Contingency Modeling Enhancements

Issue Paper

March 11, 2013

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Attachment: *Preventive-Corrective Market Optimization Model*

I. Executive Summary

In the 2012 Stakeholder Initiatives Catalog the following discretionary initiative was highly ranked by stakeholders and the ISO: *Additional Constraints, Processes, or Products to Address Exceptional Dispatch*. This umbrella initiative reflects both stakeholder concerns about the increase in exceptional dispatch and a broad range of tools the ISO may deploy to effectively address those concerns. As noted in the 2012 Stakeholder Initiatives Catalog, the most important issue for the ISO to address under the umbrella initiative, as it is responsible for a significant volume of exceptional dispatches, is the need to position resources to effectively address a contingency. After a real-time contingency, for some critical paths the ISO is required to return the paths flow to be within its System Operating Limit (SOL) within 30 minutes.

The ISO currently uses exceptional dispatch and minimum online capacity constraints to meet the reliability requirement. The ISO has proposed an alternative that will reduce the use of exceptional dispatches and minimum online capacity constraints as they do not incorporate resources' costs into locational marginal prices. In the attachment, *Preventive-Corrective Market Optimization Model*, the ISO outlines a potential solution that would add a preventive-corrective constraint to the market model and provide compensation to resources that help meet the constraint.[1] Based on the technical paper, this issue paper seeks input from stakeholders on the constraint model framework and on the appropriate level of and form of compensation under the preventive-corrective constraint. Specifically:

1. Is it appropriate to provide compensation to generators for corrective capacity, and, if so, what is the appropriate basis to determine the amount of capacity compensated? For example, a resource is moved to a lower dispatch point in order to provide a larger upward corrective capacity after a contingency. Should the appropriate compensation be based on the movement (downward in this example) or the corrective capacity that is created (for the resource to eventually move upward)?
2. Should all resource capacity contributing to meeting the corrective action be compensated at the resource location locational marginal capacity price or should only those resources that demonstrate a lost opportunity receive compensation?
3. When there are multiple system operating limit constraints binding such that a resource is contributing to meeting the corrective capacity of multiple constraints, how should the resource be compensated considering its contribution to multiple constraints?

[1] See Attachment: *Preventive-Corrective Market Optimization Model*

II. Plan for Stakeholder Engagement

The proposed schedule for stakeholder engagement is listed below. Unlike most initiatives, this schedule allows for extended review and comment submission by stakeholders. If appropriate, the schedule can be accelerated to present to the July Board of Governors.

Date	Event
Mon 3/11/13	Issue Paper Posted
Tue 3/26/13	Stakeholder Call
Tue 4/9/13	Stakeholder Comments Due
Wed 5/15/13	Draft Straw Proposal Posted
Wed 5/22/13	Stakeholder Meeting
Tue 6/4/13	Stakeholder Comments Due on Draft Straw Proposal
Mon 7/1/13	Draft Final Proposal Posted
Tue 7/9/13	Stakeholder Call
Wed 7/24/13	Stakeholder Comments Due on Draft Final Proposal
Tue 8/6/13	August ELT
Thu 9/12/13	September BOG

III. Background

In the 2012 Stakeholder Initiatives Catalog the following discretionary initiative was highly ranked by stakeholders and the ISO: *Additional Constraints, Processes, or Products to Address Exceptional Dispatch*. The initiative was highly ranked because it will explore more efficient ways to maintain reliability and reduce reliance on exceptional dispatch. As the title of the initiative suggests, there may be different approaches to addressing the underlying causes of exceptional dispatch, each with its own resource and cost profile. Therefore, this umbrella initiative reflects both stakeholder concerns about the increase in exceptional dispatch and a broad range of tools the ISO may deploy to effectively address those concerns.

As noted in the 2012 Stakeholder Initiatives Catalog, the first issue the ISO will address under the umbrella initiative is the need to position resources to effectively reposition the system after a contingency within 30 minutes. According to North American Electric Reliability Corporation (NERC)[2] and Western Electricity Coordinating Council (WECC)[3] standards, the ISO is required to return flows on critical transmission paths to its system operating limit (SOL) within 30 minutes when a real-time contingency leads to the system being in an insecure state.

[2] NERC standard TOP-007-0 R2
[3] WECC standard TOP-007-WECC-1 R1

The ISO held a stakeholder process in 2008 to discuss the need for a mechanism to provide 30 minute operating reserves. During that process several stakeholders had suggested developing an additional 30 minute reserve product or increase procurement of 10 minute reserves. At the time, it was decided to continue using exceptional dispatch to position generation in case of a contingency while we gained more experience in the MRTU market. Since then the ISO has also incorporated the use of minimum online commitment (MOC) constraints. MOC constraints also ensure real-time reliability by committing resources in the day-ahead market to ensure system security can be maintained following a contingency in real-time. The constraint identifies the minimum generation capacity requirement, the set of generators that are effective in meeting the requirement, and the effectiveness of each generator where appropriate.[4] There are currently MOC constraints in effect for the Southern California Import Transmission (SCIT) system and for the California-Oregon Intertie (COI) during planned outage work.

IV. Scope of Initiative

This stakeholder initiative is narrowly focused on alternatives to exceptional dispatch and the MOC constraints in addressing contingencies such as the post-contingency 30 minute SOL requirement from NERC and WECC. While exceptional dispatch is used for other tariff-approved purposes, we are addressing the 30 minute need as the most important issue because this aligns with the results of the 2012 Stakeholder Initiatives Catalog and addresses a significant portion of the total instances of exceptional dispatch (as noted in the attached paper).

Given the technical nature of this issue, we have attached to this issue paper a proposed modeling enhancement framework with detailed explanations to help facilitate discussion with stakeholders. The major concepts discussed in the attachment were introduced to stakeholders at the last Market Surveillance Committee meeting on January 17, 2013 by Dr. Lin Xu of the ISO. As explained in the attached technical paper, *Preventive-Corrective Market Optimization Model*, the proposed framework will maintain reliability by modeling the ISO's post-contingency need with subsequent compensation to affected generators. The enhancements include the modeling of post-contingency preventive-corrective constraints and generation contingencies in the market optimization so that the need to position units to meet applicable reliability criteria would be incorporated into the market model. The constraints will reduce exceptional dispatches, replace some MOC constraints, provide greater compensation through LMPs and may likely result in a separate capacity payment for resources (both generation and demand response) that help meet the reliability standards. The ISO currently employs a form of preventive constraint in the market modeling. The proposed framework will create a new corrective component, which calculates a separate capacity payment when applicable.

Based on the technical paper, this issue paper seeks input from stakeholders on the constraint model framework as well as the appropriate level of and form of compensation under the preventive-corrective constraint. Specifically:

[4] http://www.caiso.com/Documents/TechnicalBulletin-MinimumOnlineCommitmentConstraint.pdf

1. Is it appropriate to provide compensation to generators for corrective capacity, and, if so, what is the appropriate basis to determine the amount of capacity compensated? For example, a resource is moved to a lower dispatch point in order to provide a larger upward corrective capacity after a contingency. Should the appropriate compensation be based on the movement (downward in this example) or the corrective capacity that is created (for the resource to eventually move upward)?
2. Should all resource capacity contributing to meeting the corrective action be compensated at the resource location locational marginal capacity price or should only those resources that demonstrate a lost opportunity receive compensation?
3. When there are multiple system operating limit constraints binding such that a resource is contributing to meeting the corrective capacity of multiple constraints, how should the resource be compensated considering its contribution to multiple constraints?

V. Next Steps

The ISO will discuss the issue paper with stakeholders during a teleconference to be held on March 26, 2013. Stakeholders should submit written comments by April 9, 2013 to ContingencyModeling@caiso.com.

Technical Paper to Facilitate Discussion with ISO's Stakeholders on:

Preventive-Corrective Market Optimization Model

March 11, 2013

Preventive-Corrective Market Optimization Model

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1. INTRODUCTION

In order to operate the power system reliably, the ISO must comply with the reliability standards set forth by North American Electric Reliability Corporation (NERC) and Western Electricity Coordinating Council (WECC). Among the standards are security standards that are related to contingencies. The most fundamental one is the N-1 standard that the system must not violate any operating limit after a transmission element outage. Currently, the ISO's market optimization is able to model the N-1 standard as preventive security constraints[1]. The term "preventive" means that the optimization will produce a pre-contingency dispatch that maintains post contingency system conditions within operating limits. There are other mandatory standards that would require re-dispatch to resolve post contingency operating limits. These standards include but are not limited to System Operating Limits (SOLs) and generation contingencies. The post contingency re-dispatches are "corrective" actions taken after the contingency occurs. By incorporating the corrective actions into the preventive model, we will have a more advanced market optimization model which co-optimizes the preventive pre-contingency dispatch and the corrective post contingency re-dispatch. This new model is called the preventive-corrective model, which can help the ISO systematically meet the N-1 standard and SOL standard. Without this preventive-corrective model currently, the ISO has to meet the SOL standard by enforcing minimum online capacity constraints (MOCs) or through manual exceptional dispatches. The ISO estimated the SOL related exceptional dispatches through operator logs[2], and showed the volume by month in 2012 in Figure 1. The percentage of SOL related exceptional dispatches varied from 21% to 77% month by month in 2012.

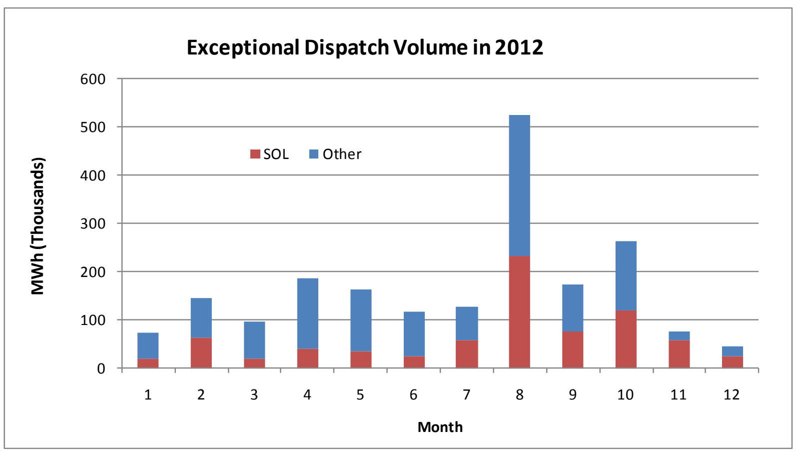

FIGURE 1: SOL RELATED EXCEPTIONAL DISPATCH VOLUME IN 2012

[1] Sometimes the impact of contingency is included in the pre contingency system operating limit (SOL), so as long as the pre contingency condition is within the SOL, the system is N-1 secure. In this case, a preventive optimization only models base case constraints for these SOLs.

[2] The numbers shown in Figure 1 may over or under estimate the actual volume of SOL related exceptional dispatches due to the complexity of analyzing operator logs.

This paper discussed how the ISO proposes to enhance the contingency model in the market optimization to handle the post contingency corrective actions. With the contingency model enhancement (CME), the market optimization advances from a pure preventive mode to a preventive-corrective mode, where both pre contingency dispatches and post contingency re-dispatches are co-optimized to meet the reliability standards. With the mandatory standards incorporated into the market optimization, the need for operators to exceptionally dispatch resources to their dispatchable Pmin or utilize MOCs to comply with the SOL standards is expected to significantly decrease.

2. PREVENTIVE-CORRECTIVE MARKET OPTIMIZATION

In this section, we will first review the power system security framework, and then discuss the modeling enhancement to the market optimization. For simplicity and ease of understanding, we use a linear lossless model throughout this paper. The ISO employs marginal loss model in the market optimization and full AC power flow in the network applications. How the preventive-corrective model works on top of the marginal loss model is excluded from this paper at the current stage. We can provide these details in the future when the need arises.

2.1 POWER SYSTEM SECURITY FRAMEWORK

The modeling enhancement is related to contingency. Contingency is the key concept in the power system security framework. It will be helpful to review the power system framework for a better understanding the modeling enhancement.

Power system security is the ability of the system to withstand disturbances without unduly impacting the service to the loads or its quality. In powers system operations, security assessment analyzes the vulnerability of the system to a set of contingencies, known as the contingency list. Contingencies are predefined disturbances/outages that have not occurred yet. The ISO maintains a contingency list that contains the most severe and/or most likely disturbances yet to occur. The classic power system security study framework is illustrated in Figure 2.

In the classic security study framework, power system can be operating under one of the three states:

- Normal state: when all loads are serviced without any operating limits being violated. Normal state can be further classified into two states:
    - Secure state: when the system is still under normal state post contingency,
    - Insecure state: when the system is under emergency state post contingency.
- Emergency state: when all loads are serviced with one or more operating limits being violated.
- Restorative state: when there is loss of load without any operating limits being violated.

A significant disturbance, e.g. loss a generator or a transmission element, may change the power system operating state. Power system state may change from secure to insecure, from insecure to emergency, and from emergency to restorative. These transitions are automatically triggered without human intervention.

System operators may take control actions that also change the power system states. The control actions either try to resolve a current violation of operating limits or prevent a violation after one of the contingencies occurs. They can be classified as follows:

- Restorative control transitions the system from restorative state to secure state.
- Corrective control transitions the system from emergency state to normal state.
- Preventive control transitions the system from insecure state to secure state.
- Controlled load shedding transitions the system from emergency state to restorative state.

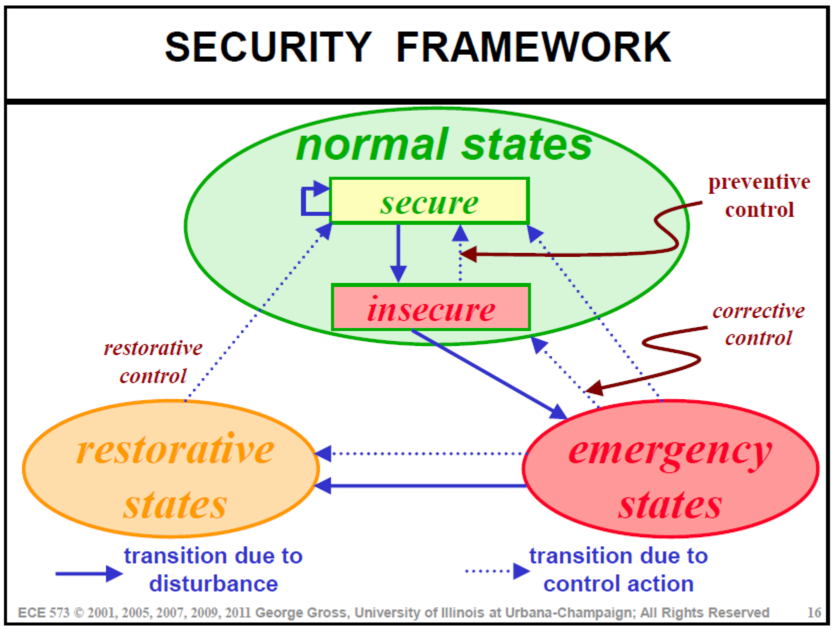

FIGURE 2: POWER SYSTEM SECURITY STUDY FRAMEWORK

Implementing the security framework into the Energy Management System (EMS) can provide the operators online security analysis functionality to closely monitor, assess and control system security.

2.2 PREVENTIVE MARKET OPTMIZATION

Section 2.1 discussed the security framework that is applicable to system operations. In this section, we will focus on the market aspect of helping power system security. As discussed in section 2.1, the preferred power system operating state is the secure state. In electricity markets, the market solution typically tries to operate the system under secure state. In order to achieve N-1 security, the market optimization, typically an optimal power flow (OPF) program or a unit commitment (UC) program, will consider every contingency in the contingency list, and include constraints of the immediate post contingency system conditions. The decision variables are the pre contingency unit commitments and dispatches. The post contingency system conditions are solely determined by the pre contingency dispatches and the post contingency network topology. If there is a violation after the contingency occurs, then the optimization will try to change the pre contingency dispatches to prevent it from occurring. That is why this model is called a preventive model.

It is easy to get confused about preventive model vs preventive control, because both have the term preventive, but they are different things. Preventive control is the actions operators take to transition the current system state from insecure state to secure state. Preventive model is the market optimizations model that produces a secure market solution for the future.

The structure of a typical preventive market optimization is as follows:

$$\min \sum_{i=1}^{n} C_i\left(P_i^0\right)$$

s.t.

$$g^0(P^0) = 0$$

$$h^0(P^0) \leq h^{0,max}$$

$$h^k(P^0) \leq h^{k,max}, \forall k = 1,2,\cdots,K$$

where

- the numeric superscript represents the case number with 0 being the based case, and 1, 2, up to K are the contingency cases,
- $g^0(\cdot)$ are the equality constraints.
- $h^k(\cdot), \forall k = 0,1,\cdots,K$ are the inequality constraints.

Market optimization has become more and more sophisticated with more and more constraints. Among these constraints, there are two crucial ones, namely the power balance constraint and the transmission constraint, because their associated Lagrangian multipliers are needed to calculate the locational marginal prices (LMPs).

The energy balance constraint is an equality constraint

$$\sum_{i=1}^{n} P_i^0 = \sum_{i=1}^{n} L_i$$

which says the total generation equals total load in a lossless model. Note that power balance constraint is only enforced in the base case, but not in any contingency case in the preventive model. This is because power injections do not change in any transmission contingency case immediately after the transmission contingency occurs, so the power balance in a transmission contingency case will be automatically satisfied if it is satisfied in the base case.

The transmission constraint is an inequality constraint, which says that for every case k, the power flow on a transmission line l has to be within its flow limit $\overline{FL}_l^k$. In a linear lossless model, the transmission constraint is

$$\sum_{i=1}^{n} SF_{l,i}^k \left(P_i^k - L_i\right) \leq \overline{FL}_l^k$$

where $SF_{l,i}^k$ is the shift factor from location i to constraint l in case k. Note that the transmission constraint is enforced for every case, including both the base case and contingency cases[3]. In addition, the shift factors are case specific , because the topology of the system changes from case to case.

Denote the Lagrangian multiplier for the power balance constraint by λ^0 and the Lagrangian multiplier for the transmission constraint by μ_l^k. The LMP at location i is

$$\lambda^0 + \sum_{k=0}^{K} \sum_{l=1}^{m} SF_{l,i}^k \cdot \mu_l^k$$

where the first term is the energy component, and the second term is the congestion component. Note that congestion in a contingency case will impact LMP in a similar way as congestion in the base case.

2.3 PREVENTIVE-CORRECTIVE MARKET OPTMIZATION

Assume the system operates at the N-1 secure state from the solution of the preventive market optimization. Suddenly, a system disturbance occurs. Because the pre contingency case is N-1 secure, the post contingency system is under a normal state without any violations. However, it may be insecure, and vulnerable to the next contingency yet to occur. NERC reliability standard NERC TOP-007-0 R2 and WECC reliability standard TOP-007-WECC-1 R1 require the ISO to transition the system back to a secure state within 30 minutes after the system disturbance. These reliability standards require the system to be not only N-1 secure, but also be able to reach another N-1 secure state 30 minutes after a contingency. After the disturbance occurs, IROLs and SOLs will receive new N-1 secure ratings. An example of SCIT is illustrated in Figure 3.

[3] Transmission constraints for contingency cases are often referred as security constraints.

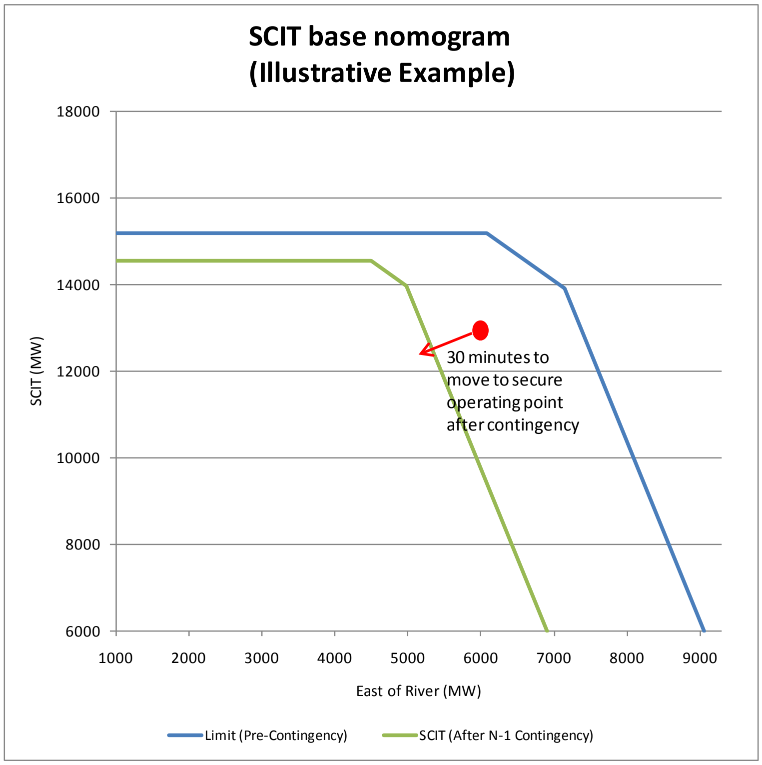

FIGURE 3: SCIT PRE CONTINGENCY RATING AND POST CONTINGENCY RATING

If all elements are in service, the normal SCIT nomogram limit is the blue curve. If the system operates inside the blue curve, it is N-1 secure. Assume that pre contingency, the system is operating at the red dot with 13,000 MW flow on SCIT and 6,000 MW flow on East of River. Suddenly, one of the SCIT lines trips. With one element out of service, the new SCIT nomogram limit is the green curve. To comply with the NERC and WECC standards, the ISO needs to bring the operating point from the red dot to inside the green curve in 30 minutes such that the system operates under new N-1 secure state 30 minutes after the disturbance. In addition, it is expected that the re-dispatch function execution set up, run time, publishing results, and resources start ramping may take some time (e.g. few minutes) to complete after the disturbance occurs. Therefore, we need to reduce the 30-minute timeframe to the practical available response time in the preventive-corrective model. In this paper, we will assume this time to be *T*. The corrective re-dispatch may or may not involve operating reserve deployment depending on the relevant NERC and WECC reliability standards.

2.3.1 PREVENTIVE-CORRECTIVE OPTIMIZATION MODEL

A preventive-corrective market optimization can explicitly model the timeframe to re-dispatch resources to comply with the new limit. The structure of a preventive-corrective model is as follows.

$$\min \sum_{i=1}^{n} C_i(P_i^0)$$

s.t.

$$g^0(P^0) = 0$$

$$h^0(P^0) \le h^{0,max}$$

$$h^k(P^0) \le h^{k,max}, \forall k = 1,2,\cdots,K$$

$$g^{kc}(P^0 + \Delta P^{kc}) = 0, \forall kc = K+1, K+2, \cdots, K+KC$$

$$h^{kc}(P^0 + \Delta P^{kc}) \le h^{kc,max}, \forall kc = K+1, K+2, \cdots, K+KC$$

$$\Delta P^{kc} \le RCU(P^0), \forall kc = K+1, K+2, \cdots, K+KC$$

$$\Delta P^{kc} \le RCD(P^0), \forall kc = K+1, K+2, \cdots, K+KC$$

where

- $kc = K+1, K+2, \cdots, K+KC$ are contingencies that require corrective re-dispatch,
- $RCU(P^0)$ is the upward ramping capability from the base case P^0 in the given timeframe T,
- $RCD(P^0)$ is the downward ramping capability from the base case P^0 in the given timeframe T.

Compared with the preventive model, the preventive-corrective model adds corrective contingency cases indexed by *kc*. The corrective contingency cases allow re-dispatching resources after the contingency occurs. There are ramp limitations on the re-dispatches from the base case, such that the re-dispatches ΔP^{kc} can be achieved within the given timeframe. Note that the re-dispatches from the base case , ΔP^{kc}, are actually corrective capacity, not real re-dispatches. Note that there is no dispatch cost associated with ΔP^{kc} in the objective function. Before the contingency occurs, the expected contingency case re-dispatch cost depends on the probability of contingency happens, which is close to zero. Therefore, even if we want to consider the contingency case dispatch cost according to probability of occurring, it will be close to zero. When the contingency occurs, ΔP^{kc} is a feasible solution to comply with the new limit. However, the actual re-dispatches may be different from ΔP^{kc}, as the energy cost would be considered in the actual re-dispatch,. The preventive-corrective model is only concerned about the feasibility of capacity to comply with the post contingency new limit, but not the energy cost of post contingency re-dispatch.

We will specifically discuss the power balance constraint and transmission constraint in the corrective contingency cases indexed by *kc*. Recall that in the preventive model, there is no power balance constraint for a contingency case, because the power balance condition remains the same immediately after the transmission contingency occurs. In the preventive-corrective model, we allow a timeframe to re-dispatch resources, and we evaluate the system at time *T* after the actual time at which the contingency occurs. In order to make sure the re-dispatches do not violate power balance, we enforce a power balance constraint for each corrective transmission line contingency case *kc* as follows:

$$\sum_{i=1}^{n} \Delta P_i^{kc} = 0$$

Denote the Lagrangian multiplier for the power balance constraint for corrective contingency case *kc* by λ^{kc}.

The transmission constraint in the corrective contingency case *kc* says the power flow on a transmission line *l* has to be within its flow limit $\overline{FL}_l^{kc}$ after the corrective re-dispatches. In a linear lossless model, for each corrective contingency case *kc*, the transmission constraint is

$$\sum_{i=1}^{n} SF_{l,i}^{kc}\left(P_i^0 + \Delta P_i^{kc} - L_i\right) \le \overline{FL}_l^{kc}$$

Note that in the preventive-corrective model, the transmission constraint is enforced for every case, including the base case, normal contingency cases indexed by *k*, and corrective contingency cases indexed by *kc*. Denote the Lagrangian multiplier for the transmission constraint for corrective contingency case *kc* by μ_l^{kc}.

If the pure preventive model market solution has enough corrective capacity to resolve any possible post contingency violation within the specified timeframe, the system wide λ^{kc} and shadow price of the post contingency transmission constraint μ_l^{kc} are zeroes, because there is no cost associated with corrective capacities in the objective function. If the pure preventive model market solution does not have enough corrective capacity to resolve the post contingency violation within the specified timeframe, then the preventive-corrective model will adjust the pre-contingency dispatch to create more corrective capacity and/or reduce the pre contingency flow such that the violation can be resolved within the timeframe after contingency occurs. In this case, because the pre contingency base case dispatch cost is included in the objective function, the marginal dispatch adjustment cost due to resolving the post contingency violation will manifest itself in λ^{kc} and μ_l^{kc}.

2.3.2 PREVENTIVE-CORRECTIVE MODEL COMPENSATION

For the base case, the LMP for energy dispatch at location *i* is

$$\lambda^0 + \sum_{k=0}^{K}\sum_{l=1}^{m} SF_{l,i}^{k} \cdot \mu_l^{k} + \sum_{kc=K+1}^{K+KC}\sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc}$$

The structure of the LMP in the preventive-corrective model is the same as the LMP in the preventive model except that the preventive-corrective model has included more contingencies, i.e. the corrective contingencies indexed by *kc*. The LMP breaks down to the energy component λ^0, and the congestion component $\sum_{k=0}^{K}\sum_{l=1}^{m} SF_{l,i}^{k} \cdot \mu_l^k + \sum_{kc=K+1}^{K+KC}\sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc}$. Note that the LMP congestion component includes congestion impact from every case. A resource will receive energy compensation at the LMP.

Because LMP includes congestion impact from every case, the local market power mitigation triggered by LMP non-competitive congestion component works effectively in the preventive-corrective model. Regardless of whether a binding constraint is uncompetitive in the base case, in a normal contingency case, or in a corrective contingency case, the potential impact will manifest itself in the LMP non-competitive congestion component so that the market power mitigation is able to mitigate the resources that are potentially benefiting from the locally uncompetitive constraint.

As discussed in the previous section, the marginal values of corrective capacities depend on λ^{kc} and μ_l^{kc}, and thus depend on location. Therefore, the corrective capacity will have a locational marginal capacity price (LMCP). The LMCP at location *i* for case *kc* is

$$LMCP_i^{kc} = \lambda^{kc} + \sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc}$$

By providing the corrective capacity, a resource may be dispatched out of merit, and thus have an opportunity cost for the corrective capacity. The marginal opportunity cost will be naturally reflected in the LMCP at the optimal solution.

As the corrective action and capacity is a new concept, additional consideration is needed regarding how the LMCP should be used for compensating resources. There are at least two questions regarding compensation using the LMCP that require further consideration:

> 1) Should all resource capacity contributing to meeting the corrective action be compensated at the resource location LMCP or should only those resources that demonstrate a lost opportunity be compensated?
>
> 2) When there are multiple SOL constraints binding such that a resource is contributing to meeting the corrective capacity of multiple constraints, how should the resource be compensated considering its contribution to multiple constraints?

2.4 EXAMPLES

This is a two-node example with three generators. Branch A-B has two circuits. Assume $K = 0$, and the $KC = 1$. Branch A-B has pre contingency SOL of 700 MW with both circuits in service, which is N-1 secure. If one of the two A-B circuits trips, and next N-1 secure SOL for branch A-B is 350 MW. The load is 1200 MW at node B.

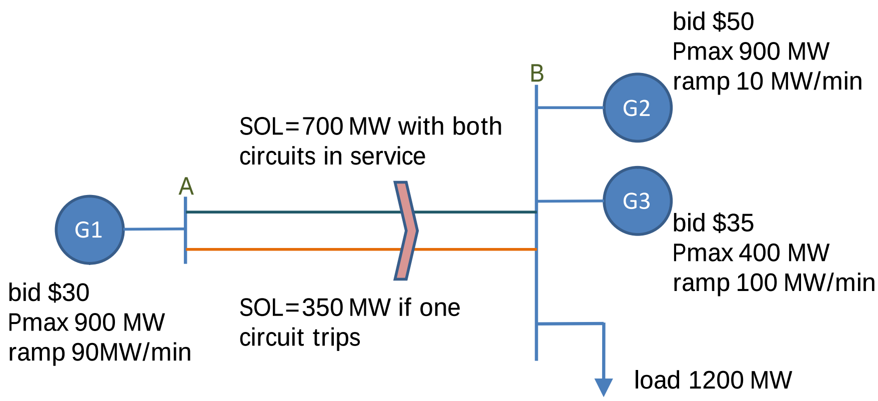

FIGURE 4: A TWO-NODE SYSTEM WITH THREE GENERATORS

We will compare the following models:

- Weak preventive model: N-1 secure, but may not be able to meet the post contingency limit within 30 minutes after the contingency occurs (or assume 20 minutes after the re-dispatch instruction) without using MOCs or exceptional dispatch. This is the model that the ISO currently uses.
- Strong preventive model: N-2 secure, enforce the post contingency rating in the pre contingency dispatch.
- Preventive-corrective model: not only N-1 secure, but also meet the post contingency rating 30 minutes after contingency occurs (or assume 20 minutes after the re-dispatch instruction).

The weak preventive solution is listed in Table 2. The total generation cost is 40,000. If the contingency occurs, the 700 MW flow on branch 2-3 will exceed the next SOL 350 MW, which protects again the next contingency. The weak preventive model produces N-1 secure solution, but may not be able to meet the new limit 30 minutes after the contingency occurs.

Generator	Dispatch	LMP^{EN}	LMP^{CONG}	LMP	Bid cost	Revenue	Profit
G1	700	$50	–$20	$30	$21,000	$21,000	$0
G2	100	$50	$0	$50	$5,000	$5,000	$0
G3	400	$50	$0	$50	$14,000	$20,000	$6,000
total	1,200	N/A	N/A	N/A	$40,000	$46,000	$6,000

TABLE 1: WEAK PREVENTIVE SOLUTION

To meet the next contingency SOL, one could enforce the new post contingency limit (350 MW) in the pre contingency dispatch even if the first contingency has not occurred yet. This is called the strong preventive model, which protects against N-2 contingency. The solution of strong preventive model is listed in Table 3. The total generation cost is $47,000. The strong preventive solution is much more costly than the weak preventive solution. The cost difference $47,000–$40,000=$7,000 is the cost to resolve the post contingency violation with the N-2 secure strong preventive model. Because it is often very costly to maintain N-2 secure, it is not a common reliability standard in power system operations. Instead, NERC and WECC allow certain timeframe (no more than 30 minutes) to reach another N-1 secure state after one contingency occurs. As will be shown in the preventive-corrective case, the solution will be more economic than the strong preventive case.

Generator	Dispatch	LMP^{EN}	LMP^{CONG}	LMP	Bid cost	Revenue	Profit
G1	350	$50	–$20	$30	$10,500	$10,500	$0
G2	450	$50	$0	$50	$22,500	$22,500	$0
G3	400	$50	$0	$50	$14,000	$20,000	$6,000
total	1,200	N/A	N/A	N/A	$47,000	$53,000	$6,000

TABLE 2: STRONG PREVENTIVE SOLUTION

In the preventive-corrective model, in addition to the N-1 secure limit (700 MW), we allow 30 minutes after the contingency occurs (or assume 20 minutes after the re-dispatch instruction) to meet the next SOL 350 MW. The preventive-corrective solution is listed in Table 4. When the A-B SOL is reduced by 350 MW in the post contingency case, G2 and G3 need to ramp up the same amount in 20 minutes in order to meet load and provide counter flow. G2 has 10 MW/minute ramp rate, and can only ramp 200 MW in 20 minutes. The rest 150 MW ramp needs to come from G3. In order to provide this 150 MW ramp, G3 needs to be dec'ed 150 MW in the pre contingency case.

	Energy					Corrective Capacity		
Gen	P^0	LMP	Bid cost	Revenue	Profit	ΔP^{kc}	LMCP | opportunity cost	Profit LMCP | opportunity cost
G1	700	$30	$21,000	$21,000	$0	–350	$0 | $0	$0 | $0
G2	250	$50	$12,500	$12,500	$0	200	$15 | $0	$3,000 | $0
G3	250	$50	$8,750	$12,500	$3,750	150	$15 | $15	$2,250 | $2,250
total	1,200	N/A	$42,250	$46,000	$3,750	0	N/A	$5,250 | $2,250

TABLE 3: PREVENTIVE-CORRECTIVE SOLUTION AND LMCP COMPENSATION

Bus	λ^0	μ_{AB}^0	λ^1	μ_{AB}^1	LMP1^{CONG}	LMCP1	LMP^{CONG}	LMP
A	$50	$–5	$15	$–15	$–15	$0	$–20	$30
B	$50	$–5	$15	$–15	$0	$15	$0	$50

TABLE 4: PRVENTIVE-CORRECTIVE LMP AND LMCP CALCULATION

The LMPs and LMCPs are listed in Table 4, with detailed breakdown in Table 5. As described in section 2.3, for each corrective contingency case, we calculate a set of case specific LMCPs. The LMP for the base case dispatch has an energy component λ^0, and a congestion component $SF_{AB,i}^0 \cdot \mu_{AB}^0 + SF_{AB,i}^1 \cdot \mu_{AB}^1$, the sum of shift factors times shadow prices over all cases. Take G3 as an example. The base case λ^0 is $50, and G3's congestion component is $0 \cdot (-5) + 0 \cdot (-15)$ =$0, so G3's LMP is $50. In this example the LMCP to compensate the corrective capacity 150 MW is equal to $\lambda^1 + SF_{AB,B}^1 \cdot \mu_{AB}^1 = 15 + 0 \cdot (-15) = \$15$. In this case, the LMCP reflects G3's the opportunity cost, which equals to the LMP minus its energy bid ($50 –$35 = $15). Without this capacity payment, G3 is under compensated because it is dec'ed to help meet the post contingency constraint, and has lost profit from the energy dispatch. It is a common misperception that bid cost recovery can make whole for the opportunity cost, so the capacity payment is unnecessary. Bid cost recovery only makes whole for dispatched energy, but not for any opportunity cost of undispatched energy. In this example, bid cost recovery cannot make whole for G3's 150 MW corrective capacity. That is why we need the capacity payment to prevent G3 from being under compensated by holding its capacity for corrective contingency.

Both the LMCP compensation option and the opportunity cost compensation option will pay G3 150*15=$2,250 for it corrective capacity. Under the LMCP compensation, G2 will also receive the same LMCP as G3, because they are located at the same location, and their corrective capacities have the same marginal value. In contrast, under the opportunity cost compensation, G2 will not receive payment for its corrective capacity 200 MW, because its opportunity cost is zero.

The total generation cost of the preventive-corrective solution is $42,250. It resolves the post contingency constraint at the cost $42,250–$40,000 = $2,250. This is much more economic than the strong preventive solution, which incurs additional cost of $7,000 compared with the weak preventive case. The relationship between these three models is summarized in Table 6.

Model properties	Weak preventive	Preventive-corrective	Strong preventive
30-minute SOL compliance	Not modeled	Accurately modeled	Over modeled
Total bid cost	Lowest	Medium	Highest

TABLE 5: COMPARISON OF DIFFERENT OPTIMIZATION MODELS

Now we consider another scenario with G3 out of service. The preventive-corrective solution is listed in Table 7. Because G2 has maximum 200 MW corrective capacity limited by its ramp rate, G1 and G2 can resolve at most 200 MW of overload in 20 minutes. The optimization dispatches G1 at 550 MW in the base case, which is 200 MW above the post contingency 350 MW SOL. In this case, the optimization cannot create more corrective capacity, so it reduces the base case flow. As a result, the transmission constraint is not binding in the base case, but it is binding in the contingency case at 350 MW. Also, the total generation cost increases to $49,000. G2's corrective capacity has a marginal value, because if there is 1 more MW corrective capacity, the base case flow can be increased by 1 MW, and result in a cost saving of $20 by dispatching up G1 1 MW at $30 and dispatching G2 down 1 MW at $50. In this case, LMCP reflects the contingency case marginal congestion cost impact.

As posited in the Section 2.3.1, there may be different ways to consider compensation. Under the LMCP compensation, G2 will receive its capacity payment 200 MW * $20=$4,000. This provides incentive for market participants to improve ramping capability at location B. In contrast, under the opportunity cost compensation, G2 will not receive payment for its corrective capacity, because its opportunity cost is zero.

	Energy					**Corrective Capacity**		
Gen	P^0	LMP	Bid cost	Revenue	Profit	ΔP^{kc}	LMCP | opportunity cost	Profit LMCP | opportunity cost
G1	550	$30	$16,500	$16,500	$0	–200	$0 | $0	$0 | $0
G2	650	$50	$32,500	$32,500	$0	200	$20 | $0	$4,000 | $0
G3	0	$50	$0	$0	$0	0	$20 | $0	$0 | $0
total	1,200	N/A	$49,000	$49,000	$0	0	N/A	$4,000 | $0

TABLE 6: PREVENTIVE-CORRECTIVE SOLUTION AND LMCP COMPENSATION WITH G3 OUT OF SERVICE

Bus	λ^0	μ_{AB}^0	λ^1	μ_{AB}^1	$LMP1^{CONG}$	LMCP1	LMP^{CONG}	LMP
A	$50	$0	$20	$–20	$–20	$0	$–20	$30
B	$50	$0	$20	$–20	$0	$20	$0	$50

TABLE 7: PRVENTIVE-CORRECTIVE LMP AND LMCP CALCULATION WITH G3 OUT OF SERVICE

3. SUMMARY

The preventive-corrective model co-optimizes the pre contingency preventive dispatch and the post contingency corrective re-dispatch. This new model will help the ISO comply with the NERC and WECC post contingency SOL by an economic market solution, and will reduce manual exceptional dispatches and MOCs that are currently used for the same purpose. In order to meet the next SOL, the preventive-corrective model may produce a solution that creates more corrective capacity or reduces the base case flow. The impact of corrective contingencies will be reflected in base case LMPs for energy. In addition, the preventive-corrective model also introduces the concept of locational marginal capacity price (LMCP), which is the marginal value of corrective capacity. LMCP may reflect opportunity cost due to out of merit dispatch or marginal congestion cost impact in the contingency case. Additional consideration is needed regarding how the LMCP should be used for compensating resources. Some questions to consider further are:

> 1) Should all resource capacity contributing to meeting the corrective action be compensated at the resource location LMCP? Or, should only those resources that demonstrate a lost opportunity be compensated?
>
> 2) When there are multiple SOL constraints binding such that a resource is contributing to meeting the corrective capacity of multiple constraints, how should the resource be compensated considering its contribution to multiple constraints?

This preventive-corrective model enhancement is a general framework, which can also help the ISO deal with other type of modeling challenges, such as generator contingency, and ancillary service deliverability and recovery.

APPENDIX: NOMENCLATURE

i: index for a location

l: index for a transmission constraint

n: total number of nodes in the system

m: total number of transmission constraints in the system

k: index for normal (preventive) contingency

kc: index for corrective contingency

K: total number of normal (preventive) contingencies

KC: total number of corrective contingencies

P: generation dispatch MW

L: load

$\overline{FL}$: transmission constraint limit

$C(\cdot)$: generation bid cost function

SF: shift factor

ΔP^{kc}: corrective capacity from base case dispatch

$RCU(\cdot)$: upward ramping capability

$RCD(\cdot)$: downward ramping capability

$g(\cdot)$: equality constraint

$h(\cdot)$: inequality constraint

λ: system marginal energy cost

μ: constraint shadow price