Note on Congestion Relief Market (CRM) Demonstration Model

Outline of dispatch and pricing formulation and example Excel models

Final

Tuesday, 7 June 2022

Author: Stephen Wallace, SW Advisory

SW Advisory

Table of Contents

Disclaimer

This report has been prepared by SW Advisory Pty Ltd and is supplied in good faith. It reflects the knowledge, expertise and experience of the consultants involved in its preparation. SW Advisory makes no representations or warranties as to the accuracy of the assumptions, models or estimates on which any forecasts, calculations or conclusions are based.

1 Introduction

This note outlines a possible formulation of on optimisation model which could be used for the congestion relief market. The model co-optimises the CRM with the energy market. The model uses full supply and demand curves for both the congestion relief and energy markets. The model provides optional participation in the CRM via the ability to offer 0 MWs for increases or decreases in generation or consumption in the CRM relative to the energy market dispatch.

The example Excel models use the same framework for 2 bus (node), 4 bus and 6 bus models.

2 General Principles of the CRM

The general principles of the CRM which needed to captured in the dispatch optimisation formulation and CRM pricing are as follows:

- The aim of the CRM is to improve the economic efficiency of the NEM's dispatch, in particular to better utilise the existing network and lower the costs of congestion.
- Participation in the CRM is optional for each dispatchable resource. A resource that is not participating in the CRM does not provide any information to the CRM.
- CRM participants indicate, for each of their dispatchable resources, the lower and upper limits for their CRM deviations from their energy market dispatch targets. These limits can be set to zero for any trading interval so the CRM deviations from the resource's energy dispatch target is zero for that trading interval.
- For each resource participating in the CRM, the CRM requires bids and offers for all of the capacity offered into the energy market.
- Energy, FCAS and CRM are co-optimised in a single pass.
- The CRM takes into account all network constraints simultaneously, not just a selected few.
- The combined energy and CRM deviations results in a secure dispatch, that is, the dispatch satisfies all the NEM's security constraints used in the energy dispatch and the technical limits of all plant.
- The CRM determines local CRM prices (nodal CRM prices or CRM LMPs).
- The CRM trades can involve multiple resources just like the NEM's energy dispatch, they do not have to be paired trades as would be the case with bilateral trades.
- All of the CRM deviations are settled at each resource's nodal CRM price.
- The settlement arrangements can be viewed as buying and selling congestion relief or an energy and CRM settlement.

3 Two Potential Models for CRM

The CRM's congestion relief intentions could be implemented in two equally valid ways where:

1. Participants offer full CRM supply / demand curves for their capacity. Under this model a participant needs to offer the same or greater capacity, for each resource, than what is offered in the energy market to ensure that the CRM doesn't reduce the energy market dispatch even when the CRM deviations from the energy dispatch are set to zero.
2. Participants make bids/offers for increments or decrements to their energy market dispatch. In this case participants in the CRM don't have to offer full supply / demand curves but may find it trickier to construct the incs and decs bids/offers because they may not know where they are going to end up with their dispatch, though this problem is considerably reduced with rebidding and pre-dispatch information.

The model spreadsheets are based on the full supply / demand curve approach. Thus, the quantities in the supply / demand curves can't be set to zero because this will result in a shortfall in meeting demand in the CRM security constrained dispatch. For those resources that don't want to participate in the CRM, in the 6 bus CRM spreadsheets, there is binary variable that indicates whether the resource participates in the CRM or not. If a resource is chosen not to participate in the CRM then its maximum CRM reductions and increases in output are set to zero and it does not contribute to the CRM dispatch costs in the objective function.

4 Overview Energy CRM market optimisation formulation

4.1 Introduction

The CRM optimisation developed in this note and the associated demonstration spreadsheets is based on:

- separate full supply and demand curve offers and bids for energy and congestion relief,
- co-optimisation of energy and congestion relief,
- security constrained dispatches for both energy and the combined energy and congestion relief.

4.2 Outline of full supply curve CRM model in terms of NEMDE like framework[1]

4.2.1 Introduction

In order to simplify the discussion we will assume no transmission losses and just a single region.

4.2.2 Energy market optimisation

For convenience we will assume that the energy market optimisation is formulated as a cost minimisation and the dispatch (decision) variables for resource i, x_i, are positive for generation and negative for dispatchable loads, pumping or battery charging. The dispatch costs $c_i(x_i)$ for resource i are based on the bids and offers (monotonic increasing prices in x_i) and hence are convex and can be modelled in a linear program (LP) as piecewise linear functions. The formulation of the energy market optimisation is as follows:

Minimise

$$\sum_{i \in NEM} c_i(\mathrm{x}_i) = \mathbf{C(X)}$$

where **X** is a vector of the x_i

Subject to:

Regional energy balance

$$\sum_{i \in NEM} \mathrm{x}_i = \mathrm{demand} = \mathbf{1'X}$$

---

[1] The framework outlined here is aligned with one that Darryl Biggar (ACCC) has developed as a model for the CRM.

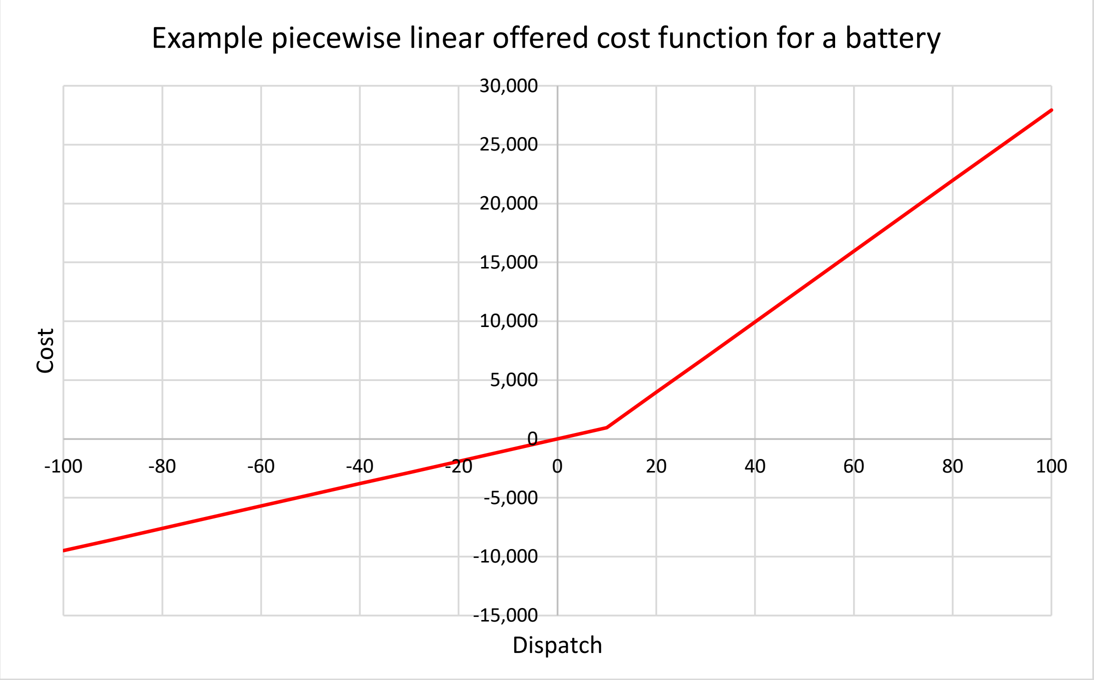
Capacity and security constraints including network constraints

$$AX \le B$$

4.2.3 Supply curve cost function for resources which can generate or consume power

Flexible loads or batteries and pumped storage are all treated like generators which can have negative dispatch targets as low as their maximum consumption. The dispatch targets for all generators, loads batteries etc. are greater than or equal to the resource's Pmin and less than or equal to the Pmax. Similarly all of the offer curves start from the Pmin. Thus, for piecewise linear cost function based on the offered price and quantities to result in a zero cost for a zero dispatch, the cost, $c_i(\mathrm{Pmin}_i)$, at Pmin must be determined. This is done in the spreadsheets and illustrated in this example where a battery has a Pmin = -100 MW and Pmax = 100.

Figure 1 Example piecewise linear cost function for a battery



4.2.4 Standalone CRM formulation using CRM offers and bids

For the CRM model and for all resources, j, participating in the CRM, we enable deviations, Δx_j, from the energy market dispatch x_j. Now the deviations have to result in a security constrained economic dispatch which uses the CRM bids and offers. If we assume that the CRM dispatch costs are $d_j(x_j)$ for resource j are based on the CRM bids and offers (monotonic increasing prices in x_j) then the formulation for a stand alone CRM optimisation is as follows:

Minimise

$$\sum_{j \in CRM} d_j(\mathrm{x}_j + \Delta\mathrm{x}_j) = \mathbf{D(X + \Delta X)}$$

Subject to:

CRM deviation limits

$$\text{lower bound} \leq \Delta\mathrm{x}_j \leq \text{upper bound}$$

Regional energy balance

$$\sum_{i \in NEM}(\mathrm{x}_i + \Delta\mathrm{x}_i) = \text{demand} = \mathbf{1'(X+\Delta X)}$$

Note that $\Delta\mathrm{x}_i$=0 for non CRM participating resources

This means that $\sum \Delta\mathrm{x}_i = 0$ if we ignore inter-regional losses

Capacity and security constraints

$$\mathbf{A(X + \Delta X) <= B}$$

Now a participant at any time may avoid being dispatched away from their energy target, x_j, by setting lower and upper deviation bounds for their CRM deviations, $\Delta\mathrm{x}_j$, to zero or by not participating in the CRM.

Note that if a resource, *j*, does not participate in the CRM, $\Delta\mathrm{x}_i = 0$ and $d_j(\mathrm{x}_j + \Delta\mathrm{x}_j)$ is set to zero in the objective function.

4.2.5 Co-optimised energy and CRM

In order to co-optimise CRM with energy all that is required is to combine the two optimisations via including their two objective function costs in the one objective function and combining their constraints. Thus, the co-optimised formulation is:

Minimise

$$\sum_{i \in NEM} c_i(\mathrm{x}_i) + \sum_{j \in CRM} d_j(\mathrm{x}_j + \Delta\mathrm{x}_j) = \mathbf{C(X) + D(X + \Delta X)}$$

Subject to:

CRM deviation limits

$$\text{lower bound} \leq \Delta\mathrm{x}_j \leq \text{upper bound}$$

Regional energy balances

$$\sum \mathrm{x}_i = \text{demand} = \mathbf{1'X}$$

$$\sum(\mathrm{x}_i + \Delta\mathrm{x}_i) = \mathrm{demand} = \mathbf{1'(X+\Delta X)}$$

Note that $\sum \Delta\mathrm{x}_i = 0$ and $\Delta\mathrm{x}_i$=0 for non CRM participating resources

Capacity and security constraints

$$\mathbf{AX <= B}$$

$$\mathbf{A(X + \Delta X) <= B}$$

Since $c_i(\mathrm{x}_i)$ and $d_j(\mathrm{y}_j)$ are piecewise linear convex functions then any linear combination of these functions will be convex hence **C(X) + D(X +ΔX)** is convex.

Note that in the co-optimisation of energy and CRM framework, the inclusion of the CRM market can influence the energy market dispatch, particularly, if the maximum CRM deviations are limited to small changes. This is like the co-optimisation of FCAS influencing energy market dispatches.

4.3 Settlement of energy and CRM dispatch

4.3.1 Introduction

Market participants' actual physical dispatch is the combination of the energy and CRM dispatch.

The energy market revenues are based on the RRP and the energy dispatched quantities. Both generators and Market Customers are settled at these prices.

The CRM revenues are based on the CRM marginal prices for each node (the nodal CRM prices or CRM LMPs) times the deviation quantities, $\Delta\mathrm{x}_i$. Note that the deviation quantities can be either positive or negative. AEMO would settle the congestion relief market. The combined energy and CRM settlement, assuming that a dispatchable resource met its dispatch targets, would be:

Energy and CRM revenue = x_i x RRP + $\Delta\mathrm{x}_i$. x LMP_i

4.3.2 Settlements in terms of buying and selling congestion relief

Even though the congestion relief market is settled by AEMO, a useful way of thinking about it is that congestion relief buyers pay congestion relief providers the local congestion relief price for the volume of congestion relief provided. This thinking can be illustrated by rearranging the settlement calculation above to the one below:

Energy and CRM revenue = $(\mathrm{x}_i + \Delta\mathrm{x}_i)$ x RRP + $\Delta\mathrm{x}_i$ x (LMP_i - RRP)

Using this settlement calculation, if we assume that the RRP is greater than the LMP_i then if a generator increases its output, $\Delta\mathrm{x}_i$ is positive then it will have to pay $\Delta\mathrm{x}_i$ x (LMP_i - RRP) for congestion relief. If a generator decreases its output, $\Delta\mathrm{x}_i$ is negative then it will get paid $\Delta\mathrm{x}_i$ x (LMP_i - RRP) for congestion relief.

4.3.3 Settlement of metered quantities

There are two main options for the settlement for metered quantities. These are:

- Metered energy priced at RRP

  Under this option the settlements would be:
  Energy and CRM revenue
  = metered energy x RRP + Δx_i x (LMP$_i$ - RRP)
  = (metered energy - Δx_i) x RRP + Δx_i x LMP$_i$
- Metered energy priced at CRM nodal price

  Under this option the settlements would be:
  Energy and CRM revenue
  = metered energy x LMP$_i$ + x_ix (RRP - LMP$_i$)
  = (metered energy - x_i) x LMP$_i$ + x_i x RRP

If the dispatchable resource follows its energy and CRM targets then both settlement options result in the same combined energy and CRM revenue.

The first option is analogous to what happens with FCAS and is the preferred model.

4.4 Outline of an incs and decs CRM model

An incs and decs CRM model uses cost functions for increases and decreases of generation (a decrease in consumption). All of the security constraints remain the same the only difference is the model uses a monotonic increasing piecewise linear cost function based on the deviations from the NEM energy market dispatch. The new objective function is:

Minimise

$$\sum c_i(x_i) + \sum f_j(\Delta x_j) = \mathbf{C(X) + F(\Delta X)}$$

Again, the objective function is a piecewise linear cost function which is convex.

To ensure full coverage of the possible deviations the cost functions need to be defined for the maximum range of deviations, that is, deviating from the maximum possible output (Pmax) down to the minimum possible output (Pmin) which could be negative for a storage plant and from the Pmin to Pmax:

$$-(\text{Pmax} - \text{Pmin}) <= \Delta x_j <= \text{Pmax} - \text{Pmin}$$

This range of changes can be narrowed to zero though the use of the CRM deviation limits

$$\text{lower bound} \leq \Delta x_j \leq \text{upper bound}$$

5 Outline of Co-optimisation Model for Examples

5.1 Management of network constraints in NEMDE

NEMDE uses generic constraints to model network flows pre and post contingencies and associated security requirements. NEMDE in effect uses a DC load flow (linear approximation) of transmission power flows. Within regions losses are not modelled. The MLFs are just used as price multipliers. In a DC load flow approximation, power flows on a line, i, from bus k to l can be approximated in terms of line susceptances, b_i, and voltage phase angle differences between the start and end of the line.

$F_i = -b_i (\theta_k - \theta_l)$

Alternatively, these flows can be approximated in terms of the nodal injections (net generation – load at bus), P(i) = G(i)-L(i), and power transfer distribution factors (PTDFs), also called power injection shift factors (PISFs) or shift factors a_i, giving equations like:

$F_i = \sum a_i P(i)$

Thus, the steady state thermal constraint on power flows could be written as

$-\text{rating} <= F_i <= \text{rating}$

Or

$-\text{rating} <= \sum a_i P(i) <= \text{rating}$

$-\text{rating} + \sum a_i L(i) <= \sum a_i G(i) <= \text{rating} + \sum a_i L(i)$

To make the above constraint accurate requires the use of the nodal loads. However, since in the NEM, nodal forecasts are not used the nodal loads are essentially approximated via proportions of the regional loads. This can lead to inaccuracies which is why many thermal constraints have been set up as feedback constraints which use the current SCADA measurements for line flows and actual generation to approximate the constraint around its current operating point.

The post contingent power flows on line i following a forced outage on line j can be determined using the same DC load flow approximation model to determine line outage distribution factors (LODFs) to calculate the post contingent power flow

$F^*_i = F_i + k(i,j) F_j$

This leads to the post contingent thermal constraint on power flows

-short term rating <= F^*_i <= short term rating

Thermal, voltage and stability constraints can be written with explicit power flow terms as above or can have these terms eliminated and only be written in terms of nodal injections and in turn these can be rewritten in terms of dispatchable terms on the left hand side (LHS) of the equations and the nodal loads moved to the right hand side (RHS).

5.2 Spreadsheet models

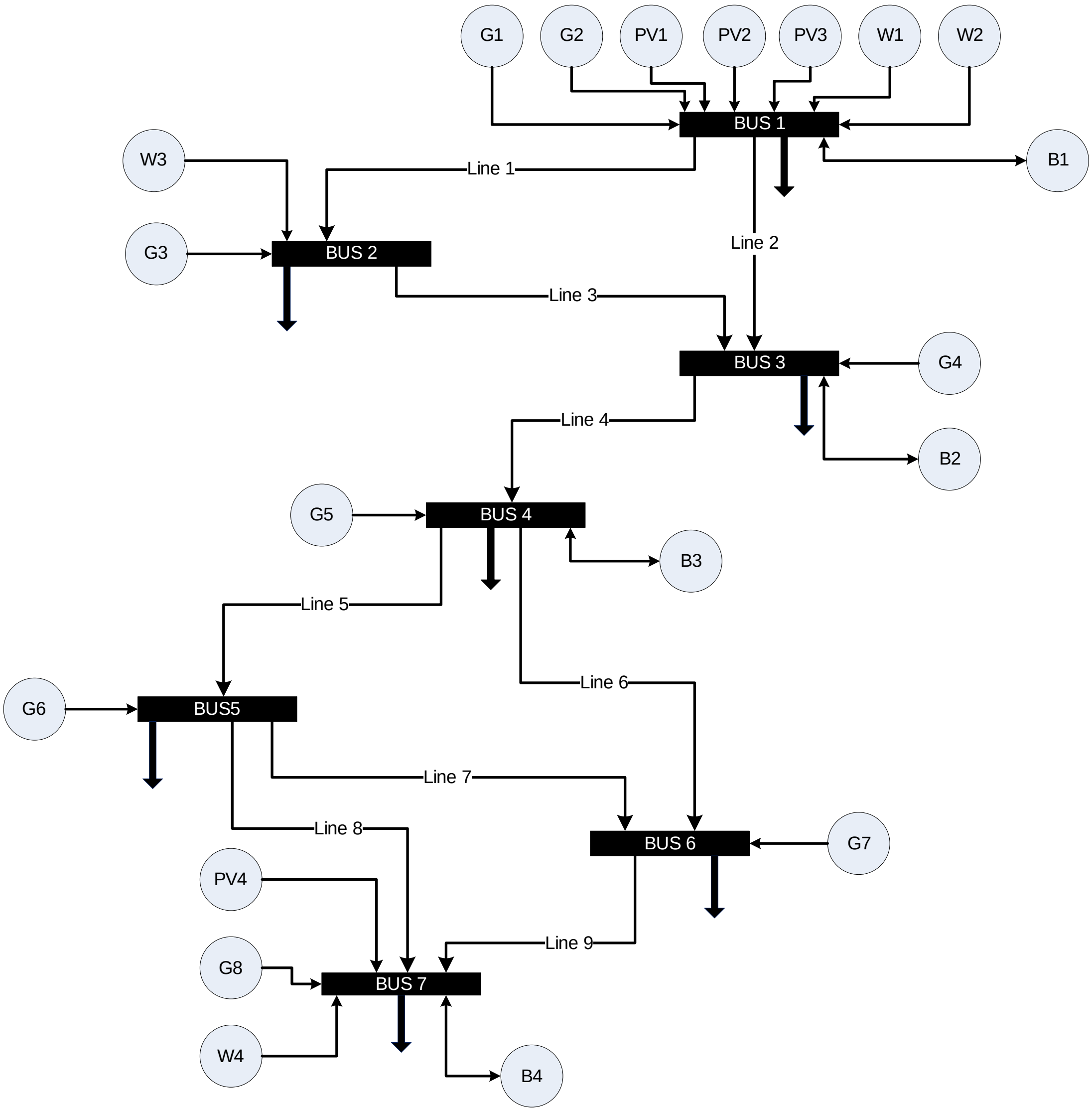
5.2.1 Introduction

For convenience the spreadsheets explicitly model the power flows on lines and use constraints on these line flows. This is largely equivalent to NEMDE's approach of using generic constraints but does not require the calculation of new PTDFs (PISFs) for a change in network topology or outages.

The spreadsheet models allow for up to 20 dispatchable resources (8 dispatchable generators, 4 PV generators, 4 wind generators and 4 batteries), 7 nodes/buses and 9 lines/branches. The resources can be allocated to any of the buses and the lines can be set up to connect any two buses.

The initial network topology for some of the examples is presented in Figure 2. For some of the examples the network is simplified by changing the connection status for some lines and resources to disconnected and setting the nodal loads to zero.

Figure 2 Network topology used in some of the examples



The spreadsheets use to following colours for inputs, calculations, decision variables etc.

Input data static
Input data dynamic
Calculated value based on input data
Decision variable
Calculated value based on decision variable value
Objective value
Shadow price

5.2.2 Generators and dispatchable loads/batteries

The dispatch of loads and battery charging is modelled as a generator with a negative power output. The model for batteries allows for “generation” to be positive or negative. Thus, a battery charging at a rate of 100MW will appear to have a dispatch target of -100MW. Under this arrangement the offers for dispatch of generation start from Pmin and in the case for a battery this could be -100 MW. This has made the modelling easier but requires care in determining the dispatch targets and dispatch costs. The actual implementation of batteries, dispatchable loads and pumped storage could be different in NEMDE but this model is quite adequate at demonstrating the CRM.

The generator and dispatchable load/battery input data consist of:

- Node/bus connection point
- Minimum power (Pmin) can be negative for a battery or load
- Maximum power output (Pmax)
- Connection status (1 if connected 0 if disconnected) which reduces the operational Pmin and Pmax to zero if a unit is not connected
- SRMC/opportunity cost (used in “profit” calculations)
- Quantities and prices for energy and CRM offers and bids
- Maximum increases and decreases in output due to CRM (can be set to zero to remove participation in CRM)

The generator and dispatchable load decision variables (dispatchable variables / left hand side variables) consist of:

- The dispatch of the two offered price bands for energy and the two offered price bands for the CRM.

The generator and dispatchable load output calculations consist of:

- Sum of dispatched energy offers
- Energy dispatch = sum of dispatched energy offers + Pmin (this is to cater for the combined charging and discharging model which is being used rather than separate charging and discharging models and dispatch)
- CRM deviation dispatch
- Energy dispatch cost = energy cost/revenue at Pmin + cost of dispatched energy offers, $\sum c_i(\mathrm{x}_i)$, this calculation is to cater for the combined charging and discharging model)
- CRM gross cost (cost of energy dispatch + CRM deviations) priced at CRM offer prices + CRM cost/revenue at Pmin, $\sum d_i(\mathrm{x}_i + \Delta\mathrm{x}_i)$, again this calculation is to cater for a combined charging and discharging model.

- The sum of the energy dispatch costs and the CRM gross cost plus the constraint violation penalties are the basis of the objective function which is to minimise costs.
- The energy revenues of dispatchable resources are based on the regional prices times the energy dispatched quantities
- The CRM revenues are based on the CRM marginal prices for each node times the deviation quantities.
- The various “profits” are based on the revenues minus the dispatched amounts times there SRMC/opportunity costs.

5.2.3 Bus information

The bus input comprises the nodal load forecasts, the minimum and maximum voltage phase angles and the nodal violation penalties which deal with any shortfalls of supply at any bus.

The decision variables for each bus are the voltage phase angles and the nodal violation quantities for both the energy and CRM dispatches.

Calculated bus information includes the bus generation, bus exports and bus imports for the energy and CRM dispatches.

The optimisation provides the nodal shadow prices (marginal costs) for the nodal energy balances for both the energy and CRM dispatches. The regional reference price is the nodal price for the regional reference node for the energy dispatch.

5.2.4 Branch information

The branch information comprises network information for transmission lines, transformers etc.

The branch input data consist of:

- Connection status,
- ‘from bus’ and ‘to bus’
- Branch resistance and reactance
- Continuous rating

The branch flows are calculated from the phase angle difference between the ‘from bus’ and the ‘to bus’ and this is done for the energy and CRM dispatches. The branch shadow prices represent the marginal cost of the branch’s capacity constraint. This is much the same as the shadow price of a network security constraint in NEMDE.

5.2.5 The optimisation

The co-optimisation of energy and CRM dispatch uses a linear program. The smaller 2 bus example model can be run just using Excel's Solver. The larger 6 bus models require the use of Open Solver (https://opensolver.org/) which is a free open source solver which can be run in Excel and uses the same otimisation model as Excel's Solver, see details in footnote[2] about installing Solver and Open Solver.

The formulation of the optimisation is:

Minimise the total energy, CRM and violation penalty costs

Subject to the following constraints:

- Dispatch of energy and CRM price bands >= 0
- Dispatch of energy price bands <= offered capacity
- Dispatch of CRM price bands <= CRM offered capacity
- Dispatch of energy >= operational Pmin
- Dispatch of energy <= operational Pmax
- CRM deviations >= minimum (negative) deviation
- CRM deviations <= maximum (positive) deviation
- Total energy + CRM dispatch >= operational Pmin
- Total energy + CRM dispatch <= operational Pmax
- Nodal energy violations >= 0
- Nodal CRM energy violations >= 0
- Energy power flows are within line limits
- Energy + CRM power flows are within line limits
- Nodal energy balance
- Nodal energy + CRM balance

The branch power flows are determined from the difference in phase angles and the branch susceptance.

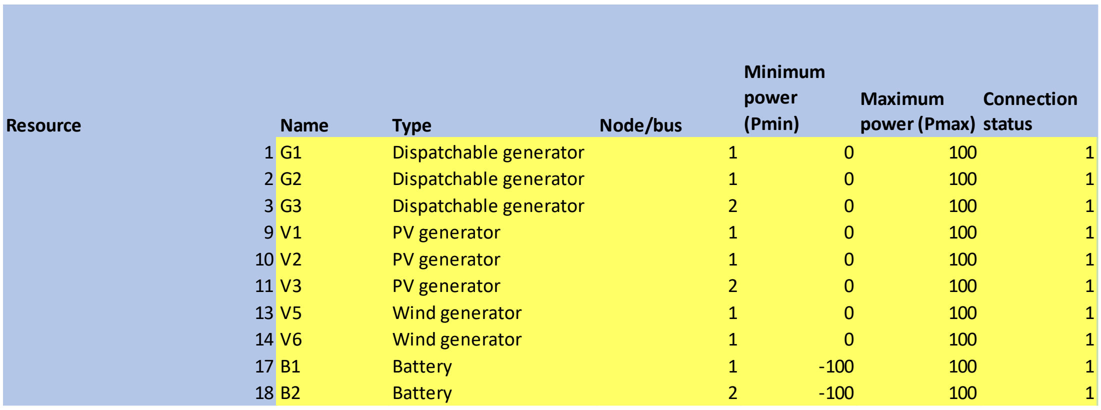
---

[2] Installation of Excel's Solver and OpenSolver:
• To install Excel's Solver: => File => Excel Options => Add-Ins => Manage Excel Add-ins tick Solver Add-inn.
• You can download the latest version of OpenSolver from https://opensolver.org/. Note that installing Open Solver can be tricky. In July 2016, Microsoft released an update to Office 365 which prevents OpenSolver from loading unless the .zip file is "unblocked" before the files are extracted. The symptoms are simply that OpenSolver does not appear in the Data tab; there is no error message shown. To fix this, delete your old OpenSolver files (but not the downloaded .zip file), right click the downloaded OpenSolver.zip file, choose Properties, and click the Unblock button which will show if the file is blocked. Once the file is unblocked, close the properties dialog, and then un-zip the files and open up OpenSolver.xlam as usual. For more details see http://opensolver.org/help/ and https://opensolver.org/installing-opensolver/.

6 Two Bus Example

The two bus example provides a simple illustration of how the CRM could work, see work book “Congestion management model 2 bus final.xlsx“. There are ten generators at two nodes. The generators are a mix of dispatchable, PV, wind and batteries and their characteristics are presented in Table 1 below.

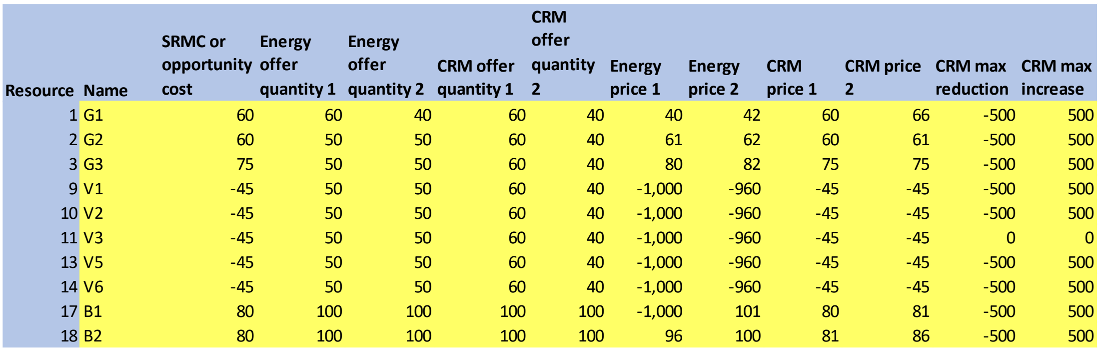
Table 1 Dispatchable resources



Resource	Name	Type	Node/bus	Minimum power (Pmin)	Maximum power (Pmax)	Connection status
1	G1	Dispatchable generator	1	0	100	1
2	G2	Dispatchable generator	1	0	100	1
3	G3	Dispatchable generator	2	0	100	1
9	V1	PV generator	1	0	100	1
10	V2	PV generator	1	0	100	1
11	V3	PV generator	2	0	100	1
13	V5	Wind generator	1	0	100	1
14	V6	Wind generator	1	0	100	1
17	B1	Battery	1	-100	100	1
18	B2	Battery	2	-100	100	1

The energy and CRM offers are in Table 2 below.

Table 2 Energy and CRM Offers



Resource	Name	SRMC or opportunity cost	Energy offer quantity 1	Energy offer quantity 2	CRM offer quantity 1	CRM offer quantity 2	Energy price 1	Energy price 2	CRM price 1	CRM price 2	CRM max reduction	CRM max increase
1	G1	60	60	40	60	40	40	42	60	66	-500	500
2	G2	60	50	50	60	40	61	62	60	61	-500	500
3	G3	75	50	50	60	40	80	82	75	75	-500	500
9	V1	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
10	V2	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
11	V3	-45	50	50	60	40	-1,000	-960	-45	-45	0	0
13	V5	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
14	V6	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
17	B1	80	100	100	100	100	-1,000	101	80	81	-500	500
18	B2	80	100	100	100	100	96	100	81	86	-500	500

In this example the regional reference node is at bus 2 and there is congestion between bus 1 and 2. The RRP is $100/MWh (the marginal price at bus 2) and the CRM marginal prices are $61/MWh at bus 1 and $86/MWh at bus 2. The marginal prices for energy are determined from the shadow prices of the energy balances at the buses and the CRM prices are determined from the shadow prices of the CRM energy balances at the buses.

Table 3 RRP and CRM Prices

Load forecast data

BUS	Region	nodal_load_forecast	nodal_load_violation_cost	Nodal price (shadow price)	CRM nodal prices
1	1	100	100,000	40.0	61.0
2	1	551	100,000	100.0	86.0
System (region)		651	regional reference price (RRP)	100.0	

The energy and CRM dispatches and prices that the resources will receive are in Table 4 below. What is interesting to note is that in the CRM dispatch, G1 and G2 have their dispatches increased by a total of 100 MW and the battery has been dispatched to charge for 100 MW.

Table 4 Energy and CRM dispatch and prices

Resource	Name	Node/bus	Dispatch energy 1	Dispatch energy 2	Dispatch CRM 1	Dispatch CRM 2	Energy dispatch (adjusted for Pmin)	CRM deviations dispatch	Total dispatch	Energy "cost"	CRM gross "cost"	Energy regional price	CRM price
1	G1	1	50	0	60	0	50	**10**	60	2,000	3,600	100	61
2	G2	1	0	0	60	30	0	**90**	90	0	5,430	100	61
3	G3	2	50	50	60	40	100	0	100	8,100	7,500	100	86
9	V1	1	50	50	60	40	100	0	100	-98,000	-4,500	100	61
10	V2	1	50	50	60	40	100	0	100	-98,000	-4,500	100	61
11	V3	2	50	50	60	40	100	0	100	-98,000	-4,500	100	86
13	V5	1	50	50	60	40	100	0	100	-98,000	-4,500	100	61
14	V6	1	50	50	60	40	100	0	100	-98,000	-4,500	100	61
17	B1	1	100	0	0	0	0	**-100**	-100	0	-8,000	100	61
18	B2	2	100	1	100	1	1	0	1	100	86	100	86
			550	**301**	**580**	**271**	**651**	**0**	**651**	**-479,800**	**-13,884**		

The impact of the CRM co-optimisation has been to result in a more efficient dispatch and increased profitability for some resources.

Table 5 Changes in resources "profitability" due to CRM

Resource	Name	Node/bus	Energy dispatch (adjusted for Pmin)	CRM deviations dispatch	Total dispatch	Energy regional price	Energy revenue	Energy short run cost	Energy profit	CRM price	CRM revenue	Energy + CRM dispatch short run cost	Total profit	Total profit - energy profit
1	G1	1	50	10	60	100	5,000	3,000	2,000	61	610	3,600	2,010	10
2	G2	1	0	90	90	100	0	0	0	61	5,490	5,400	90	90
3	G3	2	100	0	100	100	10,000	7,500	2,500	86	0	7,500	2,500	0
9	V1	1	100	0	100	100	10,000	-4,500	14,500	61	0	-4,500	14,500	0
10	V2	1	100	0	100	100	10,000	-4,500	14,500	61	0	-4,500	14,500	0
11	V3	2	100	0	100	100	10,000	-4,500	14,500	86	0	-4,500	14,500	0
13	V5	1	100	0	100	100	10,000	-4,500	14,500	61	0	-4,500	14,500	0
14	V6	1	100	0	100	100	10,000	-4,500	14,500	61	0	-4,500	14,500	0
17	B1	1	0	-100	-100	100	0	0	0	61	-6,100	-8,000	1,900	1,900
18	B2	2	1	0	1	100	100	80	20	86	0	80	20	0
			651	**0**	**651**		**65,100**	**-11,920**	**77,020**		**0**	**-13,920**	**79,020**	**2,000**

7 Four Bus Example

7.1 Four bus example using DC power flow model

To illustrate how the CRM model would work with a meshed network (one where there are loop flows) a simple four bus model was constructed, see work book “Congestion management model 4 node final.xlsx“, and within it, the spreadsheet “CRM 4 bus network model”.

In the four bus example provided, there are 14 generators at four buses (nodes). The generators are a mix of dispatchable, PV, wind and batteries and their characteristics are presented in Table 6 below.

Table 6 Dispatchable resources

Resource	Name	Type	Node/bus	Minimum power (Pmin)	Maximum power (Pmax)	Connection status
1	G1	Dispatchable generator	1	0	100	1
2	G2	Dispatchable generator	1	0	100	1
3	G3	Dispatchable generator	2	0	100	1
4	G4	Dispatchable generator	3	0	100	1
5	G5	Dispatchable generator	4	0	100	1
9	PV1	PV generator	1	0	100	1
10	PV2	PV generator	1	0	100	1
11	PV3	PV generator	1	0	100	1
13	W1	Wind generator	1	0	100	1
14	W2	Wind generator	1	0	100	1
15	W3	Wind generator	2	0	100	1
17	B1	Battery	1	-100	100	1
18	B2	Battery	3	-100	100	1
19	B3	Battery	4	-100	100	1

The energy and CRM offers are in Table 7 below.

Table 7 Energy and CRM Offers

Resource	Name	SRMC/opportunity cost	Energy offer quantity 1	Energy offer quantity 2	CRM offer quantity 1	CRM offer quantity 2	Energy price 1	Energy price 2	CRM price 1	CRM price 2	CRM max reductio n	CRM max increase
1	G1	60	50	50	60	40	40	42	60	65	-500	500
2	G2	60	50	50	60	40	60	62	60	60	-500	500
3	G3	75	50	50	60	40	80	82	75	75	-500	500
4	G4	76	50	50	60	40	100	250	76	83	-500	500
5	G5	77	50	50	60	40	300	1,000	77	86	-500	500
9	PV1	-40	50	50	60	40	-1,000	-960	-40	-40	-500	500
10	PV2	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
11	PV3	-42	50	50	60	40	-1,000	-960	-42	-42	-500	500
13	W1	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
14	W2	-45	50	50	60	40	-1,000	-960	-45	-45	-500	500
15	W3	-44	50	50	60	40	-1,000	-960	-44	-44	-500	500
17	B1	81	110	90	100	100	95	101	80	81	-500	500
18	B2	82	100	100	100	100	96	101	81	86	-500	500
19	B3	83	100	100	100	100	97	100	83	84	-500	500

In this example the regional reference node is at bus 4 and there is congestion between bus 1 and 3 and bus 3 and 4, that is, the power flows on lines 2 and 4 are at their limits. The RRP is $1000/MWh (the nodal price for bus 4) and the bus (nodal) energy and CRM marginal prices are presented in Table 8.

Table 8 RRP and CRM Prices

BUS	Region	nodal_load_forecast	nodal_load_violation_cost	Nodal price (shadow price)	CRM nodal prices
1	1	100	100,000	62.0	60.0
2	1	150	100,000	71.5	65.3
3	1	220	100,000	100.0	81.0
4	1	370	100,000	1,000.0	86.0

The energy and CRM dispatches and prices that the resources will receive are in Table 9 below. What is interesting to note is that in the CRM dispatch G1 and G2 effectively trade 43 MW of generation with G1 reducing its output and G2 increasing its. The battery B2 increases its charging demand to 48 MW which allows G4 to increase its generation by 48 MW.

Table 9 Energy and CRM dispatch and prices

Resource	Name	Dispatch energy 1	Dispatch energy 2	Dispatch CRM 1	Dispatch CRM 2	Energy dispatch (adjusted for Pmin)	CRM deviations dispatch	Total dispatch	Energy "cost"	CRM gross "cost"	Energy regional price	CRM price
1	G1	50	50	58	0	100	-43	58	4,100	3,450	1,000	60
2	G2	50	8	60	40	58	43	100	3,465	6,000	1,000	60
3	G3	0	0	0	0	0	0	0	0	0	1,000	65
4	G4	13	0	60	0	13	48	60	1,250	4,560	1,000	81
5	G5	50	20	60	10	70	0	70	35,000	5,480	1,000	86
9	PV1	50	50	60	40	100	0	100	-98,000	-4,000	1,000	60
10	PV2	50	50	60	40	100	0	100	-98,000	-4,500	1,000	60
11	PV3	50	50	60	40	100	0	100	-98,000	-4,200	1,000	60
13	W1	50	50	60	40	100	0	100	-98,000	-4,500	1,000	60
14	W2	50	50	60	40	100	0	100	-98,000	-4,500	1,000	60
15	W3	50	50	60	40	100	0	100	-98,000	-4,400	1,000	65
17	B1	0	0	0	0	-100	0	-100	-9,500	-8,000	1,000	60
18	B2	100	0	53	0	0	-48	-48	0	-3,848	1,000	81
19	B3	100	100	100	100	100	0	100	10,000	8,400	1,000	86
20	B4	0	0	0	0	0	0	0	-9,800	-6,900	1,000	100,000
		663	**478**	**750**	**390**	**840**	**0**	**840**	**-553,485**	**-16,958**		

The impact of the CRM co-optimisation has been to result in a more efficient dispatch and increased profitability for some resources.

Table 10 Changes in resources “profitability” due to CRM

Resource	Name	Node/bus	Energy dispatch (adjusted for Pmin)	CRM deviations dispatch	Total dispatch	Energy regional price	Energy revenue	Energy short run cost	Energy profit	CRM price	CRM revenue	Energy + CRM dispatch short run cost	Total profit	Total profit - energy profit
1	G1	1	100	-43	58	1,000	100,000	6,000	94,000	60	-2,550	3,450	94,000	0
2	G2	1	58	43	100	1,000	57,500	3,450	54,050	60	2,550	6,000	54,050	0
3	G3	2	0	0	0	1,000	0	0	0	65	0	0	0	0
4	G4	3	13	48	60	1,000	12,500	950	11,550	81	3,848	4,560	11,788	238
5	G5	4	70	0	70	1,000	70,000	5,390	64,610	86	0	5,390	64,610	0
9	PV1	1	100	0	100	1,000	100,000	-4,000	104,000	60	0	-4,000	104,000	0
10	PV2	1	100	0	100	1,000	100,000	-4,500	104,500	60	0	-4,500	104,500	0
11	PV3	1	100	0	100	1,000	100,000	-4,200	104,200	60	0	-4,200	104,200	0
13	W1	1	100	0	100	1,000	100,000	-4,500	104,500	60	0	-4,500	104,500	0
14	W2	1	100	0	100	1,000	100,000	-4,500	104,500	60	0	-4,500	104,500	0
15	W3	2	100	0	100	1,000	100,000	-4,400	104,400	65	0	-4,400	104,400	0
17	B1	1	-100	0	-100	1,000	-100,000	-8,100	-91,900	60	0	-8,100	-91,900	0
18	B2	3	0	-48	-48	1,000	0	0	0	81	-3,848	-3,895	48	48
19	B3	4	100	0	100	1,000	100,000	8,300	91,700	86	0	8,300	91,700	0
		Total	**840**	**0**	**840**		**840,000**	**-10,110**	**850,110**		**0**	**-10,395**	**850,395**	**285**

7.2 Four bus example using generic constraint style model

To illustrate how a DC power flow model is equivalent to a NEMDE style model, we have converted the explicit network model into one which uses generic constraints. In this model, instead of explicitly modelling the network we used power injection shift factors (PISFs), also called power transfer distribution factors (PTDFs), these line flow sensitivity factors give the change in flow on a line given a change in power injection at a bus. These shift factors can be computed using matrix algebra involving the line incidence matrix and the susceptances. These factors assume a swing bus as the balancing item. For this example, we have assumed that the swing bus is the RRN, bus 4. This results in the constraints being appropriately orientated, i.e. not involving any dispatchable resources which are located at the RRN. The power injection shift factors are presented in Table 11.

Table 11 Power injection shift factors for four bus model

Power injection shift factor (flow on line = factor x nodal injection)				
	Node			
line	1	2	3	4
1	0.429	-0.429	0	0
2	0.571	0.429	0	0
3	0.429	0.571	0	0
4	1	1	1	0

Using the power injection shift factors enables the line flow constraints in the DC load flow model to be reformulated as linear constraints on the net injections. These in turn can be reformulated as constraints on the dispatchable resources with the load offtakes moved to the RHS of the constraints.

What the model shows is that the network constraints of the “CRM 4 bus network model” can be converted into “generic” constraints in the “CRM 4 bus generic constraints” model and these will involve different coefficients for different resources depending on where they are located in the network.

The “CRM 4 bus generic constraints” spreadsheet produces the same dispatches, RRPs and underlying energy and CRM nodal prices as the explicit model when the shadow prices of the constraints are used appropriately to create the implied nodal prices, how this is done is outlined in section 8.2.

8 LMP Basis Risk Management with CRM and CMM

8.1 Introduction

When discussing the ESB's Congestion Management Mechanism (CMM) and CRM options two of the key objectives are

- to have locational prices at the margin and for generators, batteries, pumped storage, dispatchable loads etc. and
- for market participants to be able to effectively manage any LMP risk.

LMP risks are generally managed via some form of financial transmission rights (FTRs). Thus, it is useful to compare the CRM versus a CMM in terms of the implied FTRs and how well they manage LMP risks.

8.2 Settlement Surpluses, Constraint Costs and LMPs

For simplicity, this discussion assumes a lossless network, a single region and only steady state thermal constraints. The basic logic still applies to a N-1 security constrained dispatch with thermal and other network constraints.

The energy settlements surplus for an LMP model is

Surplus

$$= \sum_{j \text{ in } Loads} LMP_j \times L_j - \sum_{k \text{ in } Generating\ units} LMP_k \times G_k$$

See sheet 'CRM 4 bus network model', cell S11 for an example.

This surplus is also equal to the network constraint costs

$$= - \sum_{m \text{ in } Lines} \lambda_m \times R_m$$

where λ_m is the shadow price of the network constraint related to the rating R_m of line m.

See sheet 'CRM 4 bus network model', cell W67 for an example.

8.3 Nodal Prices, Settlement Surpluses with Loads Paying RRP

8.3.1 Regional Reference Price (RRP)

In the NEM, the RRP is the spot price at a regional reference node which represents the marginal value of supply at that location and time, this being determined as the price of meeting an incremental change in load at that location and time[3]. In other words, the RRP is LMP at the RRN. The spot price at the RRN is determined from the shadow price of the regional energy balance equation. Because this approach has been used to determine the RRP, all network constraints have to be 'oriented' such that they do not include any terms for dispatchable resources located at the RRN or on the RRN side of a network constraint, otherwise the correct RRP could not be determined from the shadow price of the energy balance equation.

8.3.2 LMPs of other nodes

For node n (bus n) which has dispatchable resources at its location its nodal price is

$$LMP_n = RRP + \sum_{k \text{ in network constraints}} \lambda_k \times c_{k,n}$$

Where λ_k is the shadow price of the k^th^ network constraint and $c_{k,n}$ is the coefficient of the dispatchable resource at node n (bus n) in constraint k. Note that λ_k will be negative for a '<=' constraint as an increase in the RHS by one unit will reduce the objective function (total of dispatch costs) whereas λ_k will be positive for a '>=' constraint as an increase in the RHS will increase the objective function.

See sheet 'CRM 4 bus generic constraints', cells Y4:Y7 for an example.

8.3.3 Settlement surplus with RRP for loads and LMPs for generators

The settlements surplus for when loads are charged the RRP and generators are paid at LMP is

Surplus

$$= \sum_{j \text{ in Loads}} RRP \times L_j - \sum_{n \text{ in Generating units}} LMP_n \times G_n$$

See sheet 'CRM 4 bus generic constraints', cell L50 for an example of a surplus calculation.

$$= RRP \times \sum_{j \text{ in Loads}} L_j - \sum_{n \text{ in Generating units}} \left(RRP + \sum_{k \text{ in constraints}} \lambda_k \times c_{k,n} \right) \times G_n$$

Since $\sum_{n \text{ in Generating units}} G_k = \sum_{j \text{ in Loads}} L_j$

---

[3] NER 3.9.2 (d)

$$= - \sum_{n\ in\ Generating\ units} \left(\sum_{k\ in\ constraints} \lambda_k \times c_{k,n} \right) \times G_n$$

If we reverse the order of summations

$$= - \sum_{k\ in\ constraints} \left(\sum_{n\ in\ Generating\ units} \lambda_k \times c_{k,n} \times G_n \right)$$

$$= - \sum_{k\ in\ constraints} \lambda_k \times \left(\sum_{n\ in\ Generating\ units} c_{k,n} \times G_n \right)$$

Now, for non binding constraints $\lambda_k = 0$ and for binding constraints $\lambda_k \neq 0$ and $\sum_{n\ in\ Generating\ units} c_{k,n} \times G_n = RHS\ of\ constraint = b_k$

Thus, the settlement surplus is equal to

$$= - \sum_{k\ in\ constraints} \lambda_k \times b_k$$

which is the total constraint costs. Note that under this formulation that the nodal loads have been moved to the RHS of the equation and thus b_k equals a line rating plus the nodal loads times their coefficients in the original explicit network model formulation of section 8.2.

See sheet ‘CRM 4 bus generic constraints’, cell AJ72 for the total constraint costs using a NEMDE formulation with generic constraints.

The implication of this is that the settlement surplus can be calculated based on either LMPs or constraint costs.

8.4 Hedging a Generator Against a NEM RRP

The ideal hedge for a generator receiving LMP who is contracting at the RRP would be a point to point FTR from the generating unit’s node n to the RRN for a quantity that matches the generator’s exposure to the RRP. For a 1 MW quantity, the FTR would have a payment of:

$$RRP - LMP_n = - \sum_{k\ in\ constraints} \lambda_k \times c_{k,n}$$

For Q_n MW of hedge this would involve a payout of

$$-Q_n \sum_{k\ in\ constraints} \lambda_k \times c_{k,n}$$

Note, that to provide a hedge against RRP-LMP_n for the generating unit at node n the amount of each constraint's costs allocated to it are $Q_n \times c_{k,n}$. Different allocations of the constraint costs won't reliably hedge the RRP- LMP_n, that is, Q_n needs to be the same for each constraint that unit n appears in.

For a particular constraint k, and for a hedge quantity of Q_n for each unit n the amount of the constraint costs allocated to it will be $Q_n \times \lambda_k \times c_{k,n}$.

The proportion of constraint costs (congestion rebate) allocated to unit n for constraint k that is binding would be:

$$\frac{Q_n \times \lambda_k \times c_{k,n}}{\lambda_k \times b_k} = \frac{Q_n \times c_{k,n}}{b_k}$$

In order to avoid over allocation

$$\sum_{n\ in\ generating\ units} Q_n \times c_{k,n} \leq RHS\ of\ constraint = b_k$$

These constraints are exactly the same as the network security constraints, therefore any allocation of the set of $\{Q_n\}$ must satisfy the network security constraints. Once an objective function for the $\{Q_n\}$ has been determined then the optimal allocation of the $\{Q_n\}$ is just a security constrained dispatch optmisation.

8.5 Allocation of Congestion Rebates under CMM

All of the CMM options allocate some proportion of each binding constraint's costs to each resource that has a non zero coefficient on the LHS of the constraint. That is each generating unit will get a rebate of:

$$CMM\ rebate = \sum_{k\ in\ constraints} p_{k,n} \times \lambda_k \times b_k$$

Where $p_{k,n}$ is the proportion of constraint k's costs rebated to generator n and $\lambda_k \times b_k$ is the cost of constraint k.

Now $p_{k,n} \times b_k$ is equivalent to a hedging MW quantity $q_{k,n}$ where

$$q_{k,n} = \frac{p_{k,n} \times b_k}{c_{k,n}}$$

Further, to provide a good hedge against (RRP – LMP_n), $q_{k,n}$ should equal a constant quantity Q_n for all k. In this case the CMM would be equivalent to a point to point FTR from the resource's node to the RRN for a quantity of Q_n. Thus, in terms of determining congestion rebates for each constraint that will hedge the difference between LMP_n and RRP, the selected mechanism should result in constant $q_{k,n} = Q_n$ for each constraint for resource n.

8.6 Optimal Determination of Congestion Rebates under CMM

As discussed in the previous sections, in order to provide a good hedge against the difference between the RRP and a generating unit's LMP the quantities $\{Q_n\}$ should be determined by some form of security constrained optimisation. If this is not done then the quality of the hedging or the amount of hedging provided by the CMM will be suboptimal. The potential CMM options should be all formulated as security constrained dispatches with a range of different objective functions.

8.7 CRM as a Combined Energy Dispatch and FTR

The settlements for the CRM co-optimisation can be expressed in three algebraically equivalent ways for an energy dispatch of x_n and a CRM deviations dispatch of $\Delta\mathrm{x}_n$:

Revenue:

$$= \mathrm{x}_n \times RRP + \Delta\mathrm{x}_n \times LMP_n$$

$$= \mathrm{Q}_n \times RRP + (\mathrm{G}_n - \mathrm{Q}_n) \times LMP_n \text{ where } \mathrm{Q}_n = \mathrm{x}_n \text{ and } \mathrm{G}_n = \mathrm{x}_n + \Delta\mathrm{x}_n$$

$$= \mathrm{G}_n \times RRP + (\mathrm{G}_n - \mathrm{Q}_n) \times (LMP_n - RRP)$$

$$= \mathrm{G}_n \times LMP_n + \mathrm{Q}_n \times (RRP - LMP_n)$$

The last formulation of the CRM settlements is equivalent to an LMP market with a point to point FTR from the local node to the RRN for a quantity Q_n determined from the NEM energy dispatch component of the CRM co-optimisation.

8.8 CRM Versus CMM Congestion Rebates

As discussed earlier the CRM can be reformulated as an FTR allocation which is also equivalent to a specific form of a congestion rebate based on the quantity Q_n determined from the NEM energy dispatch in the CRM co-optimisation. The CRM's implied congestion rebate or FTR quantity is based on a security constrained dispatch optimisation which uses the latest network information via the generic constraints which were invoked in real time.

It is not clear what network information any of the CMM rebates will use and how up to date the information will be. Further, it is not clear whether they will even be based on a security constrained dispatch. If the CMM rebate allocations don't use a security constrained dispatch optimisation then we know that they will result in suboptimal use of the congestion surpluses with respect to hedging the risks of LMPs versus the RRP.