

Multi-Area System Security: The Economic Impacts of Security Criterion Selection

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Abstract— The increasing attention paid to reliability in regional transmission organizations provide the impetus for the investigation of stricter security criteria in the operation of the large-scale multi-area systems. However, as system and market operations strongly interact, any change in the system security impacts the economics and vice-versa. While the nature of the interactions between system and market operations is well understood qualitatively, the quantification of the system security impacts on the overall economics of electricity markets is, typically, not performed. In this paper, we develop a general approach to quantify the impacts of different security criteria on market performance using the day-ahead markets. The quantification provides meaningful measures of the financial and the resource dispatch impacts on both a system and an area basis. We illustrate the proposed approach on the ISO-NE system in the quantification of the comparative impacts of two different security criteria for the 2005 day-ahead markets. Through this study, we gain insights that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of electricity markets.

Index Terms— multi-area system, system security, security criterion, security control actions, preventive control, corrective control, social welfare maximization, price responsive demand.

I. INTRODUCTION

SECURITY management is a highly challenging task, and seven more so with the prominence of electricity markets.

As system and market operations strongly interact, any change in the system security impacts the economics and vice-versa. While the nature of these interactions is well understood on a qualitative basis, the quantification of the system security impacts on the overall economics of electricity markets is, typically, not performed. In this paper, we propose an approach to quantify the interactions between system security and the performance of electricity commodity markets. The proposed approach provides meaningful measures of the financial, as well as, the resource dispatch impacts of a change in the security criterion.

The wide geographic spread and large-scale nature of the new regional transmission organizations, or RTOs, or of the earlier independent system operators, or ISOs, require the

explicit representation of the areas that make up the system as well the tie lines that interconnect them in the studies aimed to assess system security aspects. We use the generic term of independent grid operator or IGO to refer to such central entities. The IGO's responsibilities include both system and market operations, with a strong focus on system reliability. The IGO must maintain and ensure the security of the multi-area system by the effective balancing of the interconnected areas' generation and demand while maintaining the frequency of the system within acceptable bounds, the voltages within the required ranges and the operation of each component within its appropriate rating under both base case and the postulated contingency case conditions. System security is defined as the ability of the interconnected system to provide electricity with the appropriate quality under normal and contingency conditions [1]. Security is a time-dependent phenomenon and is a function of the robustness of the system with respect to imminent disturbances – the so-called contingencies. For the operating state corresponding to a snapshot of the system, the security assessment analyzes whether the occurrence of any of the postulated contingencies results in the violation of any operational constraints, and whether such violations may be removed by dispatching appropriate preventive or corrective security control actions [2]. A preventive control action associated with a postulated contingency entails the modification of the pre-contingency – base case – state, to eliminate any potential violation, were that contingency to occur. On the other hand, an associated corrective control action involves the deployment of generation redispatch/load curtailment to modify the post-contingency state only after the contingency actually occurs. For certain contingencies, such as a generator outage or a sudden change in load, the IGO may take only corrective control actions.

Security assessments are, typical, based on a deterministic criterion, such as $(n-1)$ or $(n-2)$ security. We associate with each security criterion a specific contingency list and a specified control action for every contingency on that list. For example, the contingency list of the $(n-1)$ criterion consists of all single element contingencies while that of the $(n-2)$ criterion considers all double element contingencies in addition to the single element contingencies. Since all the contingencies on the $(n-1)$ list are also included in the $(n-2)$ contingency list, the $(n-2)$ is considered to be the stricter criterion. Virtually every system operator uses, at the very least, some modified $(n-1)$ list of single line outages and preventive control to deal with their impacts. But, in many

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instances, a stricter criterion is imposed, such as a modified version of the $(n-2)$ criterion with only a subset of all the double element contingencies considered. The elements of this subset are carefully selected to include contingencies that are particularly critical for the multi-area structure of the system, such as the outages of pairs of tie lines interconnecting an export and an import area. In this paper, we consider a wide range of security criteria, which are representative of the practices of various IGOs. We next turn to a discussion of the markets managed by the IGO.

In this paper, we consider the typical day-ahead market, or *DAM*, structure widely adopted in North American markets in which uniform price auctions are used for market clearing side by side with the provision of transmission services to the bilateral transactions. Such a situation represents the ISO New England (ISO-NE) [3], the Pennsylvania-New Jersey-Maryland ISO (PJM-ISO) [4] and the New York ISO (NY-ISO) [5]. In these markets, the sellers and the buyers submit their offers and bids, respectively, indicating their willingness to sell or to buy specified quantities of electricity at specific locations. The bilateral transactions requesting transmission service from the IGO also provide their willingness to pay for the service [6]. The IGO then determines the market clearing and transmission service provision so as to maximize the social welfare, subject to the operational constraints for the base and the contingency cases under the security criterion.

As power system operations must comply with the security criterion, a change in the security criterion typically results in changes in the market outcomes brought about by the changes in the contingency list and associated control action for each postulated contingency. Consider the case in which the IGO operates the system under $(n-1)$ security. The power flows associated with the provision of transmission services to the bilateral transactions and the market clearing are such that no violations occur for the loss of a single element in the system making full use of the preventive control capability. But, under a stricter security criterion, which includes double element outages in the contingency list, a decrease in the transfer capabilities between export to import areas from those in the $(n-1)$ criterion [7] may result. Consequently, the power flows must respect the decreased transfer capabilities. As such, the various market participants in the export and the import areas may be impacted differently in terms of financial and dispatch results. For the case with all the demands fixed, the purchases of the import areas' buyers reflect the decreased import capabilities. Consequently, the buyers increase purchases from the native resources, typically, at higher prices. Hence, the overall costs to supply electricity increase with respect to the costs in the $(n-1)$ security, and therefore the market efficiency decreases. When the demand is price responsive, and so no longer fixed, some buyers in the import areas may procure less energy whenever their willingness to pay is exceeded by the offer prices of the sellers of the area's native resources. In a similar vein, some of the export area buyers, who have low willingness to pay, may nevertheless procure more energy when their willingness to pay exceeds the prices offered by the export area sellers whose sales decrease due to the lowered transfer capabilities. As a result, the market efficiency changes from that of the $(n-1)$ security

case. In either the fixed or the price responsive demand case, some market participants may gain and others may lose as a result of the change in the security criterion. The basic thrust of this study is to quantify the changes in the electricity market performance due to a change in the security criterion.

A number of papers focuses on the analysis of the interactions between the system security criterion and the associated economics. The papers may be classified into two general categories – the marginal costing aspects of system security and the evaluation of total system security costs. The studies in [8]–[11] explore the notion of the security pricing using marginal cost information [12] for a period based on the snapshots of the system, with each snapshot representing a sub-period of the specified period. The willingness of the market participants to provide security control capability for all the postulated contingencies is explicitly incorporated into the market clearing process using optimization techniques. A byproduct is the so-called security prices. The approach in [13] defines system security for a given base case as a continuous function of overloads in each line under each postulated contingency case. A decrease in overloads due to injections at a node is regarded as security improvement and the authors measure the marginal cost of security in terms of the incremental cost of improving security. The second category papers [14]–[16] evaluate system security costs using probabilistic techniques, taking explicitly into account the random nature of the outages. These papers may be viewed as using the notion of “value of reliability” [17] applied to the study of system security for the period of interest, and such approaches are particularly useful for operational planning purposes with a horizon up to one or two years [18]. The study in [14] evaluates the “expected cost of security” by computing the outage costs associated with specific operating states with the explicit representation of the security control actions. The study in [15] uses Monte Carlo simulation for a given system snapshot to evaluate the “value of system security” and is extended to a longer period in [16] with the consideration of the corrective control capabilities of the demand side. These two studies determine that the security criterion to use may be set on the basis of cost/benefit analysis taking into account the costs of operating the system and the expected outage costs.

In this work, we explicitly consider the system security from the point of view of the IGO. We emulate the way the IGO currently operates both the system and the markets under a specified security criterion. We ignore the probability of any contingency in the studies that replicate the IGO actions. We develop an approach to quantify the interactions between the specified system security criterion and the *DAM* outcomes taking explicitly into account the outages of tie lines interconnecting the multi-area system. The quantification provides measures of the financial and resource dispatch impacts of a change in security criterion vis-à-vis those corresponding to a reference security criterion. For a specified security criterion, we use the snapshot representation of the system for an hour and solve the so-called security constrained OPF (SCOPF) problem to maximize social welfare while satisfying the operational constraints for each contingency case and the base case. The solution of the

SCOPF serves to compute the values of a set of metrics that evaluate the market performance under the specified security criterion. These metrics include the financial impacts and resource dispatch impacts on both a system and an area basis. We evaluate the changes in the values of the metrics under each security criterion considered with respect to those under the reference criterion. We extend the hourly snapshot analysis to a longer period to observe the diverse market outcomes due to changes in the unit commitment decisions, network parameters, the set of resources, the market participants' behavior and the exogenous parameters, such as fuel and emission costs. We illustrate the proposed approach to quantify the impacts of different system security criteria on the ISO-NE Day-Ahead Market performance for representative days in 2005 period. The study establishes an explicit link between the system security criterion and the market efficiency impacts. The results of this study indicate that the power system may be operated under a stricter criterion without adversely impacting the economic efficiency of electricity markets when price responsive demand and appropriate control actions are present.

This paper contains five additional sections. The nature of the problem and the solution approach are discussed in section II. We devote section III to the discussion of the proposed approach. In section IV, we apply the proposed approach to the study of the ISO-NE Day-Ahead Market and discuss the study results in detail. Section V summarizes the paper and discusses future work. We have two appendices in which we provide the notation used in the paper and the scheme used for the selection of representative days for a specified month.

II. NATURE OF THE PROBLEM

The starting point in system security assessment is the snapshot analysis of the interconnected system. We introduce specific assumptions on unit commitment decisions, ancillary services and the market participants' behaviors so as to allow the side-by-side comparison of different security criteria impacts for a given system. We assume that the unit commitment decisions reflect appropriately the selected security criterion requirements. As the focus of this investigation is limited to energy only markets, the ancillary services provision and acquisition requirements under the IGO framework are assumed to impose no additional constraints on the system. We furthermore assume that the bidding behavior of each market participant is independent of the security criterion in force. Consequently, this behavior remains unaffected by the change of a criterion. The behaviors may change across time but those changes are assumed to be present under no matter which security criterion is in force. The IGO decision making problem for a given snapshot of the system under a specified security criterion takes explicitly into account the structure of the multi-area system and the constraints imposed by the tie line limits. We now obtain the statement of the problem solved by the IGO for a given snapshot of the interconnected system.

We consider a power system network consisting of K interconnected areas denoted by the set $\mathcal{A} \triangleq \{\mathcal{A}^k : k=1, \dots, K\}$ with each area \mathcal{A}^k having a node set \mathcal{N}^k with N^k buses. Each

area $\mathcal{A}^k \in \mathcal{A}$ is connected to one or more other areas via tie lines. While the interconnected system has a single market operated by the IGO, the presence of network and physical constraints necessitate that we consider the market players in each area separately. We assume without loss of generality, that at each bus $i \in \mathcal{N}^k$ there is a single seller and a single buyer. We denote by the sets $\mathcal{S}^k = \{s_1^k, \dots, s_{N^k}^k\}$ and $\mathcal{B}^k = \{b_1^k, \dots, b_{N^k}^k\}$, the collection of sellers and that of buyers of the area $\mathcal{A}^k \in \mathcal{A}$, respectively. Each seller (buyer) submits price and quantity offer (bid) function indicating the willingness to sell (buy) the amount of energy to (from) the IGO. A special case of the price sensitive bid is the fixed demand bid associated with a specified quantity but unspecified price. As such, these bids indicate the willingness of the buyers to purchase energy regardless of the price. Hence, we may interpret that these buyers have *infinite* willingness to pay for the submitted quantity.

Bilateral transactions coexist with the IGO market operations. We represent a bilateral transaction ω_w , whose *from* node is $m_w \in \mathcal{N}^k$ of \mathcal{A}^k , *to* node is $n_w \in \mathcal{N}^r$ of \mathcal{A}^r , and desired transaction amount is \bar{t}_w , by the triplet $\omega_w \triangleq \{m_w, n_w, \bar{t}_w\}$. Here k and r are indices that may represent different areas. The set of bilateral transaction is $\mathcal{W} = \{\omega_1, \dots, \omega_w\}$. Each transaction submits a willingness to pay function, which states a willingness to pay maximum transmission usage fees for receiving the requested transmission services as a function of the transaction amount delivered [6]. The IGO weighs the willingness to pay of the bilateral transactions with that of the individual market participants to determine the amount of transmission service provision to each player. For this purpose for a given snapshot of the system, the IGO solves a security constrained OPF, or SCOPF, problem with the objective to maximize the social welfare under the security criterion \mathcal{C} whose contingency index set is denoted by \mathcal{J}_c . As the willingness to pay of buyers submitting fixed demand bids is unspecified, the benefits of those buyers cannot be evaluated. We arbitrarily set the benefits of such buyers to be a constant value and state the SCOPF problem as

$$\max_{\mathcal{S}} \mathcal{S} \triangleq \sum_{k=1}^K \left(\sum_{j=1}^{N^k} \beta_{b_j^k} \left(p_{b_j^k}^{(0)} \right) - \sum_{i=1}^{N^k} \beta_{s_i^k} \left(p_{s_i^k}^{(0)} \right) \right) + \sum_{w=1}^W \alpha_w \left(t_w^{(0)} \right) \quad (1)$$

subject to

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

$$\underline{h}^{(0)} \left(\underline{p}_s^{(0)}, \underline{p}_b^{(0)}, \underline{t}^{(0)}, \underline{x}^{(0)}, \underline{\gamma}^{(0)} \right) \leq \underline{0} \quad \leftrightarrow \quad \underline{\mu}_h^{(0)} \quad (3)$$

and for every $j \in \mathcal{J}_c$

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

$$\underline{h}^{(j)} \left(\underline{p}_s^{(j)}, \underline{p}_b^{(j)}, \underline{t}^{(j)}, \underline{x}^{(j)}, \underline{\gamma}^{(j)} \right) \leq \underline{0} \quad \leftrightarrow \quad \underline{\mu}_h^{(j)} \quad (5)$$

$$\left| \underline{p}_s^{(j)} - \underline{p}_s^{(0)} \right| \leq \underline{\Delta p}_s^{(j)} \quad \leftrightarrow \quad \underline{\mu}_s^{(j)} \quad (6)$$

$$\left| \underline{p}_b^{(j)} - \underline{p}_b^{(0)} \right| \leq \underline{\Delta p}_b^{(j)} \quad \leftrightarrow \quad \underline{\mu}_b^{(j)} \quad (7)$$

$$\left| \underline{t}^{(j)} - \underline{t}^{(0)} \right| \leq \underline{\Delta t}^{(j)} \quad \leftrightarrow \quad \underline{\mu}_t^{(j)} \quad (8)$$

Here, we use the superscript (j) to denote the contingency

cases with the base case denoted by (0). The vector associated with the right-hand side of a constraint is the dual variable of that constraint. The relations in (2) and (3) represent the operational constraints for the base case, while those in (4)–(8) represent the operational constraints for the contingency cases. The $|\mathcal{F}_c|+1$ equality constraints in (2) and (4) state the nodal power balance equations for the base case and for each postulated contingency case, respectively. The base case (3) and contingency case (5) inequality constraints state the system components' operational limits, as well as, the so-called generic limitations representing the physical, engineering and policy considerations. The range of the decision variables of the security control action for each contingency $j \in \mathcal{F}_c$ is given in (6)–(8) together with the limiting values of these ranges. The preventive control actions have a zero range in contrast to the corrective actions whose non-zero range reflects the additional flexibility to address the onset of the contingency.

The market performance under the specified security criterion \mathcal{C} for the snapshot system may be quantified from the market outcomes given by the solution of (1)–(8). We define metrics to measure market outcomes on a system and an area basis, as well as, the impacts on individual player outcomes. We use the optimal value of the social welfare $\mathcal{P}|_{\mathcal{C}}$ under \mathcal{C} as a measure for the financial performance of the market as a whole; in addition, for area \mathcal{A}^k , we evaluate

$$\mathcal{P}^k|_{\mathcal{C}} \triangleq \sum_{i=1}^{N^k} \left[\beta_{b_i^k} (p_{b_i^k}^{*(0)}) - \beta_{s_i^k} (p_{s_i^k}^{*(0)}) \right] \Big|_{\mathcal{C}} \quad (9)$$

to determine the area \mathcal{A}^k contributions to the system social welfare. The *producer* (*consumer*) surplus measures the performance or the gain of each seller (buyer) for participating in the electricity market. The producer surplus a seller s_i^k is

$$\sigma_{s_i^k}^k|_{\mathcal{C}} \triangleq \left[\lambda_i^{*k(0)} p_{s_i^k}^{*(0)} - \beta_{s_i^k} (p_{s_i^k}^{*(0)}) \right] \Big|_{\mathcal{C}} \quad (10)$$

and the consumer surplus change for a buyer b_i^k in \mathcal{A}^k is

$$\sigma_{b_i^k}^k|_{\mathcal{C}} \triangleq \left[\beta_{b_i^k} (p_{b_i^k}^{*(0)}) - \lambda_i^{*k(0)} p_{b_i^k}^{*(0)} \right] \Big|_{\mathcal{C}} \quad (11)$$

where $\lambda_i^{*k(0)}$ is the locational marginal price (LMP) at node i of the area k corresponding to the base case conditions. We use the total dispatched load to evaluate the total cleared demand quantity under criterion \mathcal{C}

$$P|_{\mathcal{C}} \triangleq \sum_{k=1}^K \sum_{i=1}^{N^k} \left[p_{b_i^k}^{*(0)} + \sum_{w=1, i=n_w \in \mathcal{N}^k}^W t_w^{*(0)} \right] \Big|_{\mathcal{C}}. \quad (12)$$

We compute the area-wide net injection to indicate amount of net power imported into to an area \mathcal{A}^k with

$$P^k|_{\mathcal{C}} \triangleq \sum_{i=1}^{N^k} \left[p_{s_i^k}^{*(0)} - p_{b_i^k}^{*(0)} + \sum_{i=n_w \in \mathcal{N}^k}^W t_w^{*(0)} - \sum_{i=n_w \in \mathcal{N}^k}^W t_w^{*(0)} \right] \Big|_{\mathcal{C}} \quad (13)$$

For a different security criterion \mathcal{C}' , the IGO must solve a modified SCOPF in which the constraints in (4)–(8) reflect the changes in the contingency set $\mathcal{F}_{\mathcal{C}'}$ and in the security control actions associated with each contingency. The relative market performance under criterion \mathcal{C}' is assessed with respect to those under reference criterion \mathcal{C} using the metrics provided above. The change in the social welfare

$$\Delta \mathcal{P}_{\mathcal{C}'} = \mathcal{P}|_{\mathcal{C}'} - \mathcal{P}|_{\mathcal{C}} \quad (14)$$

quantifies the market efficiency change. The expression in (14) implicitly assumes that the benefits of the fixed demand remain equal under every security criterion. Consequently, there is no loss of generality incurred with the assumption of constant benefits for fixed demand for the evaluation of the market efficiency changes. Indeed, since our focus is on the changes of these values, we set the benefits of fixed demand to zero for simplicity. We use the metrics in (9)–(13) to evaluate the relative performance impacts under a security criterion \mathcal{C}' with respect to those under the reference criterion \mathcal{C} . These relative measures have useful interpretation. For example, the change in the contribution of an area to the social welfare indicates how that area's market participants are impacted by a change of security criterion from the reference \mathcal{C} to the criterion \mathcal{C}' under consideration. We interpret in a similar fashion the changes in producer/consumer surplus, the total dispatched load change and the area-wide net injection.

The value of the market performance metrics mentioned above is useful for the comparative assessment for the snapshot of the system. We conceptually represent the structure of the comparative assessment of a security criterion change from the reference \mathcal{C} to the criterion \mathcal{C}' for the snapshot of the system in Fig. 1.

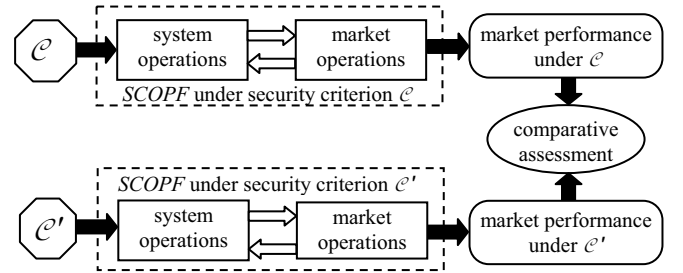


Fig. 1 Conceptual structure for snapshot comparative assessment

Under a given security criterion, system 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 available units, and the offers/bids submitted. Similarly, the change from a reference to another security criterion may also entail different market performance impacts. Consequently, these assessments must be carried out for the entire period to correctly capture the impacts over different conditions that exist. In the next section, we discuss the proposed approach for such assessments.

III. PROPOSED APPROACH

To describe the proposed approach, we focus on the comparative assessment case. However, its adaptation to the market performance analysis of a given security criterion is a straightforward modification. For the comparative assessment period, we use an hourly resolution as the shortest time unit. We represent the system for an hour h by a system snapshot. We need, therefore, many snapshots to allow the comparative assessment to be carried out for multiple hours that are representative of the range of conditions in system and market operations. We develop an approach to construct a set of such

representative hours. A key requirement is the incorporation of the unit commitment decisions which entail inter-temporal effects across the hours of the commitment. The comparative assessment must be performed for every hour of the unit commitment period. Since, for typical market applications, the unit commitment period is a day, the assessment must be performed on a daily basis. So, the selection problem becomes one of selecting representative days within the study period.

A first step in the selection process is the partitioning of the study period into sub-periods. Since many operational studies are carried out on a monthly basis, we use a month as a sub-period. For a given month i , we determine the subset of representative days and construct the set \mathcal{D}_r^i . We choose the elements of \mathcal{D}_r^i on the basis of the daily peak demand values. These values take into account both the fixed demands and the price sensitive quantities bid. We construct the monthly load duration curve, or *LDC*, for the daily peak data. The basic idea in the construction of \mathcal{D}_r^i is to use an approximation of the *LDC* by a curve with fewer levels of load. We construct such an approximation by maintaining the base and the peak load levels, and then selecting k days so that we replace the original *LDC* by at most a $(k + 2)$ load level approximate *LDC*. We measure the “goodness” of the approximation in terms of an error based on the monthly energy. If the error fails to satisfy a specified tolerance, k is increased until the tolerance check is satisfied. We provide the details of the scheme in Appendix B. A byproduct of the approximation is the number of days associated with each representative days in \mathcal{D}_r^i . We repeat this process for each of the month within the study period and determine each \mathcal{D}_r^i . We then construct the set of representative days \mathcal{D} , of the study period by the union of each monthly \mathcal{D}_r^i .

We deploy the snapshot conceptual structure shown in Fig. 1 as the basic building block of the approach. We apply the structure to each hours of the days in \mathcal{D} . We sum the hourly impacts for each day. We use the number of days each day in \mathcal{D}_r^i represents and aggregate the daily figures to obtain monthly impacts. The daily figures also serve to evaluate key statistics for each month such as mean, variance and range. The study period impacts then are aggregated from the monthly ones. Consequently, we are able to quantify the system and area-wide *MW* as well as dollar impacts on a daily, monthly and period basis.

The proposed approach has a wide range of applications from the justification by the IGO of the decision to modify the security criterion to be used, to the cost/benefit analysis of network improvements to mitigate the impacts of specific contingencies. Other applications include the formulation of the control actions for specific contingencies, and the assessment of specific behavioral changes of market participants under various security criteria. We next illustrate an application of the proposed approach to the ISO-NE *DAM* system.

IV. APPLICATION STUDY

We devote this section to illustrate the application of the proposed approach to the ISO-NE *DAM* for the assessment of the changes in the economic impacts of two specific security

criteria. We measure the changes with respect to the outcomes under the current ISO-NE security criterion. We use the system and market data from the year 2005. We start out with a brief description of the multi-area structure of the ISO-NE system. Then, we discuss the selection of the representative days for the study period. We describe the ISO-NE current security criterion, which we use as the reference criterion, and the two security criteria considered. We then summarize and interpret the results of the study.

Each area of the ISO-NE system is characterized as either import or export. The import areas are [19]

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

We treat rest of the system as a single export area and denote it by \mathcal{A}^5 . Fig. 2 illustrates conceptually the multi-area structure of the ISO-NE. A salient feature is the nested structure of the areas $\mathcal{A}^4 \subset \mathcal{A}^3 \subset \mathcal{A}^2$. From the physical and the economic point of view, the generation of the export area is required to meet the load of the import areas.

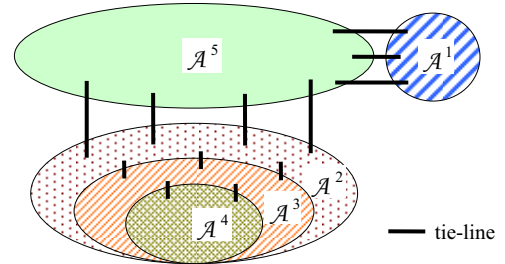


Fig. 2 Multi-area structure of the ISO-NE system

The study is performed for the second half of the year 2005. This study period was chosen to allow the use of market and system data that reflects the most up-to-date ISO-NE procedures and rules. The analysis of the load in the selected period shows that the demand levels in the summer months, July and August, are significantly higher than those in the *non-summer* months – the months from September to December. Furthermore, the range of daily peak demands in the summer months is considerably larger than that in the non-summer months. Due to the maintenance scheduling, the sets of available resources in summer months are different than those in the other months. In addition, the ratings of the system components differ in each summer month from those in the other months. The period under study is further characterized by the existence of two distinct regimes \mathcal{R}_1 and \mathcal{R}_2 – pre- and post- October 9, 2005, respectively. The ratio of the hourly price sensitive bid amounts to the total hourly demand changes markedly from a small value under the regime \mathcal{R}_1 , to a sizable fraction under the regime \mathcal{R}_2 . The hourly loads in these two regimes are further distinguished in terms of their peak, base and average values. We present the load characteristics of the regimes \mathcal{R}_1 and \mathcal{R}_2 in Table 1, respectively. The minimum, maximum and the average hourly load values are disaggregated into the fixed and price responsive components in Table 1. The significant increase in the fraction of price-sensitive demand is due to the bidding behavior change of the large buying entity whose demand corresponds to approximately 25 % of the total system demand. This buyer submits, on the average, only 15% of his demand as price sensitive under the regime \mathcal{R}_1 . However, the

buyer has no fixed demand under regime \mathcal{R}_2 as all of the buyer's bids become price sensitive. Due to the size of the buyer's demand, the marked change in his bidding behavior results in a significant portion of the total system demand that is price responsive under the regime \mathcal{R}_2 .

We select the representative days from each month using the scheme of Appendix B. We construct the LDC approximation for each summer and non-summer month by 14 and 10 representative days, respectively. Since these approximations provide acceptably small errors, we determine the elements of each \mathcal{D}_r^i , and construct \mathcal{D}_r .

TABLE 1. REGIMES \mathcal{R}_1 AND \mathcal{R}_2 LOAD CHARACTERISTICS

regime	\mathcal{R}_1		\mathcal{R}_2	
load type	fixed	price sensitive	fixed	price sensitive
minimum demand	6,232	2,944	5,394	5,139
maximum demand	21,292	4,845	12,109	9,573
average	13,075	4,294	8,756	6,964

The ISO-NE operates the system under the security criterion \mathcal{C} whose list of contingencies is

$$\mathcal{I}_{\mathcal{C}} = \mathcal{I}_{n-1} \cup \left(\bigcup_{k=1}^4 \mathcal{X}^k \right). \quad (15)$$

Here, \mathcal{I}_{n-1} is the set of single element contingencies considered by the ISO-NE and \mathcal{X}^k is the set of double tie line contingencies specified for each import area $\mathcal{A}^k \in \mathcal{A}$, $k=1, \dots, 4$. Each selected tie line pair interconnects the import area \mathcal{A}^k to any other area of the system. The set of control actions for the security criterion consists of preventive control actions which are associated with the elements of \mathcal{I}_{n-1} , and corrective control actions which are associated with the double element tie-line contingencies of $\bigcup_{k=1}^4 \mathcal{X}^k$ [19]. We select the criterion \mathcal{C} as the reference criterion and consider two specific criteria \mathcal{C}^a , a modified ($n-1$) security, and \mathcal{C}^b , a modified ($n-2$) security. For the criterion \mathcal{C}^a , the contingency list $\mathcal{I}_{\mathcal{C}^a} = \mathcal{I}_{n-1}$, and preventive control action is the deployed for each contingency in $\mathcal{I}_{\mathcal{C}^a}$. For the criterion \mathcal{C}^b , the contingency list $\mathcal{I}_{\mathcal{C}^b} = \mathcal{I}_{\mathcal{C}}$, but we replace the corrective control actions by the preventive control actions for the contingencies in $\bigcup_{k=1}^4 \mathcal{X}^k$. We next discuss the market performance impacts of the change of security criterion \mathcal{C} to each of the criteria considered and distinguish those impacts under the two regimes \mathcal{R}_1 and \mathcal{R}_2 .

We first focus on the MW impacts. For the reference criterion \mathcal{C} , we obtain the range and the average values of the total hourly dispatched load $P_{\mathcal{C}}$ under the regimes \mathcal{R}_1 and \mathcal{R}_2 . We compute the changes from the $P_{\mathcal{C}}$ values under the two security criteria and present the results in Table 2. We observe that the price responsive demand plays an important role in the DAM. For each security criterion, the changes under the regime \mathcal{R}_2 are considerably lower than those under the regime \mathcal{R}_1 . In fact, the changes are attenuated to a greater extent for the change of the security criterion from \mathcal{C} to \mathcal{C}^a than from \mathcal{C} to \mathcal{C}^b . We hypothesize that the factors that contribute to these distinct outcomes are due to the structure of the system, the effectiveness of the security control actions and the nature of the constraints imposed on the system operations.

TABLE 2. TOTAL HOURLY DISPATCHED LOAD AND THE IMPACTS

metric	regime	range (MW)	average (MW)
$P_{\mathcal{C}}$	\mathcal{R}_1	(9,177 , 25,638)	16,967
	\mathcal{R}_2	(8,733 , 23,281)	15,421
$\Delta P_{\mathcal{C}^a}$	\mathcal{R}_1	(0 , 452)	141
	\mathcal{R}_2	(0 , 273)	42
$\Delta P_{\mathcal{C}^b}$	\mathcal{R}_1	(-818 , 0)	-184
	\mathcal{R}_2	(-557 , 0)	-128

The change from the current security criterion to either of the two criteria studied impacts the value of the system transfer capability. The change in the value of the system transfer capability, in turn, affects the ability of the import areas to bring in energy from the export area. In fact, the analysis of the ISO-NE system during this 2005 study period indicates that the replacement of the security criterion \mathcal{C} by the criterion \mathcal{C}^a results in the increased import capabilities of the import areas for each hour. But, the increased capability may not be utilized in every hour. For example, the imports by the stand-alone area \mathcal{A}^1 buyers increase their imports from the export area, thereby decreasing their dependence on the less economic \mathcal{A}^1 resources. On the other hand, the imports of the nested area \mathcal{A}^2 , due to the physical constraints of the \mathcal{A}^2 network, may not utilize such increased capability in every hour. We measure the changes in the utilization of the increased import capabilities using the area-wide net injection changes defined in section II. We illustrate the results for the import areas \mathcal{A}^1 and \mathcal{A}^2 , and the export area \mathcal{A}^5 for a week in August 2005 in Fig. 3. These plots are typical for the study period, particularly in terms of the more pronounced impacts in the daily peak hours than those in the off-peak hours.

Due to the fact that the system operations under the criterion \mathcal{C}^b are more constraining than those under the criterion \mathcal{C} , the security change from \mathcal{C} to \mathcal{C}^b results in the decreased import capabilities of the import areas for every hour of the study period. In fact, the impacts on the imports of the stand alone area \mathcal{A}^1 are exactly in the opposite direction to those under the criterion change from \mathcal{C} to \mathcal{C}^a . On the other hand, the imports of the nested area \mathcal{A}^2 exhibit similar results to those under the criterion change from \mathcal{C} to \mathcal{C}^a . We plot these outcomes for the same August week in Fig. 4. We note that the impacts are pronounced in both peak and off-peak hours.

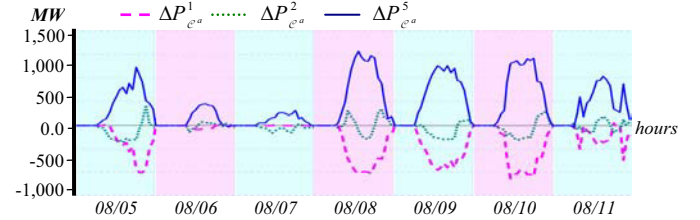


Fig. 3 Area-wide net injection impacts under \mathcal{C}^a

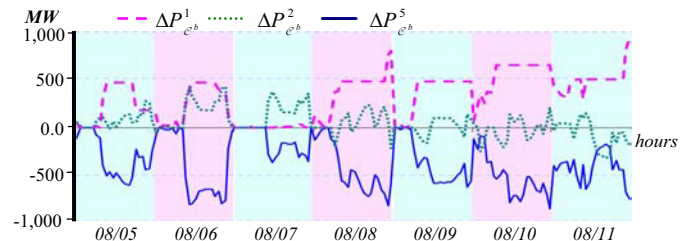


Fig. 4 Area-wide net injection impacts under \mathcal{C}^b

We next examine the financial impacts of the changes in the security criterion. We use the daily social welfare as the basic metric in this investigation. We first normalize the daily social welfare values using the average value of the daily social welfare under the reference criterion \mathcal{C} as a base value. Such normalization is needed to facilitate effective comparison of the financial impacts. We first consider the financial repercussions of the increased import capabilities arising from the relaxation of the security criterion from \mathcal{C} to \mathcal{C}^a . Throughout the study period, the increased import capabilities are utilized leading to higher market efficiencies. We may view these improvements as a measure of the “costs” of not violating the constraints due to the double element contingencies in the reference criterion. On the other hand, the decreased import capabilities arising from changing the criterion from \mathcal{C} to \mathcal{C}^b may lower the market efficiencies. Indeed, such reductions are present throughout the study period. We may interpret these reductions to be a measure of the “costs” of replacing corrective for preventive control actions. The plot of the normalized daily social welfare values under the reference criterion \mathcal{C} is given in Fig. 5 for the set of days \mathcal{D}_r . The plots of the changes of the market efficiency arising from a change of the security criterion are shown in Fig. 6. We provide some of the statistics related to the maximum, the mean and the standard deviation of the market efficiency impacts under the regimes \mathcal{R}_1 and \mathcal{R}_2 for each security criterion change in Table 3.

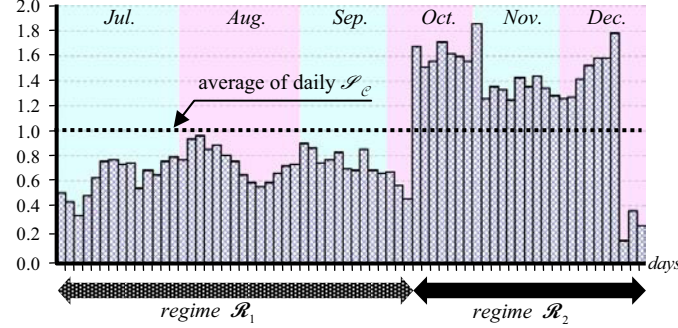


Fig. 5 Normalized daily social welfare under criterion \mathcal{C}

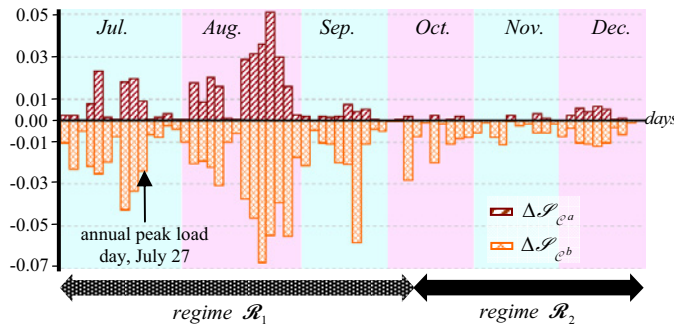


Fig. 6 The normalized daily impacts on market efficiency

TABLE 3 STATISTICAL ANALYSIS OF MARKET EFFICIENCY IMPACTS UNDER THE REGIMES \mathcal{R}_1 AND \mathcal{R}_2

criterion	regime	maximum	mean	standard deviation
\mathcal{C}^a	\mathcal{R}_1	0.0506	0.0091	0.0122
	\mathcal{R}_2	0.0065	0.0011	0.0004
\mathcal{C}^b	\mathcal{R}_1	-0.0670	-0.0210	0.0170
	\mathcal{R}_2	-0.0201	-0.0063	0.0048

We obtain some insights by studying the disaggregation of the metric $\Delta \mathcal{S}_{\mathcal{C}^a}$ and $\Delta \mathcal{S}_{\mathcal{C}^b}$ by each area. The area by area contribution is in line with the changes in the utilization of the modified import and export capabilities. We plot the changes of the import areas \mathcal{A}^1 and \mathcal{A}^2 , and the export area \mathcal{A}^5 , contribution to the social welfare in Fig. 7 (8) corresponding to shifting the security criterion from \mathcal{C} to \mathcal{C}^a (\mathcal{C}^b).

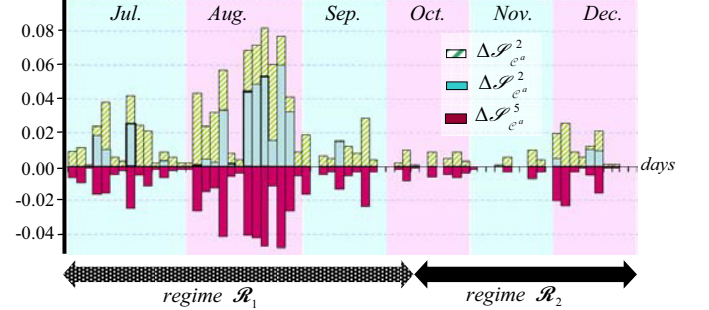


Fig. 7 Change in the contributions of each area to social welfare under \mathcal{C}^a

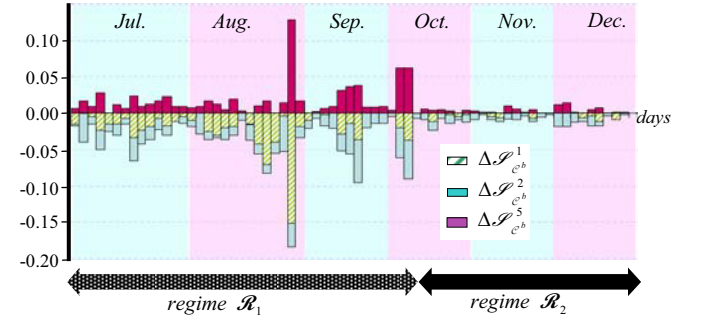


Fig. 8 Change in the contributions of each area to social welfare under \mathcal{C}^b

We note from the plots in Fig. 5 – 8 that the price responsive regime \mathcal{R}_2 leads to a strong attenuation of the economic impacts of changing security criterion to either \mathcal{C}^a or \mathcal{C}^b . Moreover, the relaxation of the security criterion from \mathcal{C} to \mathcal{C}^a , i.e. not taking into account the double element contingencies, results in a insignificantly small dollar gains under the regime \mathcal{R}_2 . It is, therefore, questionable whether such a relaxation is worthwhile given the meager impacts. The tightening of the security criterion from \mathcal{C} to \mathcal{C}^b by replacing the corrective by preventive actions leads to dollar losses. These findings of the comparative assessment lead us to conclude that the reference criterion \mathcal{C} is, for all intents and purposes, more appropriate for the ISO-NE DAM than either of the two security criteria considered. Through this study, we also gain an important insight that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of the electricity markets in the presence of price responsive demand and appropriate control actions. The proposed approach provides good insights into the ramification of changing the security criterion on both qualitative and quantitative basis.

V. CONCLUDING REMARKS

In this paper, we propose an approach for the assessment of market performance under a specified security criterion, and for the quantification of the impacts of a system security criterion change on the performance of the electricity markets.

These assessments are carried out from the point of view of the IGO. The basic concept is the emulation of the actions of the IGO under each security criterion considered. The proposed approach quantifies the *MW* as well as the market efficiency impacts of the security criterion change and has a wide range of applications. These include the studies for the justification by the IGO to modify its decision for the selected security criterion and for the cost/benefit analysis of network improvements to mitigate the impacts of specific contingencies. We apply the proposed approach to quantify the impacts of two security criteria on the ISO-NE *DAM* performance. We use the last six months of the year 2005 for the study period. Our investigation provides important insights into the role of price responsive demand and that of the security control actions. In fact, we conclude that the power systems may be operated under a stricter criterion without adversely impacting the economic efficiency of the day-ahead markets when price responsive demand and appropriate control actions are present.

As the real-time energy markets, or *RTM*, become more prominent, the comparative assessments of a security criterion change have to be broadened to include the impacts on *RTM*. To be able to accomplish this broadened scope, the incorporation of a multi-settlement system involving the *DAM* and the *RTM* [20], is required. In addition, the growing impacts of bilateral transactions also need to be explicitly considered in the quantification of security criterion change impacts. The studies extending the proposed approach to incorporate the multi-settlement system and the bilateral transactions will be reported in a future work.

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APPENDIX A: LISTING OF NOTATION

$\mathcal{A} \triangleq \{ \mathcal{A}^k : k=1, \dots, K \}$	the set of interconnected areas
\mathcal{N}^k	the set of nodes in area $\mathcal{A}^k \in \mathcal{A}$ with $ \mathcal{N}^k = N^k$
\underline{x}	the vector of the system states or dependent variables
\underline{z}	the vector of the control or independent variables that are not associated with injection and withdrawal of real power
s_i^k	the seller at node $i \in \mathcal{N}^k$
$P_{s_i^k}$	the real power supply of the seller s_i^k
$\beta_{s_i^k}(P_{s_i^k})$	the integral of the marginal offer price of the seller s_i^k as a function of the real power supply $P_{s_i^k}$
$\mathcal{S}^k = \{ s_1^k, \dots, s_{N^k}^k \}$	the set of sellers in area $\mathcal{A}^k \in \mathcal{A}$
$\underline{p}_s^k = [P_{s_1^k}, \dots, P_{s_{N^k}^k}]^T$	the vector of real power injection for the area $\mathcal{A}^k \in \mathcal{A}$
$\underline{p}_s = [(\underline{p}_s^1)^T, \dots, (\underline{p}_s^K)^T]^T$	the vector of real power injection
$\underline{\Delta p}_s$	the vector of corrective control capabilities of the sellers
b_i^k	the buyer at node $i \in \mathcal{N}^k$
$P_{b_i^k}$	the real power consumption of the buyer b_i^k
$\beta_{b_i^k}(P_{b_i^k})$	the integral of marginal bid price of the buyer b_i^k as a function of the real power consumption $P_{b_i^k}$
$\mathcal{B}^k = \{ b_1^k, \dots, b_{N^k}^k \}$	the set of buyers in area $\mathcal{A}^k \in \mathcal{A}$
$\underline{p}_b^k \triangleq [P_{b_1^k}, \dots, P_{b_{N^k}^k}]^T$	the vector of real power withdrawal for the area $\mathcal{A}^k \in \mathcal{A}$
$\underline{p}_b = [(\underline{p}_b^1)^T, \dots, (\underline{p}_b^K)^T]^T$	the vector of real power withdrawal
$\underline{\Delta p}_b$	the vector of corrective control capabilities of the buyers
$\omega_w = \{ m_w, n_w, t_w \}$	the bilateral transaction of amount t_w from the seller at node $m_w \in \mathcal{N}^k$ to the buyer at node $n_w \in \mathcal{N}^r$
$\mathcal{W} = \{ \omega_1, \dots, \omega_W \}$	the set of desired bilateral transactions

$\alpha_w(t_w)$	the benefit function of the transaction ω_w for consummating t_w
$\underline{t} \triangleq [t_1, \dots, t_w]^T$	the vector of the bilateral transaction amounts
$\underline{\Delta t}$	the vector of corrective control capabilities of the buyer and the seller pairs for corresponding bilateral transactions
\mathcal{C}	security criterion
\mathcal{J}^c	the set of indices of the contingencies under the security criterion \mathcal{C}

APPENDIX B: CONSTRUCTION OF \mathcal{D}^i

Let $\mathcal{D} = \{d_q : q = 1, \dots, D\}$ be the set of days in the month i . We denote the day d_q peak demand load by p_{d_q} . We reorder the set of the demand values $\{p_{d_1}, \dots, p_{d_D}\}$ as $\{\tilde{p}_1, \dots, \tilde{p}_D\}$ with $\tilde{p}_j \geq \tilde{p}_{j+1}$ where \tilde{p}_j denotes the j^{th} largest value of the month. We construct the ordered daily load curve using the set of points $\{(0, \tilde{p}_1), (1, \tilde{p}_2), \dots, (D-1, \tilde{p}_D)\}$. This curve has at most D distinct load levels. We normalize the time axis using D as the base value and construct the so-called load duration curve (LDC) $\mathcal{L}(\cdot)$ as a piece-wise step function using the set of points $\{(0, \tilde{p}_1), (1/D, \tilde{p}_2), \dots, ((D-1)/D, \tilde{p}_D)\}$. We superpose the grid with k equally distributed LDC factors

$$0 = \psi_0 < \psi_1 < \dots < \psi_{k+1} = 1$$

on the time axis. We determine the load level $\hat{p}_j = \mathcal{L}(\psi_j)$ for each ψ_j . We choose k so that the $(k+2)$ load values are distinct and

$$\hat{p}_0 > \hat{p}_1 > \dots > \hat{p}_{k+1}.$$

We use the load levels to subdivide the interval between \hat{p}_0 and \hat{p}_{k+1} into $(k+2)$ load tranches

$$\mathcal{P}_j = \begin{cases} \left[\hat{p}_{k+1}, \frac{\hat{p}_k + \hat{p}_{k+1}}{2} \right] & j = k+1 \\ \left(\frac{\hat{p}_{j-1} + \hat{p}_j}{2}, \frac{\hat{p}_j + \hat{p}_{j+1}}{2} \right) & j = 1, \dots, k \\ \left[\frac{\hat{p}_0 + \hat{p}_1}{2}, \hat{p}_0 \right] & j = 0 \end{cases}$$

and determine from the time axis the corresponding duration n_j of each tranche. Note that n_j is an integer multiple of $1/D$

and $\sum_{j=0}^{k+1} n_j = 1$. We define

$$\hat{\psi}_j = \sum_{s=0}^{j-1} n_s, \quad j = 1, \dots, k.$$

We construct $\mathcal{L}^a(\cdot)$ from the $(k+2)$ load levels using the set of points $\{(0, \hat{p}_0), (\hat{\psi}_0, \hat{p}_1), \dots, (\hat{\psi}_k, \hat{p}_{k+1})\}$ and use it to approximate $\mathcal{L}(\cdot)$. For each load level \hat{p}_j of $\mathcal{L}^a(\cdot)$, we identify the day d_q with $p_{d_q} = \hat{p}_j$. In case of two or more

such days, we select the most or more recent day. We construct \mathcal{D}^i using these $(k+2)$ selected days.



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