ASSESSMENT OF THE IMPACTS OF DEMAND CURTAILMENTS IN THE DAMs: ISSUES IN AND PROPOSED MODIFICATIONS OF FERC ORDER NO. 745

BY

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THESIS
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ABSTRACT

The Federal Energy Regulatory Commission (FERC), in its initiative to incentivize demand response resources (DRRs) to participate in the day-ahead markets (DAMs), enacted Order No. 745. The Order mandated each ISO/RTO to perform a monthly cost-effectiveness test, the so-called net benefits test (NBT), that determines the monthly threshold price that serves as the economic signal for the dispatch of DRRs. The determination of the threshold price without explicit consideration of the grid and its associated constraints prompted the motivation for our investigation. Analytical considerations of the issues were accompanied by extensive numerical studies based on simulation. In our studies, we identify the two key unintended consequences emanating from the DRR participation in the DAMs. One is the existence of instances where the dispatch of DRRs increases the purchase payments of loads not participating in curtailment provision so that those buyers are worse off due to the DRR demand curtailments presence in the DAMs. The second set of unintended consequences consists of the cases where the participation of DRRs results in higher prices to their remaining loads under the FERC compensation rules. The NBT fails to test for these unintended consequences and based on our simulations studies, such events may occur frequently.
In light of the results of these investigations, we propose specific modifications to the *NBT*. The modifications are in three principal areas – data usage, explicit consideration of transmission system in the determination of the threshold price and an additional test to guarantee that no buyer is worse off in the post-curtailment state than in the pre-curtailment state. We propose to limit the data to on-peak *LMPs* instead of the representative offer curve data based on data from all the hours of the month. We propose the replacement of the system-wide threshold price by node-specific threshold prices at each node to explicitly account for transmission considerations. To ensure that no post-curtailment load is worse off than in the pre-curtailment conditions, we propose the introduction of a simple test to verify that this criterion is met. The proposed modifications result in nodal threshold prices and this explicit transmission consideration is effective in avoiding the issues we identified with the *FERC NBT*. We illustrate the ability of the proposed modifications to address these issues by presenting a representative sample of simulation studies from the testing we performed. The results of the testing we performed indicate that the instances of higher post-curtailment purchase payment are reduced by at least an order of magnitude and in each case every node in the system is assured that it is not worse off due to demand curtailments. The proposed modifications result in an important reduction in the unintended consequences due to demand response participation.
To my parents
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<table>
<thead>
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DRR</td>
<td>Demand Response Resource</td>
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<tr>
<td>FERC</td>
<td>Federal Energy Regulatory Commission</td>
</tr>
<tr>
<td>ISO</td>
<td>Independent System Operator</td>
</tr>
<tr>
<td>RTO</td>
<td>Regional Transmission Organization</td>
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<tr>
<td>IGO</td>
<td>Independent Grid Operator</td>
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<td>DAM</td>
<td>Day-Ahead Market</td>
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<td>DSM</td>
<td>Demand-Side Management</td>
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<td>CSP</td>
<td>Curtailment Service Provider</td>
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<tr>
<td>LMP</td>
<td>Locational Marginal Price</td>
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<td>SMP</td>
<td>System Marginal Price</td>
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<td>NBT</td>
<td>Net Benefits Test</td>
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<td>ROC</td>
<td>Representative Offer Curve</td>
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<td>AROC</td>
<td>Adjusted Representative Offer Curve</td>
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<tr>
<td>ISO-NE</td>
<td>Independent System Operator of New England</td>
</tr>
<tr>
<td>MISO</td>
<td>Midwest Independent System Operator</td>
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<td>RLMPC</td>
<td>Representative Locational Marginal Price Curve</td>
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<tr>
<td>LTP</td>
<td>Locational Threshold Price</td>
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CHAPTER 1

INTRODUCTION

In this chapter, we lay out the contents of this thesis. Our focus is the study of the impacts of demand curtailments in the electricity markets under current regulatory initiatives. We start by discussing the motivation and background of our research to set the stage of the work presented in the thesis. We provide a brief summary of the key regulatory initiatives that have led to the current rules and we also review the state-of-the-art in the current demand response compensation schemes.

1.1 Motivation and Background

Growing environmental concerns, the need of energy independence and the push for sustainability are the key drivers of electricity-market policies. Renewable energy (RE), large-scale storage (LSE) and demand response (DR) are technologies the Federal Energy Regulatory Commission (FERC) is keen on implementing. The FERC, as the governmental agency in charge of regulating the wholesale sales of electricity, oversees the energy markets run by the Independent System Operators (ISO) and the Regional Transmission Organization (RTO). The ISOs and RTOs are non-profit organizations
responsible for administering the electricity markets within one or multiple regions. We group all the ISOs and RTOs in the term independent grid operator (IGO) to facilitate the discussion. As a result of the intermittency effects associated with RE generation and the slow penetration of LSE technologies, investors, regulators and system operators are pushing towards the demand-side to maintain the reliable operation of the power systems. The demand-side can participate in the electricity markets in the form of the so-called demand response of the consumers. Demand response consists in a reduction in electricity usage by the consumer in response to a price, emergency or reliability signal. The responsive consumers get compensated every time they curtail their electricity usage. We refer to the loads that have the capability of providing load reductions as demand response resources (DRRs).

Before the restructuring of the electricity industry, demand response activities were grouped into the term demand-side management (DSM). DSM activities were tools the integrated utilities used to attain a desired load shape and were traditionally divided into six objectives: peak clipping, valley filling, load shifting, flexible load shape, strategic conservation and strategic load growth. The first four represent objectives to alter the electricity usage at targeted times and are nowadays all incorporated into the term demand response. The integrated utilities managed all the DSM activities until the advent of the restructuring of the electricity industry.
Demand response increased its prominence when in 2005, the United States Senate passed Energy Policy Act of 2005 (Epact 2005), a bill with several provisions for electricity markets [1]. The Epact 2005 mandated the FERC to produce a comprehensive study of demand response in the United States. As a result of this study the Assessment on Demand Response and Advanced Metering (DR&AM) was published in 2006 [2]. The DR&AM recognized the benefits of demand response in the electricity markets and made some recommendations. The FERC recommended to:

(i) explore how to better accommodate demand response in wholesale markets;
(ii) explore how to coordinate with utilities, state commissions and other interested parties on demand response in wholesale and retail markets; and
(iii) consider specific proposals for compatible regulatory approaches, including how to eliminate regulatory barriers to improved participation in demand response, peak reduction and critical peak pricing programs.

By implementing these recommendations, demand response became part of FERC’s jurisdiction. Furthermore, the Energy Independence and Security Act of 2007 (EIAct 2007) mandated the FERC to conduct a national assessment on demand response. This resulted in the publication of A National Assessment of Demand Response Potential (NADRP). NADRP identified the
barriers to demand response in the electricity market: lack of a direct connection between wholesale electricity prices, ineffective demand response program design, lack of customer awareness and education, and concern over environmental impacts. The NADRP also estimated the nationwide demand response potential in 5 and 10 year horizons on a state-by-state basis, and how much of the potential can be achieved within those time horizons; and the report includes specific policy recommendations for developing incentives and for overcoming the above-mentioned barriers. According to the NADRP, the 2019 peak load in the United States can be reduced by as much as 150 GW, compared to the business-as-usual scenario.

In order to overcome these barriers, the FERC created a new type of market player. In Order No. 719, the FERC defined curtailment service providers (CSPs) as demand response aggregators [3]. These CSPs are entities that enroll customers that are willing to reduce load, into large load aggregations. Order No. 719 also amended previous FERC regulations to treat demand response comparably to other resources. To accomplish this, the FERC mandated the IGOs to:

(i) accept demand offers from demand response resources,

(ii) eliminate, during emergencies, certain charges to buyers in the energy market for voluntarily reducing demand,

(iii) permit CSPs to offer demand response on behalf of retail customers directly in to the markets.
Although the changes introduced by Order No. 719 were significant, in 2011 the FERC believed that these demand reductions still encountered barriers in the electricity markets. This is why in 2011 the FERC enacted Order No. 745. In Order No. 745 the FERC mandated all of the IGOs to compensate all of the demand response resources that clear in the energy market at the locational marginal price (LMP) when used to balance supply and demand. The FERC also mandated all IGOs to conduct a monthly cost-effectiveness test that will be used as a metric to judge when demand curtailments are allowed in the energy markets. This cost-effectiveness metric is a system-wide threshold price that is calculated using the so-called net benefits test (NBT). The NBT is a monthly procedure that uses historical offer data to determine the price at which a demand curtailment results in benefits to the system. Each IGO must follow FERC’s guidelines to run the NBT on a monthly basis.

1.2 Review of the State of the Art on the Impacts of FERC Order No. 745

The question of how much a retail customer should be paid for curtailing its demand has been the subject of considerable debate. The nearly 3800 pages of comments the FERC received after the publication of the notice of proposed rulemaking (NOPR) that eventually resulted in Order No. 745, document the various opinions on the issue [4],[5],[6]. Also, the dissenting opinion of FERC Commissioner Moeller in Order No. 745, in which, he detailed the rationale for his opposition to the rule, provides a summary of some of the key issues of
those who do not support the thrust of the ruling [7, pp. 102]. In this section, we provide a brief summary of the literature and the comments regarding demand response compensation under Order No. 745.

It is widely accepted that the implementation of demand response in the electricity markets can provide substantial benefits including improvement in the elasticity of the demand curve, reduction in the price paid by the loads, reductions of environmental emissions, betterment of the grid’s reliability, and reduction in the costs of developing addition peaking generation. Although, all agree that these benefits are attainable, there exists a difference in opinion on the way DRRs should be compensated for the curtailment services provided.

The standardization of a demand response compensation scheme was the issue the FERC faced when developing Order No. 745. During the process that led to the decision that DRRs are paid at the LMP, various opinions had to be taken into account. FERC’s decision that demand and supply-side resources can substitute each other was based on the premise that “in balancing supply and demand, a one megawatt reduction in demand is equivalent to a one megawatt increase in energy for purposes of meeting load requirements and maintaining a reliable electric system” [4, pp. 15]. Furthermore, under Order No. 745 DRRs are only to be dispatched when the cost-effectiveness conditions of the NBT are met. The FERC sought and received a large volume
of comments on the comparability of demand response and generation resources, the compensation proposal, and the implementation of the NBT.

When asked to submit comments on FERC Order No. 745, one view adopted by some is that “demand response (DR) is in all essential respects economically equivalent to supply response; and that economic efficiency requires, as the NOPR recognizes, that is should be rewarded the same LMP that clears the market” [6, pp. 24]. On the other hand, other comments assert that DRRs are not equivalent to generation resources and that paying the LMP, without some offset for some portion of the retail rate, for demand curtailments will discriminate against generation resources in the short run and will overcompensate demand response [7, pp. 21].

In support of their thesis, those who hold the view of the equivalency between DRRs and generation resources posit that DRRs provide a superior service to generation because they could provide a quicker response than traditional generation, reduce environmental emissions and, in addition, mitigate the need for the investment in new generation plants [5], [6]. Furthermore, they claim that since electricity prices fail to internalize environmental externalities, such as toxic air pollution, greenhouse gas emissions, and land and water use impacts, demand response should be compensated as mandated by Order No. 745. They extend their argument by saying that since the impacts of these externalities are especially acute at peak hours, demand response curtailments at these periods of time avoids the use of peaking plants
such as gas turbines. Although there is much truth to this claim, it is no longer valid once the DRRs resort to behind-the-meter generation. We refer to behind-the-meter generation (BMG) as a generation unit that serves a load and is not interconnected with the electricity grid. If a large percentage of demand resources use BMG to offer load curtailments to the IGO, then this type of demand response does not contribute to the reduction of environmental emissions. Also, air pollution in cities and noise levels are a main problem with BMG since more commercial buildings are participating in demand response.

Those who oppose the equivalency of DRRs with generation resources hold that DRRs should be compensated at the LMP minus the retail rate (RR) [8], [9], [10]. The rationale behind this notion is that paying the full LMP fails to take into account the savings associated with demand response and results in overcompensation for the DRR. Indeed, some argue that paying demand response at the LMP represents a double payment and that it may lead to inefficient demand response [11]. Ultimately, the FERC adopted the view that demand response is equivalent to generation when used to balance supply and demand.

In addition to the equivalence of demand response and generation resources and the appropriate compensation level for demand response resources, the utilization of the NBT created many comments after the publication of the NOPR related to Order No. 745. According to the FERC, the NBT prevents
the dispatch of demand response resources when it results in an increased cost per unit to the load and that ensures that the benefits of dispatching DRRs exceed the costs. One of the main issues raised by the NBT is that it focuses solely on the benefits to consumers. The NBT judges cost-effectiveness from the point of view of the benefits to one group of market participants and does not consider the societal cost of meeting demand. The Market Surveillance Committee of the CAISO (MSCCA), in its comments on the NBT, stated that “this is a large departure from the FERC market design principle, which is nondiscriminatory market access to promote maximum market efficiency, as measured by the usual market efficiency metric of producer plus consumer surplus.” Furthermore, the MSCCA and NYISO stated that paying DRRs at the LMP mines the RR avoids the need of a net benefits test [12].

One issue not widely discussed in the literature is the non-regional nature of the NBT. Since the NBT is based purely on offer-curve analysis and does not take into consideration the power system network, it ignores one of the key components of the price of electricity: congestion. By ignoring the power system constraints, the NBT assumes that the network runs ideally. The NBT also assumes that when a demand curtailment is made, all the consumers in the system benefit. These assumptions may be too much of a leap of faith and need to be investigated further. The reports discussed in this literature review use economic methodologies to analyze the possible impacts of Order No.
745. Although very relevant and insightful, these reports ignore the operational aspects of the power system.

1.3 Scope and Nature of the Contributions of the Thesis

In this report, we focus on the study of the impacts of demand curtailments in the ISO-run DAMs. We explicitly take into account the requirements of the FERC Order No. 745 in the transmission constrained electricity market model. Using representative simulation studies we analyze the impacts of demand curtailments in the DAMs. We identify they key unintended consequences that result from demand response: the existence of instances where the dispatch of DRRs increases the purchase payments and the fact that some market participants are worse off due to the demand curtailments. We also investigate and determine the causal factors of these issues.

In light of the identified unintended consequences and the identification of the causal factors, we propose modifications to the NBT that keep its spirit intact and do not change the nature of the procedure. We propose to use LMP data instead of offer data to determine the monthly threshold price. Our proposed modifications result in nodal thresholds. To ensure that no buyer is worse off due to demand curtailments, we propose to guarantee that this condition is met.
1.4 Thesis Outline

The remainder of the thesis is organized in the following manner. In Chapter 2, we provide a detailed description of NBT and its applications in the clearing of the day-ahead markets. We start by describing the requirements mandated by the FERC and then proceed to explain the NBT in economic terms. In this chapter, we also provide the entire procedure FERC mandates the IGOs to use in order to calculate the monthly threshold price. In Chapter 3, we discuss the unintended consequences associated with the dispatch of DRRs under the current rules. In Chapter 4, we provide the modifications to the NBT that we developed. In Chapter 5, we provide the results and our analyses of the simulation studies. We provide our concluding remarks and suggestions for future research in Chapter 6. In Appendix A, we describe the test system used to run all of the simulation studies presented in the thesis.
CHAPTER 2

THE NET BENEFITS TEST PROCEDURE

Under *FERC* Order No. 745, the clearing of a *DRR* in the *DAMs* depends on the monthly threshold price, as determined by the implementation of the net benefits test (*NBT*). The *NBT*’s goal is to determine a cost-effectiveness condition that restricts participation of *DRRs* to only those hours in which the benefits of the buyers due to the lower electricity prices outweigh the payments to the *DRRs*. Whenever the *NBT* conditions are met, the *DRRs* are compensated at the *LMP* at the node at which the curtailment is provided. In this chapter we provide the description of the *NBT* and we formulate the modified *DAM* clearing optimal power flow (*OPF*) problem with the *NBT* included. In Section 2.1, we provide a discussion of the *FERC* requirements for the *NBT*. In Section 2.2, we describe all the steps needed to determine the monthly threshold price. We devote Section 2.3 to formulate the inclusion of the *NBT* determination in the clearing of the *DAMs* with *DRR* load curtailment.
2.1 *FERC NBT Assessment*

In order to determine the hours during which demand-curtailment offers are considered in the clearing of the DAMs, each *IGO* is mandated under Order No. 745 to routinely conduct the *NBT* each month so as to determine the monthly threshold to ensure the cost-effectiveness of such curtailment offers. We start with a review of the *NBT* requirements, continue with a discussion of the degrees of freedom available to the *IGOs* and provide an economic interpretation of the *NBT*.

According to *FERC* Order No. 745, each *DRR* is compensated at the *LMP* at the node at which its load curtailment is provided whenever the *DRR* offer is used by the *IGO* to balance supply and demand and the specified *FERC* conditions are met [7]. The *NBT* mechanism is the *FERC*’s procedure to ensure that the *IGO* uses cost-effective dispatch of the *DRRs*. The *NBT*, in essence, compares the total benefits of dispatching *DRRs* to the total payments of the buyers in compensation for the demand curtailment provision. The total benefits are the net savings of the post-*DRR* curtailment loads brought about by the reduced hourly electricity prices due to the curtailments.

Each *IGO* calculates using a representative offer curve based on data from the same month of the preceding year, the price at which the dispatch of *DRRs* becomes cost-effective. Moreover, Order No. 745 mandates the *IGOs* to comply with the following requirements:
• The IGO must publish the monthly threshold price on the 15th day of the preceding month.

• The determination of the monthly threshold price requires the use of a representative offer curve for the entire month constructed from the offer data submitted for that month in the previous year; the determination may incorporate any changes in fuel prices and resource availability and may use numerical smoothing of the representative offer curve.

Order No. 745 also provides certain degrees of freedom in the implementation of the NBT by each IGO in terms of the construction of the adjusted representative curve due to

• the ability to adjust for changes in fuel prices and resource availability, and

• the ability to use a smoothing technique to construct a continuous curve.

Such degrees of freedom allow the IGO to construct the adjusted representative curve in non-unique ways due to the multiple curves that may result. There exist no clear metrics to assess whether a particular curve is better than another possible curve. As such, the selection of the adjusted representative offer curve is arbitrary since the adjusted curve is a function of
the resolution used in the offer data, the fuel price indices adopted for measuring the changes and the smoothing technique deployed [13]-[17].

We provide an economic interpretation of the effects of the NBT determination by considering a single hourly DAM. The analysis of the NBT in this section is based on the assumption used by FERC Order No. 745 that there are no transmission constraints in the grid and considers the transmission unconstrained market clearing problem (TUMCP). We represent the market corresponding to the snapshot of the system for that hour.

In the TUMCP, the IGO uses the submitted generation offers by the sellers to construct the supply curve by sorting them in order of increasing prices. Similarly, the IGO constructs the demand curve by sorting the buyers’ demand bids in order of decreasing prices. In Fig. 2.1, we illustrate graphically the clearing of a DAM using supply-side offers and the demand-side bids. The intersection of the supply and demand curves \( \left( \ell^*, \lambda^* \right) \) determines the market equilibrium with \( \ell^* \) as the total cleared demand and \( \lambda^* \) as the system marginal price (SMP). Each seller (buyer) receives (pays) the SMP for each MWh sold (bought). We next include the effects of demand curtailments in the market equilibrium in the DAM.
Figure 2.1: Equilibrium of an hourly DAM

We consider the dispatch of a DRR curtailment that reduces the system load demand by $\Delta \ell$. Such a change essentially produces a shift in the demand curve to the left. This shift results in a modified market equilibrium $\left( \left[ \ell' \right], \left[ \lambda' \right] \right)$, where $\left[ \ell' \right]$ is the modified cleared demand and $\left[ \lambda' \right]$ is the post-curtailment SMP as shown in Fig. 2.2. Since the modified cleared demand $\left[ \ell' \right]$ (where $\left[ \ell' \right] \triangleq \left[ \ell' \right] - \Delta \ell$) is necessarily lower than the demand without DRRs, the monotonic non-decreasing nature of the supply curve implies that $\left[ \lambda' \right] \leq \left[ \lambda' \right]$.

With the participation of the DRRs in the DAM, the post-curtailment SMP, $\left[ \lambda' \right]$, is used to pay/buy each MWh including the curtailment provided by the
DRR. As such, the social, consumer and producer surpluses may change with respect to the case with no DRR participation.

Figure 2.2: Modified market equilibrium with demand curtailments

Next, we examine the repercussions of the post-curtailment supply-demand curve equilibrium. Consider Fig 2.3 areas $A_\lambda$ and $A_\gamma$. For $[\lambda'] \leq [\lambda']$, $A_\lambda$ represents part of the reduction in the producer surplus with respect to the pre-curtailment equilibrium. This reduction results in potential savings for the post-curtailment loads. As a result, these loads may obtain additional benefits of using electricity at the lower price and so their consumer surplus may increase relative to the pre-DRR curtailment situation. The producers whose post-curtailment energy is sold in the DAM are compensated at the post-curtailment $SMP \ [\lambda']$ and so their producer surplus is reduced. Also, some
sellers may not be able to sell at the post-curtailment equilibrium. The area
\[ A_\lambda \] is \( \left( \left[ \lambda' \right] - \left[ \lambda \right] \right) \cdot \left[ \ell \right] \) represents the total reduction in the payments to the
supply side by the post-curtailment load in the post-curtailment market. This
is simply a transfer of some of the producer surplus to those consumers whose
loads are not curtailed. However, we have so far not considered any payment
to incentivize the DRR to provide curtailment.

Next, we consider the area \( A_\epsilon \). We view \( A_\epsilon \) to represent the total value of
dispatching the DRRs since under the FERC Order No. 745 all the DRRs
whose offers clear in the DAM are compensated at the post-curtailment SMP.
Thus, the area \( A_\epsilon \cdot \left( \left[ \ell' \right] - \left[ \ell \right] \right) \cdot \left[ \lambda \right] \) constitutes the total payments to the DRR
for the load curtailment. Since this payment must be made by the consumers
that have post-curtailment loads, in effect, this represents a reduction in the
benefits [18]-[20]. The NBT determines the point in the representative offer
curve where the benefits of dispatching demand curtailments are exactly equal
to the payments to the providers of these curtailments. In other words, the
threshold value in our discussion corresponds to the value \( \left[ \lambda' \right] \), where
\[ A_\lambda = A_\epsilon \].
2.2 The Threshold Price Determination

We devote this section to describe the procedure an *IGO* is mandated to implement in order to calculate the threshold price for each month of the year. This monthly threshold price establishes when demand curtailments are deemed to be beneficial to the *IGO’s* system for each day of that month. The determination of the monthly threshold price consists in three steps:

(i) determination of a representative offer curve for the month,

(ii) smoothing of the representative offer curve, and

(iii) determination of the point where the smoothed representative offer curve becomes inelastic.
The construction of the representative offer curve for month \( m \) of year \( y \) requires the use of the offer data for the same month \( m \) in the year \( y-1 \). The IGO collects the offer data from each hour of that month. The hours pertaining to the month \( m \) form the set

\[
H_m = \{ h : h = 1, 2, \ldots, 12 \} , \quad m = 1, 2, \ldots, 12, \text{ for year } y-1.
\]

For each hour \( h \in H_m \), the offers made by each of the \( S_m \) sellers who participated in the hourly DAM are used to construct the sets

\[
E^{\eta}_{m,h} = \left\{ \left( \tilde{p}^{s,\eta}_{m,h}, \sigma^{s,\eta}_{m,h} \right) \right\} , \quad \eta = 1, 2, \ldots, E_m, \quad s = 1, 2, \ldots, S_m ; \quad h = 1, 2, \ldots, H_m ; \quad m = 1, 2, \ldots, 12.
\]

The offer is the order pair \( \left( \tilde{p}^{s,\eta}_{m,h}, \sigma^{s,\eta}_{m,h} \right) \) with \( \tilde{p}^{s,\eta}_{m,h} \) representing the capacity offered by seller \( s \) at price \( \sigma^{s,\eta}_{m,h} \). Since at each hour a seller may offer power at various prices, we use the superscript \( \eta \) to denote each of the segments of the seller’s \( s \) offer for hour \( h \). We depict in Fig. 2.4 the aggregated offer supply curve of seller \( s \) at hour \( h \).
The construction of a representative offer curve entails the collection of all the sellers’ offers for each hour $h$ of month $m$ of year $y-1$ and their sorting them into $K_{m}+1$ “buckets”. The “bucket” $G_{m,h}^{(k)}$ is the sub-set that contains the indices $(s,\eta)$ of the sellers whose prices fall in the interval $[\gamma^{(k-1)}_{m}, \gamma^{(k)}_{m}]$; $k = 1,2,\ldots, K_{m} + 1$. These price levels may be set arbitrarily by the IGO and depend on the minimum and maximum offers permitted in the IGO’s market. The price levels satisfy

$$\gamma^{(k)}_{m} = \gamma^{(k-1)}_{m} + \Delta \gamma_{m}, \quad k = 1,2,\ldots, K_{m} ; \quad m = 1,2,\ldots, 12. \quad (2.1)$$
\( \Delta \gamma_m \) is the step size between the price levels and is selected by the IGO based on the resolution desired for the offer curve construction. We denote by \( \gamma^{(K_m)}_m \) the monthly ceiling offer price and by \( \gamma^{(0)}_m \) the monthly floor price.

The bucket \( G^{(k)}_{m,h} \) is defined formally by

\[
G^{(k)}_{m,h} = \left\{ (s, \eta) : \gamma^{(k-1)}_m < \sigma^{s,\eta}_m \leq \gamma^{(k)}_m, 1 \leq s \leq S_m, 1 \leq \eta \leq E_m^r ; k = 1, 2, \ldots, K_m ; h = 1, 2, \ldots, H_m ; m = 1, 2, \ldots, 12. \right\}
\]

For \( k = 0 \), we define a separate floor-price bucket \( G^{(0)}_{m,h} \) as

\[
G^{(0)}_{m,h} = \left\{ (s, 1) : \sigma_{m,h}^{s,1} = \gamma^{(0)}_m, 1 \leq s \leq S_m, h = 1, 2, \ldots, H_m ; m = 1, 2, \ldots, 12, \right\}
\]

where \( \eta = 1 \) because only the lowest-priced offer of each seller \( s \) may be set to the floor price.

In order to provide a representative value of how much power was offered in the month \( m \) within the interval delimited by two adjacent price levels, \( \gamma^{(k-1)}_m \) and \( \gamma^{(k)}_m, k = 1, 2, \ldots, K_m \), we use all the indices \((s, \eta)\) collected in the bucket \( G^{(k)}_{m,h}, k = 0, 1, 2, \ldots, K_m \), to evaluate \( g^{(k)}_m \), the average capacity offered:
Each $g^{(k)}_{|m}$ is paired with its corresponding price level $\gamma^{(k)}_{|m}$, for $k = 0, 1, 2, \ldots, K|_m$. In Fig. 2.5 we plot as a step function all the price levels $\gamma^{(k)}_{|m}$, for $k = 0, 1, 2, \ldots, K|_m$ with respect with the cumulative sum of all the $g^{(k)}_{|m}$, for $k = 0, 1, 2, \ldots, K|_m$. The curve constructed with the segments of length $g^{(k)}_{|m}$ at the corresponding price levels $\gamma^{(k)}_{|m}$ is called the representative offer curve (ROC).

$$
g^{(k)}_{|m} = \frac{\sum_{h \in H|_{(s,q) \in G^{(i)}}} \sum_{\tilde{p}^{(s,q)}} |_{m,h}}{\sum_{h \in H|_{k}} |_{m,h}}, \; k = 0, 1, 2, \ldots, K|_m; \; m = 1, 2, \ldots, 12. \; (2.2)$$

Figure 2.5: The representative offer curve for month $m$
The ROC is the vehicle used to determine the NBT threshold value. FERC mandated each IGO to use numerical methods to determine a smoothed and differentiable version of the ROC [7, pp. 63]. The IGO’s may use any numerical criterion to determine the expression for the continuous function \( \rho(\cdot)|_{m} \) that “best” fits the data of each monthly ROC. We refer to \( \rho(\cdot)|_{m} , m=1,2,...,12 \) as the adjusted representative offer curve (AROC) for the month \( m \) (see Fig. 2.6). Typical expressions for \( \rho(\cdot)|_{m} \) include polynomial, exponential and logarithmic functions. Each IGO has the freedom to choose which function they consider fits best the ROC.

![Figure 2.6: Adjusted representative offer curve for month \( m \)](image)

*Figure 2.6: Adjusted representative offer curve for month \( m \)
The FERC mandated threshold price is determined using the AROC for each month. This threshold determines the price beyond which the benefit to the load from the reduced LMP resulting from the demand curtailments exceeds the total payments to the DRRs. Based on FERC’s analysis, the threshold point along the AROC is located where the AROC becomes inelastic. In other words, demand curtailments are cost-effective when the nature of the AROC is such that small decreases in generation being called to serve load will result in LMP decreases that are sufficient to offset the payments to the DRRs [7, pp. 63]. The NBT condition is giving using the AROC as:

\[
\frac{d \rho(\ell_m)}{d \ell} = \frac{\rho(\ell_m)}{\ell}, \quad m = 1, 2, \ldots, 12.
\]  

(2.3)

Let \( \ell^\nu_m \) denote the solution of (2.3) and set \( v_m \) the monthly threshold price with

\[
v_m = \rho(\ell^\nu_m), \quad m = 1, 2, \ldots, 12.
\]  

(2.4)

Each IGO must use these monthly threshold prices to determine the dispatch of the demand curtailments into the DAMs. Whenever the LMP at a node is greater or equal to \( v_m \) for each month, the IGO dispatches all the DRRs that offered demand curtailment at this node. Each such DRR is paid at the post-curtailment LMP outcome of the DAM for each MW curtailed in hour \( h \).
2.3 Application of the NBT in the DAMs

In this section, we analyze the repercussions of the FERC NBT using the extended transmission constrained market model with the explicit representation of the DRRs. We use typical market performance metrics needed to assess the outcomes of the DAMs. We focus on the DAM operated by the IGO for the MWh commodity in the hour \( h \) and represent the system by a snapshot that is assumed to hold for the entire hour. To determine the offers and bids that are accepted and the associated amounts and prices for each seller and buyer, the IGO uses the solution of the market clearing OPF.

We review briefly the formulation of this problem and state its extension with the explicit representation of the DRRs.

We consider a DAM that consists of a set of \( S_{m,h} \) sellers, denoted by \( S_{m,h} \), and a set of \( B_{m,h} \) buyers, denoted by \( B_{m,h} \). For \( h \in H_{m}, m = 1,2,\ldots,12 \), let us denote the integral of the seller \( s \)'s marginal offer price by \( \chi'(p_s)_{m,h} \) as a function of the real power supply \( p_s \) and the integral of the buyer \( b \)'s marginal bid price by \( \beta^b(p^b)_{m,h} \) as a function of the real power demanded \( p^b \).

The objective of the IGO is to maximize the societal net benefits given by the difference between the benefits \( \sum_{b=1}^{B_{m,h}} \beta^b(p^b)_{m,h} \) of the buyers and the costs \( \sum_{s=1}^{S_{m,h}} \chi'(p_s)_{m,h} \) to purchase from the sellers. We next provide a statement of
the constraints that are considered in the formulation: the power flow relations at each node and the real power flow capacity in the transmission lines. We consider a transmission network with the \((N+1)\) buses in the set \(N\), with

\[
N = \{ n : n = 0,1,\ldots,N \},
\]

and the \(L\) lines in the set

\[
J = \{ j : j = 1,2,\ldots,J \}.
\]

We assume that the DC power flow conditions hold. We denote the diagonal branch susceptance matrix by \(B\), and the reduced branch-to-node incidence matrix by \(A\). We denote the slack bus nodal susceptance vector by \(b_0\) \([22],[27]\).

We define \( p_{n|m,h}^{re} \) \( p_{n|m,h}^{rd} \) as the total power generated (demanded) at node \(n\).

The expressions for these variables are

\[
p_{n|m,h}^{re} = \sum_{s \in S} p_{n|m,h}^s, \ n = 0,1,\ldots,N
\]

(2.5)

and

\[
p_{n|m,h}^{rd} = \sum_{b \in B} p_{n|m,h}^b, \ n = 0,1,\ldots,N.
\]

(2.6)

We construct the injection power vector
and in the withdrawal vector

\[
\mathbf{p}^{\text{in}} \bigg|_{m,h} \triangleq \begin{bmatrix} p_1^{\text{in}} \big|_{m,h}, p_2^{\text{in}} \big|_{m,h}, \ldots, p_N^{\text{in}} \big|_{m,h} \end{bmatrix}^T \in \mathbb{R}^N
\]

respectively.

We write the power flow equations as

\[
\mathbf{p}^{\text{in}} \bigg|_{m,h} - \mathbf{p}^{\text{out}} \bigg|_{m,h} = \mathbf{B} \mathbf{\theta} \bigg|_{m,h}, \quad (2.7)
\]

and the power flow equation for the slack node as

\[
p_0^{\text{in}} \big|_{m,h} - p_0^{\text{out}} \big|_{m,h} = \mathbf{b}_0^T \mathbf{\theta} \bigg|_{m,h}, \quad (2.8)
\]

where \( \mathbf{\theta} \big|_{m,h} \) is the vector containing the nodal voltage phase of all nodes. The real power flows at each line are calculated as

\[
\mathbf{f} \bigg|_{m,h} = \mathbf{B} \mathbf{\theta} \bigg|_{m,h}. \quad (2.9)
\]

We model the constraints on the real power flows of the lines of the system using the inequality

\[
\mathbf{f} \bigg|_{m,h} \leq \mathbf{f}^{\text{max}}, \quad (2.10)
\]
where $f^{\text{max}}$ is the vector containing all the real power flow limits at each line and we denote it as $f^{\text{max}} = \left[ f_{1, \text{max}}, f_{2, \text{max}}, \ldots, f_{J, \text{max}} \right]^T$.

We can now state the formulation of the transmission constrained DAM problem (TCDAMP) as

$$\max \sum_{h=1}^{B_{m,h}} \beta^b(p^b)|_{m,h} - \sum_{s=1}^{S_{m,h}} \lambda^s(p^s)|_{m,h}$$

subject to

$$p^g|_{m,h} - p^d|_{m,h} = B \theta^r|_{m,h} \leftrightarrow \lambda^r|_{m,h}$$

$$p^g_0|_{m,h} - p^d_0|_{m,h} = b^r \theta^r|_{m,h} \leftrightarrow \lambda_0^r|_{m,h}$$

$$B A \theta^r|_{m,h} \leq f^{\text{max}} \leftrightarrow \mu^r|_{m,h} \quad (2.11)$$

We denote (2.11) as $M\left( S_{m,h}, B_{m,h} \right)$ and since no DRRs are included as market participants we call it the pre-curtailment DAM [21]. The solution of $M\left( S_{m,h}, B_{m,h} \right)$ determines the optimum values of the dual variables associated with the power balance constraints and the line flow constraints.

We call $\left[ \lambda^r|_{m,h} \right]^*$ the pre-curtailment LMP at node $n \in N$, and $\left[ p^g_n|_{m,h} \right]^*$ and $\left[ p^d_n|_{m,h} \right]^*$ are the cleared generation and demand, respectively, at that node.
The pre-curtailment purchase payments at node $n$ are given by

$$w^B_n = \left[ \lambda_n^r |_{m,h} \right]^* \cdot \left[ p_n^{td} |_{m,h} \right]^*,$$

(2.12)

and their sum constitutes the system pre-curtailment purchase payments

$$W^B_{m,h} = \sum_{n=0}^N \left[ \lambda_n^r |_{m,h} \right]^* \cdot \left[ p_n^{td} |_{m,h} \right]^*.$$  

(2.13)

Similarly, the pre-curtailment total producer revenues are

$$W^S |_{m,h} = \sum_{n=0}^N \left[ \lambda_n^r |_{m,h} \right]^* \cdot \left[ p_n^{te} |_{m,h} \right]^*.$$  

(2.14)

In addition, we evaluate the pre-curtailment congestion rents $\kappa^r |_{m,h}$

$$\kappa^r |_{m,h} = \sum_{n=0}^N \left[ \lambda_n^r |_{m,h} \right]^* \cdot \left[ p_n^{td} |_{m,h} \right]^* - \sum_{n=0}^N \left[ \lambda_n^r |_{m,h} \right]^* \cdot \left[ p_n^{te} |_{m,h} \right]^*. $$

(2.15)

The IGO uses the outcomes of $M \left( S_{m,h} , B_{m,h} \right)$ to assess the participation of the DRRs in the DAM of hour $h$ in line with FERC NBT cost-effectiveness criterion. The IGO collects the set of nodes whose pre-curtailment LMPs are at or above the threshold price $u |_m$ to construct

$$N |_{m,h} = \left\{ n : \left[ \lambda_n^r |_{m,h} \right]^* \geq u |_{m} \right\}.$$  

Each DRR at a node $n \in N |_{m,h}$ is dispatched by the IGO. We denote the set of buyers with demand-response capability by $B |_{m,h}$. We denote $B |_{m,h}$ as the set
that contains all the pure buyers in the electricity market. The total demand-curtailment at each node \( n \in N \) is

\[
\hat{p}^d_{n|m,h} = \begin{cases} 
\sum_{b=1}^{\hat{b}} \hat{p}^b_{n|m,h} , & n \in N \\
0 , & n \notin N 
\end{cases}.
\]

(2.16)

We impose the condition that a DRR player cannot offer a demand curtailment that exceeds his demand. We construct the nodal demand curtailment vector

\[
\mathbf{p}^d_{m,h} \triangleq \left[ \hat{p}^d_{1|m,h}, \hat{p}^d_{2|m,h}, \ldots, \hat{p}^d_{N|m,h} \right]^T \in \mathbb{R}^N.
\]

In order to take into account the DRRs that cleared the NBT threshold, we modify the objective function and the power flow constraints of \( M(S_{m,h}, B_{m,h}) \) to include the nodal demand curtailments. We formulate the \( DAM \) with the demand response participation \( M(S_{m,h}, B_{m,h}, B_{m,h}) \) as:
\[
\begin{align*}
\max & \sum_{b \in B_{m,h}} \beta^b \left( p^b \right)_{m,h} + \sum_{\hat{b} \in \hat{B}_{m,h}} \beta^{\hat{b}} \left( p^{\hat{b}} \right)_{m,h} - \\
& \sum_{s \in S_{m,h}} \chi^s \left( p^s \right)_{m,h} - \sum_{\hat{b} \in \hat{B}_{m,h}} \chi^{\hat{b}} \left( p^{\hat{b}} \right)_{m,h}
\end{align*}
\]

subject to

\[
\begin{align*}
(p^d|_{m,h} - \hat{p}^d|_{m,h}) = B \theta|_{m,h} & \iff \lambda|_{m,h} \\
(p_0^d|_{m,h} - \hat{p}_0^d|_{m,h}) = b^r \theta|_{m,h} & \iff \lambda_0|_{m,h} \\
B A \theta|_{m,h} \leq \bar{f}_{max} & \iff \mu|_{m,h}
\end{align*}
\]

Equation (2.17) is referred to as the DAM with DRR participation and its solution as the post-curtailment outcomes, which are used to settle the DAM [22]-[27]. We call \( \left[ \lambda_n|_{m,h} \right]^* \) the post-curtailment LMP at node \( n \in \mathbb{N} \), and \( \left[ p_n^d|_{m,h} \right]^* \left( p_n^d|_{m,h} \right)^* \) the cleared post-curtailment generation (demand). The total purchase payments to the DRRs in hour \( h \) are

\[
\zeta|_{m,h} = \sum_{n \in \mathbb{N}} \left[ \lambda_n|_{m,h} \right]^* \cdot \left[ \hat{p}_n|_{m,h} \right]^*.
\]

The total hourly benefits are

\[
u^N|_{m,h} = \sum_{n \in \mathbb{N}} \left( \left[ \lambda_n'|_{m,h} \right]^* - \left[ \lambda_n|_{m,h} \right]^* \right) \cdot \left( \left[ p_n^d|_{m,h} \right]^* - \left[ \hat{p}_n^d|_{m,h} \right]^* \right).
\]
where \(N^+_{m,h} \subseteq N\) is the subset of nodes that benefit from the demand curtailments defined by

\[
N^+_{m,h} = \left\{ n : \left[ \lambda_n|_{m,h} \right]^* > \left[ \lambda_n'_{m,h} \right]^* \right\}.
\]

The additional hourly per-unit charge, \(v|_{m,h}\), for the buyers due to the payment to the DRRs is given by

\[
v|_{m,h} = \frac{\sum_{n \in N} \left[ \lambda_n|_{m,h} \right]^* \cdot \left[ \hat{p}^d_n|_{m,h} \right]^*}{\sum_{n \in N^+_{m,h}} \left( \left[ p^d_n|_{m,h} \right]^* - \left[ \hat{p}^d_n|_{m,h} \right]^* \right)}.
\] (2.20)

In essence, a buyer at node \(n \in N^+\) pays \(\left( \lambda_n|_{m,h} + v|_{m,h} \right) \) $/MWh for its consumption in hour \(h\). The total post-curtailment consumer payments at node \(n\), \(w^B_n|_{m,h}\), are

\[
w^B_n|_{m,h} = \left( \lambda_n|_{m,h} + v|_{m,h} \right) \cdot \left[ p^d_n|_{m,h} \right]^* - \left[ \hat{p}^d_n|_{m,h} \right]^* \). \] (2.21)

The total post-curtailment purchase payments are

\[
w^B|_{m,h} = \sum_{n \in N} \left( \lambda_n|_{m,h} + v|_{m,h} \right) \cdot \left[ p^d_n|_{m,h} \right]^* - \left[ \hat{p}^d_n|_{m,h} \right]^* \). \] (2.22)

The post-curtailment producer revenues are
\[ w^S|_{m,h} = \sum_{n \in \mathbb{N}} \left( \lambda_n|_{m,h} \right) \cdot \left( p_n^|_{m,h} \right). \]  

(2.23)

The post-curtailment congestion rents are

\[ \kappa|_{m,h} = \sum_{n \in \mathbb{N}} \left( \left( \lambda_n|_{m,h} \right) + v|_{m,h} \right) \left( \left[ p_n^d|_{m,h} \right] - \left[ \hat{p}_n^d|_{m,h} \right] \right) - \sum_{n \in \mathbb{N}} \left( \lambda_n|_{m,h} \right) \cdot \left( p_n^|_{m,h} \right) - \zeta|_{m,h} \]  

(2.24)

The pre-curtailment metrics in (2.18) – (2.24) are used to assess the impacts of the demand curtailments in the electricity markets. The benefits of demand curtailments may be evaluated by a comparative analysis of pre- and post-curtailment market outcomes. In essence, the IGO runs the DAM without considering the demand-curtailment offers, then determines the DRRs that satisfy the NBT and then runs the DAM again, this time considering the demand-curtailment offers.

2.4 Summary

In this chapter, we reviewed the thrust of the FERC Order No. 745 and provided an analytic framework for the evaluation of the impacts. We discussed the requirements of the NBT as mandated by the FERC and provided an economic analysis. We discussed in detail the procedure required to determine the monthly threshold price. We also analyzed the repercussions of the FERC NBT using the extended transmission constrained market model with the explicit representation of the DRRs.
CHAPTER 3

IMPACTS OF THE NBT IN THE DAMs

We devote this chapter to present representative results of extensive simulation studies to assess the impacts of demand curtailments in the DAMs under Order No. 745 rules. We discuss the system-wide effects of the demand curtailments and identify the key unintended consequences associated with the dispatch of DRRs. We identify two important ramifications of the FERC NBT: the increase in payments incurred by loads due to the dispatch of DRRs and the increases in the post-curtailment LMPs at some nodes of the system.

In Section 3.1, we start by a description of the test system used and discuss the nature and scope of the studies. Section 3.2, we analyze the outcomes of the DRR dispatch under the NBT requirements. In Section 3.3, we discuss the issues associated with the increase in the post-curtailment LMPs at certain nodes in the system and discuss their impacts.

3.1 Scope and Nature of the Simulations

We use the results of representative simulation studies to identify some important impacts of the NBT which were not intended by the FERC Order No. 745. In this section we summarize the key characteristics of the
representative case studies used to assess the impacts of the NBT in the outcomes of the DAMs. For all the studies presented, we use a test system based on the modified IEEE 118-bus system [28]. A detailed description of the test system can be found in Appendix A.

We use the load shapes from the year 2010 of ISO New England (ISO-NE) and the Midwest ISO (MISO). The system load demand at a given hour is the aggregated hourly demand of all the loads in the system. The load at each node in the test system is a specified fraction of the system load demand. We scale the loads so that the annual peak load equals 9,600 MW. We use the monthly ROCs of the two ISOs to construct the test system offer curves. For each month, we make the test system offer curve to have the same shape as the corresponding monthly ROC.

Each load node in the system is able to provide demand curtailments. The total capacity of demand response at each node in the system is expressed as a fraction of the annual peak load demand at the node. In the studies, we investigate the impacts of various levels of demand response capacity percentages c and evaluate the impacts of demand curtailments on the system. In these studies, we limit the DRR dispatch to the afternoon hours from 2 P.M to 7 P.M to emulate realistic conditions in the DAMs of the ISOs. In table 3.1 we summarize the characteristics of the case studies.
We refer to $N_0$ and $M_0$ as the base cases for the two sensitivity studies without demand response dispatch. We use each base case as reference with respect to which we measure the impacts of demand curtailments in the sensitivity studies.

### 3.2 System-Wide Impacts of Demand Curtailments

The system-wide benefits arising from demand curtailments have been documented earlier [18], [19], [22]. The principal benefits include a reduction in the annual peak load demand, lower purchase payments by the non-curtailed loads and a drop in the congestion rents collected by the ISO. In this section, we describe the system-wide benefits we encountered in our simulation studies due to demand curtailments. We start with the base cases $N_0$ and $M_0$ with no demand response capacity available. In Table 3.2, we show the hourly and annual values of the cleared demand, buyer payments and congestion rents for case $N_0$. Next, we present the results of the simulation with 3% demand response capacity in Table 3.3.
Table 3.2: Case $N_0$ system-wide metrics

<table>
<thead>
<tr>
<th>metric</th>
<th>hourly values</th>
<th>annual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>max</td>
</tr>
<tr>
<td>cleared demand (MWh)</td>
<td>5,443</td>
<td>9,600</td>
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<tr>
<td>buyer payments (million $)</td>
<td>0.378</td>
<td>3.824</td>
</tr>
<tr>
<td>congestion rents (million $)</td>
<td>0.033</td>
<td>0.181</td>
</tr>
</tbody>
</table>

Table 3.3: Case $N_3$ system-wide metrics

<table>
<thead>
<tr>
<th>metric</th>
<th>hourly values</th>
<th>annual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>max</td>
</tr>
<tr>
<td>cleared demand (MWh)</td>
<td>5,401</td>
<td>9,449</td>
</tr>
<tr>
<td>buyer payments (million $)</td>
<td>0.369</td>
<td>3.202</td>
</tr>
<tr>
<td>congestion rents (million $)</td>
<td>0.024</td>
<td>0.181</td>
</tr>
</tbody>
</table>

We can infer from the preceding tables that the 3% demand response curtailments result in noticeable system-wide benefits. The total cleared demand reduction was $0.37 \times 10^6$ MWh, which represents a 0.77% reduction when compared to the case with no demand response participation. The reduction in cleared demand resulted in a reduction in the system-wide buyer payments of $79$ million. An interesting by-product is the 27% reduction in
the total congestion rents. We tabulate the system-wide metrics for the cases $M_0$ and $M_3$ in the Tables 3.4 and 3.5, respectively.

Table 3.4: Base case $M_0$ system-wide metrics

<table>
<thead>
<tr>
<th>metric</th>
<th>hourly values</th>
<th>annual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>max</td>
</tr>
<tr>
<td>cleared demand (MWh)</td>
<td>6,056</td>
<td>9,683</td>
</tr>
<tr>
<td>buyer payments (million $)</td>
<td>0.352</td>
<td>1.791</td>
</tr>
<tr>
<td>congestion rents (million $)</td>
<td>0.013</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Table 3.5: Case $M_3$ system-wide metrics

<table>
<thead>
<tr>
<th>metric</th>
<th>hourly values</th>
<th>annual values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>average</td>
<td>max</td>
</tr>
<tr>
<td>cleared demand (MWh)</td>
<td>6,020</td>
<td>9,393</td>
</tr>
<tr>
<td>buyer payments (million $)</td>
<td>0.349</td>
<td>0.884</td>
</tr>
<tr>
<td>congestion rents (million $)</td>
<td>0.009</td>
<td>0.051</td>
</tr>
</tbody>
</table>

The results from $M_3$ show that the 3% demand response capacity also results in system-wide benefits. A reduction of 0.6% in cleared demand results in $30 million of savings to the consumers. The congestion rents in $M_3$ are 25% lower than the congestion rents in case $M_0$. 

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The results for these two test cases provide a representative illustration of the beneficial impacts of demand curtailments in the DAMs. However, there are also unintended consequences that may result from the dispatch of DRRs under the rules of FERC Order No. 745. We next examine the negative impacts that result from demand curtailments.

Due to the nature of the FERC NBT rules, specifically, the use of a system-wide threshold price to judge when nodal demand curtailments are beneficial to all market participants, there are instances where the societal costs of DRR participation are higher than its benefits. We say an instance where the societal costs of demand response are higher than the benefits has occurred when the payments to the DRRs outweigh the savings resulting from a lower post-curtailment LMP. This issue is called the unit billing effect in Order No. 745 and FERC accepts this result due to the “apparent computational difficulty of adopting a dynamic approach that incorporates the billing unit effect in the dispatch algorithms at this time” [7, pp. 64]. In this section, we show how often these instances occurred in our simulation studies. In Table 3.6, we show, in a monthly basis, the metrics associated with the inefficient demand curtailments in case $N_3$. We present the monthly percentage of curtailments that resulted in extra buyer payments. This is calculated by dividing the number of hours that resulted in extra payments due to demand response by the total hours during which curtailments were allowed.
Table 3.6: Extra payments due to demand response curtailments in case $N_3$

<table>
<thead>
<tr>
<th>month of 2010</th>
<th>percentage of hours with extra payments</th>
<th>extra payments due to demand curtailments ($)</th>
<th>hourly values</th>
<th>monthly values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>average</td>
<td>max</td>
</tr>
<tr>
<td>Jan</td>
<td>71</td>
<td>4,581</td>
<td>11,463</td>
<td>1,467</td>
</tr>
<tr>
<td>Feb</td>
<td>62</td>
<td>9,470</td>
<td>18,069</td>
<td>3,795</td>
</tr>
<tr>
<td>Mar</td>
<td>5</td>
<td>4,401</td>
<td>5,820</td>
<td>923</td>
</tr>
<tr>
<td>Apr</td>
<td>11</td>
<td>4,033</td>
<td>4,725</td>
<td>4,640</td>
</tr>
<tr>
<td>May</td>
<td>10</td>
<td>5,017</td>
<td>17,255</td>
<td>2,915</td>
</tr>
<tr>
<td>Jun</td>
<td>5</td>
<td>6,075</td>
<td>20,289</td>
<td>3,674</td>
</tr>
<tr>
<td>Jul</td>
<td>10</td>
<td>13,370</td>
<td>23,851</td>
<td>2,274</td>
</tr>
<tr>
<td>Aug</td>
<td>19</td>
<td>10,076</td>
<td>23,982</td>
<td>665</td>
</tr>
<tr>
<td>Sep</td>
<td>3</td>
<td>7,292</td>
<td>29,341</td>
<td>116</td>
</tr>
<tr>
<td>Oct</td>
<td>5</td>
<td>5,897</td>
<td>6,245</td>
<td>5,440</td>
</tr>
<tr>
<td>Nov</td>
<td>31</td>
<td>5,797</td>
<td>10,518</td>
<td>3,774</td>
</tr>
<tr>
<td>Dec</td>
<td>18</td>
<td>2,101</td>
<td>4,820</td>
<td>921</td>
</tr>
</tbody>
</table>

Also shown are the hourly and monthly values of the extra payments due to the inefficient dispatch of DRRs. These extra payments are computed by calculating the difference between the demand response benefits and the payments to the DRRs. We see that during the months of January and February, approximately 71 and 62 percent of the hours during which demand curtailments were allowed, resulted in an inefficient dispatch of DRRs. This means that, for these two months, the NBT incorrectly deemed cost-effective several hours that in the end resulted in higher consumer payments. In other words, the NBT was wrong for more than half of the curtailment hours.
In Table 3.7, we show demand response curtailment metrics for case $M_3$. For the months of October and November, we see that all of the demand curtailments that the NBT deemed cost-effective resulted in higher buyer payments. Contrary to what is intended from the dispatch of DRRs, they resulted in an increase of the total monthly buyer payments due to the demand curtailments. Furthermore, only the months of June, July and August have a larger number of efficient curtailments.

Table 3.7: Extra payments due to demand response curtailments in case $M_3$

<table>
<thead>
<tr>
<th>month of 2010</th>
<th>percentage of hours with extra payments</th>
<th>extra payments due to demand curtailments ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>hourly values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>average</td>
</tr>
<tr>
<td>Jan</td>
<td>69</td>
<td>2,750</td>
</tr>
<tr>
<td>Feb</td>
<td>89</td>
<td>2,679</td>
</tr>
<tr>
<td>Mar</td>
<td>81</td>
<td>2,668</td>
</tr>
<tr>
<td>Apr</td>
<td>96</td>
<td>6,453</td>
</tr>
<tr>
<td>May</td>
<td>75</td>
<td>3,608</td>
</tr>
<tr>
<td>Jun</td>
<td>40</td>
<td>2,325</td>
</tr>
<tr>
<td>Jul</td>
<td>10</td>
<td>4,015</td>
</tr>
<tr>
<td>Aug</td>
<td>21</td>
<td>5,182</td>
</tr>
<tr>
<td>Sep</td>
<td>50</td>
<td>3,083</td>
</tr>
<tr>
<td>Oct</td>
<td>100</td>
<td>4,052</td>
</tr>
<tr>
<td>Nov</td>
<td>100</td>
<td>4,907</td>
</tr>
<tr>
<td>Dec</td>
<td>61</td>
<td>3,602</td>
</tr>
</tbody>
</table>
These extra payments are a result of the very small difference between the pre- and post-curtailment LMP at some nodes. A high post-curtailment LMP results in payments to the DRR such that they are not compensated by the benefits. We see that in some instances the FERC NBT fails to capture this situation in most curtailment hours. Also, we see that there exists a situation in which some nodes experience higher post-curtailment LMPs.

3.3 Nodes Negatively Impacted By Demand Curtailments

When demand curtailments are made, the post-curtailment power demands at the DRR nodes are modified with respect to the pre-curtailment state. This modification results in different outcomes in the congestion patterns in the system. The congestion rents may decrease at the nodes where demand curtailments are made, thus reducing the post-curtailment LMPs; however, this may not be the case in nodes that have little or no demand response participation.

Due to the system-wide nature of the NBT, the threshold price may not be a representative metric to correctly judge the cost-effectiveness of a demand curtailment at all nodes. In Fig. 3.1, we show the pre- and post-curtailment LMPs at node 8 for the week May 1 – 7, 2010, for the case $N_3$. Under the NBT, a DRR at node 8 is, therefore, deemed to be non-economic and so receives no compensation during the entire week. We see that during hours with demand curtailments at other nodes, the post-curtailment LMP at node 8
was actually higher than it was before with no demand response participation. Thus, the buyers at node 8 do not benefit from demand response and, in fact, are caused to incur higher prices by the curtailments made at other nodes. Such a situation is an unintended consequence of the DRR dispatch and negatively impacts the non-DRR buyers, who buy electricity at nodes that experience increases in the post-curtailment LMPs.

Figure 3.1: Pre- and post-curtailment LMPs during the week of May 1-7 at node 8 in study case $N_3$

Another interesting situation arises for the same May week at node 116. In Fig. 3.2, we plot the node 116 pre- and post-curtailment LMPs at node 116 for the same week as in the preceding figure. This node experiences reductions in the post-curtailment LMPs at all hours at which demand curtailments were allowed. Contrary to the situation with node 8, for node 116 the level of the monthly threshold price is such that, it permitted the dispatch of DRRs at several hours during the first week of May.
The discussion of the nodes 8 and 116 is indicative of the disparity in the way the nodes in the system are impacted by the demand curtailments. Indeed, our analysis of the $N_3$ and $M_3$ case studies indicates that there are nodes in the system experience higher post-curtailment LMP so often that at the end of the year their consumer payments were higher than the case without no-DRR participation. Out of the 99 load nodes, 19 experienced an increase in the annual consumer payments due to the demand curtailments for case $N_3$. In Table 3.8, we show consumer-payment related metrics for the 10 nodes that experienced the greatest percentage increase in load payments at the end of the year for case $N_3$. The node that experienced the highest percentage increase in the consumer payments with respect to case $N_0$, is node 8 at 1.17%.
Table 3.8: Nodes with increase in buyer payments in case study $N_3$

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage of nodal reduction of energy</th>
<th>nodal consumer payments increase</th>
<th>% increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.316</td>
<td>190,872</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>0.316</td>
<td>70,815</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>0.316</td>
<td>149,245</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>0.290</td>
<td>169,688</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>0.312</td>
<td>202,248</td>
<td>0.79</td>
</tr>
<tr>
<td>8</td>
<td>0.248</td>
<td>153,291</td>
<td>1.17</td>
</tr>
<tr>
<td>11</td>
<td>0.316</td>
<td>249,220</td>
<td>0.72</td>
</tr>
<tr>
<td>12</td>
<td>0.318</td>
<td>160,341</td>
<td>0.69</td>
</tr>
<tr>
<td>13</td>
<td>0.345</td>
<td>81,697</td>
<td>0.47</td>
</tr>
<tr>
<td>16</td>
<td>0.323</td>
<td>75,630</td>
<td>0.60</td>
</tr>
</tbody>
</table>

For contrast, we show in Table 3.9 the nodes that experienced the highest decrease in consumer payments for case $N_3$. These nodes have greater demand response participation and also experience a decrease in the annual consumer payments of approximately 3% compared to case $N_0$. We also simulated cases with greater demand response penetration to study the impact on the negatively affected nodes. In Table 3.10, we show the percentage increase in consumer payments for different demand response capacities using ISO-NE data. We see that at the selected nodes the negative impacts get aggravated with the deeper penetration of demand response. We also see this situation with MISO data. Using MISO data, there are a total of 29 nodes that experience higher annual consumer payments with demand response participation.
Table 3.9: Nodes with the highest decrease in buyer payments in case study $N_3$

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage of nodal reduction of energy</th>
<th>nodal consumer payments</th>
<th>percentage decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.895</td>
<td>2,464,001</td>
<td>2.94</td>
</tr>
<tr>
<td>49</td>
<td>0.895</td>
<td>2,216,223</td>
<td>2.92</td>
</tr>
<tr>
<td>54</td>
<td>0.895</td>
<td>2,897,158</td>
<td>2.94</td>
</tr>
<tr>
<td>56</td>
<td>0.895</td>
<td>2,154,083</td>
<td>2.94</td>
</tr>
<tr>
<td>59</td>
<td>0.895</td>
<td>7,141,640</td>
<td>2.94</td>
</tr>
<tr>
<td>60</td>
<td>0.895</td>
<td>2,015,031</td>
<td>2.95</td>
</tr>
<tr>
<td>62</td>
<td>0.895</td>
<td>1,988,482</td>
<td>2.95</td>
</tr>
<tr>
<td>80</td>
<td>0.889</td>
<td>3,149,489</td>
<td>2.84</td>
</tr>
<tr>
<td>90</td>
<td>0.889</td>
<td>3,929,569</td>
<td>2.83</td>
</tr>
<tr>
<td>116</td>
<td>0.895</td>
<td>4,633,195</td>
<td>2.90</td>
</tr>
</tbody>
</table>

Table 3.10: Percent increase in buyer payments for various DRR capacities with respect to case $N_0$

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage increase in consumer payments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>case $N_3$</td>
</tr>
<tr>
<td>1</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>0.71</td>
</tr>
<tr>
<td>3</td>
<td>0.78</td>
</tr>
<tr>
<td>4</td>
<td>0.90</td>
</tr>
<tr>
<td>6</td>
<td>0.79</td>
</tr>
<tr>
<td>8</td>
<td>1.17</td>
</tr>
<tr>
<td>11</td>
<td>0.72</td>
</tr>
<tr>
<td>12</td>
<td>0.69</td>
</tr>
<tr>
<td>13</td>
<td>0.47</td>
</tr>
<tr>
<td>16</td>
<td>0.60</td>
</tr>
</tbody>
</table>
In Table 3.11, we show the percentage increase in consumer payments at the 10 nodes that experience the greatest negative impacts. We see that the percentage increase in consumer payments increases while there is more demand response capacity in the system.

Table 3.11: Percent increase in buyer payments for various DRR capacities with respect to case $M_0$

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage increase in consumer payments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>case $M_3$</td>
</tr>
<tr>
<td>1</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>0.67</td>
</tr>
<tr>
<td>3</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>0.69</td>
</tr>
<tr>
<td>7</td>
<td>0.67</td>
</tr>
<tr>
<td>8</td>
<td>0.78</td>
</tr>
<tr>
<td>11</td>
<td>0.66</td>
</tr>
<tr>
<td>12</td>
<td>0.66</td>
</tr>
<tr>
<td>117</td>
<td>0.66</td>
</tr>
</tbody>
</table>

3.4 Summary

In this chapter, we summarized the impacts of demand curtailments in the DAMs using the results of our simulation studies. We briefly discussed the system-wide benefits such as the reduction in the system consumer payments and the system congestion rents. Most importantly, we identified the two key
issues that arise when DRRs are allowed to participate in the DAM under Order No. 745 rules: the inefficient dispatch of DRRs and the negative impacts on some nodes in the system due to the increase in the post-curtailment LMPs.
The determination of the monthly threshold price at which DRRs are allowed to participate in the DAMs and be compensated for curtailment services is determined without the explicit incorporation of the transmission congestion in the power system. This may result in some cases of buyers who do not participate in curtailments of their load paying higher post-curtailment prices than under pre-curtailment conditions and the undesirable outcomes as discussed in Chapter 3. In this chapter, we propose modifications to the NBT that take explicitly into account congestion and the nodal character of the LMPs in the determination of the monthly threshold price. We propose the modifications on the basis of the identified set of causal factors that we determined in Chapter 3. In Section 4.1, we provide an overview of the proposed modifications. We describe the proposed modified NBT to determine the nodal monthly threshold prices for a system and the introduction of a guarantee that ensures that no node fares worse under demand curtailments than without them. In Section 4.2, we present the results of representative simulation studies using the proposed modified NBT and
show that they overcome the issues identified in Chapter 4. In Section 4.3, we provide a comparative analysis of the NBT and the proposed modified NBT.

4.1 Overview of the Proposed Modified NBT

We provide a concise mathematical statement of the modified NBT making use of some definitions we introduce. We define the set of indices of the weekdays of month \( m \) as

\[
\mathcal{D}_{m} = \{ d : d = d_1, d_2, \ldots, D_{m} \}, \ m = 1, 2, \ldots, 12, \text{ for the year } y - 1.
\]

Here, \( d_1 = 1 \) if the first day is a week day, \( d_1 = 2 \) if the first day of the week is a Sunday and \( d_1 = 3 \) if the first day of the week is a Saturday. We collect the indices of the on-peak hours during the weekdays of month \( m \) in the set \( \mathcal{D}_{m} \) to construct

\[
\mathcal{H}_{m} = \{ h : h = 7d, 8d, \ldots, 23d \}; d = d_1, d_2, \ldots, D_{m}, \ \ m = 1, 2, \ldots, 12.
\]

For each month of year and node of the system, we collect the LMPs that occurred during the on-peak hours of weekdays of the year \( y - 1 \) in the set

\[
\mathcal{E}_{n,m} = \left[ \lambda_{n,m,h} \right] : h \in \mathcal{H}_{m}, \ m = 1, 2, \ldots, 12; n = 0, 1, 2, \ldots, N.
\]

We define the set containing the nodal price level indices as

\[
\mathcal{K}_{n,m} = \{ \bar{k} : \bar{k} = 0, 1, 2, \ldots, \bar{K}_{n,m} \}, \ m = 1, 2, \ldots, 12; n = 0, 1, 2, \ldots, N.
\]
We collect the LMPs and sort them into $K_n^m + 1$ buckets. We define the ceiling price for each month and node as

$$\bar{\mathcal{Y}}_n^{(\ell)}\big|_m = \max_{\left[\lambda_n|_{m,h}\right] \in \mathcal{E}_n|_m} \left(\left[\lambda_n|_{m,h}\right]^*\right), \ m = 1,2,\ldots,12; \ n = 0,1,2,\ldots,N, \quad (4.1)$$

and the floor price for each month and node as

$$\bar{\mathcal{Y}}_n^{(0)}\big|_m = \min_{\left[\lambda_n|_{m,h}\right] \in \mathcal{E}_n|_m} \left(\left[\lambda_n|_{m,h}\right]^*\right), \ m = 1,2,\ldots,12; \ n = 0,1,2,\ldots,N. \quad (4.2)$$

$\bar{\mathcal{Y}}_n^{(\ell)}$ and $\bar{\mathcal{Y}}_n^{(0)}$ are the maximum and minimum price level for the month $m$ and node $n$, respectively. The rest of the price levels are calculated using the recursion formula

$$\bar{\mathcal{Y}}_n^{(k)}\big|_m = \bar{\mathcal{Y}}_n^{(k-1)}\big|_m + \Delta \bar{\mathcal{Y}}_n\big|_{m}, \ k = 1,2,\ldots,\bar{K}_n^m - 1; \ m = 1,2,\ldots,12; \ n = 0,1,2,\ldots,N, \quad (4.3)$$

where $\Delta \bar{\mathcal{Y}}_n\big|_{m}$ may be selected arbitrarily based on the level of resolution desired.

Now, we collect the indices of the hours during which the LMP at each node was between two price levels $\left[\bar{\mathcal{Y}}_n^{(k-1)}\big|_m, \bar{\mathcal{Y}}_n^{(k)}\big|_m\right]$ in the bucket

$$\mathcal{G}_n^{(k)}\big|_m = \left\{h : \bar{\mathcal{Y}}_n^{(k-1)}\big|_m < \left[\lambda_n|_{m,h}\right]^* \leq \bar{\mathcal{Y}}_n^{(k)}\big|_m \right\}, \ h \in \mathcal{H}\big|_m; \ k = 1,2,\ldots,\bar{K}_n^m; \ m = 1,2,\ldots,12; \ n = 0,1,2,\ldots,N.$$
We define a separate set for the floor price level \( \bar{\gamma}_n^{(0)} \) bucket

\[
G^{(0)}_n \big|_m = \left\{ h : \left[ \lambda_n \big|_{m,h} \right]^\ast = \bar{\gamma}_n^{(0)} \big|_m \right\}, \ h \in \mathcal{H} \big|_m, \ m = 1, 2, \ldots 12; \ n = 0, 1, 2, \ldots, N.
\]

In order to obtain a representative figure of how much power was cleared within the interval between two adjacent price levels, we use the indices collected in the buckets to calculate the average power cleared in

\[
\bar{g}^{(\bar{k})}_n \big|_m = \frac{\sum_{h \in G^{(\bar{k})}_n} \left[ p_n \big|_{m,h} \right]^\ast}{G^{(\bar{k})}_n \big|_m}, \ \bar{k} = 0, 1, 2, \ldots, K_n \big|_m; \ m = 1, 2, \ldots, 12; \ n = 0, 1, 2, \ldots, N. \tag{4.4}
\]

We assign to each \( \bar{g}^{(\bar{k})}_n \big|_m \) its corresponding price level \( \bar{\gamma}_n^{(\bar{k})} \big|_m \), for \( \bar{k} = 0, 1, 2, \ldots, K_n \big|_m \). Analogously to the way we used the ROC in Chapter 2, we plot as a step function all the price levels \( \bar{\gamma}_n^{(\bar{k})} \big|_m \) with respect to the cumulative sum of all the \( \bar{g}^{(\bar{k})}_n \big|_m \) for \( \bar{k} = 0, 1, 2, \ldots, K_n \big|_m \). We call the resulting curve the representative locational marginal price curve (RLMPC). Since each node of the system has different variations between the minimum and maximum LMP, we may use different resolutions to construct each nodal LMP curve

In order to determine the nodal threshold at each node for each month \( m \), we smooth the representative RLMPC curve using numerical methods. We denote
the smoothed \( RLMPC \) by as \( \bar{\rho}_n(\cdot)|_m \). In line with the \( FERC \) mandate, we determine the threshold point along the smoothed \( RLMPC \) beyond which demand curtailments become beneficial when the smoothed \( RLMPC \) becomes inelastic. We can express this condition analytically as

\[
\frac{d \bar{\rho}_n(\ell)|_m}{d \ell} = \frac{\bar{\rho}_n(\ell)|_m}{\ell}, \quad m = 1, 2, \ldots, 12; \quad n = 0, 1, 2, \ldots, N. \tag{4.5}
\]

We denote the solution of (4.5) as \( \bar{\ell}_n|_m \) and we define the locational threshold price \( (LTP) \bar{\ell}_n|_m \) as

\[
\bar{\ell}_n|_m = \frac{\bar{\rho}_n(\bar{\ell}_n|_m)}{\bar{\ell}_n|_m}, \quad m = 1, 2, \ldots, 12; \quad n = 0, 1, 2, \ldots, N. \tag{4.6}
\]

We use the \( LTPs \bar{\ell}_n|_m \) to determine the basis for allowing the participation of \( DRRs \) in the \( DAMs \) and for their compensation at the \( LMP \) for the demand curtailments dispatched in the cleared \( DAMs \). Whenever the pre-curtailment \( LMP \) at a particular node in the system is at or above its \( LTP \bar{\ell}_n|_m \), all the demand-curtailment offers at that node are allowed to participate in the \( DAM \) for that hour. All the \( DRRs \) whose offers are accepted are compensated at the resulting post-curtailment \( LMP \) for the services provided.

In essence, the modified \( NBT \) does not change the way the \( DAMs \) are run by the \( IGO \) environment. The use of the \( LTP \) still requires that the \( DAMs \) be run twice: once without \( DRR \) participation and a second time with the \( DRR \) offers.
Instead of a single monthly threshold price, we use a different threshold at each node to identify those which can provide demand curtailment services and be compensated at the post-curtailment LMPs.

A second issue we identified was the fact that under the rules of Order No. 745, there may be nodes in the power system that experience higher total post-curtailment payments even though they are non-DRR participants. As the basis of FERC decisions in Order No. 745 was to ensure that no participant is worse off due to DRR curtailments in the post-curtailment outcomes than in the pre-curtailment outcomes, a required step in the modified NBT is to ascertain that this condition is indeed met. We introduce a second modification in the FERC NBT to ensure that the “no participant is worse off” condition is met.

For each hour \( h \), we collect the nodes that experience higher post-curtailment LMPs than pre-curtailment LMPs and construct the set

\[
\mathcal{N}^{-}_{m,h} = \left\{ n : \left[ \lambda_{n|m,h} \right]^* < \left[ \lambda_{n|m,h} \right]^* \right\}, \quad h \in \mathcal{H}_{m}, \quad m = 1, 2, \ldots, 12.
\]

These nodes in the set \( \mathcal{N}^{-}_{m,h} \) are worse-off in the post-curtailment state and will incur in additional payments of

\[
\bar{u}^{-}_{m,h} = \sum_{n \in \mathcal{N}^{-}_{m,h}} \left( \left[ \lambda_{n|m,h} \right]^* - \left[ \lambda_{n|m,h} \right]^* \right) \cdot \left( \left[ p_{n|m,h} \right]^* - \left[ \hat{p}_{n|m,h} \right]^* \right), \quad (4.7)
\]
where the quantity \( p_n^{d'} - \hat{p}_n^{d'} \) is the net cleared demand at the node \( n \). Equation (4.7) is a positive quantity that must be taken into account when calculating the societal costs of demand curtailments. On the other hand, the subset of nodes \( N - N^{-}_{m,h} \) enjoy a post-curtailment LMP that is lower than the pre-curtailment LMP and the total benefit enjoyed by these nodes is

\[
\bar{\zeta}^N_{m,h} = \sum_{n \in N^{-}_{m,h}} \left( \lambda_n^{d'} - \lambda_n^{d''} \right) \left( p_n^{d'} - \hat{p}_n^{d'} \right). \tag{4.8}
\]

We now proceed to include the quantities in (4.7) and (4.8) in the determination of the modified societal costs and benefits of demand curtailments. The total hourly costs of demand curtailments including the payments to the DRRs and the extra payments incurred by all nodes \( n \in N^{-}_{m,h}, \bar{z}^N_{m,h} \) is

\[
\bar{z}^N_{m,h} = \bar{z}_{m,h} + \bar{\zeta}^N_{m,h}, \tag{4.9}
\]

where \( \bar{z}^N_{m,h} \) are the total hourly payments to the DRRs as defined in (2.18).

With this modification to the NBT, we ensure that no node is worse off in the post curtailment state than in the pre-curtailment. To account for the additional cost incurred by the nodes of \( N^{-}_{m,h} \), the benefits of the nodes in
\( \mathbf{N} - \mathbf{N}_{m,h}^{-} \) are decreased by the amount \( \mathbf{z}^{N-}_{m,h} \) so as to make the nodes \( n \in \mathbf{N}_{m,h}^{-} \) unaffected by the load curtailment.

We assign a fraction of \( \mathbf{z}^{N-}_{m,h} \) among all nodes that benefit and define the nodal demand curtailment cost \( \bar{\omega}^{N+}_{n,m,h} \) for \( n \in \mathbf{N}_{m,h}^{+} \) as

\[
\bar{\omega}^{N+}_{n,m,h} = \frac{\left( \left[ \mathbf{\lambda}^{\dagger}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\lambda}^{0}_{n,m,h} \right]^{\ast} \right) \cdot \left( \left[ \mathbf{p}^{d}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\hat{p}}^{d}_{n,m,h} \right]^{\ast} \right)}{\sum_{n \in \mathbf{N}_{m,h}^{-}} \left( \left[ \mathbf{\lambda}^{\dagger}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\lambda}^{0}_{n,m,h} \right]^{\ast} \right) \cdot \left( \left[ \mathbf{p}^{d}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\hat{p}}^{d}_{n,m,h} \right]^{\ast} \right) } \cdot \mathbf{z}^{N-}_{m,h}. \tag{4.10}
\]

We see in (4.10) that each node that benefits pays a pro-rata fraction of \( \mathbf{z}^{N-}_{m,h} \) that is proportional to the load that is served post-curtailment. Now, to assure that the nodes that belong to the set \( \mathbf{N}_{m,h}^{-} \) are made whole, we define the nodal side payment \( \bar{\omega}^{N-}_{n,m,h} \) as

\[
\bar{\omega}^{N-}_{n,m,h} = \left( \left[ \mathbf{\lambda}^{\dagger}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\lambda}^{0}_{n,m,h} \right]^{\ast} \right) \cdot \left( \left[ \mathbf{p}^{d}_{n,m,h} \right]^{\ast} - \left[ \mathbf{\hat{p}}^{d}_{n,m,h} \right]^{\ast} \right), \quad n \in \mathbf{N}_{m,h}^{-}. \tag{4.11}
\]

Essentially, with (4.11) we guarantee that the nodes that experienced higher \textit{LMP}s due to demand curtailments receive compensation equal to what the increase was. If an inefficient dispatch of \textit{DRRs} occurs then the total costs in (4.9) are socialized among the loads in the system.
4.2 Simulation Studies Using the Proposed Modified \textit{NBT}

We now proceed to present a set of simulation study results to show the impacts of the \textit{LTP} in the clearing of the \textit{DAMs}. For all the simulation studies presented in this chapter, we use the same test system and set-up as provided in Chapter 3. We denote the simulation studies using the proposed modified \textit{NBT} as: $N_\ell^c$ for the cases using \textit{ISO-NE} data and $M_\ell^c$ for the cases using \textit{MISO} data, with $c$ as the demand response capacity. We start by discussing the differences between the nodal thresholds and the \textit{NBT} system-wide threshold. Since now we are using the \textit{LMP}s at each node to determine an \textit{LTP}, the situation where a node does not meet the threshold price does not occur.

In Fig. 4.1, we show the pre- and post-curtailment \textit{LMP}s at node 8 during the first week of May 2010 in case study $N_3^c$. We note that the nodal threshold $\tilde{b}_8^{1}$ is such that it allows demand curtailments to occur during this week. The system-wide threshold for this month is so high compared to the \textit{LMP}s at this node that the \textit{DRR}s at this location cannot participate with demand-curtailment offers. The \textit{LTP} is a more appropriate metric for this node because it will always fall within the month’s maximum and minimum \textit{LMP}s at the node. In Fig. 4.2, we show the pre- and post-curtailment \textit{LMP}s during the first
week of May at node 116 in study case $N_3^p$. We note that the nodal threshold is slightly higher than the system-wide threshold.

Figure 4.1: Pre- and post-curtailment LMPs during the week of May 1-7 at node 8 in study case $N_3^p$. 
This is the situation at the nodes that experience higher LMPs and higher benefits from the demand curtailments. With the LTP methodology, the nodes that had little or no demand response participation have a cost-effectiveness metric that is commensurate with the prices of electricity. Also, the nodes that had disproportionate demand response participation due to a low system-wide threshold have a nodal threshold that correctly captures the cost-effectiveness of demand curtailments. Next, we explore the impacts of the LPT methodology on the unintended consequence of the instances where the payments to the DRRs exceed the benefits attained.

In Table 4.1, we summarize the number of instances where the payments to the DRRs exceeded the benefits attained for some representative simulation
studies using the \textit{LTP} methodology. In case $N^p_3$, a total of 39 instances resulted in higher \textit{DRR} payments than system benefits, which represents approximately 5.7\% of the total curtailment hours. Compared to case $N_3$, where 17.8\% of the curtailment hours resulted in extra payments due to the demand curtailments, the \textit{LPT} methodology captured more of the hours that resulted in unintended consequences. The percentage of hours with unintended consequences is reduced for all cases with the \textit{LPT} methodology, compared to the \textit{FERC NBT} cases. We note that the case studies with more demand response capacity result in fewer instances of higher payments due to demand curtailments. As more MWh are curtailed, the post-curtailment \textit{LMPs} are further reduced, which in turn mitigates the payments to the \textit{DRRs}.

We note that with the proposed changes to the \textit{NBT} there are still hours in which the societal costs exceed the benefits of \textit{DRR} participation. This is due to the fact the benefits enjoyed did not mitigate payments to the \textit{DRRs}. We note that the indices of the hours with higher costs than benefits are a subset of the same type of hours in the cases with less demand response capacity.
Table 4.1: Number of instances with extra payments due to demand curtailments for cases using ISO-NE data

<table>
<thead>
<tr>
<th>month</th>
<th>case $N_3^p$</th>
<th>case $N_5^p$</th>
<th>case $N_7^p$</th>
<th>case $N_9^p$</th>
<th>case $N_{11}^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Feb</td>
<td>3</td>
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<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Mar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Apr</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>May</td>
<td>10</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jun</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jul</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Aug</td>
<td>20</td>
<td>16</td>
<td>14</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sep</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Oct</td>
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<td>0</td>
<td>0</td>
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<td>Nov</td>
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<td>1</td>
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<tr>
<td>Dec</td>
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<tr>
<td>Total</td>
<td>43</td>
<td>31</td>
<td>18</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

In Table 4.2, we show the number of instances where the societal costs of DRR participation exceed the benefits using the MISO data. For all the cases using the MISO data there was a significant drop in the number of curtailment hours. This is to be expected because when using the FERC NBT the MISO cases had a large number of unintended consequences. As much as 66% of the curtailment hours resulted in higher payments than benefits in case $M_3$. In case $M_3^p$, the 31 instances of higher DRR payments than benefits represent a 20% of the total curtailment hours. With the MISO cases we also note that the
indices of the hours with higher costs than benefits are a subset of the same type of hours in the cases with less demand response capacity.

Table 4.2: Number of instances with extra payments due to demand curtailments for cases using MISO data

<table>
<thead>
<tr>
<th>month</th>
<th>case $M_3^p$</th>
<th>case $M_5^p$</th>
<th>case $M_7^p$</th>
<th>case $M_9^p$</th>
<th>case $M_{11}^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Feb</td>
<td>2</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Mar</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Apr</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>May</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jun</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Jul</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Aug</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sep</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Oct</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Nov</td>
<td>12</td>
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<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Dec</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>31</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>17</td>
</tr>
</tbody>
</table>

To show the impacts of the modifications of the NBT made to ensure that no one is worse off we show the percentage decrease in consumer payments in the same nodes that were worse off in the cases using the FERC NBT as presented in Chapter 3. In Table 4.3, we see that due to the side-payment in (4.11) no node incurs in higher payments due to demand curtailments. In fact,
all these nodes benefited from the curtailments. These percentages are calculated using the base case \( N_0 \).

Table 4.3: Percent decrease in buyer payments in selected nodes that were worse off with FERC NBT using the ISO-NE data

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage decrease in consumer payments</th>
<th>case ( N_3^p )</th>
<th>case ( N_5^p )</th>
<th>case ( N_7^p )</th>
<th>case ( N_9^p )</th>
<th>case ( N_{11}^p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.80</td>
<td>1.03</td>
<td>1.20</td>
<td>1.39</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.80</td>
<td>1.03</td>
<td>1.20</td>
<td>1.40</td>
<td>1.58</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
<td>1.03</td>
<td>1.20</td>
<td>1.38</td>
<td>1.56</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.79</td>
<td>1.00</td>
<td>1.15</td>
<td>1.32</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.80</td>
<td>1.03</td>
<td>1.20</td>
<td>1.38</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.81</td>
<td>1.00</td>
<td>1.15</td>
<td>1.30</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.81</td>
<td>1.04</td>
<td>1.22</td>
<td>1.41</td>
<td>1.59</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.81</td>
<td>1.04</td>
<td>1.22</td>
<td>1.42</td>
<td>1.61</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.80</td>
<td>1.05</td>
<td>1.23</td>
<td>1.43</td>
<td>1.64</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.81</td>
<td>1.05</td>
<td>1.23</td>
<td>1.43</td>
<td>1.63</td>
<td></td>
</tr>
</tbody>
</table>

On the other hand, in Table 4.4 we show the percentage decrease in consumer payments in the same nodes that benefited the most from demand curtailments under the FERC NBT. All these nodes continue to benefit from demand curtailments but, as expected with the modified NBT, these benefits are reduced due to the inclusion of the payment to the nodes that were worse off. We show the same results for the MISO data in Tables 4.5 and 4.6.
Table 4.4: Percent decrease in buyer payments in selected nodes that benefited with FERC NBT using the ISO-NE data

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage decrease in buyer payments</th>
<th>case $N_3^p$</th>
<th>case $N_5^p$</th>
<th>case $N_7^p$</th>
<th>case $N_9^p$</th>
<th>case $N_{11}^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td></td>
<td>1.76</td>
<td>2.71</td>
<td>3.50</td>
<td>4.23</td>
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</tr>
<tr>
<td>49</td>
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<td>2.67</td>
<td>3.45</td>
<td>4.17</td>
<td>4.91</td>
</tr>
<tr>
<td>54</td>
<td></td>
<td>1.75</td>
<td>2.68</td>
<td>3.46</td>
<td>4.18</td>
<td>4.92</td>
</tr>
<tr>
<td>56</td>
<td></td>
<td>1.75</td>
<td>2.68</td>
<td>3.46</td>
<td>4.18</td>
<td>4.92</td>
</tr>
<tr>
<td>59</td>
<td></td>
<td>1.75</td>
<td>2.68</td>
<td>3.47</td>
<td>4.19</td>
<td>4.93</td>
</tr>
<tr>
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<td>1.75</td>
<td>2.68</td>
<td>3.47</td>
<td>4.19</td>
<td>4.93</td>
</tr>
<tr>
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<td></td>
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<td>2.68</td>
<td>3.47</td>
<td>4.19</td>
<td>4.93</td>
</tr>
<tr>
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<td></td>
<td>1.71</td>
<td>2.62</td>
<td>3.38</td>
<td>4.09</td>
<td>4.81</td>
</tr>
<tr>
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<td>1.72</td>
<td>2.62</td>
<td>3.39</td>
<td>4.09</td>
<td>4.81</td>
</tr>
<tr>
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<td>1.75</td>
<td>2.69</td>
<td>3.48</td>
<td>4.21</td>
<td>4.95</td>
</tr>
</tbody>
</table>

Table 4.5: Percent decrease in buyer payments in selected nodes that were worse off with FERC NBT using the MISO data

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage decrease in consumer payments</th>
<th>case $M_3^p$</th>
<th>case $M_5^p$</th>
<th>case $M_7^p$</th>
<th>case $M_9^p$</th>
<th>case $M_{11}^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.256</td>
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<td>0.242</td>
<td>0.237</td>
<td>0.235</td>
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<tr>
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<td>0.256</td>
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<td>0.254</td>
<td>0.257</td>
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<tr>
<td>3</td>
<td></td>
<td>0.272</td>
<td>0.273</td>
<td>0.279</td>
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<td>0.292</td>
</tr>
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<td>0.238</td>
</tr>
<tr>
<td>6</td>
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<td>0.273</td>
<td>0.279</td>
<td>0.284</td>
<td>0.293</td>
</tr>
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<td>0.257</td>
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</tr>
<tr>
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<td>0.261</td>
<td>0.263</td>
<td>0.265</td>
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<tr>
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<td>0.268</td>
<td>0.275</td>
<td>0.282</td>
<td>0.291</td>
</tr>
<tr>
<td>117</td>
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<td>0.275</td>
<td>0.273</td>
<td>0.282</td>
<td>0.289</td>
<td>0.300</td>
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</table>
Table 4.6: Percent decrease in buyer payments in selected nodes that benefited with FERC NBT using the MISO data

<table>
<thead>
<tr>
<th>node number</th>
<th>percentage decrease in consumer payments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>case $M_3^p$</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>54</td>
<td>0.260</td>
</tr>
<tr>
<td>56</td>
<td>0.252</td>
</tr>
<tr>
<td>59</td>
<td>0.258</td>
</tr>
<tr>
<td>60</td>
<td>0.259</td>
</tr>
<tr>
<td>62</td>
<td>0.258</td>
</tr>
<tr>
<td>80</td>
<td>0.241</td>
</tr>
<tr>
<td>90</td>
<td>0.241</td>
</tr>
<tr>
<td>116</td>
<td>0.252</td>
</tr>
</tbody>
</table>

4.3 Comparison of the NBT and the Proposed Modified NBT

Our goal is to propose modifications to the NBT without changing its nature and providing additional considerations to ensure efficiency of load curtailment services. In this section, we provide an overview of the modifications. The modifications of the FERC NBT were made based on the issues identified in Chapter 3. The modifications introduced are:

- use of more appropriate data, i.e., rather than use the offer set for the entire period we only use the on-peak LMPs,
- determination of a location-dependent threshold price, and
- the explicit assurance that a demand curtailment does not negatively impact any load.
The rationale behind using on-peak $LMP$s instead of the offers is to explicitly include the impacts of transmission congestion. The failure to incorporate the impacts of transmission congestion in the determination of the threshold price may lead to the setting of an inappropriate threshold price. Since the $LMP$s explicitly account for the congestion impacts and the offer prices, the determination of the threshold price on the basis of the $LMP$s overcomes this problem. Furthermore, as demand curtailments rarely occur during off-peak hours, we restrict the data to on-peak $LMP$s and so we eliminate the reliance on the off-peak data so as not to distort the determination of the location-dependent threshold price towards the lower $LMP$s.

In Chapter 3, we identified that because of the non-nodal nature of the $FERC\ NBT$, some nodes may not participate in the $DAM$ to be compensated for demand curtailments due to the high threshold price. On the other hand, the monthly system-wide threshold may be so low that a node may have demand curtailments much more often than others. In other words, a system-wide threshold does not measure properly when a demand curtailment is appropriate in a node by node basis. With the proposed modifications, each node has its own monthly threshold price determined from the actual $LMP$s for the same month in the previous year and provides an appropriate nodal signal in the setting of the threshold price on a nodal basis.

We assure that no one is worse off with the introduction of a side payment to the nodes that incur in higher payments due to the demand curtailments. As a
result, the test ensures that only in those cases when the societal benefits exceed the societal costs, are the DRRs compensated at the LMP.

We start out with the scheme to determine nodal threshold prices for DRR participation. The modifications are in the “spirit” of Order No. 745, i.e., analogous to the process deployed for determining the monthly threshold price, and we introduce the explicit consideration of locational topological information into the NBT. In this way, we are able to incorporate transmission congestion effects into the determination of the threshold at each node. For each month and node we determine a locational threshold price (LTP) using the LMP data of the same month in the previous year. Since DRR participation is very limited during hours with low LMPs, we only consider on-peak LMPs during the weekdays to determine the LTPs. We construct a representative LMP curve for each node of the system, we use the smoothing techniques for this curve and then we determine the nodal threshold by finding the point on the curve where (2.3) condition is met.

4.4 Summary

In this chapter, we presented a set of three proposed modifications to the FERC NBT that address the issues identified in Chapter 3. These modifications take into account transmission congestion in the determination of the threshold price and ensure that no one is worse off in the post-curtailment state. We also presented results from simulation runs using the
proposed modified $NBT$ showing the lessening in the impacts due to the instances with higher societal costs than benefits of $DRR$ participation and the assurance that no node incurs higher post-curtailment payments.
CHAPTER 5
CONCLUSIONS

In this thesis, we study the impacts of demand curtailments in the DAMs under the procedure and the accompanying compensation scheme mandated by the FERC in Order No. 745. By including the FERC NBT in the extended transmission constrained market model with the explicit representation of the DRRs, we identify and analyze certain unintended consequences that result from the nature of the determination of the threshold price that we observed in our extensive simulation studies of the impacts of FERC Order No. 745. Due to the lack of consideration of transmission-grid effects for the FERC NBT, the system-wide threshold may not be the appropriate metric to determine the dispatch of DRRs in all nodes of the system. Due to congestion patterns and location, the LMPs at some nodes may be lower than the monthly threshold price at all hours of the month. This situation does not allow any demand response participation at these nodes. On the other hand, nodes that experience higher LMPs may meet the monthly threshold at all hours of the month. We also identify that under the FERC’s scheme, there are instances in which the incentive payments to the DRRs exceed the benefits of the entire system. We also identify that there are nodes in the system that incur higher
payments in the post-curtailment state than in the pre-curtailment state even though they make no modifications of their loads. These affected nodes consistently have higher post-curtailment LMPs due to the fact that demand curtailments made at other nodes modify the congestion patterns in the system.

We propose modifications to the NBT so as to explicitly address the identified issues. The modifications are in three principal areas – data usage, explicit consideration of transmission system in the determination of the threshold price and an additional test to guarantee that no buyer is worse off in the post-curtailment state than in the pre-curtailment state. We propose to use on-peak LMPs instead of the offer data to construct a representative LMP curve. The use of the LMP data provides a more meaningful basis for the determination of the threshold price. We propose the replacement of the system-wide threshold price by node-specific threshold prices at each node to explicitly account for transmission considerations. To guarantee that no load incurs in higher post-curtailment payments than in the pre-curtailment state, we propose the introduction of a simple test to verify that this criterion is met.

The proposed modifications keep both the spirit and nature of the NBT intact while addressing the issues identified in our studies.

To test the ability of the proposed modifications to address the identified unintended consequences, we run simulation studies with the proposed modified NBT and compare them with the FERC NBT study cases. The results
of the testing we performed indicate that the instances of higher post-curtailment purchase payment are reduced by at least an order of magnitude and in each case every node in the system is assured that it is not worse off due to demand curtailments.

Due to the increasing use of renewable energy sources, an interesting extension of the work presented in this thesis is the inclusion of such generation technologies in the studies. Adding the variability and uncertainty of renewable energy sources in the study of the impacts of demand curtailments would give insight into how the NBT and the proposed modified NBT perform under such conditions. Another extension is the study of the impacts of demand curtailments under contingency conditions. A study of how well the proposed modified NBT performs in the event of losing a line is of great interest.
APPENDIX A

DETAILS OF THE TEST SYSTEM

For the studies presented in this thesis, we use the modified IEEE 118-bus system. This system, which is based on the ISO-NE network, has 54 generators and 186 lines. We use load shapes from ISO-NE and MISO from the year 2010. For each hour of the year, we aggregate the load and then scale it and distributed proportionally among the nodes of the test system. The peak load of the test system has a value of 9,600 MW. We assume that the demand of the buyers is a fixed quantity and is not responsive to price. In Fig. A.1 we show the scaled load for the first two weeks of the month of July.

Figure A.1: Scaled hourly load for the IEEE 118-bus test system during the first week of July 2010
We make use the ROCs of each month to construct monthly offer curves for the test system. We distribute the prices and quantities of the monthly ROC among the 54 generators so as to construct an offer curve for the test system that mimics the shape of the original ROC. We then scale this offer curve to the test system level. By doing this, we take into consideration the seasonal variations of the offer curve. In Fig A.2 we show the ROC and the test-system offer curve (before scaling) during the month of July.

![Graph showing ROC and test-system offer curve during the month of July](image)

Figure A.2: ROC and test-system offer curve during the month of July

To determine the monthly threshold prices we apply the procedure described in Chapter 2 to the test system offer curves. In Table A.1 we show the monthly threshold prices for both the ISO-NE and MISO data.
Table A.1: Monthly threshold prices

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REFERENCES


