Harnessing Flexible Transmission: Corrective Transmission Switching for ISO-NE

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***Abstract*—Despite the significant attention transmission switching (TS) has gained over the last decade, important challenges remain. This paper addresses the state of the art challenges of transmission switching by studying the benefits of corrective switching using authentic ISO-NE data and software. Thus, the results and analyses presented in this paper are more convincing than any other study conducted to date. Transmission switching is successfully implemented for reliability applications as a corrective mechanism. ISO-NE maintains N-1 reliability based on preventive dispatch and enforcing proxy reserve requirements along with N-1-1 reliability based on reserves and interface limits. This paper incorporates transmission switching as a corrective mechanism in response to both N-1 and N-1-1 events. Not only does the paper investigate the capability of corrective switching to alleviate thermal overloads, but also the economic benefits of corrective switching with actual market data and in-house market software at ISO-NE. The results show that corrective transmission switching can improve the reliability of the system and save millions of dollars each year by providing a cheaper corrective action alternative for ISO-NE. The results also suggest that transmission switching would provide more significant benefits for systems with more transmission congestion such as PJM, MISO, and ERCOT.**

***Index Terms*—Power system economics, power system reliability, power transmission control, transmission switching, interface limits.**

I. Introduction

POWER system operators put a premium on ensuring security against disturbances. There is an ongoing effort to diminish the impact of potential resource outages. One of the main ways Independent system operators (ISOs) maintain reliability is through operating margins that are enforced by reserve and transmission requirements. Such policies play a crucial role for ensuring continuous service for consumers.

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Markets run by the Independent System Operator of New England (ISO-NE) are designed to protect against first and second contingency events (e.g., a sudden generator outage followed by a transmission outage). There is an economic cost incurred when additional, more expensive generators are dispatched out of merit to ensure availability of reserves. About 25% of binding real-time transmission constraints in ISO-NE are for contingencies that have not occurred but may occur in the near future. Another large cost comes from committing additional generators for reliability. Reliability commitments within import-constrained areas cost ISO-NE several million dollars in day-ahead markets (DAM) during 2014[1].

The high cost of ensuring reliability has motivated discussions in the literature on more efficient ways to ensure reliability. One potential mechanism to manage congestion is transmission switching (TS), also known as transmission topology control, and one near-term application is corrective TS.

Transmission switching has been shown to have both economic [1]-[5] and reliability benefits [6]-[8], when used as either a preventive or corrective mechanism. Cost savings are reported even with consideration of conservative probabilistic reliability measures [9]. TS is also shown to be an effective tool in other applications such as planning [10] and integration of intermittent renewable resources [11]. However, there are still challenges that need to be overcome before TS can be implemented in various stages of power system operations. These challenges include: stability concerns [12], AC feasibility [13], and computational complexity [14]. Moreover, most of the studies in this domain are carried on simplified test cases; studies on actual large-scale systems are very limited [15]-[20]. No prior work has demonstrated the benefits of a particular TS application while using actual historical market data combined with in-house market software. This paper addresses this issue and contributes to the state of the art challenges of TS for N-1 and N-1-1 reliability applications on actual ISO-NE data. Furthermore, the analysis, presented in this paper, is performed using the authentic market management system (MMS) software employed today at ISO-NE, which is produced by Alstom Grid.

TS can provide power flow control, rerouting power from the lines that are more heavily loaded to alternative paths.

[1] The cost of reliability commitments are estimated from uplift payments as described in the Appendix. The exact numbers are suppressed for publication; however, the range is \$1–10 million per year for ISO-NE and will be much higher for larger and more congested control areas.

Therefore, TS can be employed as a corrective action during a post-contingency situation, when some transmission lines are loaded above their limits [6]-[8]. TS can be seen as a cheaper alternative to generation re-dispatch. TS can also provide the required transfer capability to enhance the deliverability of reserve [21]-[22]. TS can also help reduce post-contingency voltage violations by providing the necessary voltage support [16]-[20].

This paper analyzes corrective switching to manage congestion during the first few minutes after a contingency. As such, we do not model the dispatch of contingency reserves, which typically occurs over five to fifteen minutes. The focus is instead on ensuring thermal transmission constraints are satisfied in steady state after automatic generation control and corrective switching.

This analysis considers first contingencies (N-1) and second contingencies (N-1-1) in the ISO-NE system. The term N-1-1 refers to two contingencies separated by roughly 30 minutes. This relates to NERC requirements guiding how quickly operators should restore N-1 reliability following a contingency [23]-[25]. It is computationally expensive to directly model combinations of N-1-1 events in the market, so this reliability criterion is addressed by proxy interface constraints. The interface constraints are calculated ahead of time based on simulation and expert judgment to constrain the market solution away from solutions that are likely to be unreliable.

The main contributions of this work are the following:

1. The application of TS for N-1 and N-1-1 reliability requirements is studied using authentic ISO-NE data and market software. Studies on TS with real power system data are very limited [15]-[21]. To our knowledge, this paper is the first to use both actual data and market software. This study, thus, closes an important gap in the literature by providing the industry with trustworthy insight into an innovative technology.
2. This paper does not only focus on reliability gains of TS, but also evaluates economic impacts of corrective switching on market outcomes. The current paradigm is to operate the system so it is always N-1 and N-1-1 reliable. So far as meeting this requirement, corrective switching can allow greater utilization of the transmission network in the base case before a contingency occurs. As a result, less money is spent preemptively committing and dispatching generators out of merit for purposes of congestion management. Analyzing such impacts with authentic MMS software and real system data is another contribution of this work.

Corrective switching is first incorporated in the real-time market (RTM) model of ISO-NE. Here it is applied to protect against thermal violations that could occur following an N-1 contingency. Corrective switching is shown to alleviate congestion in 25 randomly-selected cases. The sample comes from a larger pool of historical cases and corrective switching benefits are found in every instance. While switching consistently alleviates binding transmission constraints, the overall benefit is modest because ISO-NE is rarely congested in real time: Fig. 1 shows that more than 70% of days since 2012 had no binding contingency constraints in the RTM at any point. Corrective switching benefits, based on the application of relieving post-contingency thermal overloads in the ISO-NE system, are projected to fall between $200 thousand and $600 thousand per year when applied solely to the RTM. As will be discussed later on in this paper, the cumulative benefits will be much larger when TS is applied at earlier scheduling stages (e.g., in the DAM or reliability unit commitment); TS is beneficial for a variety of applications and to realize the full benefit of TS, it should be integrated into multiple applications. Furthermore, while these cost savings are modest for this one particular TS application, the consistent benefit observed whenever there is congestion is a signal that corrective switching is expected to have a much greater cost savings impact in more congested systems such as PJM, MISO, and ERCOT.

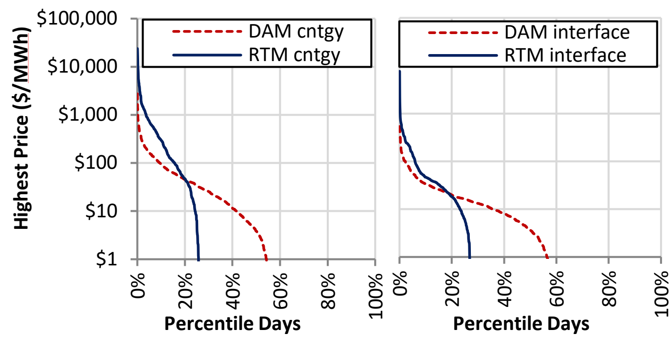

Fig. 1. The highest shadow price (absolute value) for contingency and interface constraints across days in ISO-NE for the DAM and real-time market (RTM).

Corrective switching is then integrated with interface limit calculations for N-1-1. These interface limits are also rarely binding in real time for the ISO-NE system, as shown in Fig. 1. However, they drive and impact reliability commitments made in local areas during the DAM and subsequent reliability runs [26]. The testing results in this study suggest that adding corrective switching to thermal interface limits could save several million dollars in reliability commitments per year without hindering N-1-1 reliability.

While this paper only investigates corrective TS for two out of many different potential applications, the benefits are estimated to be in the millions of dollars for a moderately sized system like ISO-NE, despite the fact ISO-NE frequently operates without congestion due to massive upgrades in their 345 kV network. Further benefits may also be realized from other TS applications not studied in this paper, e.g., taking transmission lines out of service during pre-contingency states in order to enhance transfer capabilities [1]-[5]. Finally, the benefit from TS for much larger systems, especially systems that regularly experience congestion, is expected to be at least in the tens of millions of dollars if not in the hundreds of millions of dollars per year for larger systems like PJM, [15].

Several obstacles must be overcome before it becomes viable to rely on corrective switching on a more regular basis. This study focuses on the potential economic impact. Other concerns include potential vulnerabilities for system stability, the time to reclose a line when it becomes needed, cultural norms, N-1-1 reliability, and operator training and experience. We acknowledge that TS is a complex issue with many facets and we focus our attention the potential economic impact of corrective switching within the scope of this study.

The rest of the paper is organized as follows. Sections II and III describe transmission constraints for N-1 and interface limits for N-1-1 in ISO-NE. Section IV describes the methodology used in this paper to identify corrective switching actions. Section V provides results. Finally, Section VI concludes.

II. *N-1* Security Constraints

The real-time market model in ISO-NE co-optimizes procurement of energy and reserves. It has a 15-minute look ahead and is solved approximately every five to ten minutes. The model is a mixed-integer linear program taking the form:

$$min\ c^T x + b^T y, \quad (1)$$
$$s.t.\ Ax + By \leq b, \quad (2)$$
$$x \in \{0,1\}, \quad (3)$$

where x and y are the vectors of decision variables. The model includes binary commitment decisions x for offline fast-start generators, which must be available to start in 30 minutes or less [27]-[28]. The continuous decision variables y include generator outputs, reserves, network flows, and other continuous decisions. The power flows are approximated via linear equations, such as the following post-contingency constraints:

$$-F_k^c \leq \hat{f}_k^c + \sum_{n\in N} \psi_{nk}^c p_n^{\Delta} \leq F_k^c, \qquad \forall\, k \in K, c \in C \quad (4)$$[2]

where F_k^c is the thermal limit for branch k and the constrained term is the projected power flow for contingency c. The power flow has a fixed component and a variable component. The fixed parameter $\hat{f}_k^c$ estimates the flow on branch k during contingency c if all nodal injections remain equal to a prescribed baseline level. The variable p_n^{Δ} represents the relative change in injections at node n, while ψ_{nk}^c corresponds to the flow sensitivity in the post-contingency network; the product of these two terms captures how the flow changes after primary frequency control actions. The transmission constraints in (4) project what the line flows would be if all controls from the real-time market solution remain unchanged after the contingency. This strategy is generally conservative because the thermal limits F are often derived based on how much flow the line can sustain over a prolonged period of several minutes or hours, during which time operators have the opportunity to take various corrective actions to alleviate overloads [29].

Operators may adjust constraint (4) to anticipate corrective actions. The range of corrective actions can include voluntary load curtailment (demand response), dispatching reserves, or adjusting the network properties. Network controls can include corrective TS, which has the benefit of being quick and relatively cheap [6]-[8]. Corrective TS is modeled here by revising parameters $\hat{f}_k^c$ and ψ_{nk}^c to reflect the new network topology after the contingency and after corrective switching. The revised constraint (4) then constrains flow under the new topology after the line has been removed from service.

This modeling framework is not new. Such corrective actions are modeled by several ISOs for select contingencies with pre-defined special protection schemes (SPS) [30]. PJM has roughly 100 switching solutions listed; this list is generated based on prior operator experience as opposed to having the flexibility of their transmission topology built within their energy management system (EMS) or market management system (MMS). Therefore, PJM must manually investigate these possible corrective switching solutions, which is cumbersome; as a result, there is a real need for innovative software solutions that no longer neglect transmission flexibility within EMS and MMS. Operators may also plan and account for corrective switching for individual contingencies in an ad-hoc manner. The contributions of this paper are the legitimate cost savings and reliability enhancements that have been demonstrated on actual ISO-NE data based on the use of ISO-NE's EMS and MMS software, while separate ongoing work by the authors is dedicated to addressing the lack of a flexible transmission decision support (FTDS) software tool that can enhance EMS and MMS capabilities [31]. The benefit of an online real-time FTDS tool is that candidate TS actions are evaluated on the fly based on real-time operating conditions, which goes beyond approximate offline studies conducted to identify a subset of the full potential set of corrective switching solutions as well as ensures a timely evaluation and verification, in real-time, of the potential corrective TS actions.

[2] This is a simplified version of the actual constraints.

A. Contingency Constraints Calculation

This study solely considers transmission contingencies that do not already have pre-defined special protection schemes. Real-time operations follow the process in Fig. 2.

The EMS continually estimates the state of the system (voltage magnitude and angle, power injections, etc.) and gauges reliability using real-time contingency analysis (RTCA). When RTCA identifies potential contingencies of concern, the information is passed to the operator and some constraints may be passed to the market based SCED in the RTM model. The constraints they add restrict future market solutions to protect against network violations that would occur following a contingency. Note that, the study presented in this paper only adds a corrective switching module to the RTCA tool, as shown in Fig. 2, and does not change other blocks of the EMS such as state estimation.

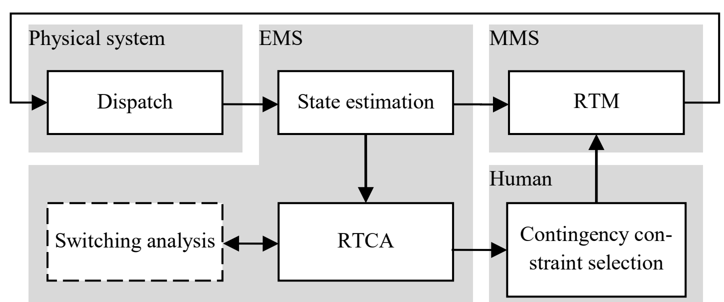

Fig. 2. Summary of real-time operations relevant to this study. This study simulates the RTCA, switching analysis, and the RTM. All other steps are replaced by historical data.

This study uses historical data coming from ISO-NE's state estimator. We consider contingencies that were identified by system operators and added to the market model. Simulation of RTCA is performed with a full network AC power flow to derive $\hat{f}$ and ψ using PowerWorld (these values are later fed into (4) in ISO-NE's market model simulator). Simulation of the RTM is performed using the actual market management software (MMS) in production today by Alstom Grid.

This study investigates historical cases where constraint (4) is binding and attempts to identify a single beneficial TS action for each case. The study then evaluates how the market solution would change if the corrective switching action is assumed in constraint (4). The assumptions of this study are,

1. Transient stability is maintained as we do not perform stability analysis for corrective switching. Corrective switching after an initial contingency can be seen as an N-1-1 event.
2. The identified switching action can be implemented in a timely manner (within minutes) to limit temporary overloads above F_k^c. There are acceptable limits for such brief overloads on thermally-constrained lines because overheating is not immediate [29]. One of the benefits of TS that has been widely discussed in the literature is its capability for fast implementation.
3. The new dispatch in the study periods does not adversely affect other periods. This assumption arises because we do not study how the system evolves five or more minutes after the contingency occurs.

The other RTM assumptions are independent of corrective switching and inherent to the current version of the MMS. Model inaccuracies are generally identified as the system evolves and are mitigated in future RTM runs.

III. Thermal Interface Limits

Contingency constraints in the RTM are meant to ensure N-1 reliability. In contrast, interface limits are important because they address N-1-1, i.e., two contingencies separated in time. The full process behind an N-1-1 set of events is described in Fig. 3. There are multiple downstream steps that occur after the first contingency, including 30 minutes of re-dispatch prior to the second contingency. Modeling all of the downstream steps poses a computational challenge because several decisions are associated with the re-dispatch following each first contingency[3]. The purpose of interface limits is to address all of the downstream steps and represent the reliability requirements within a single constraint that governs the initial dispatch. For simplicity, as Fig. 3 shows, this paper focuses on corrective TS only after N-1-1 and not immediately following the first contingency, though corrective switching can be applied at that stage as well.

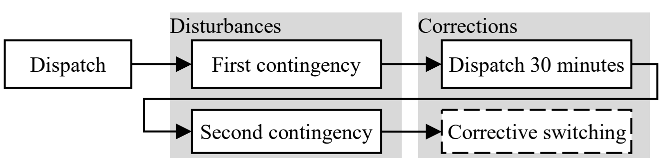

Fig. 3. The N-1-1 process and where corrective switching may be added.

Interface constraints are used in practice to limit power flows and to ensure enough capacity is committed in import-constrained regions [26], [32]. Sufficient commitments of local second-contingency protection resources (LSCPRs) is ensured by capacity constraints similar to

$$\sum_{g\in G(j)} \bar{P}_g u_{gt} \geq \sum_{n\in N(j)} D_{nt} - I_t^j, \qquad \forall\, j \in J, t \in T \qquad (5)$$

where $\bar{P}_g$ is the maximum output of generator g, u_{gt} is the commitment status in period t, D_{nt} is the load at node n, I_t^j is the interface limit into area j, J represents the set of areas, and T represents the time periods. Constraint (5) specifies that the local capacity must exceed demand minus the import capability across the interface. This constraint was responsible for additional commitments in the DAM on over 120 days in 2014[4]. Thermal limits alone led to over 200 additional commitments that cost the system an estimated $25 million.

A. *Interface Limits Calculation*

This study solely studies those thermal interfaces that are limited by thermal transmission limits and not stability. The limit calculation for each interface follows Fig. 4. There are many steps and assumptions involved in this process, but the steps are roughly as follows. The analysis takes an initial dispatch and evaluates N-1-1 reliability (by simulating the steps in Fig. 3). If the system is reliable, the interface flow is increased iteratively until the system is no longer reliable. The interface limit I^j is then set as the highest flow that yielded a reliable solution.

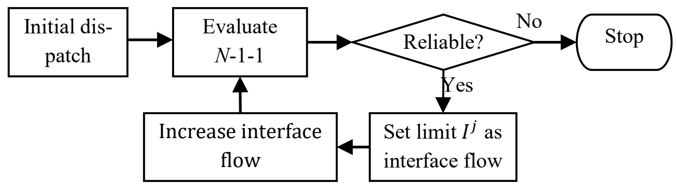

Fig. 4. The iterative process to calculate the limit for interface j. The evaluation of N-1-1 reliability simulates the steps in Fig. 3.

Corrective switching is incorporated into the N-1-1 evaluation to study the impact of interface limits. The limit calculation follows the process in Fig. 4 using software internal to ISO-NE. The same assumptions listed above for the contingency constraints calculations also hold here.

The above describes a general process of interface limits calculation but does not capture details that can cause a difference in day-ahead and real-time limits. For example, operators can correct generation patterns in real-time in response to invalid assumptions based on the day-ahead study. The limits calculated in this study should not be interpreted as the actual change in interface limits due to corrective switching because of the many assumptions involved; rather, they demonstrate that corrective switching can potentially impact interface limits in a general sense. We will provide sensitivity analysis in the results to evaluate the potential economic impact for various degrees of limit improvements.

IV. Switching Methodology

As discussed previously, TS is a computationally expensive problem [18]. A number of fast heuristics have been proposed in the literature to quickly identify potential switching solutions [13], [33]-[34]. Optimal power flow (OPF) based heuristics [13], [31] in their original form aim to minimize the production cost. In corrective applications, such heuristics should be reformulated with the objective of minimizing the load-not-served, which would be computationally challenging. Given the characteristics of ISONE, that rarely more than a single contingency constraint is binding at a time, line outage distribution factor (LODF), seems to be a proper heuristic. LODF

[3] Furthermore, the many combinations of two contingencies pose an additional computational challenge. However, this concern is not insurmountable because scenario selection can identify a reasonable set of critical contingencies.

[4] Commitment causation is identified by running the market model with and without the locational capacity constraints (5).

estimates the change in line k's flow due to the outage of line l. It is defined as:

$$LODF_{kl} = \frac{\Delta f_k}{f_l}, \tag{6}$$

where f_l is the flow on branch l and Δf_k is the change of flow on branch k if branch l opens [35]. Line outage distribution factors are a function of the network and are independent of the system state. Thus, using LODF as the TS heuristic does not require solving an OPF [13], [34]. It also directly identifies the overload relief on the overloaded lines. The following steps summarize the switching algorithm:

1. The line associated to the binding constraint is identified as k*. Consequently, the LODFs related to the change on the flow of line k*, with respect to the outage of other lines are taken out of the database.
2. The lines are sorted by their expected impact on the flow of line k*: $LODF_{k^*l} \times f_l$. A limited number of lines from the top of this list (that would likely have the most significant overload relief) are identified as the switching candidates.
3. Each of the candidates is tested for effectiveness through running an AC power flow. A successful candidate would relieve the overload without introducing additional voltage or flow violations in the RTM study.
4. The corrective switching action, with the biggest thermal reductions on critical lines, is adopted when multiple candidates provide a benefit.

The above switching methodology is selected for this analysis due to its ease of implementation. Other appropriate approaches from the literature may also be used in general without hindering the overall process.

V. Results

This study evaluates corrective switching for N-1 contingency constraints in the RTM and for N-1-1 interface constraints in the DAM. The study uses historical EMS data from ISO-NE to retrospectively study the impact of corrective switching for select cases.

Analysis of first-contingencies utilizes the RTM model produced by Alstom Grid. The software is run in a testing environment and is equivalent to that used in practice by ISO-NE. For each historical case, a beneficial switching action is identified using the process in Section IV and the corresponding contingency constraint (4) is revised accordingly.

Analysis of interface limits utilizes a transfer capability calculator developed by ISO-NE. The software applies the calculations used in practice to recommend interface limits to operators. The interface limits are determined based on a real-time data across two consecutive weeks in 2014. Beneficial switching actions are identified for the most limiting contingencies and modeled by re-defining contingencies to include the respective corrective actions.

The analyses are repeated with and without corrective switching, referred to as vanilla studies. These vanilla results serve as the benchmark for corrective switching. All reported savings are with respect to the vanilla results.

A. RTM Contingency Constraints

Corrective switching is analyzed for 25 historical RTM cases with binding thermal transmission constraints. At least one beneficial switching action is identified for each case. A relationship is also drawn with the following index for congestion:

$$\alpha_k^c = |F_k^c \times \lambda_k^c|, \tag{7}$$

where F_k^c is the branch capacity and λ_k^c is the shadow price for constraint (4). Constraints with large α_k^c are of interest because the market surplus is sensitive to percent changes in the respective transmission capacities. The selected metric for the overall congestion in a given market case is

$$\tilde{\alpha} = \max_{k \in K, c \in C} \{\alpha_k^c\}. \tag{8}$$

This metric is convenient because it is easy to compute and track as an outcome of the market clearing solution. It is also available for all historical market cases. Market cases with large $\tilde{\alpha}$ are referred to as more congested because the most limiting constraint has a large economic impact. The benefit of corrective switching tends to grow with congestion $\tilde{\alpha}$, and observing the historical congestion provides some insight into the potential impact of corrective switching if it were to be fully implemented. Note that, this metric is calculated on the margin; it does not capture the full cost of congestion. Such a metric is used due to data availability of historical data. It provides an estimate of the congestion cost simply to identify potential operating periods that are considered to be situations where transmission switching may be of more significant value. The actual cost savings of transmission switching on each of those historical cases are calculated directly through actual RTM simulations with and without TS, not based on this estimation metric.

A.1. Sample Cases

The test data is sampled from historical data in ISO-NE. Twenty-five cases are selected from years 2012–2014.

The sampled cases also have congestion that is representative of general cases. Fig. 5 shows the empirical cumulative distribution function (CDF) for historical congestion when $\tilde{\alpha} \geq 0$. The Fig. reads: 50% of congested cases have $\tilde{\alpha} \geq$ \$10,000. The sample of 25 cases covers a broad range of congestion, and cases with small $\tilde{\alpha}$ are ignored because they have less economic impact (the potential impact of TS is assumed to be effectively zero for small $\tilde{\alpha}$).

The biggest omission is that the sample cases only consider transmission contingencies. This study omits generator contingencies because the locations of the rebalancing injections were not readily available to perform the study accurately.

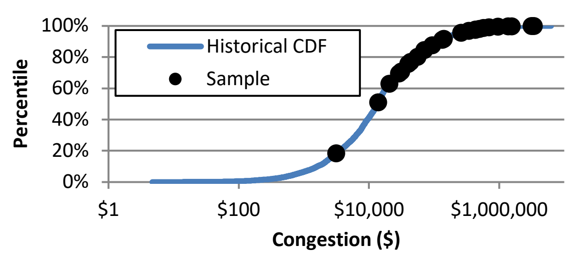

Fig. 5. Congestion $\tilde{\alpha}$ in the sample cases relative to historical congestion. The line is an empirical cumulative distribution function (CDF) for congestion conditioned on $\tilde{\alpha} \geq 0$.

A.2. Sample Results

Of the 25 cases tested, TS provides some benefit to each.

The ten cases with the most economic benefit are shown in Fig. 6. The cost savings represent how the RTM objective changes, which is scaled to reflect hourly production costs (i.e., the cost savings for case "1" in Fig. 6 is approximately $30,000/hr). To provide a basis for comparison, the RTM is resolved with the binding constraints removed altogether. This hypothetical solution would provide an upper bound for the possible savings. The figure shows that the savings with corrective switching often achieve half of the potential benefit. It is interesting to note that corrective TS is very beneficial even when it does not, by itself, completely prevent the possibility of post-contingency violations. Fig. 6 shows several cases where corrective switching achieves all potential congestion relief cost savings.

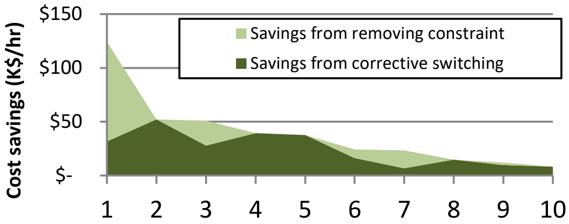

Fig. 6. Cost savings captured for the top 10 cases with the most expensive congestion.

The cost savings arise from allowing access to cheaper generation previously stuck behind transmission bottlenecks. In three of the 25 cases, corrective switching also provides a reliability benefit by reducing constraint violations. For example, part of the savings observed in case "1" from Fig. 6 comes from reducing a shortage of 30-minute reserves. Corrective switching reduces reserve shortages by allowing flexible units to be ramped down to provide reserve instead of being dispatched to manage congestion. Corrective switching reduces the reserve shortage from 346 MW to 287 MW in this case. It is worth noting that such reserve shortages are a major concern for system operators because they typically occur when reliability risks falling below the standard set by the operator and regulating bodies. The other reliability benefits come from reducing transmission violations in two cases. The savings in cases "4" and "5" from Fig. 6 are a result of eliminating transmission violations in the RTM case.

The RTM monetizes reliability improvements via administrative penalty factors for constraint violations (reserve shortages and transmission overloads). The penalty factor for 30-minute reserve shortages in ISO-NE is $500/MWh and is incurred whenever there is a reserve shortage. The penalty factor for transmission violations is assumed to be $5000/MWh in accordance with CAISO market rules [36] (the penalty factor from CAISO is used here because ISO-NE does not publish a corresponding value). In general, cost savings are observed for all of the cases tested.

Samples from the morning are sometimes associated with "local minimum generation" warnings, which indicate there is a reliability threat due to too much committed capacity [37] . Corrective switching can help with these cases by increasing the export capability from areas with over generation. Thus, TS can even enhance reliability during a minimum generation emergency situation, which is yet another example, among a long list of potential benefits which demonstrates that TS can enhance system efficiency and security in ways that are often not considered.

The largest cost savings are captured when congestion is high. The relationship between savings and congestion is shown in Fig. 7. There is a strong correlation between savings and congestion, which can be exploited to derive a more general relationship.

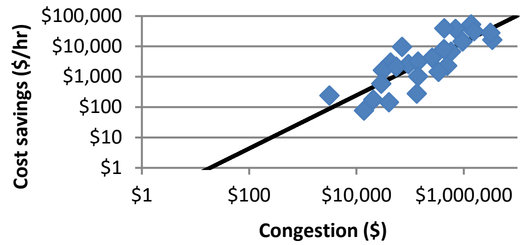

Fig. 7. Relationship and regression fit for cost savings vs. congestion $\tilde{\alpha}$. Note the scale is log-log.

A.3. Regression Model

The overall relationship between savings and congestion can be described using a log-log regression model:

$$log(s) = \beta_0 + \beta_1 \, log(\tilde{\alpha}) + \epsilon, \qquad (9)$$

where s and $\tilde{\alpha}$ are the vectors of cost savings and congestion for different RTM cases. The vector ϵ represents Gaussian random errors with zero mean that are independent and identically distributed (i.i.d.). A linear regression analysis is performed to estimate β_0 and β_1. The maximum likelihood estimates for these coefficients are $\beta_0 = -1.13$ and $\beta_1 = 0.877$ (these represent the intercept and slope of the line in Fig. 8). The residuals for this model are consistent with the assumption of i.i.d Gaussian errors, suggesting that (9) is a valid model for the relationship between congestion and cost savings. The cost savings are derived by inversing the log on both sides of (9):

$$s = 10^{\beta_0} \times \tilde{\alpha}^{\beta_1} \times 10^{\epsilon}, \qquad (10\text{-}1)$$
$$\approx 0.074\tilde{\alpha}^{0.877} \times 10^{\epsilon}. \qquad (10\text{-}2)$$

The regression model has two forms of uncertainty that are important to consider. First, the error term 10^{ϵ} describes how cost savings may differ from the regression line in Fig. 8. The fitted regression model (9) has a root mean square error of 0.51, suggesting savings differ by a factor of $10^{0.51} = 3.3$ on average for cases with the same congestion. This shows that congestion $\tilde{\alpha}$ is only a rough predictor and does not accurately predict the savings for individual cases. However, the average savings over a longer time period is much more predictable.

The second form of uncertainty arises from uncertain estimates of the fitted regression coefficients β_0 and β_1. This makes the expected value of $log(s)$ uncertain even in the long run. Confidence intervals for the expected value of $log(s)$ are readily available from the fitted regression model [38], and the corresponding 90% confidence interval is shown in Fig. 9. The expected savings have a wide confidence interval because the "true" values for coefficients β_0 and β_1 are unknown.

Lower and upper bounds on expected savings are calculated using a logarithmic regression fit. The expected savings per case has a 90% confidence interval of $(23.5, 66.3)/hr. This translates into a yearly savings between $205 thousand and $581 thousand. These yearly savings are relatively small in the best case because ISO-NE experiences relatively little congestion. For example, since 2012, the RTM in ISO-NE proceeded the entire day without a binding contingency constraint (4) more than 70% of the time. However, the overall relationship between congestion and savings in Fig. 8 suggests that the overall savings will be larger in systems that are more congested and congested more frequently. This cost savings is only reflective of incorporating corrective TS within the real-time market; future work would focus on incorporating it into the DAM as well since the DAM solution from ISO-NE exhibits more congestion within its solution.

B. *Interface Limits*[5]

The impact of corrective switching is potentially larger for interface limits because they have a direct influence on commitment in the DAM. We study the impact of corrective switching on Interface A and Interface B for 14 consecutive days in 2014. The respective interface limits lead to reliability commitments in the DAM through constraint (5). These reliability commitments provide protection from second contingencies but come at an economic cost. The potential benefit of corrective switching is to allow higher limits and thereby relax constraint (5) without hindering N-1-1 reliability.

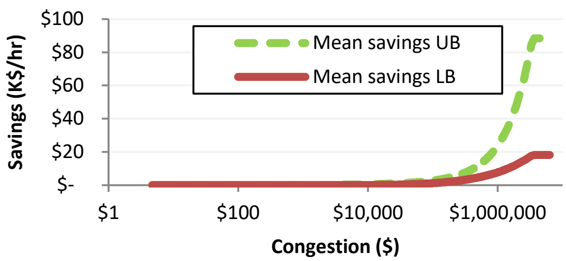

Fig. 8. 90% confidence interval on expected cost savings for different levels of congestion $\tilde{\alpha}$ (assuming $\epsilon = 0$).

This study first demonstrates how much corrective switching can increase the respective interface limits. The vanilla and switching limits are calculated using real-time data from 5pm (the peak hour) for each respective day. The new limits are then studied to measure the potential economic impact that can come from reducing reliability commitments in the respective local areas.

Interface limits are evaluated against several N-1-1 contingencies and constraints. As such, alleviating one N-1-1 contingency may lead to the new limit coming from a different contingency. This study only applies corrective switching for the three most limiting N-1-1 contingencies. In some instances, the resulting limit could be further improved by applying corrective switching to more than three contingencies, but those opportunities are not explored in this study.

B.1. *Sample Results*

The respective interface limits with and without corrective switching are summarized in Fig. 9 and 10. All limits are normalized by the largest observation. We refer to the normalizing value as the *baseline capability* for the respective interface. Corrective switching has the biggest impact on the Interface B, increasing the interface limit by 10–70% relative to the baseline capability in each of the days tested. Most of the benefit comes from switching out the same three lines in response to critical contingencies (the number of switching actions per contingency is limited to one, but the preferred action can differ by the contingency and the day). Only one switching action corresponds to the limiting line and the others redirect flow away from congested areas. Note that the limits calculated here are obtained via the same tools ISO-NE adopts today for such calculations. However, the improvements for Interface B are likely optimistic due to unit commitment decisions during 30-minutes between contingencies are not captured in this study.

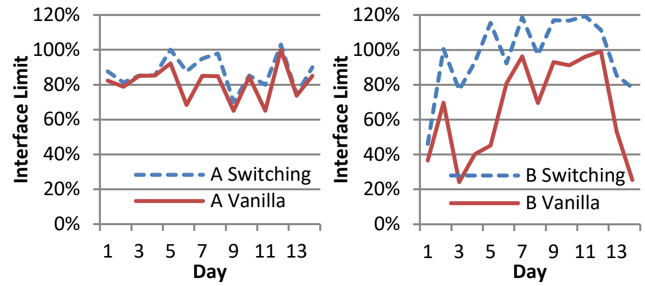

Fig. 9. Interface limit improvements with corrective switching. The values are normalized by the largest limit observed over the study period.

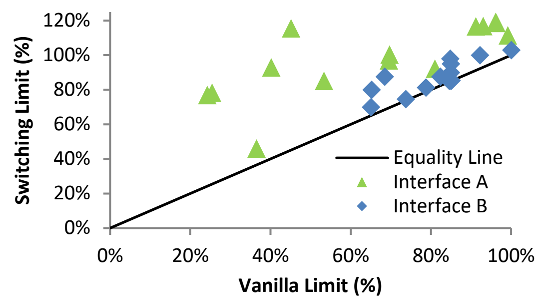

Fig. 10. Combined graph of interface limit improvements with corrective switching.

The economic impact of increasing interface limits largely comes from relaxing constraint (5) via TS. This leads to fewer reliability commitments in local areas because more power can be imported during contingency events. The potential yearly savings are estimated from historical DAM commitments made in 2014 based on the following assumptions:

1. Due to limited data availability for this investigation, instead of reporting on the direct cost savings, which would be preferable, we report on the savings based on uplift calculations for individual units. The uplift payment is talked about in more detail in the Appendix. The actual total cost savings are expected to be higher since uplift only captures profit loss of the reliability based commitment whereas the reliability based committed unit is displacing cheaper generation.
2. At least one reliability commitment is avoided per day.
3. Reliability commitments are only avoided when corrective switching increases the interface limit by more than the generator capacity. This is a conservative assumption.
4. The potential yearly savings are shown in Fig. 11 for different levels of interface increase. Each value on the horizontal axis is associated with a MW increase applied to every day of the year. The two week study period has a minimum improvement of 10% of the baseline capability on the Interface B and applying this increase to every day of 2014 would lead to an estimated $1.5 million in savings. The savings for

[5] The interface names, as well as their values, are purposely concealed due to the sensitive nature of the data.

Interface A are smaller due to the smaller percent gains and are not reported here. We argue that much larger savings are reasonable to expect in larger systems that regularly experience more congestion; overall, savings would be expected to be in the tens to hundreds of millions for a more comprehensive integration of TS into all phases of scheduling, operational planning, and real-time operations.

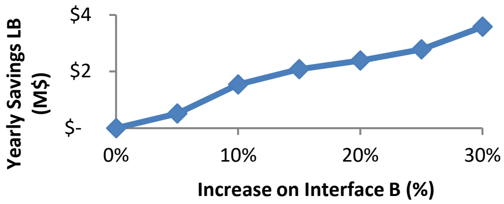

Fig. 11. Estimated cost savings from increasing the Interface B limits consistently across days.

VI. Conclusions

The industry uses corrective TS, to a very limited extent, to alleviate congestion following disturbances. In the current practice, corrective switching actions are identified offline and encoded into special protection schemes (SPS). It may also be implemented on a case-by-case basis according to operator discretion. This study evaluates the impact of determining corrective switching on the fly to reflect the current system state. This paper closes an important gap in the literature of TS by successfully testing the technology using authentic ISO-NE data with the use of authentic ISO-NE market software.

This study evaluates corrective switching in the context of ISO-NE markets. The corrective actions are considered in the market model so fewer preventative actions are required to maintain reliability. Adaptive[6] corrective switching is shown to improve the market surplus in all 25 of the real-time market cases studied, in most cases reducing the cost of congestion by half or more compared to removing contingency constraints altogether. The long-run benefit is more modest because the ISO-NE system is infrequently congested: the yearly benefit of corrective switching adoption, for N-1 reliability application, falls between \$200 thousand and \$600 thousand. A larger benefit is expected to come from updating interface limit calculations for N-1-1 reliability. The potential benefit for interface limits may be several million dollars per year due to decreasing local reliability commitments in the DAM.

Future work is needed to validate that the corrective switching actions studied in this work do not diminish N-1-1 reliability. Potential switching actions should be validated based on stability analysis. The preferred time that is needed to reclose the line is also a question that should be addressed along with the potential coordination issues with local control centers and transmission operators. Finally, this study did not include the expected cost of a switching action on a circuit breaker; however, prior work on this issue estimates that the additional incurred cost of operating the breaker is by far less than the cost savings due to TS.

[6] The word “adaptive” is used to distinguish the approach used in this paper from a look-up table predetermined method that is being used in PJM. Adaptive switching identifies solutions based on the state of the system on a real-time basis.

VII. Appendix – Uplift

The minimum capacity constraint (5) encourages commitment of additional units in areas with constrained imports. These commitments are made for reliability purposes. Since energy prices do not capture the value of binary decisions [38], resources committed due to this constraint tend to receive high uplift payments, known in ISO-NE as net commitment-period compensation (NCPC). NCPC are side payments made to generators so they at least break even over an operating horizon [39]. A generator m with positive uplift would receive the following payment for a single-period problem:

$$uplift_m = cost_m - revenue_m = cost_m - LMP_m \times production_m, \quad \text{(A1)}$$

where $cost_m$ is the generator's offer cost, LMP_m is the price it receives, and production_m is the amount of energy it produces.

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