Economic Impacts of Security Criterion Compliance
Contribution to the Panel
"The Effect of System Security on Electricity Markets"

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Abstract—Market and system operations are tightly coupled in the restructured environment. Such coupling requires a thorough understanding of the interdependence between the market performance and the way the power systems are operated. There is a particular need to go beyond the qualitative characterization and to quantify the dependence of the market performance on the system security. In this work, we describe a general approach to quantify the monetary impacts of complying with a specified security criterion when the deployment of security control actions is fully taken into account. We illustrate the application of the proposed approach on the large-scale ISO-NE system to quantify the monetary impacts associated with changing from the current security criterion to two other criteria using the actual 2005 day-ahead data – the historical system model and the bids/offers submitted – with the actual market clearing methodology. Through this study, we gain important insights on the role of price-responsive demand and the selected security control action. An important finding of this study is that the economic efficiency of electricity markets need not decrease when the system is operated under a stricter criterion.

***Index Terms*—electricity market economics, social welfare maximization, locational marginal price, price-responsive demand, power system security, (*n* – 1) and (*n* – 2) security, corrective and preventive security control actions.**

I. Introduction

In the restructured environment, the improvement of the economic efficiency of electricity markets has been the focus of recent efforts [1], [2]. A key aspect of these efforts is the better understanding of the nature of the tight coupling between market and system operations, particularly the dependence of the market outcomes on the way the system is operated. A key driver in system operations is the security criterion, with which compliance must be ensured. In this paper, we describe an approach to quantify the market performance as a function of a specified security criterion and illustrate the application of the proposed approach on a large-scale system.

System security is defined as the ability of the interconnected system to provide electricity with the appropriate quality under normal and contingency conditions [3]. The security criterion, with which the power system operations must comply, consists of the set of postulated contingencies and the associated preventive and/or corrective control actions [4]. For a given operating state, security assessment entails the verification that no violation occurs for any of the postulated contingencies taking fully into account the deployment of the associated security control actions. As these actions affect the market outcomes, a key step in the efforts to improve market performance is the assessment of these impacts of complying with the security criterion in monetary terms.

In this work, we explicitly consider the market and the system operations from the point of view of the *RTO*s. We consider the day-ahead market, or *DAM*, structure. In the proposed approach, we quantify the market performance for a system snapshot under a specified security criterion. This quantification, based on the emulation of the way the *RTO* currently operates the markets and the system for a specified point of time, serves as the basic building block of the methodology. The evaluation of the impacts over a longer period requires an extension of the snapshot analysis. In this way, we are able to capture the impacts of changes in the topology of the system, the network parameters, the set of generating resources and the market participants' behaviors over time. We repeat this procedure to study the corresponding impacts of a different criterion, so that, we can carry out comparative market performance assessments. Such assessments provide the measures of the monetary and resource dispatch impacts of a change in security criterion.

The proposed approach has a wide range of applications such as the justification by the *RTO* of the decision to modify the security criterion to be used and the cost/benefit analysis of network improvements to mitigate the market performance impacts of a set of specified contingencies. We illustrate the application of the proposed approach on the ISO-NE *DAM* to quantify the performance impacts of operating the system under different system security criteria for representative days in 2005 period. For this study, we use the historical day-ahead data – the system model and the bids/offers submitted – with the actual market clearing methodology. These studies capture, in a meaningful way, the impacts of the changes with respect to the current security criterion. An important characteristic of the study period is the role of price-responsive demand in ensuring compliance with the system security criterion. We evaluate explicitly the impacts of such demand has on market outcomes. An important finding of this study is that the economic efficiency of electricity markets need not decrease when the power systems are operated under a stricter criterion when price-responsive demand is present and appropriate control actions are effectively deployed.

The nature of the problem and the market performance quantification for a system snapshot, as well as the proposed approach, are described in section II. In section III, we apply the proposed approach to the ISO-NE *DAM* and present the study results in detail. Section V summarizes the paper and discusses future work.

II. Market Assessment for a System Snapshot and Proposed Aproach

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 [5]. We consider a power system network consisting of K interconnected areas denoted by the set $\mathcal{A}$ with each area $\mathcal{A}^k$ having a node set $\mathcal{N}^k$ with N^k buses. We associate a security criterion $\mathcal{C}$ with a specific contingency list and a specified control action – preventive or corrective – for every contingency on that list. Salient characteristics of these control actions are discussed in [5]. 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 $\mathcal{S}^k = \{s_1^k, \cdots, s_{N^k}^k\}$ and $\mathcal{B}^k = \{b_1^k, \ldots, b_{N^k}^k\}$, the collection of sellers and that of buyers of the area $\mathcal{A}^k \in \mathcal{A}$, respectively. 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 $\overline{t}_w$, by the triplet $\omega_w \triangleq \{m_w, n_w, \overline{t}_w\}$, $\omega_w \in \mathcal{W}$. The *RTO* 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 *RTO* solves a security constrained OPF, or SCOPF, problem with the objective to maximize the social welfare under the security criterion $\mathcal{C}$. We state the SCOPF problem as [5]

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

subject to

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

$$\underline{\boldsymbol{h}}^{(0)} \left(\underline{\boldsymbol{p}}_{\boldsymbol{s}}^{(0)}, \underline{\boldsymbol{p}}_{\boldsymbol{b}}^{(0)}, \underline{\boldsymbol{t}}^{(0)}, \underline{\chi}^{(0)}, \underline{\gamma}^{(0)} \right) \leq \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\mu}_h^{(0)} \quad (3)$$

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

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

$$\underline{\boldsymbol{h}}^{(j)} \left(\underline{\boldsymbol{p}}_{\boldsymbol{s}}^{(j)}, \underline{\boldsymbol{p}}_{\boldsymbol{b}}^{(j)}, \underline{\boldsymbol{t}}^{(j)}, \underline{\chi}^{(j)}, \underline{\gamma}^{(j)} \right) \leq \underline{\boldsymbol{0}} \qquad \leftrightarrow \quad \underline{\mu}_h^{(j)} \quad (5)$$

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

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

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

Here, we use the superscript (j) to denote the contingency cases with the base case denoted by (*0*). The $|\mathcal{J}_{\mathcal{C}}|+1$ 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 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 use the optimal value of the social welfare $\mathcal{S}\,|_{\mathcal{C}}$ under $\mathcal{C}$ as a measure for the economic efficiency of the market as a whole. In addition, for area $\mathcal{A}^k$, we evaluate

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

to determine the area $\mathcal{A}^k$ contribution to the social welfare. The *producer* (*consumer*) surplus measures the performance or the gain of each seller (buyer) for participating in the electricity market. We use the total dispatched load to evaluate the total cleared demand quantity under criterion $\mathcal{C}$

$$P\Big|_{\mathcal{C}} \triangleq \sum_{k=1}^{K} \sum_{i=1}^{N^k} \left[p_{b_i^k}^{*(0)} + \sum_{w=1, i=n_w \in \mathcal{N}^k}^{W} t_w^{*(0)} \right] \Bigg|_{\mathcal{C}} . \quad (10)$$

The value of the metrics mentioned above is useful for the performance quantification of market for a given snapshot and constitutes the basic building of the approach. When a different security criterion $\mathcal{C}'$ is considered, the *RTO* must solve a modified SCOPF in which the constraints in (4)–(8) reflect the changes in the contingency set $\mathcal{J}_{\mathcal{C}}$ and in the security control actions associated with each contingency. To measure the impacts on market performance due to the change in the security criterion from $\mathcal{C}$ to $\mathcal{C}'$, we introduce for each metric the relative performance metric which measures the difference of the values under $\mathcal{C}'$ and $\mathcal{C}$, respectively.

We distinguish between fixed demand buyers and those with price-responsive demand. The fixed demand bid is a special case of the price sensitive bid in which a specified quantity is submitted with no price information. In order to include fixed demand buyers' benefits in the SCOPF problem formulation (1) – (8), we use a constant per *MWh* benefit value, τ, for the fixed demand.

Under a given security criterion, the snapshots corresponding to different system and market conditions may result in marked changes in the market performance outcomes. Such differences are caused by many factors including changes in the loads, the set of available units, and the offers/bids submitted. In turn, these changes may also result in different values of the relative performance metrics. Consequently, these assessments must be carried out over a period to correctly capture the impacts of the different conditions that exist during that period.

Conceptually, we assess the market performance assessment at each hour of a given study period. To assess the market performance impacts due to a change in the security criterion, the entire multiple snapshot procedure must be repeated for the security criterion under consideration. 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. However, for a large–scale system, such an approach may impose a large burden on computing resources. We use the scheme described in [5] to systematically select smaller representative sample of the hours for the period of interest.

The proposed approach has a wide range of applications such as the justification by the *RTO* of the decision to modify the security criterion to be used and the cost/benefit analysis of network improvements to mitigate the market performance impacts of a set of specified 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.

III. Application Study

We illustrate the application of the proposed approach on the ISO-NE *DAM*. The objective of this study is to analyze whether the economic efficiency of the ISO-NE *DAM* is adversely impacted by the system operations complying with the security criterion in force. For this purpose, we quantify the market performance as a function of three security criteria and perform comparative assessments. We use the system and market data from the year 2005 and utilize the actual market clearing software used for the ISO-NE *DAM*. We measure the changes with respect to the outcomes under the current ISO-NE security criterion.

Each area of the ISO-NE system is characterized as either import or export. The import areas are [5]

- $\mathcal{A}^1$: 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, $\mathcal{A}^5$.

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 period under study is 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 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 10% 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, as shown in Fig. 1. 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 described in [5].

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

$$\mathcal{J}_{\mathcal{C}} = \mathcal{J}_{n\text{-}1} \cup \left(\bigcup_{k=1}^{4} \mathcal{M}^{k} \right). \qquad (11)$$

Here, $\mathcal{J}_{n\text{-}1}$ is the set of single element contingencies considered by the ISO-NE and $\mathcal{M}^k$ is the set of double tie line contingencies specified for each import area $\mathcal{A}^k \in \boldsymbol{\mathcal{A}}$, k=1,..,4. 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 $\mathcal{J}_{\mathcal{C}^a} = \mathcal{J}_{n\text{-}1}$, and preventive control action is the deployed for each contingency in $\mathcal{J}_{\mathcal{C}^a}$. For the criterion $\mathcal{C}^b$, the contingency list $\mathcal{J}_{\mathcal{C}^b} = \mathcal{J}_{\mathcal{C}}$, but we replace the corrective control actions by the preventive control actions for the contingencies in $\bigcup_{k=1}^{4} \mathcal{M}^k$. 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 $\mathcal{R}_2$.

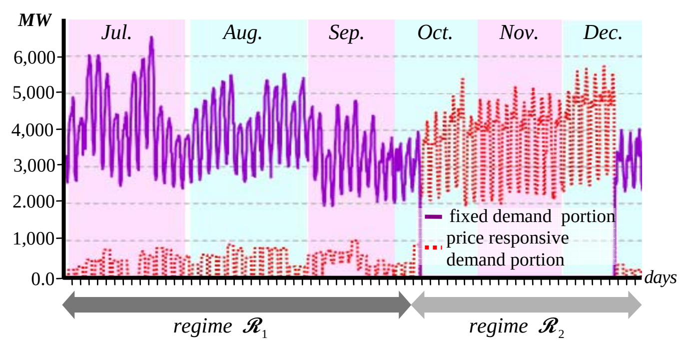

Fig. 1 The bidding behavior change of the larger buying entity

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 1. 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 more pronounced for the change of the security criterion from $\mathcal{C}$ to $\mathcal{C}^b$ than from $\mathcal{C}$ to $\mathcal{C}^a$. 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 1. Total hourly dispatched loads and range of 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 relative area-wide net injection metric for the areas $\mathcal{A}^1$, $\mathcal{A}^2$ and $\mathcal{A}^5$. 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. 2. 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. The discussion of the impacts of the security change from $\mathcal{C}$ to $\mathcal{C}^b$ is provided in [5].

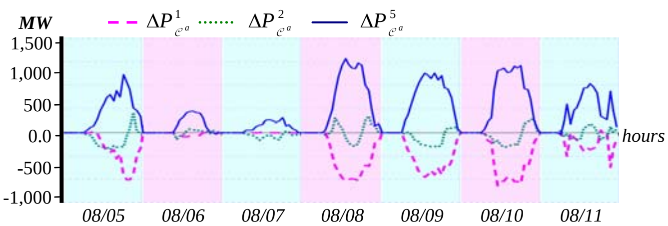

Fig. 2 Area-wide net injection impacts under $\mathcal{C}^a$

We next examine the monetary impacts of the changes in the security criterion as measured by the relative social welfare metric. 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. We use the normalized values to compare the impacts with respect to the values under the reference criterion, as well as, across study periods of different durations. In this way, the comparisons are both consistent and meaningful. For concreteness, we use a value of τ=1,000 *\$/MWh/h* for evaluating the benefits of the buyers submitting fixed demand. We first consider the economic 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 social welfare. 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 plots of the changes in social welfare arising from a change of the security criterion are shown in Fig. 3. In this figure, we also provide the normalized impacts considering a different value of τ'=10,000 *\$/MWh/h*. Note that, the different values of τ and τ' impact the normalized values but do not affect the nature of the impacts.

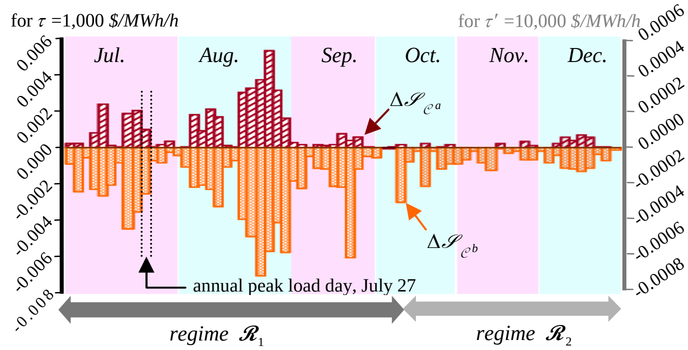

Fig. 3 The normalized daily impacts on social welfare

We obtain additional insights into the impacts of the security criterion change on the market participants in each area by studying the disaggregation of the metrics $\Delta\mathcal{S}_{\mathcal{C}^a}$ and $\Delta\mathcal{S}_{\mathcal{C}^b}$. The area by area contribution is in line with the changes in the utilization of the modified import/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. 4 corresponding to shifting the security criterion from $\mathcal{C}$ to $\mathcal{C}^a$.

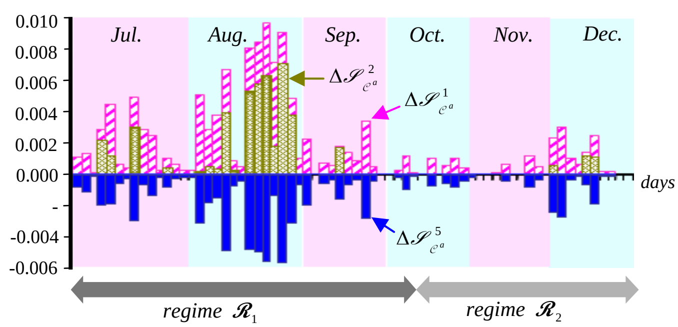

Fig. 4 Change in each area's contributions to social welfare under $\mathcal{C}^a$

The price-responsive demand that characterizes regime $\mathcal{R}_2$ plays an important role in the nature of the results. In general, as the willingness to pay of the buyers increases, the absolute value of the relative social welfare metric increases, attaining its highest value for fixed demand for each security criterion considered. Therefore, the impacts of the change in security criterion to either $\mathcal{C}^a$ or $\mathcal{C}^b$ on the social welfare are more pronounced for the fixed demand regime $\mathcal{R}_1$ than the price responsive regime $\mathcal{R}_2$. Also, for a price-responsive demand with a uniformly low willingness to pay, the impacts may be small, and in certain cases may be negligibly so. The relaxation of the security criterion from $\mathcal{C}$ to $\mathcal{C}^a$ by not taking into account the double element contingencies, results in an insignificantly small relative social welfare metric values under the regime $\mathcal{R}_2$. The tightening of the security criterion from $\mathcal{C}$ to $\mathcal{C}^b$ using preventive actions to replace corrective ones reduces the social welfare. In fact, by utilizing the corrective control capabilities of the resources in the presence of price-responsive demand, the ISO-NE is able to decrease the economic impacts of the double tie line contingencies. Note that the extent of such an ability depends on various factors including the topology of the system, the characteristics of the generating units and the bids/offers of the market participants.

These findings of the comparative assessment lead us to conclude that the reference criterion $\mathscr{C}$ 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 important insights on the role of price-responsive demand and the selected security control action. In fact, a key finding of the ISO-NE study is that the economic efficiency of the electricity markets need not decrease when a power system is operated under a stricter criterion as long as there is price-responsive demand. The proposed approach provides good insights into the ramification of changing the security criterion on both qualitative and quantitative basis.

IV. Concluding Remarks

In this paper, we propose an approach for the assessment of market performance under a specified security criterion and quantification of the market performance impacts due to a change in the criterion. The ability to quantify the monetary impacts of complying with a specified security criterion makes the approach useful in regulatory studies, longer–term planning activities and short–term activities related to the market and system operations. In fact, the tool enables the *RTO* to make better informed decisions. The proposed approach has a wide range of applications. These include the studies for the justification by the *RTO* to modify its decision for the selected security criterion and for and the cost/benefit analysis of network improvements to mitigate the market performance impacts of a set of specified contingencies. We illustrate the application of the proposed approach on the ISO-NE *DAM* to analyze whether the economic efficiency of the ISO-NE *DAM* is adversely impacted with the current security criterion in force. Our investigation provides important insights into the role of price-responsive demand and that of the security control actions. In fact, a key finding of this study is that the economic efficiency of the electricity markets need not decrease when a power system is operated under a stricter criterion as long as there is effective price-responsive demand and appropriate control actions are deployed

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