RTO*) of secure system operations strongly depends on, and directly impacts, electricity markets. Typically, electricity is traded in a sequence of markets that are cleared at different frequencies and with different lead times. In this paper, we focus on the hourly day-ahead markets (*DAM*s) and their associated real-time markets (*RTM*s) that clear, typically, every 5 to 10 minutes. The *DAM*s' clearing impacts the nature and the extent of the participants' responses to real-time conditions and, therefore, the real-time system operations, which, in turn, impact system security. The basic thrusts of this work are to quantitatively characterize the linkages between the real-time system security and the day-ahead markets as well as to investigate the role of the financial entities in a multi-settlement system. We develop a systematic approach that allows us to quantify the auction surplus attained through the multi-settlement system and evaluate the impacts of the *DAM*s on market participants' bid/offer surpluses as well as on improving the ability to facilitate real-time secure power system operations. We illustrate the application of the approach on the large-scale ISO-NE multi-settlement system using the historical 2005 - 2006 data – the system model and the bids/offers submitted – and the actual market clearing methodology. The studies bear out the well known fact that the participation of financial entities leads to the convergence of the *DAM* and the associated *RTM* prices. Moreover, these studies also illustrate that such participation leads to improved forecasts of the real-time system operations, and consequently results in improving the assurance of system security.

***Index Terms*— power system security management, security criterion, day-ahead and real-time electricity markets, auction surplus maximization, multi-settlement system, financial entities.**

I. INTRODUCTION

The design and implementation of electricity markets in many jurisdictions involves two or more interrelated markets that are cleared at different points in time. The sequence of markets trades the commodity that is *physically* produced and consumed in real time. Each market, be it a day-ahead hourly market or one of the real-time markets associated with that hour, trades the *MWh* commodity at different prices that reflect the information on the system and market conditions available at the time the *MWh* commodity is cleared. As these conditions are subject to continuous changes in real time, real-time markets (*RTM*s) are cleared at a high frequency, typically every 5 minutes. On the other hand, markets run ahead of real-time system operations have a lower clearing frequency, e.g., hourly clearing in the day-ahead markets (*DAM*s), reflecting the lower resolution of the imperfect information on the real-time conditions in the next day. The hour *h DAM* is cleared on the forecasts of the real-time conditions for that hour the next day. The hourly clearing influences each *RTM* in the near real-time during that hour. The *RTM* clearing determines the volume of deviations from the hour *h DAM* value and the associated price. Such a market design with different lead times and clearing frequencies is commonly referred to as a *multi-settlement system* [1]-[3].

A key issue in system operations is the specification of, and the compliance with the system security criterion. System security is defined as the ability of the interconnected system to provide electricity with the appropriate quality under normal and contingency conditions [4]. The security criterion entails the specification of the set of the postulated contingencies together with the associated preventive and/or corrective control actions for each contingency in the set. For a system operating state, security assessment requires the verification that no violation occurs under the base case and any postulated contingency, taking fully into account the deployment of the associated security control actions. Such verification is further complicated in the market environment as some market participants may not have physical resources or loads. Moreover, the sequence of markets is one of strongly interrelated markets and therefore their outcomes are strongly interrelated.

The regional transmission organization (*RTO*) or the independent system operator (*ISO*) manages system operations through market forces. The various inter-relationships between the physical network security management and the clearing of the sequence of markets imply the strong interdependence between system security and market outcomes. The typical electricity market structure employs a *sequence* of markets consisting of the hourly *DAM*s, and the *RTM*s, which take place every 5 to 10 minutes [1]. Although the *DAM*s are financial markets in contrast to the purely physical *RTM*s, both markets are cleared using the same approach. A key difference between these markets is the nature of the participants. While financial entities may

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participate in the *DAM*s, only players with physical resources or loads can participate in the *RTM*s. In addition, while the demand may be price responsive in the *DAM*s, the demand is, typically, fixed in the *RTM*s. As the *DAM* outcomes impact the associated *RTM*s, financial entities may very well impact the system operations in real-time. The basic thrusts of this work are to quantitatively characterize the linkage between real-time system security, with the underlying real-time physical commodity markets and the financial entity participation in the multi-settlement environment.

The economic benefits of multi-settlement systems have been previously analyzed [3], [5]-[7]. The study in [3] discusses the role of the *DAM*s in terms of providing incentives for accurate forecasts in real-time operations and for facilitating trades through *ex-ante* price discovery. The duopoly model in the simple two-node network shows that for small probabilities of congestion, multi-settlement systems are welfare enhancing when compared to single settlement market designs [5]. The analysis of the impacts of congestion in a multi-settlement environment makes clear that the welfare enhancing role of multi-settlement system is highly sensitive to the presence of real-time congestion [6]. Further evidence of the welfare enhancing impacts of multi-settlement systems comes from the empirical analysis of the PJM and NY-ISO markets [7]. We note that when the market design misaligns system and market operations, as was the case in the California prior to the 2000-2001 crisis, the market participants may manipulate markets resulting in decreased overall market performance [8]. Much of the analysis of the role of financial entities has a focus on the monetary impacts of such participants [9]-[11]. As the participation of financial entities not only increases market liquidity but may also result in price convergence, multi-settlement systems are viewed as improving the economic efficiency of electricity markets when compared to the single settlement markets [9]-[11]. The ISO-NE study [9] identifies that after the introduction of “virtual bidding”, the actual offer/bid mechanism that enables financial entity participation in the *DAM*s, the *RTM* and *DAM* prices tend to converge. The convergence implies an improvement in market performance as temporal arbitrage opportunities diminish. Under speculative trading, financial entity participation may lead to increased market efficiency and decreased average electricity price [10]. The interrelationship between the price convergence and the profits of the financial entities is a “self-correcting” feature of multi-settlement systems [11]. As such, multi-settlement systems provide appropriate price signals to the financial entities, which they may use to make profitable trades that may lead to price convergence. However, there is a clear need to analyze whether the behavior of financial entities driven by such price signals can impact, in some measurable way, system security. This paper is intended as a concrete step towards meeting this need by extending the work developed in [12] for single settlement systems to the multi-settlement environment.

We develop a systematic approach that allows us to quantify the auction surplus [13] attained through the multi-settlement system. We evaluate the impacts of the *DAM*s on market participants’ bid/offer surpluses and assess the improvement in the ability of the *RTO* to ensure real-time secure power system operations. The basic building block is the system snapshot analysis for quantifying market performance as a function of system security criterion [12] and we present its extension to explicitly account for the inter-temporal relationships between an hour *h* *DAM* and its associated *RTM*s. The approach allows us to explicitly analyze the price convergence issues and to quantify the financial entity participation impacts on real-time system security.

We illustrate the application of the approach on the large-scale ISO-NE multi-settlement system using the historical 2005 - 2006 data – the system model and the bids/offers submitted – and the actual market clearing methodology. The studies bear out the well known fact that the participation of financial entities leads to the convergence of the *DAM* and the associated *RTM* prices. Moreover, these studies also illustrate that such participation leads to improved forecasts of the real-time system operations, and consequently results in improving the assurance of system security.

This paper contains five additional sections. The nature of the problem and the market performance quantification for a *DAM* and its associated *RTM*s are described in section II. We devote section III to the discussion of the proposed approach. In section IV, we apply the proposed approach to the ISO-NE *DAM* and present the study results in detail. We conclude in section V with a summary of the paper.

II. Market Performance Quantification of a *DAM* and of its Associated *RTM*s

We consider a power system consisting of (N+1) nodes and denote by $\mathcal{N} = \{0,1,...,N\}$ the set of buses, with the slack bus at bus 0. The security criterion $\mathcal{C}$ has the contingency list $\mathcal{J}_{\mathcal{C}}$ and the specified control action for each contingency [12]. Let $\mathcal{S}$ ($\mathcal{B}$) denote the collection of sellers (buyers). Each seller (buyer) submits its price and quantity offer (bid), indicating the willingness to sell (buy) the amount of energy for the duration represented by the snapshot to (from) the *RTO*. We note that the offers and bids need not necessarily be the true marginal costs and benefits of the participants [13]-[15]. We represent a bilateral transaction ω_w by $\omega_w = \{m_w, n_w, \bar{t}_w\}$. Here, m_w denotes the *from* node, n_w the *to* node, and $\bar{t}_w$ the desired transaction amount. The set of all the bilateral transactions is denoted by $\mathcal{W} = \{\omega_1, ... , \omega_W\}$. Each transaction also submits a willingness to pay for the requested transmission services as a function of the transaction amount delivered [16]. The *RTO* uses the willingness to pay of the bilateral transactions and that implied by the offers and bids by the individual market participants to determine the amount of transmission service provision to each player when market clearing is performed [16]. The *RTO* clears the market at time t using the system snapshot corresponding to that instant.

The *RTO* market clearing involves the solution of the security-constrained market problem for the system snapshot. The objective is to maximize the auction surplus $\mathcal{S}$ [13] under the security criterion $\mathcal{C}$. We state the security-constrained market problem as:

$$max\,\mathcal{S} = \sum_{i=0}^{N} \left(\sum_{\substack{b\in\mathcal{B} \\ at\ node\ i}} \beta_b\left(p_b\right) - \sum_{\substack{s\in\mathcal{S} \\ at\ node\ i}} \beta_s\left(p_s\right) \right) + \sum_{w=1}^{W} \alpha_w\left(t_w\right) \quad (1)$$

subject to

$$\underline{\boldsymbol{g}}^{(0)}\left(\underline{\boldsymbol{p}}_s, \underline{\boldsymbol{p}}_b, \underline{\boldsymbol{t}}\ , \underline{\chi}^{(0)}, \underline{\gamma}^{(0)}\right) = \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\lambda}^{(0)} \qquad (2)$$

$$\underline{\boldsymbol{h}}^{(0)}\left(\underline{\boldsymbol{p}}_s, \underline{\boldsymbol{p}}_b, \underline{\boldsymbol{t}}\ , \underline{\chi}^{(0)}, \underline{\gamma}^{(0)}\right) \le \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\mu}_h^{(0)} \qquad (3)$$

and for every $j \in \mathcal{J}_{\mathcal{C}}$,

$$\underline{\boldsymbol{g}}^{(j)}\left(\underline{\boldsymbol{p}}_s, \underline{\boldsymbol{p}}_b, \underline{\boldsymbol{t}}\ , \underline{\chi}^{(j)}, \underline{\gamma}^{(j)}\right) = \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\lambda}^{(j)} \qquad (4)$$

$$\underline{\boldsymbol{h}}^{(j)}\left(\underline{\boldsymbol{p}}_s, \underline{\boldsymbol{p}}_b, \underline{\boldsymbol{t}}\ , \underline{\chi}^{(j)}, \underline{\gamma}^{(j)}\right) \le \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\mu}_h^{(j)}. \qquad (5)$$

Here, we consider a lossless system and use the superscript (*j*) to denote the contingency case $j \in \mathcal{J}_{\mathcal{C}}$ and denote the base case by the superscript (*0*). The power flow equations are specified by $\underline{\boldsymbol{g}}(\cdot)$ and $\underline{\boldsymbol{h}}(\cdot)$ denote the constraints considered. We use $\underline{\boldsymbol{p}}_s$ ($\underline{\boldsymbol{p}}_b$) to denote the injection (withdrawal) vector and $\underline{\boldsymbol{t}}$ to denote the net total injections of the bilateral transactions in set $\mathcal{W}$ [16]. $\underline{\chi}$ is the system state vector and $\underline{\gamma}$ is the vector of all the control variables except the net real power outputs. We associate the indicated dual variable vector with the right-hand side of each constraint. Note that for a lossless system under preventive control actions, the injection and the withdrawal at each node remain unchanged for both the base and the contingency cases. We denote the security-constrained market problem (2)-(5) by $\mathcal{M}\left(\mathcal{S},\mathcal{B},\mathcal{W};\mathcal{C}\right)$.

We distinguish explicitly between the fixed demand buyers and those with price-responsive demand. The fixed demand bid is a special case of the price-sensitive bid since a specified quantity is submitted without price information implying an infinite willingness to pay. There are, however, difficulties in determining the appropriate value of the benefits of such fixed demand buyers. In order to include these buyers' benefits in the objective function of the $\mathcal{M}\left(\mathcal{S},\mathcal{B},\mathcal{W};\mathcal{C}\right)$, we use a constant τ per *MWh* benefit value for the fixed demand, where τ is set to have a high value to indicate the payments that may be incurred due to outages, say as much as 10,000 *$/MWh* [17].

The market performance of the snapshot system under the specified security criterion $\mathcal{C}$ is quantified from the market clearing given by the solution of $\mathcal{M}\left(\mathcal{S},\mathcal{B},\mathcal{W};\mathcal{C}\right)$. We quantify the market performance in dollar terms on a system-wide basis, as well as for each individual market participant. We use the optimal auction surplus attained under $\mathcal{C}$ as the measure of the overall economic performance of the market[1]. As market participants are not obligated to reveal their actual costs and benefits, we use the bids and the offers to evaluate the bid/offer surplus of each participant at the optimum of (1) - (5). We denote the values of the optimal variables by the superscript *. The seller s at node *i* has an offer surplus of

$$\mathcal{S}_s = \lambda_i^* p_s^* - \beta_s\left(p_s^*\right), \qquad (6)$$

where, λ_i^* is the locational marginal price (*LMP*) at node *i*, i.e., the price at which each *MWh* at node *i* is bought and sold. The bid surplus of the buyer b with demand at node *i* is similarly given by

$$\mathcal{S}_b = \beta_b\left(p_b^*\right) - \lambda_i^* p_b^* \qquad . \qquad (7)$$

When the grid becomes constrained, the *LMP* at each node may change: in fact, for a lossless system, the nonzero *LMP* difference provides a measure of the congestion impacts. Absent congestion, the revenues collected in a lossless system from the buyers exactly equal the payments made to all the sellers. When congestion occurs, however, the two quantities are no longer equal. The difference between the revenues and the payments

$$\mathcal{K} = \sum_{i=0}^{N} \sum_{\substack{b\in\mathcal{B} \\ at\ node\ i}} \lambda_i^* p_b^* - \sum_{i=0}^{N} \sum_{\substack{s\in\mathcal{S} \\ at\ node\ i}} \lambda_i^* p_s^* + \sum_{w=1}^{W}\left(\lambda_{m_w}^* - \lambda_{n_w}^*\right) t_w^* \qquad (8)$$

is the congestion rents collected by the *RTO*, with the last term in (8) being the payments by the bilateral transactions [16].

In a multi-settlement environment, we deal with interrelated electricity markets. The actual system conditions during the hour *h* may differ from those used to determine the *DAM* hour *h* outcomes. The *RTO* uses market forces to manage such deviations and runs the *RTM*s, typically, every 5-10 minutes. As such, we may refer to *RTM*s as *balancing energy markets*. We associate with the *DAM* $\mathcal{D}\big|_h$ for the hour *h*, the *M RTM*s $\mathcal{R}\big|_{(h,1)}, \mathcal{R}\big|_{(h,2)}, \ldots, \mathcal{R}\big|_{(h,M)}$.

The *DAM*s are 24 separate hourly energy markets, one for each hour of the next day. Their financial nature makes possible the participation of financial entities, in addition to the players with physical resources. We use a snapshot to represent the system for the hour *h DAM* and an "updated" snapshot for each $\mathcal{R}\big|_{(h,m)}$, $m = 1, \ldots ,M$. In what follows, we suppress the hour *h* notation so as to simplify the notation. We analyze the hour *h DAM* $\mathcal{D}$ operated in compliance with the security criterion $\mathcal{C}$ using $\mathcal{M}\left(\mathcal{S},\mathcal{B},\mathcal{W};\mathcal{C}\right)$. The problem statement explicitly takes into account all the entities that constitute the set of sellers and the set of buyers in hour *h* – both financial and physical players. We use the superscript $r\,(f)$ to denote the participants with physical resources (financial players). Therefore, the set of sellers $\mathcal{S}$ (buyers $\mathcal{B}$) is given by $\mathcal{S} = \mathcal{S}^r \bigcup \mathcal{S}^f$ $\left(\mathcal{B} = \mathcal{B}^r \bigcup \mathcal{B}^f\right)$. We denote the subset with nonzero cleared quantities in the *DAM* by $\mathcal{S}^{*r} \subseteq \mathcal{S}^r$ and the subset of transactions that receive transmission services by $\mathcal{W}^* \subseteq \mathcal{W}$. Even though a physical buyer b^r may have $p_{b^r}^* = 0$ in $\mathcal{D}$, b^r participates in the *RTM* to meet his fixed demand.

Each *RTM* is designed to be a purely physical market restricting participation to only those players with actual loads and physical generation assets who have nonzero outcomes in the *DAM*. For each $\mathcal{R}\big|_m$, the *RTO* uses the offers of the

[1] In a highly competitive market environment with a uniform price auction mechanism, the market participants tend to reveal their true marginal costs and benefits. Under such conditions, the auction surplus becomes a good proxy for the social welfare and, therefore, an appropriate approximation of the economic efficiency of the markets.

physical sellers in $\mathscr{S}^{*r}$, the willingness to pay of the bilateral transactions cleared in $\mathscr{W}^*$ and the real-time fixed demand of the physical buyers in $\mathscr{B}^r$. We use the identical system snapshot approach for $\mathscr{R}|_m$ and so we formulate and solve the market problem $\mathscr{M}\left(\mathscr{S}^{*r},\mathscr{B}^r,\mathscr{W}^*;\mathscr{C}\right)$ for $\mathscr{R}|_m$ [2].

The metrics of interest – the auction surplus, the market participants' bid/offer surpluses and the congestion rents collected – are evaluated using the relations in (1) and (6)-(8) for $\mathscr{M}\left(\mathscr{S}^{*r},\mathscr{B}^r,\mathscr{W}^*;\mathscr{C}\right)$ for the subperiod *m*. We depict the interrelationships between $\mathscr{D}$ and an associated $\mathscr{R}|_m$ in Fig. 1. We use the notation "^" to denote the optimal values attained in the clearing of $\mathscr{R}|_m$. The figure clearly indicates the players who participate in each market, as well as the inputs and the outcomes of these markets.

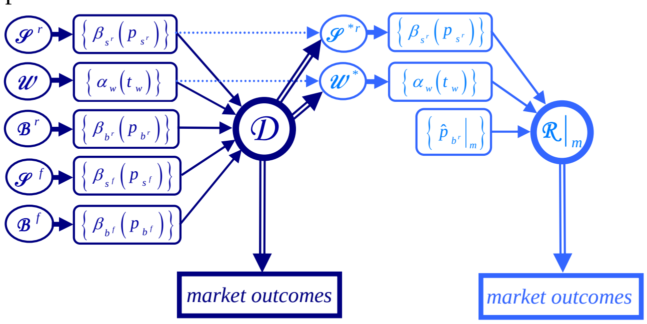

Fig. 1 Information flow in $\mathscr{D}$ for a given hour and an associated $\mathscr{R}|_m$

The outcomes of $\mathscr{D}$ and those of $\mathscr{R}|_m$ are inputs into the settlement – the mechanism that specifies the payments to or by each market participant after the fact. We consider a system where the same *MWh* may be sold in two different markets – $\mathscr{D}$ and a specific $\mathscr{R}|_m$ – and so we deal with a multi-settlement system. Each of the *M* subperiods of the hour *h* has a duration of $1/M$ of an hour and we consider the multi-settlement for such a subperiod. A physical seller $s^r \in \mathscr{S}^{*r}$, located at node *i*, who has cleared $p^*_{s^r}$ in $\mathscr{D}$ receives revenues of $1/M\left(\lambda_i^* p^*_{s^r}\right)$ over that subperiod. As his real-time production $\hat{p}_{s^r}\big|_m$ may deviate from $p^*_{s^r}$, there is an adjustment to account for the production deviation $1/M\left(-p^*_{s^r} + \hat{p}_{s^r}\big|_m\right)$, which is paid at the $\mathscr{R}|_m$ *LMP* $\hat{\lambda}_i\big|_m$. The subperiod *m* revenues of s^r are

$$\eta_{s^r}\big|_m = \frac{1}{M}\left\{\lambda_i^* p^*_{s^r} + \hat{\lambda}_i\big|_m\left(-p^*_{s^r} + \hat{p}_{s^r}\big|_m\right)\right\} \quad . \qquad (9)$$

We note that if the seller s^r production in real time does not deviate from its *DAM* value, i.e., $p^*_{s^r} = \hat{p}_{s^r}\big|_m$, then the revenues $\eta_{s^r}\big|_m$ are simply the *DAM* revenues. As such, the $\mathscr{R}|_m$ *LMP* $\hat{\lambda}_i\big|_m$ has no impact on the subperiod *m* of s^r.

A financial seller s^f, located at node *i*, has revenues of $1/M\left(\lambda_i^* p^*_{s^f}\right)$ for his *DAM* "production". As s^f cannot participate in $\mathscr{R}|_m$, his real-time production $\hat{p}_{s^f}\big|_m = 0$, resulting in a deviation of $-p^*_{s^f}$. As a result, the *RTM* produces an adjustment of $-\hat{\lambda}_i\big|_m p^*_{s^r}$ to the *DAM* revenues of s^f. We may view the financial seller s^f as selling $p^*_{s^f}$ in the *DAM* at λ_i^* and buying back the same amount in the *RTM* at $\hat{\lambda}_i\big|_m$. The revenues of the seller s^f in subperiod *m* are

$$\eta_{s^f}\big|_m = \frac{1}{M}\left\{p^*_{s^r}\left(\lambda_i^* - \hat{\lambda}_i\big|_m\right)\right\} \quad . \qquad (10)$$

We note that as long as the *DAM LMP* λ_i^* is above the *RTM LMP* $\hat{\lambda}_i\big|_m$ the financial seller s^f has positive revenues.

In an analogous manner, the physical buyer b^r located at node *i* makes payments in the subperiod *m* of

$$\gamma_{b^r}\big|_m = \frac{1}{M}\left\{-\lambda_i^* p^*_{b^r} - \hat{\lambda}_i\big|_m\left(-p^*_{b^r} + \hat{p}_{b^r}\big|_m\right)\right\} \quad . \qquad (11)$$

The buyer b^r pays λ_i^* for the portion $p^*_{b^r}$ cleared in $\mathscr{D}$ and $\hat{\lambda}_i\big|_m$ for the remainder of his real-time demand. The payments of a financial buyer b^f in the subperiod *m* are

$$\gamma_{b^f}\big|_m = \frac{1}{M}\left\{p^*_{b^f}\left(-\lambda_i^* + \hat{\lambda}_i\big|_m\right)\right\} \quad . \qquad (12)$$

We use the same reasoning to determine the payments by the bilateral transaction $w \in \mathscr{W}^*$ in the subperiod *m* to be

$$\gamma_w\big|_m = \frac{1}{M}\left\{\left(\lambda^*_{m_w} - \lambda^*_{n_w}\right)t^*_w + \left(\hat{\lambda}_{m_w}\big|_m - \hat{\lambda}_{n_w}\big|_m\right)\left(-t^*_w + \hat{t}_w\big|_m\right)\right\}. \quad (13)$$

We note that if the bilateral transaction w does not deviate from the *DAM* clearing outcomes in the subperiod, then his payments are independent on the *RTM* outcomes.

The *RTO* makes the payments in (9) and (10), to the sellers and receives from the buyers and the bilateral transactions the payments in (11)-(13). The difference between these payments are the subperiod *m* congestion rents collected by the *RTO*

$$\begin{aligned}\mathscr{K}_{\Sigma}\big|_m = {} & \frac{1}{M}\left\{\sum_{b^r \in \mathscr{B}^r}\gamma_{b^r}\big|_m + \sum_{b^f \in \mathscr{B}^f}\gamma_{b^f}\big|_m + \sum_{w \in \mathscr{W}^*}\gamma_w\big|_m\right\} - \\ & \frac{1}{M}\left\{\sum_{s^r \in \mathscr{S}^{*r}}\eta_{s^r}\big|_m + \sum_{s^f \in \mathscr{S}^f}\eta_{s^f}\big|_m\right\} \quad .\end{aligned} \qquad (14)$$

We use the results in (9) - (14) for the quantification of the performance of the multi-settlement system in the subperiod *m*. The output of the seller $s^r \in \mathscr{S}^{*r}$ is produced in the real time, i.e., in the subperiod *m*, and is offered for sale for $1/M\,\beta_{s^r}\left(\hat{p}_{s^r}\big|_m\right)$. The offer surplus of the seller s^r in the subperiod *m* are expressed in terms of the difference between the revenues and the offer, i.e.,

$$\mathscr{S}_{s^r}\big|_m = \eta_{s^r}\big|_m - \frac{1}{M}\left\{\beta_{s^r}\left(\hat{p}_{s^r}\big|_m\right)\right\} \quad . \qquad (15)$$

The fact that the financial seller s^f has no real-time produc-

[2] Note that it is possible for a physical seller, not cleared at the *DAM*s, to participate in the *RTM*s under certain conditions. For example, the *RTO* may commit additional units after the clearing of the *DAM*s to ensure the system security in the real time. Furthermore, an *RTO* may also allow "self-commitment" of those resources. We do not consider these situations in the paper.

tion implies that the offer surplus of s^f equals his revenues

$$\mathcal{S}_{s^f}\Big|_m = \eta_{s^f}\Big|_m \quad . \tag{16}$$

The physical buyer b^r consumes the energy in the subperiod resulting in the bid surplus given by the difference between the b^r willingness to pay in real time and the actual payments:

$$\mathcal{S}_{b^r}\Big|_m = \frac{1}{M}\left\{\hat{\beta}_{b^r}\left(\hat{p}_{b^r}\Big|_m\right)\right\} - \gamma_{b^r}\Big|_m \quad . \tag{17}$$

We note that the real-time $\hat{\beta}_{b^r}$ may differ from β_{b^r} due to the fact that the real-time demand is viewed as fixed.

The financial buyer b^f cannot consume in the real time and so has the bid surplus

$$\mathcal{S}_{b^f}\Big|_m = -\gamma_{b^f}\Big|_m \quad . \tag{18}$$

The bilateral transaction $w \in \mathscr{W}^*$ receives the actual transmission service in the real time resulting in a surplus of

$$\mathcal{S}_{w}\Big|_m = \frac{1}{M}\left\{\alpha_w\left(\hat{t}_w\Big|_m\right)\right\} - \gamma_w\Big|_m \quad . \tag{19}$$

We make use of the market participants' bid/offer surpluses, including those of the bilateral transactions and the congestion rents collected by the *RTO*, to evaluate the total auction surplus attained in the multi-settlement system:

$$\begin{aligned}\mathcal{S}_{\Sigma}\Big|_m = &\sum_{s^r \in \mathscr{P}^{*r}} \mathcal{S}_{s^r}\Big|_m + \sum_{b^r \in \mathscr{B}^r} \mathcal{S}_{b^r}\Big|_m + \sum_{s^f \in \mathscr{P}^f} \mathcal{S}_{s^f}\Big|_m + \\ &\sum_{b^f \in \mathscr{B}^f} \mathcal{S}_{b^f}\Big|_m + \sum_{w \in \mathscr{W}^*} \mathcal{S}_{w}\Big|_m + \mathcal{K}_{\Sigma}\Big|_m \quad .\end{aligned} \tag{20}$$

We substitute (14) - (19) into (20) to simplify and get

$$\begin{aligned}\mathcal{S}_{\Sigma}\Big|_m = &\frac{1}{M}\left\{\sum_{b^r \in \mathscr{B}^r} \hat{\beta}_{b^r}\left(\hat{p}_{b^r}\Big|_m\right) - \sum_{s^r \in \mathscr{P}^{*r}} \beta_{s^r}\left(\hat{p}_{s^r}\Big|_m\right)\right\} + \\ &\frac{1}{M}\sum_{w \in \mathscr{W}^*} \alpha_w\left(\hat{t}_w\Big|_m\right) \quad .\end{aligned} \tag{21}$$

Now, the auction surplus attained in the *RTM* $\mathcal{R}|_m$ is $\hat{\mathcal{S}}\Big|_m$ and its value is given by (1):

$$\begin{aligned}\hat{\mathcal{S}}\Big|_m = &\frac{1}{M}\left\{\sum_{b^r \in \mathscr{B}^r} \hat{\beta}_{b^r}\left(\hat{p}_{b^r}\Big|_m\right) - \sum_{s^r \in \mathscr{P}^{*r}} \beta_{s^r}\left(\hat{p}_{s^r}\Big|_m\right)\right\} + \\ &\frac{1}{M}\sum_{w \in \mathscr{W}^*} \alpha_w\left(\hat{t}_w\Big|_m\right) \quad .\end{aligned} \tag{22}$$

We conclude that

$$\mathcal{S}_{\Sigma}\Big|_m = \hat{\mathcal{S}}\Big|_m \quad . \tag{23}$$

Therefore, the total auction surplus of the multi-settlement system attained in the subperiod *m* is precisely the auction surplus attained in $\mathcal{R}|_m$. We, furthermore, conclude that the outcomes of $\mathcal{D}$ do not explicitly impact the total auction surplus $\mathcal{S}_{\Sigma}\Big|_m$, but impact the allocation of the total auction surplus among the market participants.

The performance metrics in (14) - (21) are for the subperiod *m* of the hour *h*. We aggregate them for the *M* subperiods of hour *h* to evaluate the hourly metrics. In particular, we compute the hour *h* auction surplus $\mathcal{S}_{\Sigma}$ attained in the multi-settlement system to be

$$\mathcal{S}_{\Sigma} = \sum_{m=1}^{M} \mathcal{S}_{\Sigma}\Big|_m = \sum_{m=1}^{M} \hat{\mathcal{S}}\Big|_m \quad . \tag{24}$$

The performance quantification of the multi-settlement system clearly makes use of the interrelationships between the *DAM* and its associated *RTM*s, as illustrated in Fig. 2.

We note the clearing of the financial entities in $\mathcal{D}$ impacts the clearing of the physical generation as well as the clearing of the physical loads. As such, the participation of the financial entities impacts the deviations of the physical resources clearing in the real time. Such deviations have implications on the market and the system operations. In particular, they impact the ability of the *RTO* to ensure real-time system security. In the next section, we describe the proposed approach to quantitatively assess the impacts of operating a system under a specified criterion $\mathcal{C}$ on the market performance in a multi-settlement environment. Also, we quantify the impacts of financial entities on the ability of the *RTO* to meet system security $\mathcal{C}$ in the near real time.

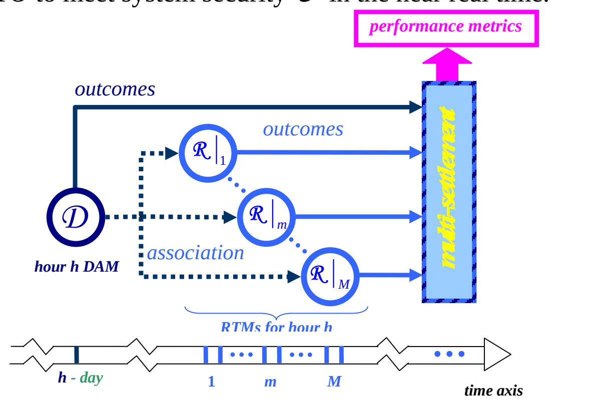

Fig. 2 Interactions between $\mathcal{D}$ and $\mathcal{R}|_m$ and the performance quantification in a multi-settlement environment

III. PROPOSED APPROACH

The maintenance of secure power system operations is a task that strongly depends on the outcomes of the *DAM*s. We may view the *DAM* physical generation and consumption as a rough *guess* of the actual outcomes in the associated *RTM*s. As the system and the market conditions in the near to real time may change from those forecast and cleared in the *DAM*, the *RTM*s are run to manage the resulting deviations.

The actual physical demand in the *M RTM*s give rise to the physical demand deviation in hour *h*:

$$\delta\hat{p}_{\mathscr{B}^r} = \frac{1}{M}\left[\sum_{m=1}^{M}\left(\sum_{b^r \in \mathscr{B}^r} \hat{p}_{b^r}\Big|_m + \sum_{w \in \mathscr{W}^*} \hat{t}_w\Big|_m\right)\right] - \left[\sum_{b^r \in \mathscr{B}^r} p^*_{b^r} + \sum_{w \in \mathscr{W}^*} t^*_w\right] . \tag{25}$$

A non-zero $\delta\hat{p}_{\mathscr{B}^r}$ indicates that the physical buyers' *DAM* purchases are either below or above the consumption in real time. Similarly, the physical generation deviation in hour *h* is

$$\delta\hat{p}_{\mathscr{P}^{*r}} = \frac{1}{M}\left[\sum_{m=1}^{M}\left(\sum_{s^r \in \mathscr{P}^{*r}} \hat{p}_{s^r}\Big|_m + \sum_{w \in \mathscr{W}^*} \hat{t}_w\Big|_m\right)\right] - \left[\sum_{s^r \in \mathscr{P}^{*r}} p^*_{s^r} + \sum_{w \in \mathscr{W}^*} t^*_w\right] . \tag{26}$$

The participation of the financial entities in the *DAM* gives rise to the lack of balance between physical demand deviation $\delta\hat{p}_{\mathscr{B}^r}$ and the physical generation deviation $\delta\hat{p}_{\mathscr{P}^{*r}}$. A positive net injection of the financial participants in the *DAM* corresponds to $\sum_{s^f \in \mathcal{S}^f} p^*_{s^f} > \sum_{b^f \in \mathcal{B}^f} p^*_{b^f}$, which implies that $\sum_{s^r \in \mathcal{S}^{*r}} p^*_{s^r} < \sum_{b^r \in \mathcal{B}^r} p^*_{b^r}$. In this case, the physical generation deviation exceeds the physical demand deviations so that $\delta \hat{p}_{\mathcal{S}^{*r}} > \delta \hat{p}_{\mathcal{B}^r}$. Therefore, more generation is required in real time than cleared in $\mathcal{D}$ leading to the deviations in the physical sellers' outcomes. In case of $\sum_{s^f \in \mathcal{S}^f} p^*_{s^f} < \sum_{b^f \in \mathcal{B}^f} p^*_{b^f}$ – a negative net injection of the financial entities – some of the physical generation serves the demand of the financial buyers in $\mathcal{D}$ and so $\sum_{s^r \in \mathcal{S}^{*r}} p^*_{s^r} > \sum_{b^r \in \mathcal{B}^r} p^*_{b^r}$. In this case, $\delta \hat{p}_{\mathcal{S}^{*r}} < \delta \hat{p}_{\mathcal{B}^r}$. Whenever there is zero net injection by the financial entities, the physical generation deviation and the physical demand deviation are in exact balance. The absence of financial entity participation is a special case of this zero net injection. While the injection/withdrawal deviation metrics of (25) and (26) provide system-wide aggregate measures, we can also introduce analogous metrics for zonal, as well as, nodal measures in order to meet the requirements at the different levels of granularity.

We use the auction surplus in (24), the total congestion rents in (14) and each market participants' bid/offer surplus metric in (15) - (19) to evaluate the overall economic performance of the multi-settlement system and that of each market participant, respectively. In addition, we need appropriate metrics to analyze the combined impacts of the *DAM-RTM* clearing outcomes.

As market and system conditions may change, the price of the *MWh* commodity in each $\mathcal{R}\big|_m$ at a specified node may deviate from that in $\mathcal{D}$. The hour *h* price deviation at node *i* is

$$\delta\lambda_i = \frac{1}{M}\sum_{m=1}^{M}\left[\lambda^*_i - \hat{\lambda}_i\Big|_m\right] \quad . \qquad (27)$$

Whenever $\delta\lambda_i \neq 0$ over a nontrivial subset of hours, arbitrage opportunities exist, implying market inefficiency [10]. A financial entity can participate in the market to take advantage of price arbitrage opportunities at such a node. As more and more financial entities eye such opportunities, leading to their participation in the markets to arbitrage the price deviation, the arbitrage opportunities begin disappearing. As such, $\delta\lambda_i \rightarrow 0$, leading to the improved economic efficiency of the markets. Thus, price convergence is a desirable outcome in multi-settlement systems. We also note that $\delta\lambda_i - \delta\lambda_j,\ i \neq j$, quantifies how well the $\mathcal{D}$ outcomes forecast the nodal price difference between nodes *i* and *j* in real time taking into account the actual system congestion and losses.

The price deviation $\delta\lambda_i$ also impacts the surplus of each market participant. The output of the seller $s^r \in \mathcal{S}^{*r}$, located at node *i*, is produced in the real time. Therefore, his offer is, unlike his revenues in (9), independent of the $\mathcal{D}$ outcomes. Therefore, the $\mathcal{D}$ outcomes impact the surplus of the seller s^r in hour *h*. Using (15), the s^r offer surplus in hour *h* is

$$\mathcal{S}_{s^r} = \frac{1}{M}\sum_{m=1}^{M}\left\{\hat{p}_{s^r}\Big|_m \hat{\lambda}_i\Big|_m - \beta_{s^r}\left(\hat{p}_{s^r}\Big|_m\right)\right\} + \delta\mathcal{S}_{s^r} \quad . \qquad (28)$$

Here, $\delta\mathcal{S}_{s^r}$ is the physical seller offer surplus deviation metric

$$\delta\mathcal{S}_{s^r} = p^*_{s^r}\,\delta\lambda_i \qquad (29)$$

and quantifies the impact of the $\mathcal{D}$ outcomes on the revenues of the seller s^r. A positive (negative) $\delta\mathcal{S}_{s^r}$ implies that s^r captures more (less) revenues for his real-time production than those in $\mathcal{D}$. We consider a specific case to illustrate the nature of $\delta\mathcal{S}_{s^r}$. For a system with s^r, the marginal seller in both $\mathcal{D}$ and an associated $\mathcal{R}\big|_m$ and with $\hat{\lambda}_i\big|_m > \lambda^*_i$ and $\hat{p}_{s^r}\big|_m > p^*_{s^r}$. While $p^*_{s^r}$ is paid at λ^*_i the $\hat{p}_{s^r}\big|_m - p^*_{s^r}$ is paid at $\hat{\lambda}_i\big|_m$. Therefore, the portion $p^*_{s^r}$ receives less revenues per *MWh* than $\hat{p}_{s^r}\big|_m - p^*_{s^r}$. The fact that s^r participates in $\mathcal{D}$ and sells $p^*_{s^r}$ implies that for this case he receives lower revenues than had he participated in only $\mathcal{R}\big|_m$. As such, s^r is better off clearing a lesser amount than $p^*_{s^r}$ whenever $\hat{\lambda}_i\big|_m > \lambda^*_i$ so as to increase revenues for its actual production $\hat{p}_{s^r}\big|_m$. The negative $\delta\mathcal{S}_{s^r}$ is illustrated in Fig 3. Whenever a financial buyer b^f realizes such a price deviation, then his participation in $\mathcal{D}$ that may result in an increase in λ^*_i. In turn, the revenues of s^r may increase and he may be willing to produce more in $\mathcal{D}$ than in the case of without the financial buyer b^f. We note that the surplus driven offer/bid decisions furthermore impact the deviation of the physical production/consumption. Under the conditions of the example, as the physical seller has the incentive to clear a lesser amount in $\mathcal{D}$ due to the price deviation, the need may arise for additional amounts cleared in the near-real-time. We conclude that such incentives may result in conditions that the physical production/consumption in $\mathcal{D}$ does not appropriately forecast the real-time conditions, and may lead to "stressed" real-time operations, thereby lessening the ability to ensure secure power system operations.

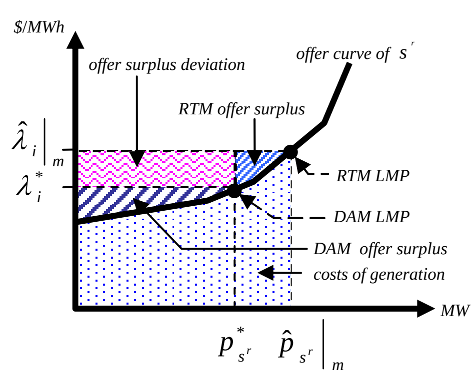

Fig. 3 The effects of $\mathcal{D}$ and $\mathcal{R}\big|_m$ clearing on the offer surplus deviation of the physical seller s^r located at node *i* for the case $\hat{\lambda}_i\big|_m > \lambda^*_i$

Once we compute the individual offer surplus deviation of a physical seller, we can determine the offer total surplus deviation of the subset of the physical sellers using

$$\delta\mathcal{S}_{\mathscr{S}^{*r}} = \sum_{i=0}^{N} \sum_{s^r \in \mathscr{S}^{*r}} p^*_{s^r}\, \delta\lambda_i \varepsilon_{is^r}, \quad \varepsilon_{is^r} = \begin{cases} 1, & s^r \text{ is at node } i \\ 0, & \text{otherwise} \end{cases} . \quad (30)$$

Similarly, we can evaluate the total physical buyers' bid surplus deviations

$$\delta\mathcal{S}_{\mathscr{B}^r} = \sum_{i=0}^{N} \sum_{b^r \in \mathscr{B}^r} p^*_{b^r}\, \delta\lambda_i \varepsilon_{ib^r}, \quad \varepsilon_{ib^r} = \begin{cases} 1, & b^r \text{ is at node } i \\ 0, & \text{otherwise} \end{cases} . \quad (31)$$

A positive $\delta\mathcal{S}_{\mathscr{B}^r}$ implies that the physical buyers pay less for their aggregate real-time demand in $\mathcal{D}$ than in the associated *RTM*s. This happens because the physical buyers benefit from the lower *DAM* prices that they pay for the portion of the demand cleared in the *DAM*.

The *MW* deviation metrics along with the price and the bid/offer surplus deviation metrics capture important aspects of system and market operations in a multi-settlement environment. The physical generation and demand deviation metrics quantify how "close" the real-time system conditions are to those forecasted in the clearing of the *DAM*. Smaller magnitude deviations imply improved "forecasts" of the system conditions in the *DAM*, which, in turn, result in the improved ability of the *RTO* to ensure real-time system security. Therefore, the *DAM* clearing is strongly interrelated with the real-time system operations. The price and the physical participants' bid/offer surplus deviation metrics, on the other hand, quantify the impacts of the *DAM* outcomes on the market participants' bid/offer surpluses. As price deviations increase, the financial entity participation becomes more pronounced in the *DAM*s [10], [11]. Such participation leads to changes in the *DAM* outcomes, which, in turn, impact how the real-time system conditions are forecasted in the *DAM*. A desirable market outcome is that the deviation metrics of surplus and of production/consumption tend to zero since the lower the absolute values of these metrics, the "better" the markets perform. The ability to quantify the economic impacts of compliance with a specified security criterion renders these metrics highly appropriate in the preparation of various regulatory filings, as well as in applications to longer-term planning and shorter-term studies with the explicit representation of the financial entities in addition to the physical asset owners. The proposed metrics capture the strong interrelationships between system and market operations in the multi-settlement environments. Therefore, they effectively quantify the performance of the multi-settlement systems.

Each *MW* or surplus deviation metrics given in (25) - (31) depends on the specified security criterion $\mathcal{C}$. Under a different security criterion $\mathcal{C}'$, the *RTO* explicitly considers the solution of the problem $\mathcal{M}(\mathscr{S},\mathcal{B},\mathcal{W};\mathcal{C}')$ at each system snapshot, be it a *DAM* or an *RTM*. The constraints expressed in (4)-(5) apply to each contingency in the set $\mathscr{J}_{\mathcal{C}'}$. We measure the impacts on market performance due to the change in the security criterion from $\mathcal{C}$ to $\mathcal{C}'$ by the change in each metric of interest from one criterion to the other. For example, the change in the auction surplus metric is given by

$$\Delta\mathcal{S}_{\Sigma}\Big|_{\mathcal{C}\to\mathcal{C}'} = \mathcal{S}_{\Sigma}\Big|_{\mathcal{C}'} - \mathcal{S}_{\Sigma}\Big|_{\mathcal{C}} \quad (32)$$

and provides a proxy measure for the change in the economic efficiency of the markets in a multi-settlement environment due to a change in the security criterion from $\mathcal{C}$ to $\mathcal{C}'$. We deploy analogous expressions for each metric in (14)-(31) to measure the relative change in response to the security criterion change from $\mathcal{C}$ to $\mathcal{C}'$. The changes in the bid/offer surpluses, the total dispatched load and the multi-settlement system deviation metrics are all of interest in our assessment. We also need the changes in the physical demand and generation deviation to quantify the impacts on the ability of the *RTO* to meet system security in real time. For example, to evaluate the impacts on the physical generation deviation, we use

$$\Delta\delta_{\mathscr{S}^{*r}}\Big|_{\mathcal{C}\to\mathcal{C}'} = \delta\hat{p}_{\mathscr{S}^{*r}}\Big|_{\mathcal{C}'} - \delta\hat{p}_{\mathscr{S}^{*r}}\Big|_{\mathcal{C}} \quad . \quad (33)$$

These metrics effectively capture the multi-settlement system performance for the security criterion change from $\mathcal{C}$ to $\mathcal{C}'$ for a given hour *h*. For example, the *RTO* can quantify the economic impacts of operating the system under a tightened security criterion by including additional contingencies in the postulated contingency list.

Under a specified security criterion, the hourly snapshots corresponding to different system and market conditions, may result in markedly different market performance outcomes. Such differences arise for many reasons including changes in the load, the set of selling entities, and the offers/bids submitted. Consequently, these hourly assessments must be carried out over a longer period to appropriately capture the impacts of the different conditions that exist during that period. Conceptually, we need to assess the market performance of the *DAM* and the associated *RTM*s at each hour of the study period. The needs are similar in assessing the market performance impacts due to a change in the security criterion. The hourly values of the relative performance metrics are summed to obtain the daily values which, in turn, are used to compute the relative performance metrics for the entire study period. As the computing requirements to clear each market over a study period for a large-scale system may be large, a practical way to reduce them is to perform the assessments for a smaller *representative* sample of the hours. In this work, we use the scheme introduced in [12] to systematically construct the set of sample days for the *DAM*s. We then carry out the evaluation only for the selected sample days and their associated *RTM*s. The quantification of the multi-settlement system performance based on the selected representative multiple snapshots constitutes the proposed approach for evaluating the impacts of a security criterion or in its change in a multi-settlement system, as well as to quantify the impacts of financial entity participation on the ability of the *RTO* to ensure real-time system security.

The proposed approach provides a useful tool to the *RTO* to analyze the interdependence between market performance and the system security in a multi-settlement environment. The ability to quantify the financial impacts of compliance with a specified security criterion makes the approach highly useful in regulatory proceedings, as well as in longer term planning and shorter term investigations with the explicit representation of both the financial and the physical asset owning players. These applications include the justification by the *RTO* of the decision to modify the specification of the security criterion in force and the costs/benefits analysis of network improvements to mitigate the market performance impacts of a set of specified contingencies. The proposed approach furthermore allows us to investigate the role of the *DAM*s in reallocating the auction surplus among market participants, to analyze the *DAM – RTM* price deviation issues and to quantify the impacts of the financial entities participation on real-time system security.

IV. Illustrative Example: The ISO-NE System

We illustrate the application of the proposed approach to the study of the ISO-NE system and markets. The objectives of our studies are to quantify the economic efficiency of the ISO-NE multi-settlement markets as a function of the security criterion in force, to investigate the impacts of the of the financial entity participation on the ISO-NE system and markets and to quantify the impacts on the ISO-NE market performance of a security criterion change from the criterion in force to a modified (*n*–1) security. We apply the proposed approach to quantitatively analyze the ISO-NE multi-settlement system performance. We assess the impacts of the participation of financial entities in the *DAM*s by performing a side-by-side comparison of the outcomes of the *DAM*s and the associated *RTM*s without and with such players. A particularly insightful aspect of the comparison is the set of values for the deviation metrics of the physical entities. In the following study, we quantify the impacts of a change in the security criterion from the current security criterion in force to a modified (*n*–1) security criterion and compare the observed impacts under the two criteria.

We make use, in the studies, of the system and market data from the years 2005 and 2006 and of the ISO-NE actual market clearing software. We represent the large-scale ISO-NE system multi-area structure with the appropriate level of detail. Each area of the ISO-NE system is characterized as being either an import or an export area [18]. The import areas are

- $\mathcal{A}^1$: Boston/NE Massachusetts;
- $\mathcal{A}^2$: Connecticut;
- $\mathcal{A}^3$: SW Connecticut; and
- $\mathcal{A}^4$: Norwalk/Stamford.

We treat the remainder of the system as a single export area and denote it by $\mathcal{A}^5$. We refer the reader to a more detailed discussion of the ISO-NE system used in these studies [18].

We select 40 representative days from 2005 and 2006 to study the *DAM*s and their associated *RTM*s. For the discussion in this paper, we focus specifically on the four contiguous peak demand hours of each selected day and analyze the values of metrics of interest for those 160 hours. We start out with the evaluation of the ISO-NE multi-settlement system performance under the security criterion in force to determine the values of the metrics for the reference case for the study.

The ISO-NE operates the system under a modified (*n*-2) security criterion [18], which we denote by $\mathscr{C}_0$. We perform market clearing for the *DAM*s and their associated *RTM*s for the selected 160 hours and quantify the market performance metrics under the security criterion $\mathscr{C}_0$. We first focus on the *DAM-RTM MW* deviations. As the real-time demand in each *RTM* is considered to be fixed, the cleared demand values are not a function of the security criterion, per se, as long as the security-constrained market problem is feasible. We compare the fixed real-time demand in each of the *M RTM*s associated with the demand cleared in a *DAM* to evaluate the deviation metrics. We plot in Fig. 4 the demand values for the selected 160 hours. We note that the real-time demand values exceed the *DAM* demand in the selected 160 hours. As these hours are representative of the ISO-NE system past behavior, they correctly indicate that the *RTM* demands, typically, exceed the *DAM* demands. Therefore, there may be a need for additional physical generation in the real time over the amounts cleared in the *DAM*s.

We examine the physical demand and generation deviations and use the plots in Fig. 5 to gain insights into their nature. These plots indicate that both the physical demand and the generation deviations are positive for the hours under consideration. Also, the positive values indicate that as much as 75% of the real-time demand and generation are cleared in the *DAM*. This result indicates that there is a need for additional generation in the real time. The plot of the net differences between the generation and the load deviations, also given in Fig. 5, indicate the impacts of the net positions of the financial players in the *DAM*s. While there are daily variations in the financial entities' net positions, their range is up to 10 % of the real-time demand, with the more pronounced impact in the higher demand days.

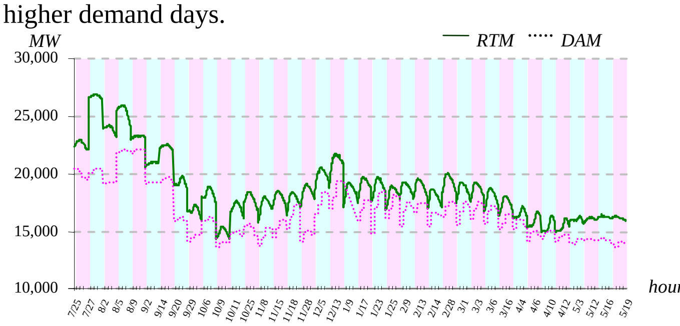

Fig. 4 Cleared demand in the *DAM*s and in their associated *RTM*s for the selected 160 hours in the study period

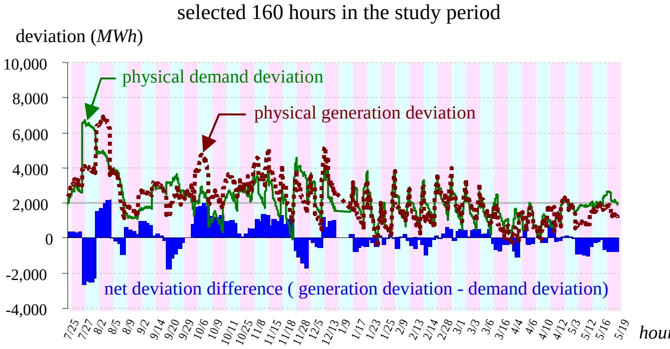

Fig. 5 The physical demand deviation, the physical generation deviation and the net deviation difference for the selected 160 hours in the study period

We now discuss the economic aspects of the secure operations of the power system. Analysis of the *DAM-RTM* price deviation metric indicates that, on average, the prices are higher in the *DAMs* than in their associated *RTM*s. Such results are clearly visible in the plots of the price deviation duration curves of the import areas $\mathcal{A}^1$, $\mathcal{A}^2$ and the export area $\mathcal{A}^5$, shown in Fig. 6. The area-wide price deviation measure of an area is evaluated using the load-weighted average of the prices in the area for a snapshot system. We observe that the price deviations are more pronounced for the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$ than for the export area $\mathcal{A}^5$. For the study hours selected, the area $\mathcal{A}^2$ price deviations are larger than those of any other area indicating that congestion has more pronounced impacts on this area than other areas. The price deviation results also indicate that the physical sellers in the import areas capture more revenues for their real-time production in the 160 hours of the study period. Under these conditions, financial entities have more incentives to be sellers in the import area $\mathcal{A}^2$ than in any other area. If the financial sellers were to participate more intensely in the import area $\mathcal{A}^2$, then a decrease in the import area $\mathcal{A}^2$ *DAM* prices would result and, therefore, the price convergence would be improved. Given the nature of the physical generation and the demand deviations, we conjecture that financial entities may expect higher price deviations in the peak-demand periods and therefore they may adjust their bidding behaviors to clear more quantities in the *DAM*s in which they participate.

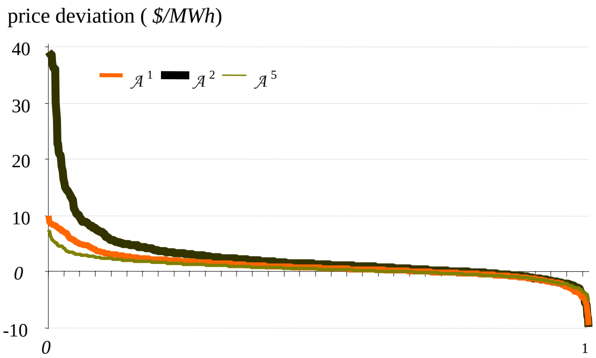

Fig. 6 Price deviation duration curves for the areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$ for the selected 160 hours in the study period

Next, we turn our attention to assessing the auction surplus of multi-settlement markets. We use the value of τ = 1,000 *\$/MWh* for the fixed demand. We choose this value on the basis of that it is the authorized bid/offer price cap in the ISO-NE markets and it is a reasonable proxy of the willingness to pay of the buyers with fixed demands. We evaluate using τ the auction surplus for the *DAM*s and the associated *RTM*s. We summarize the results in the plots given in Fig. 7 of the normalized auction surplus values for the 160 hours in the study period. We normalize the auction surplus values using the average *RTM* auction surplus value so as to provide a meaningful comparison of the observed results. The positive load deviations and the fact that they represent fixed demands imply that the auction surplus outcomes are higher in the *RTM*s than in the *DAM*s. We next examine the individual components of the deviations of the auction surplus in the *DAM*s and their associated *RTM*s.

We investigate the deviations in the bid/offer surpluses of the physical market participants using their normalized values, with the base value being the *RTM* auction surplus. We provide the plots of the physical buyers and sellers in Fig. 8. We note that the physical sellers capture additional revenue for their real-time production for the majority of the hours in the simulation period. Therefore, the physical buyers pay a "premium" for that portion of their real-time demand needs that is cleared in the *DAM*. The plots clearly demonstrate that the sum of the bid/offer surplus deviations is not equal to zero, due to the financial entity participation, the bilateral transact-tions and the congestion rents. The metrics in (14)-(31) serve to provide the quantification of the multi-settlement system performance for the 160 hours of the study period under the reference criterion $\mathcal{C}_0$. We use these results as the reference basis for the comparative studies which we discuss next.

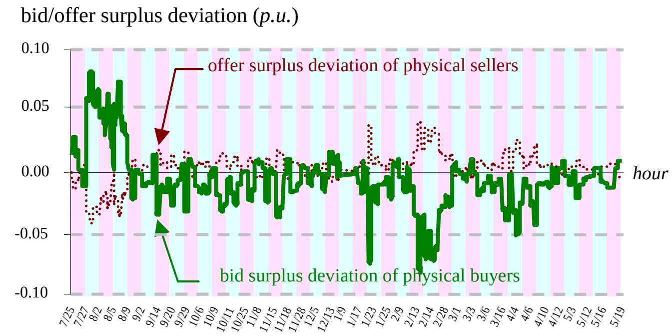

Fig. 8 Deviations in the offer (bid) surpluses of the physical sellers(buyers) for the selected 160 hours in the study period

We examine the impacts that the financial players have on the market performance under the ISO-NE security criterion $\mathcal{C}_0$ in force. We first evaluate the impacts by considering the market operations without and with the participation of the financial entities in the *DAM*s. The difference between the two cases quantifies the contribution of the financial players in the multi-settlement environment. We evaluate the physical demand deviations, as well as the price deviations observed for the two cases.

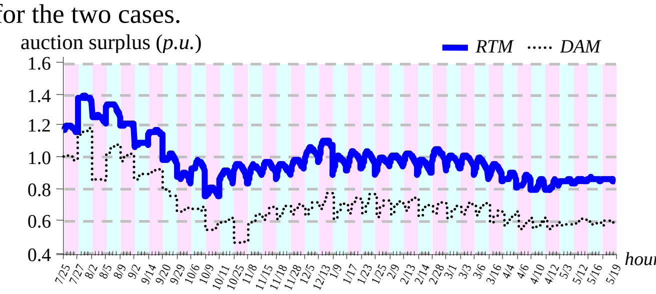

Fig. 7 The normalized auction surplus attained in the *DAM*s and the associated *RTM*s for the selected 160 hours in the study period

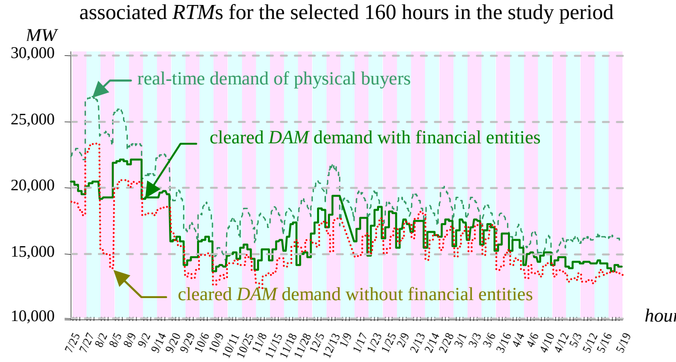

Fig. 9 Comparison of the cleared demands in the *DAM*s without and with financial entities for the selected 160 hours in the study period

Without financial entities in the *DAM*, lower physical demand is cleared in the *DAM* than in the case with the financial entity participation. Therefore, more generation is required in real time to compensate for the lower demand in order to ensure near-real-time system security. In fact, the ISO-NE study indicates that, on average, 700 *MW* additional output is required in real time without financial entity participation. Such an increase clearly indicates that the absence of financial entity participation makes the task to operate the near-real-time ISO-NE system securely more difficult. We find that financial entity participation leads to better forecasts of physical generation and consumption resulting in improved near-real-time system security. The plots of the cleared *DAM* demand without and with financial entity participation together with the real-time demand needs for the 160 hours in the study period are given in Fig. 9.

The most striking fact about financial entity participation can be discerned from examining the *DAM*-*RTM* price deviation results without and with financial entities. We superimpose in Fig. 10 the price deviation duration curves for the areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$ without the financial entity participation on those with their participation shown above in Fig. 6. The financial entity participation markedly reduces the deviation values for the areas $\mathcal{A}^1$ and $\mathcal{A}^2$. Since such a decrease corresponds to the desirable price convergence, its impact is very significant and attains the desired objective of price convergence that leads to improved market efficiency. Furthermore, our findings indicate that absent financial entity participation, the system is more congested in the *DAM*s, leading to the attainment of higher congestion rents than those obtained with the financial entity participation. In addition, system congestion impacts the prices of the import areas $\mathcal{A}^1$ and $\mathcal{A}^2$ more markedly than the case with financial entity participation. Therefore, financial entity participation reduces inter-area system congestion.

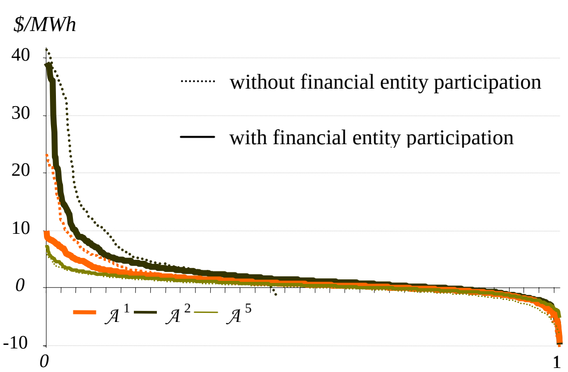

Fig. 10 Price deviation duration curves for the areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$ with and without financial entity participation

This side-by-side comparison results indicates very clearly the important role that financial entities play in electricity markets. Their participation decreases the magnitude of the physical demand deviations. In turn, these lower deviations make the management of near-real-time operations easier and, moreover, improve near-real-time system security. In terms of market performance, the participation of financial entities decreases the magnitude of the price deviations.

We next study the impacts on the multi-settlement performance of a security criterion change from the reference criterion $\mathcal{C}_0$ to a modified (n–1) security criterion $\mathcal{C}_1$. The contingency set $\mathcal{J}_{\mathcal{C}_1}$ consists of the single element contingencies in $\mathcal{J}_{\mathcal{C}_0}$. For the security criterion $\mathcal{C}_1$, we perform market clearing of the *DAM*s and their associated *RTM*s for the selected hours in the study period and evaluate the market performance metrics. We compare the values of the metrics of interest with respect to those under the reference criterion $\mathcal{C}_0$.

The change from the security criterion $\mathcal{C}_0$ to $\mathcal{C}_1$ impacts the available transfer capability of the system, which, in turn, affects the ability of the import areas to bring in energy from the export area. Indeed, the examination of the ISO-NE results indicates increased import capabilities of the import areas for each hour of the given study period [12]. The increase in transfer capability has economic impacts, which we quantify from the changes in the auction surplus. We compute the hourly auction surplus values under the security criterion $\mathcal{C}_1$ for each selected hour of the study period and normalize them using the average value of the hourly auction surplus under the reference criterion $\mathcal{C}_0$. We note that the utilization of the increased import capabilities leads to increased auction surplus. We may view such an improvement as a measure of the “costs” of not violating the constraints associated with the double element contingencies in $\mathcal{J}_{\mathcal{C}_0}$. There are also a number of hours during which the change in security criterion from $\mathcal{C}_0$ to $\mathcal{C}_1$ has no impacts on the auction surplus. For such hours, the double element contingencies have zero economic impacts. We plot the changes in the normalized auction surplus values corresponding to the security criterion change in Fig. 11.

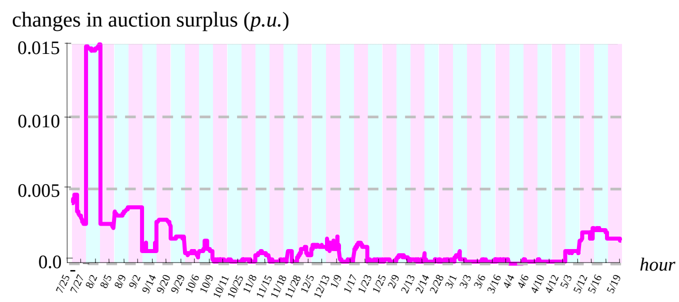

Fig. 11. Auction surplus change due to the criterion change from $\mathcal{C}_0$ to $\mathcal{C}_1$

We next discuss the impacts of the change of security criterion from $\mathcal{C}_0$ to $\mathcal{C}_1$ on the market participants’ bid/offer surpluses. The change of security criterion from $\mathcal{C}_0$ to $\mathcal{C}_1$ has widely varying impacts on the different market participants within the different areas. For illustration purposes, we consider five specific days to discuss the impacts. The security criterion change results in the greater utilization of the export area sellers and, therefore, in the decreased production of the import area physical sellers. Such a change leads to a corresponding change in the surpluses of the players in the various areas. In Fig. 12, we plot changes in the physical sellers’ offer surpluses in areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$ for the five selected days.

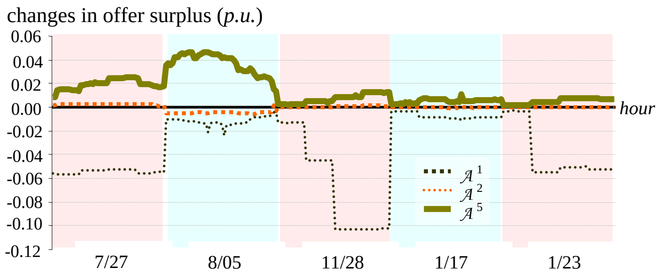

Fig. 12 Changes of the physical sellers' offer surpluses in response to the security criterion change from $\mathcal{C}_0$ to $\mathcal{C}_1$

The impacts have almost the opposite effects on the surpluses of the physical buyers: while the bid surpluses of the export area physical buyers are decreasing, those in the import areas are increasing. The physical buyers within the import areas are able to meet their demand using more economic resources from the export area $\mathcal{A}^5$ to take advantage of the increased transfer capabilities, thereby decreasing their payments. In fact, the changes in the bid surpluses are particularly more pronounced for the import area $\mathcal{A}^2$ physical buyers than other areas' physical buyers as shown in Fig. 13.

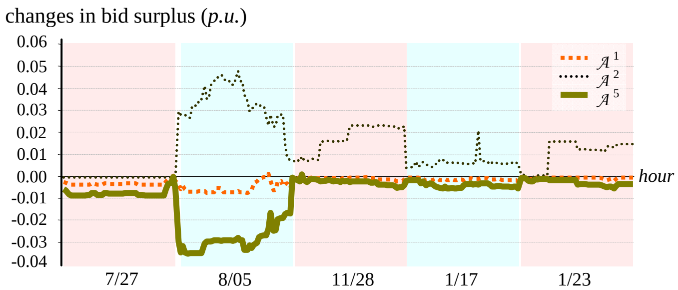

Fig. 13 Changes of the physical buyers' bid surpluses in response to the security criterion change from $\mathcal{C}_0$ to $\mathcal{C}_1$

The impacts of changing the security criterion on the surpluses of the financial entities are minor and of little significance compared to those impacts on the players with physical assets for a change in the security criterion. Overall, the relatively small dollar impacts due to the change of the security criterion from $\mathcal{C}_0$ to $\mathcal{C}_1$, as evident from the Figs. 11-13, furthermore justify that the current security criterion in force, $\mathcal{C}_0$, is appropriate for the ISO-NE markets [12].

Through the ISO-NE study, we gain important insights into the system security and its economics in a multi-settlement environment. The proposed approach effectively captures the impacts of the *DAM* clearing on the market participant bid/offer surpluses. Furthermore, the price signals, provided by the multi-settlement system, encourage financial entity participation which, in turn, leads to not only improvements in the overall market performance but also in the ability of the *RTO* to ensure near-real-time system security.

V. Concluding Remarks

In this paper, we explicitly show that the total auction surplus attained through multi-settlement system is equivalent to that attained in *RTM*s. As such, the mere presence of the *DAM*s results in surplus transfers among market participants. We develop a systematic approach to analyze such surplus transfers and investigate their implications on real-time system security. The proposed approach enables us to analyze the prominent role of financial entities on market performance as well as the ability of the *RTO* to ensure real-time security. Our investigation provides practical insights into the significant roles of financial entities and of the *DAM*s. A key finding of this study is that the financial entity participation not only results in reduced *DAM-RTM* price deviations but also leads to *DAM* dispatch results that are "closer" to those of *RTM*s. Therefore, financial player participation improves the ability of the *RTO* to ensure system security.

References

[1] ISO-NE, "The Multi-Settlement System." Available: http://www.iso-ne.com/nwsiss/grid_mkts/how_mkts_wrk/multi_ settle/index.html.

[2] K. W. Cheung, "Standard market design for ISO New England wholesale electricity market: An Overview," *Proc. of IEEE Int. Conf. Electric Utility Deregulation, Restructuring Power Tech.*, vol.1, pp. 38-43, 2004.

[3] X. Ma and D. Sun, "Key elements of a successful market design," *Proc. of IEEE/PES Trans. Dist.: Asia and Pacific, Dalian*, 2005.

[4] NERC, Available: http://www.nerc.com/~filez/standards/Reliability_ Standards.html.

[5] R. Kamat and S. S. Oren, "Multi-settlement systems for electricity markets: zonal aggregation under network uncertainty and market power," *Proc. of 35th Hawaii Inter. Conf. Syst. Sci.*, pp. 739-748, Jan. 2002.

[6] R. Kamat and S. S. Oren, "Two-settlement systems for electricity markets under network uncertainty and market power," *Journal of Regulatory Economics*, vol. 25, issue 2, pp. 5-37, Jan. 2004.

[7] I. Arciniegas, C. Barrett and A. Marathe, "Assessing the efficiency of US electricity markets," *Utilities Policy*, vol. 11, pp. 75-86, Jan. 2003.

[8] S. Borenstein, J. Bushnell, C. R. Knittel, and C. Wolfram, "Inefficiencies and market power in financial arbitrage: a study of California's electricity markets," *Center for the Study of Energy Markets (CSEM)*, Working Paper -138, Dec. 2004.

[9] ISO-NE, "Impact of Virtual Transactions on New England's Energy Market", Nov. 2004.

[10] C. Saravia, "Speculative trading and market performance: the effect of arbitrageurs on efficiency and market power in the New York electricity market," *Center for the Study of Energy Markets (CSEM)*, Working Paper -121, Nov. 2003.

[11] A. Isomenger, "The benefits and risks of virtual bidding in multi-settlement markets," *Electricity Journal*, vol. 19, issue. 9, pp. 26-36, Nov. 2006.

[12] T. Guler, G. Gross, E. Litvinov and R. Coutu, "Quantification of Market Performance as a Function of System Security," *IEEE Trans. on Power Syst.*, vol. 22, pp. 1602-1611, Nov. 2007.

[13] J. Bulow, J. Levin, and P. Milgrom, "Winning Play in Spectrum Auction," NBER Working Paper No. 14765, Mar. 2009. Available: http://www.nber.org/papers/w14765

[14] P. Klemperer, *Auctions: Theory and Practice*, Princeton University Press, Princeton, NJ, 2004.

[15] P. Milgrom, *Putting Auction Theory to Work*, Cambridge University Press, Cambridge, UK, 2004.

[16] M. Liu and G. Gross, "Congestion Rents and FTR Evaluations in Mixed Pool-Bilateral Systems," *International Journal of Electrical Power and Energy Systems*, vol. 30, issue 8, pp. 447 - 454, Oct. 2008.

[17] ISO-NE, "Value of Lost Load." Available: http://www.iso-ne.com/committees/comm_wkgrps/inactive/rsvsrmoc_wkgrp/Literature_Survey_Value_of_Lost_Load.rtf.

[18] ISO-NE, "Operating Reserves White Paper," June 2006. Available: http://www.isone.com/pubs/whtpprs/operating_reserves_white_paper.pdf.

[19] T. Guler, “Multi-area power system security analysis and economic aspects of system security,” Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical and Computer Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2009.

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