California ISO

Contingency Modeling Enhancements

CRR Alternatives Discussion Paper

March 3, 2016

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Revision History

Date	Revision
01/28/2016	Initial Release
02/03/2016	Correction to pro-ratio equations in Sections 5.2.2 and 5.2.3
03/03/2016	Further correction to pro-ratio equations in Sections 5.2.2 and 5.2.3. Add clearing prices to examples in Section 5.2 and clarify example information headers in Section 5.2.

1. Introduction

In early 2013, the ISO began the Contingency Modeling Enhancements initiative to explore more efficient ways to maintain reliability and reduce reliance on exceptional dispatch. The issue the ISO addresses is the need to position available resources on the system in a manner that allows the ISO to successfully return the system to a secure state after a contingency occurs and within 30 minutes.

In mid-2014, the ISO committed to market participants to develop a prototype of the preventive-corrective constraint to provide a proof of concept by testing it on actual production save cases. The ISO continues to test the prototype implementation with production save cases and will share prototype results with stakeholders in February 2016.

During prototype development and testing, the ISO policy team performed a review of the proposals seeking the cause of the apparent need for uplift in the examples provided; the need for uplift was counter-intuitive to the notion of pricing the constraints into the market. The ISO found that the CRR market requires complimentary enhancements to align with the proposed changes to the day-ahead market. A CRR market that does not recognize the limited post-contingency transmission capability would over-allocate CRRs to market participants leading to revenue inadequacy and additional uplift requirements.

In its third revised straw proposal, the ISO proposed one method to enhance the CRR market/settlement to correct the over-allocation of CRRs to market participants consistent with the proposed preventive-corrective day-ahead market design changes. The ISO received valuable feedback from market participants through its stakeholder meeting, the market surveillance committee meeting, and written comments in response to the third revised straw proposal.

The purpose of this discussion paper is to explore various alternatives to align the CRR market with the proposed changes to the day-ahead market and protect the integrity of the CRR product.

2. Stakeholder engagement

The schedule for stakeholder engagement is provided below and targets the June 2016 Board of Governors meeting for implementation in fall of 2017.

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	Straw proposal posted
Wed 5/22/13	Stakeholder meeting
Tue 5/28/13	Stakeholder comments due on straw proposal
Tue 6/18/2013	Revised straw proposal posted
Tue 6/25/2013	Stakeholder call
Mon 7/1/2013	Stakeholder comments due
Thu 3/13/14	Second revised straw proposal posted
Thu 3/20/14	Stakeholder call
Thu 3/27/14	Stakeholder comments due on second revised straw proposal
Mon 11/20/15	Third revised straw proposal posted
Mon 12/10/15	Stakeholder call
Tue 12/22/15	Stakeholder comments due on third revised straw proposal
Wed 1/28/16	CRR Alternatives Discussion Paper posted
Thu 2/11/16	MSC meeting; discuss CRR alternatives
Wed 2/19/16	Stakeholder comments due on CRR Alternatives Discussion Paper
Wed 2/24/16	Prototype Technical Analysis Results posted
Wed 3/8/16	Stakeholder meeting
Wed 3/16/16	Stakeholder comments due on Prototype Technical Analysis Results
Wed 3/23/16	Publish fourth revised straw proposal
Wed 3/30/16	Stakeholder meeting
Wed 4/6/16	Stakeholder comments due on fourth revised straw proposal
Wed 4/20/16	Publish draft final proposal
Wed 4/27/16	Stakeholder call
Wed 5/11/16	Stakeholder comments due on draft final proposal
Tue-Wed 6/28/16-6/29/16	June BOG
Fall 2017	Implementation

3. Background

The ISO provides a summary of the contingency modeling enhancements initiative proposal along with an example to aid the discussion later.

3.1. Summary of proposed market design changes

3.1.1. Preventive-corrective market optimization

Assume the system operates in an 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. The ISO must transition the system back to a secure state within 30 minutes after the system disturbance. The system must not only be N-1 secure (below the original SOL rating), but also be able to reach another N-1 secure state (below the new SOL rating) 30 minutes after a contingency. An example of SCIT is illustrated in Figure 1.

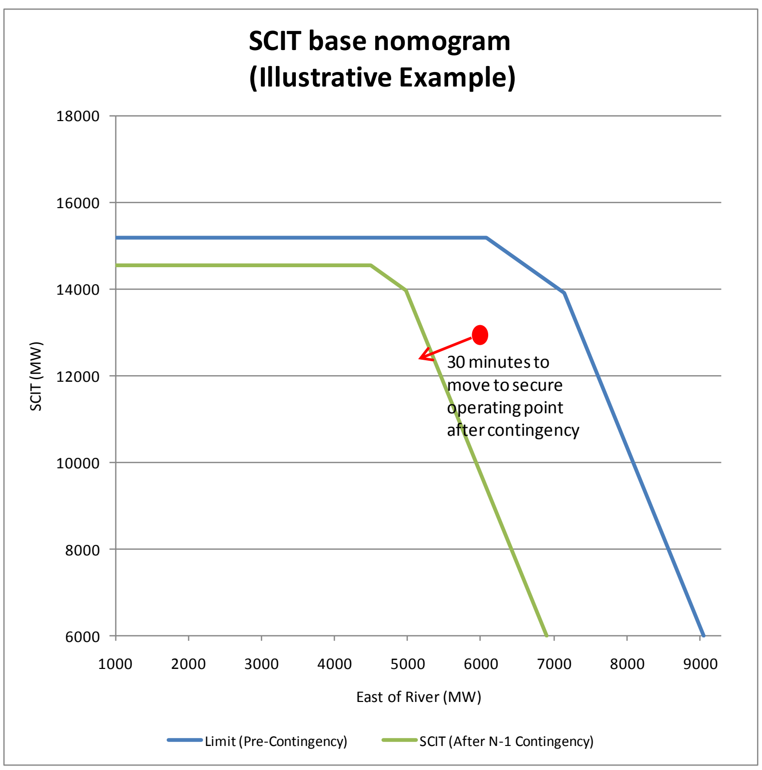

Figure 1: SCIT Pre-contingency rating and post-contingency rating

If all elements are in service, the normal SCIT nomogram limit (SOL) 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. The ISO must 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 20 minutes and denote it as *T*.

3.1.2. 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.

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

s.t.

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

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

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

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

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

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

where

- $kc = K+1, K+2, \cdots, K+KC$ are contingencies that involve 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. The re-dispatch capability from the base case dispatch is ΔP^{kc}, which is limited by the resource's ramp rate and the given timeframe. 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. This is because the probability that a contingency would occur is close to zero, and thus the expected re-dispatch cost is also close to zero.

We will specifically discuss the power balance constraint and transmission constraint in the corrective contingency cases indexed by *kc*. 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 a 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 power balance constraint for the base case is energy constraints. In contrast, the new power balance constraints for corrective contingencies are capacity constraints. If there is transmission constraint violation in any contingency case, the optimization may resolve the violation with corrective capacities. The capacity balance constraints are needed to make sure the established energy balance in the base case is not adversely affected in the transmission congestion management process, such as resulting in involuntary load shedding. The capacity balance constraints do not directly affect the feasibility of the energy balance constraint in the base case, because the energy dispatches do not participate in the capacity balance constraints; however, the total capacity dispatched in the base case and reserved as corrective capacity ($P^0 + \Delta P^{kc}$) must be within the applicable resource capacity limits (e.g., lower and upper operating limits), considering also ancillary services awarded in the base case.

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

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

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 already has enough corrective capacity to resolve any possible post contingency violation within the given timeframe, the system wide λ^{kc} and shadow price of the post contingency transmission constraint μ_l^{kc} are zeroes. This is because there is no cost associated with corrective capacities in the preventive-corrective model objective function, and thus the preventive-corrective model will produce the same pre-contingency dispatch as the pure preventive model. 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 (base case) 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}.

3.1.3. 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.

The marginal values of corrective capacity 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

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

The LMCP may reflect

- a resource's opportunity cost of being dispatched out of merit,
- the marginal congestion cost saving, and/or
- the marginal capacity value to null the incentive of uninstructed deviations in order to support the dispatch.

3.2. Example

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 trip, and next N-1 secure SOL for branch A-B is 350 MW. The load is 1200 MW at node B.

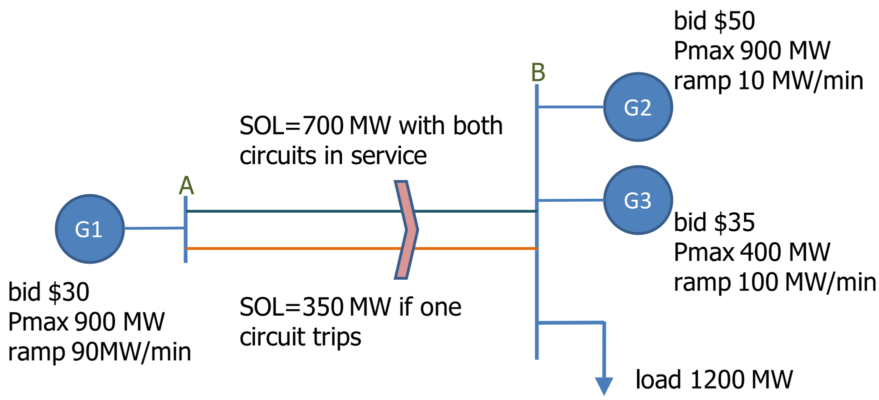

Figure 2: A two node system with three generators

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 of 350 MW. The preventive-corrective solution is listed in Table 1. 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 must come from G3. In order to provide this 150 MW ramp, G3 needs to be dec'ed 150 MW in the pre contingency case.

The LMPs and LMCPs are listed in Table 1. 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 $SF^0_{AB,i} \cdot \mu^0_{AB} + SF^1_{AB,i} \cdot \mu^1_{AB}$, 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 $\lambda^1 + SF^1_{AB,B} \cdot \mu^1_{AB} = 15 + 0 \cdot (-15) = \$15$. 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 reduced energy dispatch.

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. Providing the G2 the LMCP payment gives the correct incentive for infra marginal resources to improve the ramp rate. If the ramp rate is improved by, say 0.1 MW/minute, G2 could be awarded 0.1*20 = 2 MW of more corrective capacity, and be paid 2*15 = $30.

Table 1
Preventive-corrective solution and LMCP compensation

Energy in base case								
Generator	P^0	λ^0	SF^0_{AB}	μ^0_{AB}	LMP	Bid cost	Revenue	Profit
G1	700	$50	1	$–5	$30	$21,000	$21,000	$0
G2	250	$50	0	$–5	$50	$12,500	$12,500	$0
G3	250	$50	0	$–5	$50	$8,750	$12,500	$3,750
Corrective Capacity in contingency *kc*=1								
Generator	ΔP^1	λ^1	SF^1_{AB}	μ^1_{AB}	$LMCP^1$	Bid cost	Revenue	Profit
G1	–350	$15	1	$–15	$0	$0	$0	$0
G2	200	$15	0	$–15	$15	$0	$3,000	$3,000
G3	150	$15	0	$–15	$15	$0	$2,250	$2,250

A summary of the preventive-corrective model settlement is provided below.

Table 2
Preventive-corrective model settlement

Resource	**MW**	**LMP**	**Bid cost**	**Revenue**	**Profit**	**Uplift**
Total gen energy	1,200	N/A	$42,250	$46,000	$3,750	
Total gen capacity	350	N/A	N/A	$5,250	$5,250	
Load	1,200	$50	N/A	–$60,000		

4. The day-ahead market, congestion costs, and corrective capacity revenue

The ISO reviewed previous proposals seeking the cause of the apparent need for uplift in the examples provided; the need for uplift was counter-intuitive to the notion of pricing the constraints into the market.

While achieving transmission feasibility through the market, the preventive-corrective model produces LMPs that when paid by load serving entities include congestion revenues associated with the available transmission capability in the base case and the post-contingency cases. Payments also include revenues required to pay for the corrective capacity that enables the higher flows in the post-contingency case. The day-ahead market alone does not require additional uplift because it collects all revenues required to pay for the corrective capacity from load. Corrective capacity payments are completely revenue adequate because they are paid for through energy schedules; when load pays the LMP at a node, the associated revenues include a corrective capacity payment.

Currently, the CRR market does not model the proposed post-contingency constraints. The examples provided in previous proposals did not attempt to change the CRR market and instead showed what the resulting CRR revenues would have been if left unchanged; this is what leads to the uplift requirements. The ISO found that the CRR market requires complimentary enhancements to align with the proposed changes to the day-ahead market. A CRR market that does not recognize the limited post-contingency transmission capability would over-allocate CRRs to market participants leading to revenue inadequacy and uplift requirements.

There are several ways to ensure that the Contingency Modeling Enhancements initiative does not exacerbate revenue inadequacy in the CRR market due to a CRR market that does not additionally model the new post-contingency constraints introduced in this initiative. This particular revenue inadequacy is introduced solely due to this initiative, and as such should be resolved as part of this initiative.

4.1. Achieving transmission feasibility

In today's market design, congestion costs on transmission paths are shown through the differences in LMPs when energy schedules and power flow cause transmission constraints to bind. Typically the LMP accurately represents the cost of this congestion. However, in certain circumstances, the ISO relies on exceptional dispatch (ED) and minimum online commitments (MOC) to support the operation of the transmission path at greater flows than would be feasible without the exceptional dispatch or minimum online commitment. When the ISO relies on ED or MOC, the LMPs do not fully reflect all of the congestion costs because the exceptional dispatches or minimum online commitments are compensating for constraints not modeled in the market and are paid through uplift. These un-modeled additional constraints are essentially the corrective constraints the ISO proposes to enforce.

When we fully model the preventive-corrective constraints we expose this "hidden" cost of preventive-corrective action through the kc shadow price. When the constraint binds and corrective capacity is procured, it is to maintain transmission feasibility instead of using exceptional dispatches and minimum online commitments to maintain transmission feasibility. The energy transactions that contribute to flows on the kc contingency constraints above the kc limit, and so drive the procurement of corrective capacity, are using transmission service provided by the corrective capacity. A schedule that does not contribute to flow on a given kc contingency constraint (including load schedules) does not use transmission service provided by corrective capacity and does not generate rents from the kc constraint.

Let us use example from above to illustrate infeasible transmission dispatch and associated shadow prices versus a feasible transmission dispatch and associated shadow prices. Today's market would produce the weak-preventive dispatch:

Energy in base case					
Resource	P^0	λ^0	SF^0_{AB}	μ^0_{AB}	LMP
G1	700	$50	1	-$20	$30
G2	100	$50	0	-$20	$50
G3	400	$50	0	-$20	$50

Table 3: Energy in base case from example

The weak-preventive dispatch yields $20/MWh in congestion from A to B as calculated under the existing market model. This dispatch is not actually transmission feasible because the operator will have to intervene using exceptional dispatch to position resources G2 and G3 to ensure that the transmission system is capable of returning to a secure state to meet post contingency limits. The cost of transmission feasibility is not incorporated into the market through LMPs and is instead only in the cost of exceptional dispatch.

At this dispatch, one can see that we are unable to meet the N-1-1 criteria within 30 minutes.

- This is a transmission infeasible solution.
- Operators intervene via exceptional dispatch to make it feasible; this results in uplift.
- Operators reserve capacity but the value of the capacity is not exposed.

When we actually model the constraints that allow transmission feasibility, the cost of transmission feasibility is now exposed in the corrective constraint shadow price. Let us use the example from above to illustrate. Recall the preventive-corrective dispatch:

Energy in base case					
Resource	P^0	λ^0	SF^0_{AB}	μ^0_{AB}	LMP
G1	700	\$50	1	-\$5	\$30
G2	250	\$50	0	-\$5	\$50
G3	250	\$50	0	-\$5	\$50
Corrective capacity in contingency case = kc					
Resource	ΔP^1	λ^1	SF^1_{AB}	μ^1_{AB}	LMCP
G1	-350	\$15	1	-\$15	\$0
G2	200	\$15	0	-\$15	\$15
G3	150	\$15	0	-\$15	\$15

Table 4: Preventive-corrective market results

The preventive-corrective dispatch yields $5/MWh in congestion from A to B in the base case and $15/MWh in congestion from A to B due to the corrective constraint. This dispatch is transmission feasible because it respects the post-contingency 350 MW path limit; the operator will not have to intervene using exceptional dispatch. The cost of transmission feasibility for flows above the kc limit is exposed in the corrective constraint shadow price.

At this dispatch, one can see that we are able to meet the N-1-1 criteria within 30 minutes.

- This is a transmission feasible solution.
- Operators do not have to intervene via exceptional dispatch to make it feasible; no uplift required.
- Capacity is reserved and the value of the capacity is exposed.

Under either model discussed above, in reality, 700 MW of flow is feasible in the base case, but only 350 MW of flow is feasible in the post-contingency case; the preventive-corrective model respects both constraints while the weak preventive model only respects the former.

4.2. Congestion rent & corrective capacity revenue

The goal of the initiative is to achieve a transmission feasible dispatch without relying on exceptional dispatch or minimum online commitments. In earlier proposals we compared achieving transmission feasibility through a strong preventive model versus a preventive-corrective model. Both models would yield a transmission feasible solution without using ED or MOC, but the strong preventive model would rely on a very restricted transmission system. The preventive-corrective model maximizes the use of the transmission system, which is why the ISO proposes this approach.

The preventive-corrective model changes the LMP formulation. It can be shown that the congestion component, when viewed in terms of the flow-related revenue of energy scheduled to the node (that is the LMP multiplied by the generation at the node minus the load at the node), includes the revenue required to pay the corrective capacity.[1]

LMP_i flow related revenue =

$$\underbrace{\underbrace{\sum_{k=0}^{K}\sum_{l=1}^{m}\left[\mu_l^{k*}\cdot F_l^{k,\max}\right]}+\underbrace{\sum_{kc=K+1}^{KC}\sum_{l=1}^{m}\left[\mu_l^{kc*}\cdot F_l^{kc,\max}\right]}}_{\text{congestion rent collected}}-\underbrace{\sum_{kc=K+1}^{K+KC}\sum_{i}\left[\left(\lambda^{kc*}+\sum_{l=1}^{m}SF_{l,i}^{kc}\cdot\mu_l^{kc*}\right)\cdot\Delta P_i^{kc*}\right]}_{\text{corrective capacity revenue collected}}$$

Equation 1: LMP flow related revenue

It is clear from this breakdown that there are congestion revenues associated with the k case transmission limits, congestion revenues associated with the kc case transmission limits, and corrective capacity revenue bundled into the total revenues received from load through LMP. One can see that the corrective capacity revenue collected is the summation of LMCPs multiplied by the respective quantities of corrective capacities procured at that location. Intuitive to the notion of pricing products into the day-ahead market, the payment for the product itself is covered by day-ahead market revenues. The day-ahead market is revenue sufficient. When a market participant serving load pays the LMP at a node, those payments include the portion of revenue required to compensate the corrective capacity.

We can use bar graphs to visualize these revenues and help understand the portion of revenue attributable to the available transmission capability in each case verses the portion of revenue attributable to the corrective capacity in each case. Recall the example from above where the k limit is 700 MW, the kc limit is 350 MW, the k congestion is $5, and the kc congestion is $15.

[1] See "Appendix A – Flow related revenue and its allocation" for a derivation of the flow related revenue.

Below, the green bar on the left shows a total of \$3,500 in revenues associated with the k constraint up to the 700 MW normal limit (\$5×700 MW), the green portion of the bar on the right shows \$5,250 in revenues associated with the kc constraint up to the 350 MW post-contingency case limit (\$15×350 MW), and the blue portion of the bar on the right shows \$5,250 in revenues associated with the corrective capacity above the 350 MW post-contingency case limit (\$15×350 MW).

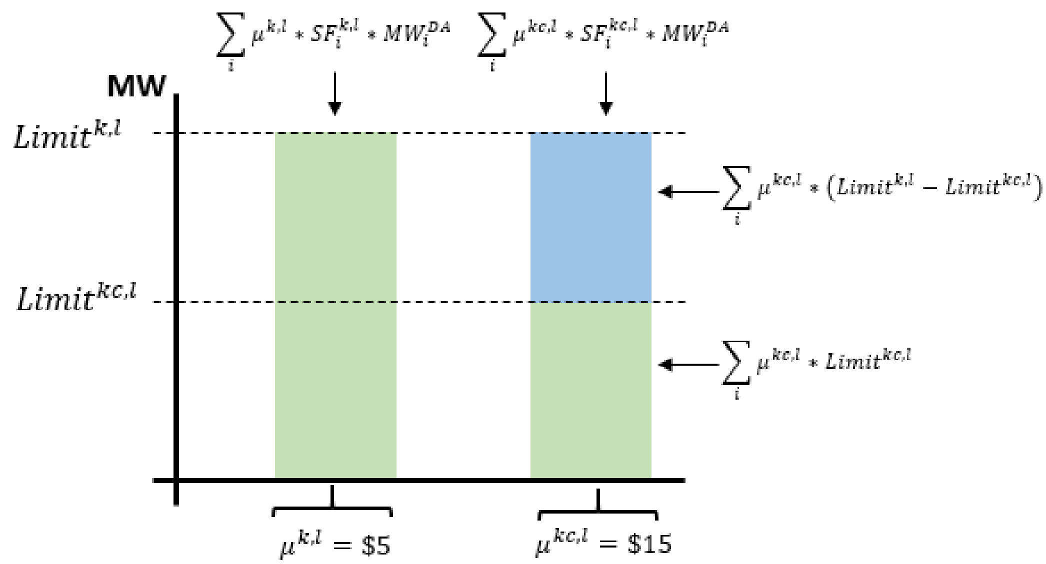

Figure 3: Graphic representation of market revenues

Through the LMP, the day-ahead market will collect \$5,250 as corrective capacity revenue (shown as the blue portion in the bar graphs above) and will collect a total of \$8,750 in congestion rent (shown as the total of the green portions in the bar graphs above). The revenue represented by the green portion is the revenue attributable to the total available transmission capability (\$5×700+\$15×350=\$8,750). Note that there is a full 700 MW of available transmission in the base case but only 350 MW of available transmission in the post-contingency case.

It is easier to appreciate the difference between the post-contingency case congestion rent and the post-contingency case corrective capacity revenue if we create an example where we isolate the total congestion to the post-contingency case. This can be done by creating a case where the k constraint does not bind but the kc constraint does bind.

Consider an example with a fast ramping resource at Node A, two very slow ramping resources at Node B, and comparably lower load at Node B.

	Bid (\$/MW)	Pmax (MW)	Ramp (MW/m)	Load (MW)
G1	\$30	600	100	
G2	\$50	900	1	
G3	\$35	900	1	
Load				600

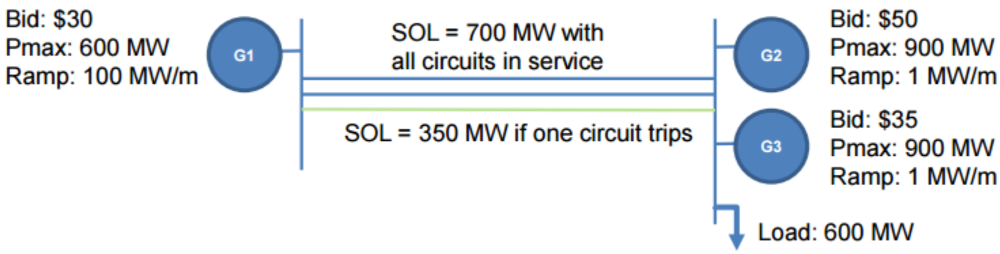

Figure 4: Example system where k constraint does not bind

The preventive-corrective market yields the following results. Notice that only 390 MW flow over the constrained path. This is enough to only make the 350 MW post-contingency limit bind.

Preventive-corrective model energy in base case					
Generator	P^0	λ^0	SF^0_{AB}	μ^0_{AB}	LMP
G1	390	$35	1	$0	$30
G2	0	$35	0	$0	$35
G3	210	$35	0	$0	$35
Corrective capacity in contingency kc=1					
Generator	ΔP^1	λ^1	SF^1_{AB}	μ^1_{AB}	$LMCP^1$
G1	-40	$5	1	-$5	$0
G2	20	$5	0	-$5	$5
G3	20	$5	0	-$5	$5

Table 5: Preventive-corrective market results

Because of the very limited upward ramping capability available on G2 and G3, the overall flow on the path is limited to 390 MW. The market reserves as much corrective capacity as is available on G2 and G3 (20 MW per resource) and limits the path flow to the post-contingency limit plus the available ramping capability (390 MW). The base case does not bind, but the post-contingency case does bind at a congestion shadow price of -$5. LMP at Node B is set at $35 and LMCP at Node B is set at $5.

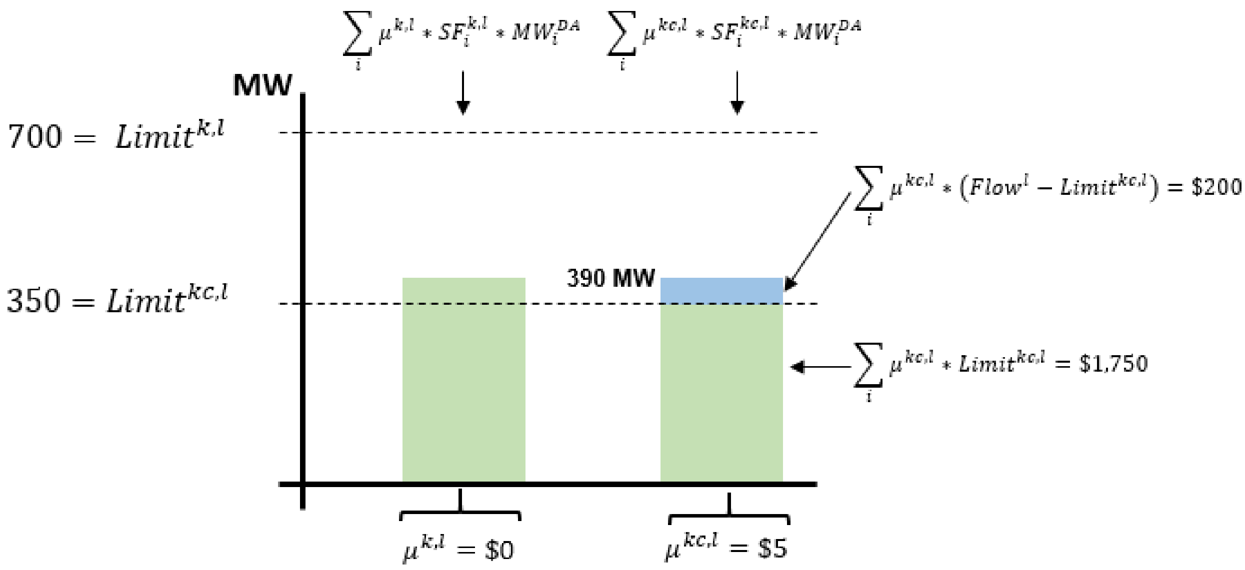

Figure 5: Graphic representation of market revenue

Through LMPs, the day-ahead market will collect $200 in corrective capacity revenue (shown as the blue portion in the bar graph above) and will collect $1,750 in congestion rent (shown as the green portions in the bar graph above). The revenue represented by the green portion is the revenue attributable to the total available transmission capability ($0×390+$5×350=$1,750). Note that there is a full 700 MW of available transmission in the base case, of which 390 MW is used, but only 350 MW of available transmission in the post-contingency case.

An entity that serves 600 MW of load at Node B with 600 MW of generation from Node A would potentially acquire 600 MW of CRRs from A to B. Without the preventive-corrective constraint in the day-ahead market and with no change to the CRR market and/or settlement, nothing would bind and the CRR holder would receive payment of 600 MW × $0 = $0 (CRRs held multiplied by the total congestion from A to B). However, with the preventive-corrective constraint in the day-ahead market but no change to the CRR market and/or settlement, those CRRs would receive payment of 600 MW × $5 = $3,000 while the total congestion revenue and corrective capacity revenue collected by the market is $1,950 ($1,750 in congestion rent + $200 in corrective capacity revenue).

It is apparent that if the ISO does not update its CRR market and/or settlement to be consistent with the changes to the day-ahead market, CRR settlement will be revenue inadequate when the kc constraint binds because CRRs would be allocated/auctioned up to the 700 MW limit and paid the sum of both congestion components up to 700 MW when there is actually only 350 MW of transmission available in the post-contingency case.

5. Congestion revenue rights enhancements

5.1. The CRR market does not model the new post-contingency constraints

The ISO proposes to resolve revenue inadequacy in the CRR market caused by a simultaneous feasibility test (SFT) in the CRR auction and allocation process that does not model the new post-contingency constraints introduced in this initiative. This particular revenue inadequacy is introduced solely due to this initiative, and as such should be resolved as part of this initiative.

The security constrained economic dispatch (SCED), which is the core component of the ISO market, determines a dispatch that produces feasible flows considering transmission constraints in the base case as well as in the N-1 preventive contingency cases. That is, the SCED produces a single dispatch that will be feasible for the base case and for all N-1 contingencies without any re-dispatch. To ensure the congestion revenues resulting from the dispatch will be adequate to compensate CRRs (absent any changes to the transmission system as modeled in the base case and contingencies), the CRR allocation and auction process assesses the simultaneous feasibility of the CRRs that it allocates and auctions. The simultaneous feasibility test for CRRs evaluates whether scheduling injections and withdrawals that correspond to the CRRs would produce flows on the transmission constraints that are feasible in the base case and N-1 contingency cases that are reflected in the CRR FNM. That is, the CRR SFT attempts to model the same transmission constraints that are modeled in SCED. It also models a fixed set of CRRs for the base case and a subset of N-1 contingencies in the same way that SCED models a fixed dispatch in the base case and N-1 contingencies. One can show that the SCED market will collect sufficient congestion revenue to pay the CRRs.

When the preventive-corrective framework with contingencies are added to the SCED, the market will model transmission constraints differently. Similar to the current SCED, a single dispatch will produce feasible flows considering transmission constraints in the base case as well as in the N-1 preventive contingency cases. However, for a given corrective contingency, the dispatch that is feasible for the base case and N-1 contingencies may no longer be feasible in the corrective contingency. SCED determines corrective capacity to procure whose deployment in the corrective contingency restores feasible transmission flows. The SFT for CRRs must take into account that transmission flows in the corrective contingencies and net congestion rents may change when the ISO purchases corrective capacity for use in the corrective contingencies.

In previous proposals the ISO offered to distribute post-contingency case congestion revenue up to post-contingency transmission limits, but did so in a manner that appeared as an overall rescission of payment because it did not attempt to change the current CRR settlement. While, it appeared to be an overall rescission of revenue, the ISO actually proposed to pay CRR holders additional congestion revenue associated with the available transmission in the post-contingency case without exacerbating revenue inadequacy.

The ISO explored various alternatives to align the CRR market with the proposed changes to the day-ahead market and protect the integrity of the CRR product. The ISO proposes to adjust CRR auction, allocation, and settlement appropriately to recognize the mechanics of the new day-ahead market constraints and maintain revenue adequacy.

5.2. Discussion of CRR alternatives

In response to the Third Revised Straw Proposal, market participants provided different approaches to consider in resolving the revenue shortfalls in the CRR market caused by a simultaneous feasibility test that does not additionally model the new post-contingency constraints introduced in this initiative. Stakeholders also asked the ISO to weigh the cost/benefit of implementing various solutions.

The ISO will need to adjust the CRR model and/or CRR compensation to reflect corrective capacity and its effect on congestion costs so that the CRR modeling and settlement is consistent with the proposed changes to the day-ahead market. Broad areas of approach to consider include either adjusting CRR compensation for the portion of the congestion revenue in excess of the available transmission capability settled at the kc constraint shadow price, or settling the base case congestion in one CRR product and settling the post-contingency case congestion in another CRR product.

The ISO discusses several approaches below. The approaches are organized into three paradigms: (1) minimal implementation, (2) use a new product to rescind congestion revenue in excess of available transmission capability, or (3) create all new products that distribute congestion revenue associated with available transmission capability. The first paradigm includes potential quick fixes that do not harmonize the CRR market to the proposed changes to the day-ahead market. Each of the other two paradigms include multiple flavors that range from full market solutions with separate biddable products to allocation of secondary products.

5.2.1. Minimal implementation

This paradigm includes options that are easy to implement, require no settlement system changes, and require only minor changes to the CRR market setup process.

In this paradigm, two options are apparent:

- ***Option 1(a)*** no change, or
- ***Option 1(b)*** enforce N-1-1 limits in a strong preventive fashion.

Option 1(a): No change. This option is to make no changes to the CRR market, process, and settlement. The ISO does not consider this option viable because it results in revenue inadequacy and does not recognize the mechanics of the new constraints proposed for the day-ahead market, posing market alignment risk; doing nothing leads to the additional uplift requirement and is the issue that the ISO proposes to resolve.

Option 1(b): Enforce N-1-1 limits in a strong preventive fashion. This option is to enforce the N-1-1 limits in a strong preventive fashion. Drawing a comparison to the example power system from above, under this option the ISO would limit the MW quantity of CRRs awarded on the path to the 350 MW post-contingency limit. While this option would result in revenue adequacy because it ensures that all CRRs awarded are feasible in both the pre-contingency case as well as the post-contingency case, the ISO does not consider it viable because it is very restrictive and does not recognize the mechanics of the new constraints in the day-ahead market. It would also result in revenue surplus any time the post-contingency constraint binds in the day-ahead market.

5.2.2. New Product to rescind congestion revenue in excess of available transmission capability (CCRR paradigm)

This paradigm is also known as the Contingency CRR paradigm ("CCRR paradigm"). In this paradigm, the ISO defines a new product: the CCRR. This product's purpose is to rescind congestion revenues associated with the portion of transmission that is not actually available in the post-contingency case (the corrective capacity revenue). The ISO would leave the CRR product allocation, auction, and settlement exactly the same as today, but it would distribute new CCRRs to rescind the portion of revenues in excess of available transmission capability in the post-contingency case; the rescission is necessary because in this paradigm, the ISO would not update the CRR market to respect the new post-contingency constraints introduced into the day-ahead market leading to an over-allocation of the CRR product.

CRRs will be awarded up to the k limit and be settled on the difference in congestion components of both the k and kc constraints. CCRRs will be awarded in the opposite direction and up to the MW quantity in excess of the kc constraint. CCRRs will be settled on the difference in congestion components of the kc constraint, resulting in a rescission of a portion of the CRR payment.

The CRR and CCRR will settle as follows:

$$CRR\ Payment = CRR\ MW_{AB} \times \left(MCC_B^k - MCC_A^k + MCC_B^{kc} - MCC_A^{kc}\right)$$

$$CCRR\ Payment_{BA} = CCRR\ MW_{BA} \times \left(MCC_A^{kc} - MCC_B^{kc}\right)$$

Recalling the example from above, if CRRs were awarded in excess of the 350 MW kc limit, then CCRRs in the opposite direction would also be awarded for each MW awarded over the 350 MW kc limit and up to the 700 MW k limit.

In this paradigm, three options are apparent:

- ***Option 2(a)*** Separate bids for simultaneous allocation/auction of CRR and CCRR,
- ***Option 2(b)*** Single bid for allocation/auction of CRR and CCRR, and
- ***Option 2(c)*** Single bid for allocation/auction of CRR and sequential allocation of CCRR pro-rata.

Option 2(a): Separate bids for simultaneous allocation/auction of CRR and CCRR. This is the Cadillac version of the CCRR paradigm. In this option, market participants would provide nominations and bids for CRRs as they do today, but they would also be able to separately provide nominations and bids for CCRRs.

In the allocation process, once the ISO receives nominations for both CRRs and CCRRs, it will clear an appropriate amount of CRR and CCRR respecting both the k limit and kc limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. Drawing on our example system from above, if no one nominates CCRRs then only 350 MW of CRRs will be awarded.

In the auction process, once the ISO receives bids for both CRRs and CCRRs, it will clear an appropriate amount of CRR and CCRR respecting both the k limit and kc limit while maximizing auction revenue. Drawing on our example from above, if no one bids for CCRRs then only 350 MW of CRRs will be awarded.

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

<table>
<tr><th>Participant</th><th>CRR Ask (MW)</th><th>CRR Bid ($/MW)</th><th>CRR Award (MW)</th><th>Auction Clearing Price</th><th>DAM CRR Settlement</th></tr>
<tr><td>X</td><td>600 CRR_{AB}
350 $CCRR_{BA}$</td><td>$20
-$15</td><td>600 MW CRR_{AB}
350 MW $CCRR_{BA}$</td><td rowspan="2">$19 CRR_{AB}
-$15 $CCRR_{BA}$</td><td>$12,000.00
-$5,250.00</td></tr>
<tr><td>Y</td><td>600 CRR_{AB}
350 $CCRR_{BA}$</td><td>$19
-$16</td><td>100 MW CRR_{AB}
0 MW $CCRR_{BA}$</td><td>$2000.00
$0.00</td></tr>
</table>

This option would result in revenue adequacy. This option requires no changes to the settlements system as it relates to the settlement of the CRR product, but does require updates to the settlements system to settle the CCRR product. This option would allow market participants the opportunity to separately value and price each product. Valuation of products under this option would require a fairly advanced understanding of the purpose and use of the CCRR. From a product standpoint, the purpose of CCRR is different from the purpose of the CRR which may lead to confusion.

This option is very difficult to implement because it requires heavy changes to the core CRR market systems. The ISO would have to process as many auctions as there are post-contingency constraints. Market participants would be required to participate in all auctions if they intend to hedge the congestion between two locations in the market.

Option 2(b): Single bid for allocation/auction of CRR and CCRR. In this option, the ISO would use the same bid to award both CRRs and CCRRs. Market participants would provide nominations or bids for CRRs as they do today.

In the allocation process, once the ISO receives nominations for CRRs, it will clear CRRs respecting the k limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. For the MW quantity of CRRs cleared above the kc limit the ISO will additionally clear CCRRs to the CRR award holders on a pro-rata basis. Note that other approaches to the allocation of CCRR in the allocation process could be developed, such as utilizing a weighted least squares technique.[2]

In the auction process, once the ISO receives bids for CRRs, it will clear CRRs respecting the k limit while maximizing auction revenue; this will be the CRR award. The ISO will then use the same bids to clear a second auction iteration respecting the kc constraint using the kc case shift factors while maximizing auction revenue. The difference between the CRR MW award from the first auction iteration and the CRR MW award from the second auction iteration is the MW quantity of the CCRR award; note that the CCRR flows in the opposite direction.

$$MWCCRR_{BA} = MWCRR_{AB,1} - MWCRR_{AB,2}$$

Where:

The numeric subscript (1, 2) represents the auction iteration

The highest bidders would potentially have lower ratios of CCRR awards to CRR awards while the lowest bidders would potentially have higher ratios of CCRR awards to CRR awards; note that the ratio of CCRR to CRR is dynamic and depends on the bids from other market participants.

[2] See "Appendix B – Weighted least squares approach to allocation of CCRR" for a description of how weighted least squares would work for the allocation of CCRR.

Below, results are provided using the same power system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600	$20	600 MW CRR_{AB} 250 MW $CCRR_{BA}$	$18 CRR_{AB}	$12,000.00 -$3,750.00
Y	600	$18	100 MW CRR_{AB} 100 MW $CCRR_{BA}$		$2,000.00 -$1,500.00

Participant X would receive 600 MW of CRR in the first auction iteration and 350 MW of CRR in the second auction iteration, so it receives 600 - 350 = 250 MW of CCRR. Participant Y would receive 100 MW of CRR in the first auction iteration and 0 MW of CRR in the second auction iteration, so it receives 100 - 0 = 100 MW of CCRR. The lowest bidder receives a higher ratio of CCRR MW to CRR MW while the highest bidder receives a lower ratio of CCRR MW to CRR MW.

Using this approach, it is possible to be awarded a CCRR but not be awarded the CRR. Below, we extend the example to include two more auction participants to highlight some possible oddities in this approach for the benefit of evaluation. Here, participants Z and W offer counter-flow.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600 CRR_{AB}	$20	600 MW CRR_{AB} 0 MW $CCRR_{BA}$	$18 CRR_{AB}	$12,000.00 $0.00
Y	350 CRR_{AB}	$18	300 MW CRR_{AB} 300 MW $CCRR_{BA}$		$6,000.00 -$4,500
Z	200 CRR_{BA}	-$10	-200 MW CRR_{AB} 0 MW $CCRR_{BA}$		-$4,000.00 $0.00
W	50 CRR_{BA}	-$19	0 MW CRR_{AB} 50 MW $CCRR_{BA}$		$0.00 -$750.00

Participant X would receive 600 MW of CRR in the first auction iteration and 600 MW of CRR in the second auction iteration, so it receives 600 - 600 = 0 MW of CCRR. Participant Y would receive 300 MW of CRR in the first auction iteration and 0 MW of CRR in the second auction iteration, so it receives 300 - 0 = 300 MW of CCRR. Participant Z would receive -200 MW of CRR in the first auction iteration and -200 MW of CRR in the second auction iteration, so it receives -200 - (-200) = 0 MW of CCRR. Participant W would receive 0 MW of CRR in the first auction iteration and -50 MW of CRR in the second auction iteration, so it receives 0 - (-50) = 50 MW of CCRR. In this scenario, Participant W will receive no compensation from the ISO (0 MW of CRR_{AB} awarded), but will take on the risk associated with the CCRR if the kc constraint binds.

This option would result in revenue adequacy. This option requires no changes to the settlements system as it relates to the settlement of the CRR product. Valuation of the CRR and CCRR products under this option would require a fairly advanced understanding of the purpose and use of the CCRR and require the market participant to reflect that value in a single bid price. Using this approach, the ratio of CCRR to CRR is dynamic and depends on the bids from other market participants, potentially making it more difficult to value. From a product standpoint, the purpose of CCRR is different from the purpose of the CRR which may lead to confusion.

This option has a moderate/high implementation difficulty because it requires the creation of a new post-process to generate awards of CCRRs to market participants which uses kc case shift factors. It also requires updates to the settlements system to settle the CCRR product.

Option 2(c): Single bid for allocation/auction of CRR and sequential allocation of CCRR pro-rata. This option was previously proposed in the third revised straw proposal. In this option, the ISO would not change the CRR clearing mechanisms, but sequentially allocate CCRRs to the holders of CRRs on a pro-rata basis.

In the allocation process, market participants would provide nominations or bids for CRRs as they do today. Once the ISO receives nominations for CRRs, it will clear CRRs respecting the k limit utilizing the WLS technique currently employed in the CRR market. For the MW quantity of CRRs cleared above the kc limit the ISO will additionally clear CCRRs to the CRR award holders on a pro-rata basis.

In the auction process, once the ISO receives bids for CRRs, it will clear CRRs respecting the k limit while maximizing auction revenue. For the MW quantity of CRRs cleared above the kc limit, the ISO will additionally clear CCRRs to the CRR award holders on a pro-rata basis. Each market participant would receive a complimentary CCRR award with its CRR award. Using the pro-rata method, the market participant will know prior to auction the maximum MW of CCRR award it could receive for each MW of CRR award received.

Pro-rata allocation of CCRR in both the allocation and auction would be based on the MW of CRR awarded to a market participant multiplied by the total MW of CRR awarded to all market participants above the kc limit divided by the total MW of CRR awarded.

$$MWCCRR_{BA,X} = MWCRR_{AB,X} \times \alpha^{kc}$$

Where,

$$\alpha^{kc} = \max\left\{0, \frac{\sum_p \left(SF^{kc}_{l,src(p)} - SF^{kc}_{l,snk(p)}\right) \cdot CRR_p - F^{kc,max}_l}{\sum_p \left(SF^{kc}_{l,src(p)} - SF^{kc}_{l,snk(p)}\right) \cdot CRR_p}\right\}$$

$$CRR_p = CRRs\ awarded$$

$$p = \ index\ of\ CRR\ awards$$

$$X = index\ of\ market\ participants$$

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600	$20	600 MW CRR_{AB} 300 MW $CCRR_{BA}$	$18 CRR_{AB}	$12,000.00 -$4,500.00
Y	600	$18	100 MW CRR_{AB} 50 MW $CCRR_{BA}$		$2,000.00 -$750.00

Participant X receives 600 × (350/700) = 300 MW of CCRR and Participant Y receives 100 × (350/700) = 50 MW of CCRR.

Note that other approaches to the allocation of CCRR in the auction and allocation process could be developed, such as utilizing a weighted least squares technique.[3]

This option would result in revenue adequacy. This option requires no changes to the settlements system as it relates to the settlement of the CRR product. A market participant would have some certainty in its valuation because it can determine the maximum MW of CCRR award it could receive for each MW of CRR award received. This method ensures that the market participant would never receive a CCRR obligation that would completely eliminate the revenues received from the CRR award. Valuation of the CRR and CCRR products under this option would require a fairly advanced

[3] See "Appendix B – Weighted least squares approach to allocation of CCRR" for a description of how weighted least squares would work for the allocation of CCRR.

understanding of the purpose and use of the CCRR and require the market participant to reflect that value in a single bid price. From a product standpoint, the purpose of CCRR is different from the purpose of the CRR which may lead to confusion.

This option has a moderate/high implementation difficulty because it requires the creation of a new post-process to generate awards of CCRRs to market participants which uses kc case shift factors. It also requires updates to the settlements system to settle the CCRR product.

5.2.3. New products to distribute congestion revenue associated with available transmission capability (CRR^k/CRR^{kc} paradigm)

This paradigm is also known as the CRR^k/CRR^{kc} paradigm.[4] In this paradigm, the ISO re-defines the CRR product as the CRR^k and creates another new product: the CRR^{kc}. Both the CRR^k and the CRR^{kc} distribute congestion revenue associated with the available transmission capability; when constraints bind, these products are paid the respective congestion revenues. The CRR^k will settle on the congestion associated with the k constraint and each CRR^{kc} will settle on the congestion associated with the kc constraint.

CRR^k will be awarded up to the k limit and be settled on the difference in congestion components of the k constraint. CRR^{kc} will be awarded in the same direction up to the kc limit and be settled on the difference in congestion components of the kc constraint.

The CRR^k and CRR^{kc} will settle as follows:[5]

$$CRR^k\ Payment = CRR^k MW_{AB} \times \left(MCC_B^k - MCC_A^k\right)$$

$$CRR^{kc}\ Payment = CRR^{kc} MW_{AB} \times \left(MCC_B^{kc} - MCC_A^{kc}\right)$$

Recalling the example from above, CRR^k will be awarded up to the 700 MW k limit and CRR^{kc} will be awarded up to the 350 MW kc limit.

In this paradigm, four options are apparent:

- ***Option 3(a)*** Separate bids for allocation/auction of CRR^k and CRR^{kc},
- ***Option 3(b)*** Single bid for allocation/auction of CRR^k and CRR^{kc},

[4] We could similarly express the CRR^k as $CRR^{0:K}$. We intend to keep the discussion paper conversational by referring to the CRR^k as a product that is awarded up to the k limit and settles on the k congestion; this narrative fits the examples provided herein. In reality, the CRR^k will be awarded similar to today respecting the base case and the preventive contingencies, that is for k=0,…,K. Further, the product will settle using the terms in the MCC of the LMP that arise from congestion in the base case and preventive contingencies only, that is for k = 0,…,K.
[5] See "Appendix D – CRR^k/CRR^{kc} settlement" for further breakdown of the settlement of each of the CRR^k and CRR^{kc} product.

- ***Option 3(c)*** Single bid for allocation/auction of CRR^{k} and sequential allocation of CRR^{kc} pro-rata, and
- ***Option 3(d)*** Single bid for allocation/auction of CRR^{k} only.

Option 3(a): Separate bids for allocation/auction of CRR^{k} and CRR^{kc}. This is the Cadillac version of the CRR^{k}/CRR^{kc} paradigm. In this option, market participants would provide nominations or bids for CRR^{k} as they do today, but they would also be able to separately provide nominations or bids for CRR^{kc}.

In the allocation process, once the ISO receives nominations for both CRR^{k} and CRR^{kc}, it will clear an appropriate amount of CRR^{k} and CRR^{kc} respecting both the k limit and kc limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. The award of CRR^{k} does not in any way depend on the award of CRR^{kc}.

In the auction process, once the ISO receives bids for both CRR^{k} and CRR^{kc}, it will clear an appropriate amount of CRR^{k} and CRR^{kc} respecting both the k limit and kc limit while maximizing auction revenue. The award of CRR^{k} does not in any way depend on the award of CRR^{kc}.

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600 CRR^{k} 350 CRR^{kc}	$5 $15	600 MW CRR^{k} 0 MW CRR^{kc}	$4 CRR^{k} $16 CRR^{kc}	$3,000.00 $0.00
Y	600 CRR^{k} 350 CRR^{kc}	$4 $16	100 MW CRR^{k} 350 MW CRR^{kc}		$500.00 $5,250.00

Each products is paid its respective congestion. If in the day-ahead market the k constraint binds the CRR^{k} would pay the difference in k constraint congestion. If the kc constraint binds, the CRR^{kc} would pay the difference in kc constraint congestion.

This option would result in revenue adequacy. This option requires changes to the settlements system as it relates to the settlement of the CRR product along with updates to the settlements system to settle the CRR^{kc} product. Valuation of products under this option would be very similar to the valuation of the CRR product today. From a product standpoint, the purpose of both the CRR^{k} and CRR^{kc} products is aligned which is easier to understand. This option would allow market participants the opportunity to separately value and price each product. The ISO would have to process as many auctions as there are post-contingency constraints. Market participants would be required to participate in all auctions if they intend to hedge the congestion between two locations in the market.

This option is extremely difficult to implement because it requires heavy changes to the core CRR market systems and settlement systems.

Option 3(b): Single bid for allocation/auction of CRR^k and CRR^{kc}. In this option, the ISO would use the same bid to award both CRR^k and CRR^{kc}.

In the allocation process, market participants would provide nominations for CRR. Once the ISO receives nominations for CRR, it will clear CRR^k respecting the k limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. The ISO will separately clear CRR^{kc} respecting the kc limit using the WLS technique.

In the auction process, once the ISO receives bids for CRR, it will clear CRR^k respecting the k limit while maximizing auction revenue. The ISO will then use the same bids to additionally clear each CRR^{kc} respecting the kc limits using the kc case shift factors. The highest bidders would receive CRR^k and CRR^{kc} awards and the lowest bidders may only receive CRR^k awards. Market participants would only pay for the CRR^k received at the CRR^k clearing price; the CRR^{kc} clearing price is not used.

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600	$20	600 MW CRR^k 350 MW CRR^{kc}	$18 CRR	$3,000.00 $5,250.00
Y	600	$18	100 MW CRR^k 0 MW CRR^{kc}		$500.00 $0.00

This option would result in revenue adequacy. This option requires changes to the settlements system as it relates to the settlement of the CRR product along with updates to the settlements system to settle the CRR^{kc} product. Valuation of products under this option would be very similar to the valuation of the CRR product today, but may be difficult because a market participant uses one price to try to value multiple products. This option introduces a disconnect between the clearing prices of CRR^k and CRR^{kc}; the ISO derives the CRR^{kc} clearing price from a bid intended to be used to purchase both products, but does not use that clearing price in the auction. This option would not allow market participants the opportunity to separately value and price each product; a market participant bids one price in an attempt to acquire as much CRR^k and CRR^{kc} as possible. This option does not guarantee the market participant acquisition of CRR^{kc} for each CRR^k acquired. Whether or not a market participant receives CRR^{kc} along with the CRR^k depends on where its single bid stacks up relative to other market participant bids which may complicate the valuation process. From a product standpoint, the purpose of both the CRR^k and CRR^{kc} products is aligned which is easier to understand.

This option has a moderate/high implementation difficulty because it requires the creation of a new post-process to generate awards of CRR^{kc} to market participants which uses kc case shift factors. It also requires updates to the settlements system to settle the CCRR product.

Option 3(c): Single bid for allocation/auction of CRR^k and sequential allocation of CRR^{kc} pro-rata. In this option, the ISO would not change the CRR clearing mechanisms, but sequentially allocate CRR^{kc} to the holders of CRR^k on a pro-rata basis.

In the allocation process, market participants would provide nominations or bids for CRR^k as they do today. Once the ISO receives nominations for CRR^k, it will clear CRR^k respecting the k limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. The ISO will additionally clear CRR^{kc} to the CRR^k award holders on a pro-rata basis.

In the auction process, once the ISO receives bids for CRR^k, it will clear CRR^k respecting the k limit while maximizing auction revenue. The ISO will additionally clear CRR^{kc} to the CRR^k award holders on a pro-rata basis respecting the kc limit. Each market participant would receive a complimentary CRR^{kc} award with its CRR^k award. Using the pro-rata method, the market participant will know prior to auction the minimum MW of CRR^{kc} award it could receive for each MW of CRR^k award received.

Pro-rata allocation of CRR^{kc} in both the allocation and auction would be based on the MW of CRR^k awarded to a market participant multiplied by the total MW of CRR^k awarded to all market participants below the kc limit divided by the total MW of CRR^k awarded.

$$MWCRR^{kc}{}_{AB,X} = MWCRR^{k}_{AB,X} \times \alpha^{kc}$$

Where,

$$\alpha^{kc} = \frac{min\left(F_l^{kc,max}, \sum_p (SF^{kc}_{l,src(p)} - SF^{kc}_{l,snk(p)}) \cdot CRR^k_p\right)}{\sum_p (SF^{kc}_{l,src(p)} - SF^{kc}_{l,snk(p)}) \cdot CRR^k_p}$$

$$CRR^k_p = CRR^k\ awarded$$

$$p = \ index\ of\ CRR\ awards$$

$$X = index\ of\ market\ participants$$

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement

X	600	$20	600 MW CRR^{k} 300 MW CRR^{kc}	$18 CRR	$3,000.00 $4,500.00
Y	600	$18	100 MW CRR^{k} 50 MW CRR^{kc}		$500.00 $750.00

Participant X receives 600 × (350/700) = 300 MW of CRR^{kc} and Participant Y receives 100 × (350/700) = 50 MW of CRR^{kc}.

Note that other approaches to the allocation of CRR^{kc} could be developed, such as utilizing a weighted least squares technique.[6]

This option yields the same result as ***Option 2(c)*** discussed above. This option would result in revenue adequacy. This option requires changes to the settlements system as it relates to the settlement of the CRR product along with updates to the settlements system to settle the CRR^{kc} product. Valuation of products under this option would be very similar to the valuation of the CRR product today, but will need to incorporate the expectation of the pro-rata allocation of CRR^{kc}. This option guarantees the market participant acquisition of some MW of CRR^{kc} for each MW of CRR^{k} acquired. From a product standpoint, the purpose of both the CRR^{k} and CRR^{kc} products is aligned which is easier to understand.

This option has a moderate/high implementation difficulty requiring creation of a sequential pro-rata allocation process that uses kc case shift factors and updates to the settlements system.

Option 3(d): Single bid for allocation/auction of CRR^{k} only. In this option, the ISO would not change the CRR clearing mechanisms. Market participants would provide nominations or bids for CRR^{k} as they do today.

In the allocation process, once the ISO receives nominations for CRR^{k}, it will clear CRR^{k} respecting the k limit utilizing the weighted least squares technique (WLS) currently employed in the CRR market. The ISO will not additionally clear CRR^{kc}.

In the auction process, once the ISO receives bids for CRR^{k}, it will clear CRR^{k} respecting the k limit while maximizing auction revenue. The ISO will not additionally clear CRR^{kc}. At the end of the CRR process, market participants would only hold CRR^{k} that will only settle on the differences in the k constraint congestion components.

[6] See "Appendix C – Weighted least squares approach to allocation of CRR^{kc}" for a description of how weighted least squares would work for the allocation of CRR^{kc}.

Below, results are provided using the same system from the example above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints bind in the market.

Participant	CRR Ask (MW)	CRR Bid ($/MW)	CRR Award (MW)	Auction Clearing Price	DAM CRR Settlement
X	600	$20	600 MW CRR^k	$18 CRR	$3,000.00
Y	600	$18	100 MW CRR^k		$500.00

This option would result in revenue adequacy. This option requires changes to the settlements system as it relates to the settlement of the CRR^k product. Valuation of the product under this option would be very similar to the valuation of the CRR product today, but will need to incorporate the expectation of lack of kc constraint congestion revenue. From a product standpoint, the purpose of the CRR^k products is aligned with the mechanics of the new constraints.

This option has a moderate implementation difficulty requiring only a settlements system change.

5.3. Example results for each alternative considered

The table below is provided to evaluate the differences between the various proposals considered above. The CRR payment column represents amount the products will pay out when the both the k and kc constraints binds in the market.

In a simple two bus system, there is a transmission path from Node A to Node B which is limited by a 700 MW normal transfer capability and a 350 MW post-contingency transfer capability. There are two participants seeking CRRs on the path in this market, participant X and participant Y. The base case congestion is $5 and the post-contingency case congestion is $15.

Minimal implementation paradigm:					
Option	**Participant**	**CRR Ask (MW)**	**CRR Bid ($/MW)**	**CRR Award (MW)**	**DAM CRR Settlement**
1(a)	X	600	$20	600 MW CRR	$12,000
	Y	600	$18	100 MW CRR	$2,000
1(b)	X	600	$20	350 MW CRR	$7,000
	Y	600	$18	0 MW CRR	$0
CCRR paradigm:					
Option	**Participant**	**CRR Ask (MW)**	**CRR Bid ($/MW)**	**CRR Award (MW)**	**DAM CRR Settlement**
2(a)	X	600 CRR_{AB} 350 $CCRR_{BA}$	$20 $15	600 MW CRR_{AB} 350 MW $CCRR_{BA}$	$12,000.00 -$5,250.00
	Y	600 CRR_{AB} 350 $CCRR_{BA}$	$19 $16	100 MW CRR_{AB} 0 MW $CCRR_{BA}$	$2000.00 $0.00
2(b)	X	600	$20	600 MW CRR_{AB} 250 MW $CCRR_{BA}$	$12,000.00 -$3,750
	Y	600	$18	100 MW CRR_{AB} 100 MW $CCRR_{BA}$	$2,000.00 -$1,500
2(c)	X	600	$20	600 MW CRR_{AB} 300 MW $CCRR_{BA}$	$12,000.00 -$4,500
	Y	600	$18	100 MW CRR_{AB} 50 MW $CCRR_{BA}$	$2,000.00 -$750.00
CRR^{k}/CRR^{kc} paradigm:					
Option	**Participant**	**CRR Ask (MW)**	**CRR Bid ($/MW)**	**CRR Award (MW)**	**DAM CRR Settlement**
3(a)	X	600 CRR^{k}_{AB} 350 CRR^{kc}_{AB}	$5 $15	600 MW CRR^{k}_{AB} 0 MW CRR^{kc}_{AB}	$3,000.00 $0.00
	Y	600 CRR^{k}_{AB} 350 CRR^{kc}_{AB}	$4 $16	100 MW CRR^{k}_{AB} 350 MW CRR^{kc}_{AB}	$500.00 $5,250.00
3(b)	X	600	$20	600 MW CRR^{k}_{AB} 350 MW CRR^{kc}_{AB}	$3,000.00 $5,250.00
	Y	600	$18	100 MW CRR^{k}_{AB} 0 MW CRR^{kc}_{AB}	$500.00 $0.00
3(c)	X	600	$20	600 MW CRR^{k}_{AB} 300 MW CRR^{kc}_{AB}	$3,000.00 $4,500.00
	Y	600	$18	100 MW CRR^{k}_{AB} 50 MW CRR^{kc}_{AB}	$500.00 $750.00
3(d)	X	600	$20	600 MW CRR^{k}_{AB}	$3,000.00
	Y	600	$18	100 MW CRR^{k}_{AB}	$500.00

Appendix A – Flow related revenue and its allocation

In the lossless model considered in the proposal, the **flow related revenue** collected from the settlements of energy transactions is given by:

$$\sum_i \left[LMP_i \cdot \left(P_i^{0*} - L_i\right)\right] = \sum_i \left[\left(\lambda^{0*} + \sum_{k=0}^{K}\sum_{l=1}^{m} SF_{l,i}^{k} \cdot \mu_l^{k*} + \sum_{kc=K+1}^{K+KC}\sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc*}\right) \cdot \left(P_i^{0*} - L_i\right)\right]$$

We could add treatment of losses, but do not do so at this stage to focus on congestion rents and corrective capacity payments.

In this expression, a negative value indicates monies collected by the ISO from participants while positive values indicate payments by the ISO to participants.

The expression on the right hand side of this equation is equal to

$$\sum_{k=0}^{K}\sum_{l=1}^{m}\left[\mu_l^{k*} \cdot \sum_i \left[SF_{l,i}^{k*} \cdot \left(P_i^{0*} - L_i\right)\right]\right] + \sum_{kc=K+1}^{KC}\sum_{l=1}^{m}\left[\mu_l^{kc*} \cdot \sum_i \left[SF_{l,i}^{kc} \cdot \left(P_i^{0*} - L_i\right)\right]\right]$$

which takes into account that

$$\sum_i \left(P_i^{0*} - L_i\right) = 0$$

in a lossless model as treated in the proposal.

A preventive transmission constraint, k, will have a non-zero shadow price only if the preventive transmission constraint is tight, that is if $\sum_i \left[SF_{l,i}^{k*} \cdot \left(P_i^{0*} - L_i\right)\right] = F_l^{k,\max}$. A corrective transmission constraint, kc, will have a non-zero shadow price only if the corrective transmission constraint it tight, that is if $\sum_i \left[SF_{l,i}^{kc} \cdot \left(P_i^{0*} + \Delta P_i^{kc*} - L_i\right)\right] = F_l^{kc,\max}$.

Taking into account this complimentary slackness at the solution to the dispatch model, the last expression for the flow related revenue can be written as

$$\sum_{k=0}^{K}\sum_{l=1}^{m}\left[\mu_l^{k*} \cdot F_l^{k,\max}\right] + \sum_{kc=K+1}^{KC}\sum_{l=1}^{m}\left[\mu_l^{kc*} \cdot F_l^{kc,\max}\right] - \sum_{kc=K+1}^{K+KC}\sum_i \left[\left(\sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc*}\right) \cdot \Delta P_i^{kc*}\right]$$

Taking into account that

$$\sum_i \Delta P_i^{kc*} = 0$$

we can rewrite the last expression as

$$\sum_{k=0}^{K}\sum_{l=1}^{m}\left[\mu_l^{k*}\cdot F_l^{k,\max}\right]+\sum_{kc=K+1}^{KC}\sum_{l=1}^{m}\left[\mu_l^{kc*}\cdot F_l^{kc,\max}\right]-\sum_{kc=K+1}^{K+KC}\sum_{i}\left[\left(\lambda^{kc*}+\sum_{l=1}^{m}SF_{l,i}^{kc}\cdot\mu_l^{kc*}\right)\cdot\Delta P_i^{kc*}\right]$$

The congestion rent arising in the market is defined as the marginal value of available capacity on the transmission constraints. This is just

$$\sum_{k=0}^{K}\sum_{l=1}^{m}\left[-\mu_l^{k*}\cdot F_l^{k,\max}\right]+\sum_{kc=K+1}^{KC}\sum_{l=1}^{m}\left[-\mu_l^{kc*}\cdot F_l^{kc,\max}\right]$$

The ISO collects this amount in the flow related revenues from the settlements of energy transactions according to the first two terms.

The amount that the ISO pays for corrective capacity in settlements of corrective capacity transactions is

$$\sum_{kc=K+1}^{K+KC}\sum_{i}\left[\left(\lambda^{kc*}+\sum_{l=1}^{m}SF_{l,i}^{kc}\cdot\mu_l^{kc*}\right)\cdot\Delta P_i^{kc*}\right]$$

The ISO collects this amount in the flow related revenues from the energy settlements according to the third term. Note that the parenthetical term is the definition of the LMCP at node i which is then multiplied by the corrective capacity procured at node i; the corrective capacity price multiplied by the corrective capacity MW is the revenue needed to pay the corrective capacity.

This shows that flow related revenues arising from settlements of energy transactions exactly equals the congestion rents plus the revenue needed to pay for corrective capacity.

The energy transactions pay once to cover congestion rents and once to cover corrective capacity. The cost of corrective capacity is covered in the market requiring no additional uplift.

Appendix B – Weighted least squares approach to allocation of CCRR

Suppose that we allocate CRRs for contingency kc equal to the CRRs that were provided for the base case and preventive contingencies; that is $\left\{CRR_q^{kc} = CRR_q^{0:K*} \middle| q = 1, \ldots, NQ\right\}$. These CRRs may not satisfy the transmission flow limits in contingency kc since they were not considered when evaluating the $CRR^{0:K}$. We want to allocate Contingency CRRs $\left\{CCRR_q^{kc} \middle| q = 1, \ldots, NQ\right\}$ to achieve feasible transmission flows for contingency kc while reducing the effective MWs of CRRs for contingency kc as little as possible.

The net MW of the CRR and CCRR assigned for q in contingency kc would be $MWCRR_q^{0:K*} - MWCCRR_q^{kc}$. To implement a WLS approach to size the CCRRs, we would want to size the $\left\{CCRR_q^{kc} \middle| q = 1\ldots, NQ\right\}$ so that the net MWs $\left\{MWCRR_q^{0:K*} - MWCCRR_q^{kc} \middle| q = 1, \ldots, NQ\right\}$, are as close to $\left\{MWCRR_q^{0:K*} \middle| q = 1, \ldots, NQ\right\}$ in a WLS sense as possible.

$$\min \sum_{q=1}^{NQ} \left(\frac{1}{MWCRR_q^{0:K*}} \left(MWCRR_q^{0:K*} - \left(MWCRR_q^{0:K*} - MWCCRR_q^{kc} \right) \right)^2 \right)$$

over all $MWCCRR_q^{kc}$ subject to

$$\sum_{q=1}^{NQ} \left(SF_{l,u(q)}^{kc} - SF_{l,w(q)}^{kc} \right) \cdot \left(MWCRR_q^{0:K*} - MWCCRR_q^{kc} \right) \le F_l^{kc,\max} \quad \text{for } l = 1, \ldots, m$$

$$0 \le MWCCRR_q^{kc} \le MWCRR_q^{0:K*} \qquad \text{for } q = 1, \ldots, NQ$$

Or

$$\min \sum_{q=1}^{NQ} \left(\frac{1}{MWCRR_q^{0:K*}} \left(MWCCRR_q^{kc} \right)^2 \right)$$

over all $MWCCRR_q^{kc}$ subject to

$$\sum_{q=1}^{NQ} \left(SF_{l,u(q)}^{kc} - SF_{l,w(q)}^{kc} \right) \cdot MWCCRR_q^{kc} \ge \sum_{q=1}^{NQ} \left(SF_{l,u(q)}^{kc} - SF_{l,w(q)}^{kc} \right) \cdot MWCRR_q^{0:K*} - F_l^{kc,\max} \quad \text{for } l = 1, \ldots, m$$

$$0 \le MWCCRR_q^{kc} \le MWCRR_q^{0:K*} \qquad \text{for } q = 1, \ldots, NQ$$

Appendix C – Weighted least squares approach to allocation of CRR^{kc}

In **Option 3(c)**, as discussed above, the ISO treats the awards in the auction as nominations for an allocation of CRRs in the several corrective contingencies (CRR^{kc}). That is, we assume that each party awarded a CRR for the base case and preventive contingencies (CRR^{k}) by the auction would like to be awarded the same size CRR for each corrective contingency so that it would acquire a complete hedge, if possible.

We assume the set of nominations for an allocation in each corrective contingency is given by:

- $src(q)$ which is the source of CRR_q^k is also the source of CRR_q^{kc}
- $snk(q)$ which is the sink of CRR_q^k is also the sink of CRR_q^{kc}
- $MWCRR_q^k$ is the requested size in MW of CRR_q^{kc}

For each corrective contingency, $kc \in \{K+1, \ldots, K+KC\}$, the WLS problem that will be used to allocate CRRs covering that contingency is given by:

$$\min \sum_{q=1}^{NQ} \left(\frac{1}{MWCRR_q^k} \left(MWCRR_q^k - MWCRR_q^{kc} \right)^2 \right)$$

over all $MWCRR_q^{kc}$ subject to

$$\sum_{q=1}^{NQ} \left(SF_{l,src(q)}^{kc} - SF_{l,snk(q)}^{kc} \right) \cdot MWCRR_q^{kc} \le F_l^{kc,\max} \quad \text{for } l = 1, \ldots, m$$

$$0 \le MWCRR_q^{kc} \le MWCRR_q^k \qquad \text{for } q = 1, \ldots, NQ$$

The SFT constraints are embedded in the auction and allocation problems so the overall result will be simultaneously feasible.

Appendix D – CRR^k/CRR^{kc} settlement

Suppose that the ISO defines a set of CRRs for the set of contingencies consisting of the base case and preventive contingencies. These CRRs will be settled using the terms in the Marginal Congestion Components (MCCs) of the LMPs that arise from congestion on the transmission system in the base case and the preventive contingencies (*i.e*. for k = 0,…,K). These CRRs will not be settled using the terms in the MCCs of the LMPs that arise from congestion on the transmission system in the corrective contingencies. That is, these CRRs will be settled using:

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

These CRRs will **not** be settled using the full MCCs of the LMPs; they are not settled using:

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

We denote these CRRs as CRR_q^k (or $CRR_q^{0:K}$ for the more technically inclined) for q = 1,…,$NQ^{0:K}$ where $NQ^{0:K}$ is the number of these CRRs.

For each corrective contingency, kc, the ISO would define CRRs that will be settled using the terms in the Marginal Congestion Components of the LMCPs that arise from congestion on the transmission system in the corrective contingency kc. That is, they will be settled using:

$$\sum_{l=1}^{m} SF_{l,i}^{kc} \cdot \mu_l^{kc*} .$$

We will denote these CRRs as CRR_q^{kc} for q = 1,…,NQ^{kc} where NQ^{kc} is the number of these CRRs for the corrective contingency kc.

The CRRs would each settle as follows:

$$CRR^k\ Payment = CRR^k MW_{AB} \times \left(\sum_{k=0}^{K}\sum_{l=1}^{m} SF_{l,B}^{k} \cdot \mu_l^{k*} - \sum_{k=0}^{K}\sum_{l=1}^{m} SF_{l,A}^{k} \cdot \mu_l^{k*} \right)$$

$$CRR^{kc}\ Payment = CRR^{kc} MW_{AB} \times \left(\sum_{l=1}^{m} SF_{l,B}^{kc} \cdot \mu_l^{kc*} - \sum_{l=1}^{m} SF_{l,A}^{kc} \cdot \mu_l^{kc*} \right)$$