Notice of Market Rules Modification

Paper No.:	EMC/RCP/64/2012/313
Rule Reference:	Market Rules/App 6D, D2, D3, D4, D5, D9, D14, D16 & D20A
Proposer:	Energy Market Company
Date Received by EMC:	1 April 2011
Category Allocated:	2
Status:	Approved by EMA
Effective Date:	18 April 2013

The Market Clearing Engine (MCE) currently allocates scheduled quantities to generation registered facilities (GRFs) and load registered facilities (LRFs) with tied marginal offers in a random manner. Such random allocation could result in dispatch instability for a given unit. This paper thus evaluates proposed tie-breaking formulations to address this issue.

Following a survey of tie-breaking practices in other jurisdictions, the pair-wise linear programming tie-breaking method, which both AEMO and MISO employ, was found to be most suitable for the SWEM. This method attaches a tie-breaking constraint with a penalty factor of 10^{-6} to the objective function such that any ties between a pair of units that are not addressed will reduce net benefit insignificantly (in the order of between 10^{-4} and 10^{-6}) for a dispatch period. It breaks ties by accurately apportioning tied GRFs/LRFs' scheduled quantities based on their individual offered quantities. In addition, it can be applied across all products and all facilities.

MCE simulations were carried out to determine the effectiveness of this proposed formulation in breaking ties. It was found that tie-breaking constraints were able to resolve both units that were tied at the clearing price and non-marginal units that were tied due to other MCE constraints, without compromising the objective of maximising net benefit.

The RCP unanimously recommends that the EMC Board adopt this rule modification as set out in Annex 3.

Date considered by Rules Change Panel:	06 November 2012
Date considered by EMC Board:	22 November 2012
Date considered by Energy Market Authority:	19 December 2012

Proposed Rule Modification:

Refer to attached paper.

Reasons for rejection/referral back to Rules Change Panel (if applicable):

PAPER NO.	:	**EMC/BD/**
PAPER NO.	:	**EMC/RCP/2012/64/313**
SUBJECT	:	**TIE-BREAKING OF OFFERS**
FOR	:	**DECISION**
PREPARED BY	:	**NERINE TEO** **SENIOR ECONOMIST**
REVIEWED BY	:	**PAUL POH LEE KONG** **SVP, MARKET ADMINISTRATION**
DATE OF MEETING	:	**22 NOVEMBER 2012**

Executive Summary

The Market Clearing Engine (MCE) currently allocates scheduled quantities to generation registered facilities (GRFs) and load registered facilities (LRFs) with tied marginal offers in a random manner. From a fairness perspective, these random allocations should not be of concern to marginal units, given that offers are assumed to be representative of a facility's marginal costs. A Market Participant (MP) whose unit's offer is at marginal price should be indifferent as to whether its unit gets dispatched or not. Also, given that the MCE allocates quantities to tied units on a random basis, the probability of each tied marginal unit being scheduled for a product should equate over time. However, random allocation could result in dispatch instability for a given unit. This proposal thus evaluates proposed tie-breaking formulations to address this issue.

Re-runs were first conducted to determine the type of facility and product that the proposed formulation should be applied on. Results showed that ties may potentially occur across all products and affect all facilities (both GRFs and LRFs).

Following a survey of tie-breaking practices in other jurisdictions, the pair-wise linear programming tie-breaking method, which both AEMO and MISO employ, was found to be most suitable for the SWEM. This method attaches a tie-breaking constraint with a penalty factor of 10^{-6} to the objective function such that any ties between a pair of units that are not addressed will reduce net benefit insignificantly (in the order of between 10^{-4} and 10^{-6}) for a dispatch period. It breaks ties by accurately apportioning tied GRFs/LRFs' scheduled quantities based on their individual offered quantities. In addition, it can be applied across all products and all facilities.

MCE simulations were carried out to determine the effectiveness of this proposed formulation in breaking ties. It was found that tie-breaking constraints were able to resolve both units that were tied at the clearing price and non-marginal units that were tied due to other MCE constraints, without compromising the objective of maximising net benefit.

Thus, it is advantageous to implement this proposed formulation to energy, regulation and reserve across all GRFs and LRFs in the SWEM.

The TWG and the RCP unanimously support the proposed rule modifications to implement tie-breaking in the SWEM. The RCP unanimously **recommends** that the EMC Board adopt the proposed rule modifications set out in Annex 3.

1. Introduction

The Market Clearing Engine (MCE) currently allocates scheduled quantities to different generation registered facilities (GRFs) and load registered facilities (LRFs) with tied marginal offers in a random manner. This observation was especially pronounced from November 2007 to April 2010 where total reserve offered by LRFs exceeded reserve limits imposed on them. This paper addresses a proposal to incorporate a more equitable method of resolving these situations into the MCE.

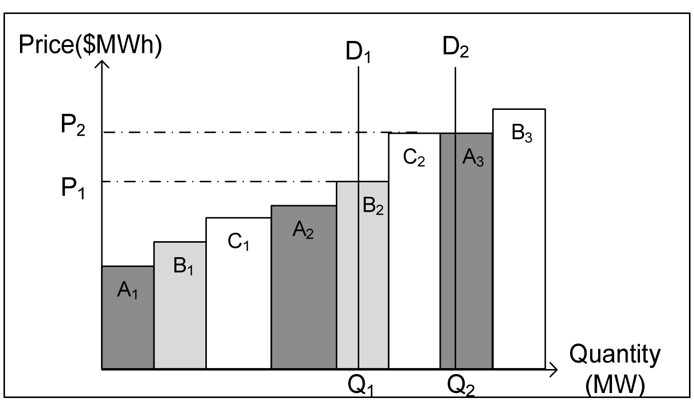
2. Background

2.1 Market clearing process in the event of tied offers

The MCE employs a security constraint economic dispatch (SCED) to determine the facilities that can be scheduled for energy, reserve and regulation in a given dispatch period. Under this dispatch model, the MCE attempts to come up with price and quantity schedules for each product in the least cost manner while respecting any security constraints in the system. It also factors in the opportunity cost of scheduling a facility for a particular product. In addition, the MCE adopts a nodal pricing model for energy in the Singapore Wholesale Electricity Market (SWEM), incorporating transmission losses and congestions in the price discovery process. As such, the energy price that a facility receives is dependent on the location (or node) it resides in. Facilities that are located in nodes with congestion receive higher energy prices, which results in a population of different nodal energy prices in the SWEM.

Figure 1 below exemplifies the least-cost dispatch model described above. For the purposes of illustration, assume a scenario without congestion, losses and constraints. Suppose 4 generators, A, B C and D, each submits energy offers in a given dispatch period. The MCE then arranges these energy offer tranches (price-quantity pairs) in ascending order and selects enough energy tranches with quantities to meet the Power System Operator's (PSO) forecast demand for that dispatch period. The price and corresponding scheduled energy quantity for that dispatch period thus occurs where the forecast demand, D_1, intersects with energy offer tranche, B_2, in Figure 1. Generator B, at offer tranche B_2, is thus the marginal unit, determining the marginal price, P_1, for this dispatch period. This process is applied to all products dispatched in the Singapore Wholesale Energy Market (SWEM), while respecting other constraints in the MCE.

Figure 1: Merit-Order Dispatch in the MCE



The price and quantity process discussed above applies for most dispatch periods, where the offered prices differ across tranches. However, there are instances under which prices of two or more marginal offer tranches are equal. The MCE currently clears such tied offers randomly. With reference to Figure 1, suppose the forecast demand for energy is now D_2.

At this level of demand, since both tranches C_2 and A_3 are offered at price, P_2, both units are equally eligible to be cleared by the MCE. However, given the MCE's current random allocation of tied offers, the MCE can either, fully clear C_2 and partially clear A_3, or vice versa. In Figure 1, C_2 is fully cleared while A_3 is partially cleared at P_2, Q_2.

2.2 Should the issue of tied offers be addressed?

From a fairness perspective, these random allocations should not be of concern to marginal units, given that offers are assumed to represent a facility's marginal costs. A Market Participant (MP) whose unit's offer determines the market price should be indifferent as to whether its unit gets dispatched for an additional MW of generation. Also, given that the MCE allocates quantities to tied units on a random basis, the probability of each tied marginal unit being scheduled for a product should equate over time.

However, these random allocations will be of concern to MPs from a dispatch stability perspective. For example, suppose 2 units, A and B, are tied at the marginal level across 2 dispatch periods. Also, assume that both units are competing for 50 MW, 80MW and 100MW of generation across 3 consecutive dispatch periods. With the current random allocation method, A may be dispatched for 50MW in the first period, 0 MW in the second, and 100MW in the third dispatch period. This implies that B will get dispatched for 0 MW in the first dispatch period, 80MW in the second period and 0MW in the third dispatch period, as reflected in Figure 2 below. This random dispatch scheduling may result in large generation swings of each tied unit from one period to the next. Without tie-breaking in this scenario, these tied units will face dispatch uncertainty and instability in attempting to meet their respective dispatch schedules. With a proportionate allocation of quantities between tied units, both units' dispatch schedules will be more stable, allowing each unit to steadily ramp up from 25MW to 40MW and finally, to 50MW across the 3 dispatch periods. This dispatch profile with tie-breaking is indicated in Figure 3 below.

Figure 2: Dispatch Instability Without Tie-breaking

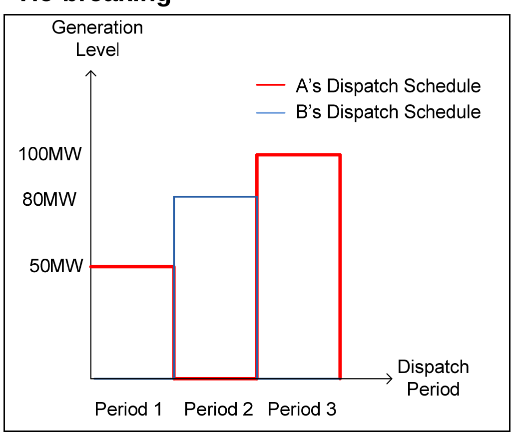
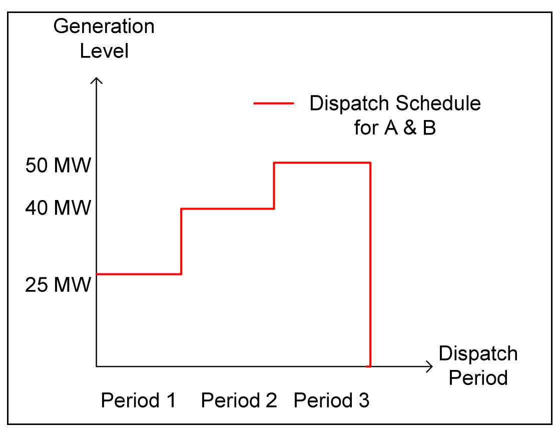


Figure 3: Dispatch Stability With Tie-breaking



While fairness may not form the basis for addressing tied scenarios, there is ground to establish a suitable tie-breaking methodology for the purposes of achieving dispatch stability for each tied unit.

2.3 Situations under which ties may occur

Prior to establishing suitable allocation method for tied offers, there is a need to first identify potential scenarios under which tied scenarios may occur. These can be examined from a few aspects, as follows:

a. Types of Facilities – Generation Registered Facilities or Load Registered Facilities

Given that the MCE does not distinguish between facilities in its dispatch process, ties are likely to affect both GRFs and LRFs.

b. Type of product – Energy, Regulation or Reserve

(i) Energy

Currently, only GRFs offer energy into the market. As such, any tied situations in the energy class of product will only impact GRFs' offers. However, it is unlikely for there to be any equal-priced marginal offers in this product type due to the presence of nodal pricing in the SWEM.

Under nodal pricing, the energy price that a GRF receives is dependent on its location, taking into account costs of generation, transmission loss and congestion at that node. This implies that energy prices usually differ between nodes, with prices generally higher in a location with congestion, and vice versa. After accounting for differences in transmission costs between nodes, there is a low likelihood for two or more marginal units at different nodes to be priced equally.

Even if two GRFs are physically located at the same site i.e. connected to the same bus bar and are price-tied, it is likely that these GRFs belong to the same generation company. Given that either of these two units will be scheduled (albeit in a non-proportionate manner), tie-breaking should not be a financial concern for this market participant.

(ii) Regulation

Similar to energy, only GRFs offer regulation in the SWEM. Thus, an LRF will not be impacted by any tied situation for this product type. Nonetheless, there is a possibility of equal-priced offers occurring for regulation.

Unlike energy, the price of regulation does not depend on a GRF's location. Thus, the MCE only produces one regulation price that applies to all regulation providers in a given dispatch period. It is likely for two or more GRFs with equal-priced marginal offers that match this single regulation price, resulting in a tied situation.

(iii) Reserve

Ties are likely to affect both GRFs and LRFs in all classes of reserve (primary, secondary and contingency).

Similar to regulation, the prices for all reserve classes do not depend on the provider's location. The MCE only produces one reserve price for each class of reserve in a given dispatch period, resulting in the possibility of tie-breaking situations.

Current reserve provision limits imposed on interruptible load may also contribute to increased tie-breaking situations. Table 1 reflects reserve provision limits imposed on LRFs based on the respective reserve class. These limits may result in tied scenarios on non-marginal offers submitted by interruptible load.

Table 1: Reserve provision limits imposed on LRFs

	Class of Reserve	Limit (% of Reserve Requirement)	Average Reserve Requirement in 2011 (in MW)
1	Primary Reserve	10% (When Intertie is not connected)	185MW
		20% (When the intertie is connected)	
2	Secondary Reserve	20%	252MW
3	Contingency Reserve	30%	522MW

With reference to Table 1, suppose the primary reserve requirement for a given period is 185MW and the intertie is not connected. In such a situation, the maximum amount of primary reserve that can be provided by LRFs will be 18.5MW. A tie-breaking situation will occur if 2 LRF providers each offer 10MW of primary reserve at an equal price due to the limit of 18.5MW. Such situations are likely to occur if the capacity of LRF in the SWEM increases.

Another factor that may increase the likelihood of ties is the current low reserve prices. Table 2 below summarises the average prices for all products in 2011. It can be seen that prices averaged $0.32 for primary reserve, $2.19 for secondary reserve and $16 for contingency reserve. Given these relatively low prices, it is likely for GRFs/LRFs to submit low reserve offer prices to ensure that the MCE schedules their units for reserve. For example, given the low primary reserve prices to ensure being scheduled for primary reserve, a group of GRFs/LRFs may submit a primary reserve offer price of $0.01. It is thus likely for a tied situation to occur in this scenario if the marginal price happens to be at $0.01.

Table 2: Prices across all reserve products in 2011

Class of Reserve	Average	Minimum Price	Maximum Price
Primary	$0.32	$0.01	$113.13
Secondary	$2.19	$0.01	$1410.94
Contingency	$16.00	$0.01	$3250

This likelihood may also vary between the 3 classes of reserve. Table 2 shows that primary reserve prices averaged only $0.32 in 2011, as opposed to $2.19 for secondary reserve and $16 for contingency reserve. Drawing on the same logic of low prices affecting likelihood, it is thus more likely for there to be tied situations in primary reserve, followed by secondary reserve and contingency reserve.

Table 3 below summarises the likelihood of tied situations in the MCE across the aspects discussed above.

Table 3: Situations under which ties may occur

Types of Facilities	Likelihood	Energy	Regulation	Reserve
GRF	**Likelihood**	Low likelihood	Likely	Likely
	Reasons	Nodal pricing	Price determination does not vary with location	• Price determination does not vary with location • Low reserve prices
LRF	**Likelihood**	N.A.		Likely
	Reasons			• Price determination does not vary with location • Limits imposed by PSO on LRF provision across all reserve classes

2.4 Likelihood of tied offers across various products and types of facilities

To verify the postulations described in Section 2.3 above, 2 MCE re-runs (herewith labelled MCE Re-run 1 and MCE Re-run 2) were conducted for all dispatch periods from 1 January 2012 to 3 January 2012 (144 periods). These re-runs were conducted to demonstrate the random effect. This section describes the method, period of study, and results of these re-runs.

a. Period of Study

Re-runs were conducted for the real-time dispatch schedules (RTDS) that were produced from 1 to 3 January 2012, totalling 144 periods[1].

b. Method of Simulation

As discussed in section 2, tied situations occur in a random manner. This allocation method implies that 2 or more tied GRFs/LRFs may be scheduled for different amounts on separate occasions with the exact same inputs.

The steps involved in the simulation are as follows:

(i) Conduct MCE Re-run 1

Re-shuffle the order of how offer prices are entered into the MCE

To simulate the random effect in the re-run, the order of how GRFs'/LRFs' offers are fed into the MCE was re-arranged. For example, in the original RTDS, GRF 1's offers could have been considered by the MCE first before GRF 2. Changes were thus made such that the MCE considered GRF 2's offer before GRF 1's offer.

[1] These dates were randomly selected.

Re-compute real-time dispatch schedules using the same inputs used in the original RTDS

Following a reshuffling of the order of offers, the real-time dispatch schedules for the study period were re-computed using the same inputs as that used in the original RTDS.

The reshuffling of the order of offers appeared to result in random changes to scheduled quantities of tied GRFs/LRFs despite using the same inputs for the re-run.

(ii) Conduct MCE Re-run 2

Re-shuffle the orders of how offer prices are entered into the MCE in Re-run 1 while retaining all inputs used in the original RTDS

Re-run 2 was conducted to further demonstrate the random effect of allocation. Re-run 2 was conducted with inputs used in original RTDS, but using a different order of how offers were fed into the MCE as that used in the Re-run 1.

(iii) Comparison of results derived in re-runs with results derived in the original RTDS

Results from both re-runs were thereafter compared to the original RTDS. Specifically, if a GRF/LRF's scheduled quantity was found to have changed after the re-run, this dispatch period would constitute as one with a tied situation.

To verify that all inputs were kept equal the objective function, prices and requirements for all products after the MCE re-run should be the same as that derived in actual dispatch schedules.

c. Results of 2 MCE Re-runs

Table 4 summarises price information for all products for the study period, while Table 5 summarises results from 2 MCE re-runs conducted with that produced in the original RTDS for the same period of study.

Table 4: Price[2] information based on original RTDS from 1-3 January 2012 (144 Periods)

Product		Average Prices	Range
Energy (USEP)		$199.70	$162.08-$513.48
Regulation		$69.32	$0.01 - $259.91
Reserve	Primary	$0.53	$0.01-$7.05
	Secondary	$0.81	$0.01-$14.8
	Contingency	$13.52	$0.01-$282.58

[2] Prices should not differ between that derived in the original RTDS and those derived from the 2 re-runs.

Table 5: No of periods with tied offers across 1-3 January 2012 (144 Periods) based on 2 separate MCE re-runs

Product		MCE Re-run No.	GRF				LRF
			No of Periods with ties	%	Periods with Ties between Different MPs	%	
Energy		1	13	9.03%	0	0%	N.A.
		2	13	9.03%	0	0%	
Regulation		1	3	2.08%	0	0%	
		2	1	0.69%	0	0%	
Reserve	Primary	1	53	36.80%	23	15.97%	0
		2	53	36.80%	20	13.89%	0
	Secondary	1	40	27.78%	9	6.25%	0
		2	29	20.14%	7	4.86%	0
	Contingency	1	49	34.03%	30	20.83%	0
		2	54	37.50%	19	13.19%	0

The MCE re-runs show that tied situations affected all products in the study period, with reserve being characterised by more tied situations as opposed to energy and regulation. This observation fits in with the postulations described in section 2.3.

(i) Regulation had the lowest number of periods with ties

Regulation had the lowest percentage of periods with ties as compared to other products, at 2.08% for the first re-run and 0.69% for the second re-run. This observation runs contrary to the postulation that regulation is more likely to be affected by ties than energy. A plausible explanation for the low number of tied situations could be the relatively high average regulation price of $69.32 as compared to reserve prices of $0.32 to $13.52. With the relatively high clearing prices of regulation, it is less likely for 2 or more GRFs to submit offers that exactly equal these clearing prices.

(ii) Ties that occurred in energy were all between GRFs owned by the same generation company

Although energy was found to have more tied situations than that of regulation, it still had a much lower number of ties as compared to reserve, at 13% in both re-runs. Also, all the tied situations occurred between different GRFs owned by the same MP, with 0 ties between different MPs. This result supports the deduction that ties that occur in energy are most likely to occur between marginal units under the same MP. This is because some of these GRFS are usually sited at the same location, implying that these units will incur similar losses. After adjusting for losses, it is highly likely that the nodal prices of these GRFs will be equal.

(iii) On average, primary reserve had the highest number of tied situations as compared to other classes of reserve

As described in section 2.3, the relatively low primary reserve price, as compared to other classes of reserve, is the likely cause of primary reserve having the highest number of observed tied situations in the re-runs. While contingency reserve had the highest number of periods with ties in MCE Re-run 2 at 37.5%, it still had a lower number of tied scenarios on average as compared to primary reserve.

(iv) Tied scenarios are random

The difference in tied situations between the 2 re-runs across all other products demonstrates that tied situations occur randomly. For example, under the contingency class of reserve, there were 49 occurrences of tied situations in the first re-run as compared to 53 periods in the second re-run even though the same inputs are fed into the MCE in both runs. This observation suggests that there may potentially be more tied scenarios than those identified in these 2 re-runs.

Incidentally, energy and primary reserve had the same number of periods with ties in both re-runs. A closer comparison of these 2 re-runs showed that tied situations occurred in different periods. For example, in the first re-run, tied situations occurred in energy for periods 6 and 25 on 1 January 2012, but did not occur in the second re-run. As such, these identical numbers between both runs are purely coincidental.

(v) LRFs were not impacted by ties

The simulations showed that LRFs were not affected by ties in all 3 categories of reserve, which runs contrary to the postulations described in section 2.3. This could arise from the possibility that the total MW of reserve offered by LRFs remained below the LRF reserve provision limits throughout these 144 periods.

d. <u>Reallocation of Revenue Arising from Ties</u>

In a perfectly competitive market, a unit's offers should represent its marginal costs. As such, at the marginal price level, an MP should be indifferent as to whether its unit gets dispatched for an additional MW of generation. At this level, revenue received from additional MW generated is only sufficient to recover additional marginal cost incurred. Thus, random allocations of generation should not financially affect MPs with tied offers at the marginal price level.

While an MP will not gain additional profit or incur any loss arising from random allocations in tied scenarios at the marginal price level, it is still advantageous to estimate the amount of revenue that an MP may potentially gain or lose due to the random reallocation of tied quantities.

There are 3 aspects that affect the amount of reallocation of revenue in a tied scenario:

i. Ties that occur between GRFs/LRFs owned by two different MPs
ii. High product prices
iii. Large tied quantity (in MW)

These aspects form the basis of our analysis of the reallocation of revenue in tied situations, as summarised in Table 6 below.

Table 6 reflects the average, minimum and maximum prices for each product in the study period. It also shows the potential reallocation of revenue arising from a change in scheduled quantities under the MCE's random reallocations of tied units. The methodology used to compute this revenue reallocation for a given period is described below and illustrated in Box 1.

Step 1: Compare scheduled quantity of tied units in the original RTDS and in the re-run for a given product
Step 2: Identify unit with the largest absolute change in scheduled quantity after the re-run
Step 3: The change in revenue arising from reallocation of tied quantities is given by the multiplication of this quantity with the product's price for that dispatch period

Box 1: Example on computing reallocation of revenue

Tied units: A, B, C
Product: Primary Reserve
Price of Product: $0.01

Tied Units	Sch. MW in original RTDS	Sch. MW in Re-Run 1	Change in Sch. MW
A	10 MW	13 MW	+ 3 MW
B	5 MW	1 MW	- 4 MW
C	5 MW	6 MW	+1 MW
Financial Impact			4 MW x $0.01 =$0.04

Table 6: Reallocation of revenue in tied situations

Product	Re-run	Average Rev Reallocation ($/MWh)	Min Rev. Reallocation ($/MWh)			Max Rev. Reallocation ($/MWh)		
			Price ($/MW)	Tied MW	Revenue	Price	Tied MW	Revenue
Energy	1	$916.50	$181.19	0.463	$84.66	$175.59	9.69	$1701.40
	2	$820.23	$175.96	0.458	$80.58	$169.92	9.22	$1567.33
Regulation	1	$248.65	$0.01	0.48	$0.0048	$259.91	2.87	$754.94
	2	$7.76	N.A.					
Pri Reserve	1	$1.34	$0.01	0.049	$0.00049	$1.04	8.31	$8.64
	2	$2.07	$0.01	0.22	$0.002	$6.31	2.42	$15.28
Sec Reserve	1	$4.93	$0.01	4.42	$0.044	$10.50	2.35	$24.76
	2	$5.54	$0.01	0.20	$0.002	$10.50	2.31	$24.31
Cont. Reserve	1	$9.25	$0.01	0.415	$0.00415	$273.59	1.55	$423.06
	2	$8.20	$0.01	0.415	$0.00415	$273.59	1.55	$423.06

Albeit the low number of tied situations, energy had the highest average revenue reallocation as compared to the other 3 products, at $916.50 for the first re-run and $820.23 for the second re-run. It also had the largest range of revenue reallocation of $84.66 to $1701.40 for the first re-run and $80.58 to $1567.33 for the second re-run. This is due to the relatively higher prices of energy and larger tied quantities, as compared to reserve and regulation.

Conversely, primary reserve had the lowest average revenue reallocation of $1.34 for the first re-run and $2.07 in the second re-run due to relatively lower primary reserve prices.

The results suggest that revenue reallocation of energy may be potentially large even with the low number of tied periods. However, it must be emphasised that all tied scenarios in energy occurred between GRFs owned by the same MP, which implies a reallocation of revenue within the same company.

On the other hand, although revenue reallocation for reserve is lower, an MP may potentially face greater reallocation of revenue arising from high reserve prices and a higher likelihood for ties to occur between GRFs owned by different MPs. For example, Table 6 indicates that the maximum revenue reallocation under contingency reserve was $423.06 due to a high contingency reserve price of $273.59 for that dispatch period. This high contingency reserve price incidentally exceeded the maximum energy prices of $175.59 and $169.92. Although this tied scenario occurred between 2 different GRFs under the same MP, an MP would have had a revenue reallocation of $423.06 had this tied situation occurred between 2 different MPs. In addition, this reallocation may increase as reserve prices increase.

2.5 Should tie-breaking apply to all facilities and all products?

Using the likelihood and potential revenue reallocation of tied scenarios discussed in section 2.4, this section analyses the extent upon which the tie-breaking methodology should be applied to.

With reference to Table 7 below, it can be seen all the products are affected by tied situations. While energy and regulation had a lower number of periods with ties, the revenue reallocation in these tied scenarios was much higher than that of reserve. However, from an MP's perspective, the MP will not be affected by ties in energy as these ties were observed to have occurred between GRFs owned by the same MP. Nevertheless, from a GRF's perspective, it makes sense to introduce a tie-breaking mechanism to ensure dispatch stability and certainty for a GRF. In terms of regulation, the likelihood of ties might increase if regulation prices fall. Thus, consideration should be given to impose tie-breaking constraints on energy, regulation and reserve.

In addition, the absence of ties affecting LRFs during this study period does not discount the possibility that LRFs may be impacted by ties in practice. There may be selected dispatch periods in which total reserve offered by LRFs exceeds that imposed by reserve provision limits. The likelihood of such tied situations may also increase if more LRFs come on board. Therefore, the tie-breaking formulation should be extended to LRFs in the SWEM.

Table 7: Tied Scenarios and Revenue Reallocation Amount

Product	Periods with Ties	Revenue Reallocation Amount	Affected Facilities	Ties between Different MPs?
Energy	Low	High	GRFs	No
Regulation	Low	High	GRFs	
Primary Reserve	High	Low	GRFs[3]	Yes

[3] During the study period, ties were not observed under LRFs for 2 reasons. Firstly, LRFs' offer tranches were below the clearing prices of reserve. Secondly, the total reserve offered quantities were also below the reserve limits imposed on LRFs.

Product	Periods with Ties	Revenue Reallocation Amount	Affected Facilities	Ties between Different MPs?
Secondary Reserve	High	Low	GRFs	Yes
Contingency Reserve	High	Low	GRFs	Yes

It is thus reasonable to explore a tie-breaking methodology that applies to all products and all facilities.

3. Formulating a Suitable Tie-breaking Constraint in the SWEM

This section analyses the potential tie-breaking methods that can be employed in the SWEM.

3.1 Factors Affecting the Tie-breaking Formulation

There are several aspects to consider prior to formulating a suitable tie-breaking constraint in the SWEM, namely, an ex-ante or ex-post mechanism, the identification of ties, and retention of primary objective function.

(i) Ex-ante or Post-processing Tie-Breaking Mechanism

Since the SWEM operates an ex-ante market, the tie-breaking mechanism, ideally, should be included in the MCE co-optimisation process rather than be applied on quantities derived from the co-optimisation process (herewith termed the post-processing mechanism).

A post-processing mechanism will involve a 2-step approach that first derives a set of optimal quantities followed by the identification and pro-rating of tied units. A 2-step post-processing mechanism may result in sub-optimal outcomes following pro-rating on optimal dispatch quantities derived from the co-optimisation process. For example, suppose the MCE determines that marginal unit GRF A should be scheduled for 100MW of energy at $200. However, suppose that GRF B also offered energy at $200 but was not scheduled, the post-processing tie-breaking mechanism will prorate these 2 units such that part of GRF A's 100MW will be apportioned to GRF B. This mechanism fails to recognise that dispatching GFR A for 100MW might be the optimal schedule from a system-wide perspective.

As such, the tie-breaking mechanism should be included in the co-optimisation process.

(ii) Identification of Ties Using Nominal Offers or Effective Offers

Having established that the tie-breaking mechanism should be incorporated into the MCE in determining dispatch schedules, the next consideration arises from identifying such tied GRFs/LRFs on an ex-ante basis. The tie-breaking constraints will thereafter apply on this group of tied units.

It may appear that using equal-priced offers would be the appropriate method of identifying tied units. However, the MCE currently uses a co-optimisation approach, which factors in the opportunity cost of procuring energy, regulation and reserve when determining an optimal solution. For example, suppose a GRF with a maximum capacity of 200 MW is scheduled for 20 MW of reserve at $1 and 180MW of energy at $100. In this instance, the GRF forgoes the opportunity to be scheduled for an additional 20MW of energy at $100, resulting in a trade-off or cost. This trade-off also factors in losses and congestion costs. Given that the MCE incorporates such costs when optimising schedules, the effective offers for a GRF/LRF for a product should thus be higher than its nominal offers and unlikely to be equal to other GRFs/LRFs.

Ideally, it would be optimal to use effective offers as a means to identify tied GRFs/LRFs. In practice, it may be possible to identify tied units with effective offers that happen to occur at the marginal prices. However, it is almost impossible to determine non- marginal GRFs/LRFs with such trade-offs and resultantly, effective offers on an ex-ante basis. Nominal offers may thus be the best proxy to single out tied GRFs/LRFs in the absence of any potential methods to identify effective offers.

(iii) Retention of Primary Objective Function

The MCE's primary objective is to achieving a feasible dispatch schedule that maximises the net benefit. As such, ties should not be resolved at the expense of the primary objective of optimality and feasibility.

3.2. Tie-Breaking in Other Jurisdictions

Prior to establishing a suitable tie-breaking method that addresses the above considerations, there is merit in examining if other jurisdictions employ the use of such methodologies, and if so, the specific formulation of these methods.

Other jurisdictions were found to include tie-breaking constraints as part of their market clearing engines, namely, Australian Energy Market Operator (AEMO), Independent Electricity System Operator (IESO) and Midwest ISO (MISO). Annex 1 describes the method used in each of these markets, categorising the tie-breaking methods in terms of the type of market, product that the constraints are applied on, method of identifying ties and the formulation of the tie-breaking methods. These are briefly summarised below.

(i) Tied quantities are allocated in proportion to offered quantities

The 3 markets surveyed generally adopt similar approaches to resolve tied situations. In terms of tie-breaking methodology, all 3 markets resolve tied offers by allocating the required quantity in proportion to the individual offered quantities of tied units.

(ii) Tie-breaking formulations are incorporated as part of the optimisation engine

In addition, the tie-breaking formulations in all 3 markets indicate that tie-breaking is resolved as part of their respective optimisation engine and are allocated as penalty costs. This implies that tied offers in these markets are resolved in conjunction with the derivation of optimal dispatch schedules.

(iii) Nominal offers are used to identify tied units

Although all 3 markets undertake co-optimisation to determine dispatch schedules, nominal equal-priced offers are used to identify tied units. In IESO, the method further states that trade-offs are not considered when using offers to identify ties even though it applies the constraints on both energy and reserves. AEMO also indicates that the tie-breaking formulation applies to both tied marginal offers and non-marginal equal-priced offers. This suggests that these markets consider nominal offers to be the best proxy in identifying tied units, albeit the possibility that trade-offs may occur.

(iv) Small penalty factor imposed to ensure primary objective function is not compromised

Each of the 3 markets also attaches a small penalty of either $1 x 10^{-6} (AEMO and MISO) or $5 x 10^{-4} (IESO) to the tie-breaking constraints, which implies that the clearing engines will prefer to violate the tie-breaking constraints rather than violate the primary objective function. This ensures that the optimisation engines do not compromise the primary objective functions of either cost minimisation or maximisation of net benefit when resolving ties.

(v) Only IESO uses a quadratic function to resolve ties

While both AEMO and MISO use linear formulations, IESO uses a quadratic formulation to resolve ties. This implies that tie-breaking penalty costs will increase regardless of whether the amount scheduled for a given band as a result of prorating increases or decreases. This distinction largely stems from the solver that the co-optimisation engine each market adopts.

In summary, all 3 jurisdictions surveyed appear to employ similar methods in identifying ties and resolving such ties. Except for the identification of ties, all 3 methods employed appear to address the factors discussed in section 3.1.

3.3 Potential Tie-breaking Formulations applicable to the SWEM

Taking note of the factors described in section 3.1 and following an examination of the respective formulations in the 3 markets summarised in section 3.2, this section explores potential tie-breaking formulations that may be used in the SWEM.

3 potential tie-breaking options that were explored by our consultant, Power Systems Consultants (refer to Annex 2 for a detailed discussion of these options). These are summarised as follows:

<u>Option 1: Pro-rate equal-priced offer blocks based on total cleared quantities of tied groups</u>

Following the MCE's determination of dispatch schedules, cleared quantities are grouped according to their offered prices. The individual offered quantities and total cleared quantities of each group are then computed. Tied groups are then pro-rated based on the individual offer prices and total cleared quantities.

Option 2: Include a tie-breaking breaking constraint as a linear cost in the objective function

Option 2 closely follows AEMO and MISO's models in resolving ties. Specifically, all equal-priced offers are paired[4] up and represented as a cost constraint in the MCE. The MCE then attempts to equalise these tied pairs on a pro-rated basis as a secondary objective when determining optimal dispatch schedules.

Option 3: Include a tie-breaking constraint as a non-linear cost in the objective function

Option 3 is similar to AEMO and MISO's approach except that it uses a quadratic function to represent tied offer blocks.

Option 2 was found to be the most suitable tie-breaking formulation that can be adopted in the SWEM for the following reasons:

a. Ties can be resolved on an ex-ante basis

   Option 2 resolves ties as part the MCE co-optimisation process, which bears advantages described in section 3.1(i). As compared to option 1, option 2 does not require the need to first compute total cleared quantities for a tied group before imposing a post-processing tie-breaking mechanism. Instead, constraints are incorporated as a cost in the objective function which implies that the MCE will determine optimal dispatch schedules while resolving ties.

b. Primary objective of maximising net benefit is retained

   While it is advantageous to incorporate the tie-breaking formulation as part of the MCE, measures must be taken to ensure the primary objective is not compromised in the process of breaking ties. As such, Option 2, which tags a small penalty factor to the tie-breaking constraint, ensures that system-wide net benefit overrides pro-rating tied quantities.

c. Pair-wise approach ensures that resolution of ties are not restricted by binding constraints

   Suppose there are 3 tied units and in the co-optimisation process, 1 unit happens to be bounded by a constraint (e.g. operating at its maximum capacity) such that its scheduled quantities cannot be increased or decreased. If a group approach is adopted, the MCE will not resolve ties between the other 2 unconstrained units, but instead randomly schedule these units. This approach (i.e. allocate 3 or more equal-priced offers as a tied group) will therefore not resolve ties in the presence of binding constraints on any of units in a tied group.

   Conversely, Option 2 groups tied units in pairs. Therefore, if there are 3 tied units, A, B and C, the MCE will create 3 tie-breaking pairs for that dispatch period (A-B, B-C and A-C). Under such a formulation, if A is bounded by another constraint, the pairing will ensure that the MCE continues to pro-rate the other unconstrained units, B and C. This is possible because the paired-wise set-up MCE will continue to resolve the tie-breaking constraint formulated between B and C for that dispatch period (refer to sections 3.3.1 and 3.3.2 of Annex 2 for an example of this discussion).

[4] This implies that 4 equal-priced offers will result in 6 tied pairs.

d. Formulation addresses non-marginal tied units

   The formulation is applied across all equal-priced offers regardless of whether tied units are marginal or non-marginal. Thus, this addresses non-marginal ties that may occur due to potential binding constraints. For example, ties due to reserve provision limits on LRFs.

e. Option 2 adopts a linear programming approach

   Although not discussed as a factor in formulating a tie-breaking solution, the current solver used in the MCE has limitations when solving non-linear problems. Solutions derived are often inconsistent, and affects system performance. Option 2 adopts a linear programming approach, which avoids such system issues.

The above reasons demonstrate that Option 2 is a more suitable method as compared to other potential tie-breaking methods explored.

4. Tie-breaking in the SWEM: A Pair-wise Linear Programming (LP) Method

Based on the discussion in previous sections, Option 2 was found to be the most suitable method of tie-breaking for the SWEM. This section discusses this method and simulation of its impact on tied units.

4.1 Tie-breaking Formulation

<u>Products that formulation will apply to</u>

As discussed in section 2.5, the tie-breaking formulation should apply to all products (energy, regulation and reserve) and both GRFs and LRFs.

<u>Tie-breaking Constraints</u>

Option 2 will introduce an additional penalty component in the objective function, with associated tie-breaking constraints. These are represented below.

1. Objective Function

$$\text{NetBenefit} = \sum_{\{j,p|j \in \text{PURCHASEBIDBLOCKS}_p, \text{ where } p \in \text{BIDS}\}} \mathit{PurchaseBidPrice}_{p,j} \times \text{PurchaseBlock}_{p,j}$$
$$- \sum_{\{j,g|j \in \text{GENERATIONOFFERBLOCKS}_g, \text{ where } g \in \text{ENERGYOFFERS}\}} \mathit{GenerationOfferPrice}_{g,j} \times \text{GenerationBlock}_{g,j}$$
$$- \sum_{\{j,r|j \in \text{RAWRESERVEBLOCKS}_r, \text{ where } r \in \text{RAWRESERVEOFFERS}\}} \mathit{ReserveOfferPrice}_{r,j} \times \text{RawReserveBlock}_{r,j}$$
$$- \sum_{\{j,l|j \in \text{REGULATIONOFFERBLOCKS}_l, \text{ where } l \in \text{REGULATIONOFFERS}\}} \text{RegulationOfferPrice}_{l,j} \times \text{RegulationBlock}_{l,j}$$
$$- \sum_{\{j,n|j \in \text{EXCESSGENERATIONBLOCKS}_n, \text{ where } n \in \text{NODES}\}} \text{ExcessGenerationPenalty}_{n,j} \times \text{ExcessGenerationBlock}_{n,j}$$
$$- \sum_{\{j,n|j \in \text{DEFICITGENERATIONBLOCKS}_n, \text{ where } n \in \text{NODES}\}} \mathit{DeficitGenerationPenalty}_{n,j} \times \text{DeficitGenerationBlock}_{n,j}$$
$$- \text{ViolationPenalties}$$
$$- \text{TieBreakingPenalty}$$

2. Tie-breaking penalty component

$$\text{TieBreakingPenalty} = \varepsilon \times \sum_{i,j} (\text{TieBreakSlack1}_{i,j} + \text{TieBreakSlack2}_{i,j})$$

Where:

- ε = Penalty Factor of 10^{-6}

- $\text{TieBreakSlack1}_{i,j}$ and $\text{TieBreakSlack2}_{i,j}$ are non-negative slack variables for a tied pair i and j in each product. Higher values of these slack variables indicate a greater disproportionate allocation between tied units.

  The slack variables for respective products are represented by the constraints in Table 8 below.

Table 8: Associated tie-breaking slack variable constraints for each product

Tie-breaking Constraint	**Formulation**
Energy	$\frac{\text{GenerationBlock}_i}{\text{GenerationBlockMax}_i} - \frac{\text{GenerationBlock}_j}{\text{GenerationBlockMax}_j} = \text{TieBreakSlack1}_{i,j} - \text{TieBreakSlack2}_{i,j}$ Where: GenerationBlock = Scheduled energy for a given offer block (Variable) GenerationBlockMax = Maximum MW that can be scheduled from a price-quantity pair (Input)
Regulation	$\frac{\text{RegulationBlock}_i}{\text{RegulationBlockMax}_i} - \frac{\text{RegulationBlock}_j}{\text{RegulationBlockMax}_j} = \text{TieBreakSlack1}_{i,j} - \text{TieBreakSlack2}_{i,j}$ Where: RegulationBlock = Scheduled regulation for a given offer block (Variable) RegulationBlockMax = Maximum MW that can be scheduled from a price-quantity pair (Input)

Tie-breaking Constraint	Formulation
Reserve	$\frac{RawReserveBlock_{r,i}}{RawReserveBlockMax_{r,i}} - \frac{RawReserveBlock_{r',j}}{RawReserveBlockMax_{r',j}} = TieBreakSlack1_{i,j} - TieBreakSlack2_{i,j}$ Where: RawReserveBlock = Scheduled reserve for a given offer block (Variable) RawReserveBlockMax = Maximum MW that can be scheduled from a price-quantity pair (Input) $\frac{ReserveOfferPrice_{r,i}}{EstReserveEffectiveness_{r(g,c)}} = \frac{ReserveOfferPrice_{r',j}}{EstReserveEffectiveness_{r'(g,c)}}$ (In the simulation, effective prices are rounded to 4 decimal places for comparison purposes)

Tie-breaking Method

Step 1: The MCE first identifies tied units. For energy, tied units are identified based on nominal offers. While these offers may be effectively different after accounting for losses or congestion, the proposed formulation is structured such that tie-breaking will not take place so as to meet the primary objective of maximizing net benefit under such circumstances. This also implies that a small penalty amount for such units will be incurred. For regulation, tied units are identified based on nominal offer prices. For reserves, this is identification is based on offers that are accounted for by each unit's reserve effectiveness[5].

Step 2: The MCE then pairs identified tied units for each product using the tie-breaking constraints in Table 8.

Step 3: The MCE then pro-rates these tied units by attempting to search for optimal scheduled quantities of each unit such that differences in ratio between 2 units scheduled quantity to their respective offered amounts are minimised. This is achieved through the minimisation of the difference between the 2 slack variables, TieBreakSlack1 and TieBreakSlack2, herewith termed the “ratio delta”. This value is represented by the following formula:

$$\text{Ratio Delta} = \frac{\text{Cleared MW}_{GRF1}}{\text{Offer Band}_{GRF1}} - \frac{\text{Cleared MW}_{GRF\ 2}}{\text{Offer Band}_{GRF2}}$$

A non-zero ratio delta indicates that the tied units cannot be pro-rated due to binding constraints, while tied units that can be proportionately reallocated will yield a ratio delta of 0.

Step 4: The MCE then attaches a small penalty factor of 10^{-6} to non-negative tie breaking slack variables. This value is significant enough to ensure that tie-breaking occurs, while small enough to maintain the primary objective function. It also coincides with values used in AEMO and MISO.

[5] For example, suppose GRF A and GRF B with respective reserve effectiveness of 0.85 and 0.95 each submits offers of $0.01. The effective reserve offer for GRF A is thus $0.0118 ($0.01/0.85) while that of GRF B is given by $0.0105. In this instance, GRF A and B are not tied.

Box 2 below gives an example of this tie-breaking mechanism.

Box 2: A Worked Example

Suppose 3 GRFs, A, B and C, are tied for primary reserve at an effective offer price of $2.

Required Primary Reserve: 4MW

GRF A: 5MW, GRF B: 5MW, GRF C: 10MW

Number of tie-breaking pairs required: A-B, B-C, C-A

Tied Pair A-B: $\frac{A}{5}-\frac{B}{5}=TieBreakSlack1_{A,B}-TieBreakSlack2_{A,B}$

Tied Pair B-C: $\frac{B}{5}-\frac{C}{10}=TieBreakSlack1_{B,C}-TieBreakSlack2_{B,C}$

Tied Pair A-C: $\frac{A}{5}-\frac{C}{10}=TieBreakSlack1_{A,C}-TieBreakSlack2_{A,C}$

A penalty factor of 10^{-6} is then attached to each of the 6 TieBreakSlacks identified above. The MCE will then attempt to search for optimal scheduled primary reserve quantities A, B and C in order to minimise the penalty attached to these slack variables.

The optimal scheduled primary reserve quantities of each GRF is thus given by:
A=1MW, B=1MW, C = 2MW

These values ensure that the right hand side of the 3 tied pairs are set to 0.

With the proposed tie-breaking, the 3 tied units are therefore accurately pro-rated based on their offered quantities, where GRF C is scheduled for ½ of the total requirement, while GRF A and GRF B is scheduled for ¼ of the total reserve requirement.

Suppose GRF C is now bounded by a constraint that restricts its scheduled primary reserve at 3MW.

The constraints thus produces the optimal values of: A= 0.5 MW, B=0.5 MW, C=3 MW (constrained)

The tied pairs are now given by the values:

Tied Pair A-B: $\frac{0.5}{5}-\frac{0.5}{5}=0-0$

Tied Pair B-C: $\frac{0.5}{5}-\frac{3}{10}= 0-0.2$

Tied Pair A-C: $\frac{0.5}{5}-\frac{3}{10}= 0-0.2$

A small penalty of 10^{-6} x [(0+0.2) + (0+0.2)] = 0.4 x 10^{-6} is now attached to the objective function due to binding constraints set by C.

4.2 Simulation of tie-breaking formulation

To analyse the impact of this formulation on resolving ties for all products, a simulation was conducted on each dispatch period from 1 January 2012 to 3 January 2012 (refer to Section 4 of Annex 2 for a detailed discussion of this simulation)

Simulation Method

The simulation looked at 2 scenarios as described in Table 9.

Table 9: Scenarios applied in simulation for 1 January 2012 to 3 January 2012 (144 periods)

	Scenario 1	Scenario 2
Objective	To determine impact of tie-breaking formulation on schedules	To determine consistency of tie-breaking formulation and ensure that results do not vary with the order in which data is read from the Oracle database.
Method	1. Include tie-breaking formulations in EMSTAT 2. Conduct a re-run (herewith termed Re-run A)	1. Include tie-breaking formulation in EMSTAT 2. Re-order the manner in which offers are read from the Oracle data base 3. Conduct 3 re-runs (herewith termed Re-runs B, C and D) with a different order of how offers are read in each re-run.
Products	Energy, Regulation, Reserve (Primary, Secondary, Contingency)	Energy, Regulation, Reserve (Primary, Secondary, Contingency)
Method of Comparison	1. Compare Re-run A to the original RTDS produced. 2. Identify periods with changes in GRFs/LRFs' scheduled quantities	1. Compare Re-runs B, C and D with Re-run A. 2. Identify periods with changes in GRFs/LRFs' scheduled quantities

Simulation results

Simulation results of both scenarios are summarised in Table 10 and discussed in this section.

Table 10: Impact of tie-breaking formulation on all products

Product	Scenario	No of Periods (out of 144 periods)	Between Different MPs	Marginal Ties	Non-Marginal Ties	Maximum Change in Scheduled Quantity
Energy	1	19 (13.19%)	0	19 (13.19%)	0	5.00 MW
	2	No change				
Regulation	1	5 (3.47%)	0	2 (1.38%)	3 (2.08%)	3.47 MW
	2	No change				
Pri. Reserve	1	109 (75.69%)	37 (25.69%)	109 (75.69%)	0	9.29 MW
	2	No change				
Sec. Reserve	1	72 (50%)	12 (8.33%)	72 (50%)	0	8.43 MW
	2	No change				
Cont. Reserve	1	70 (48.61%)	47 (32.64%)	63 (43.75%)[6]	11 (7.63%)	31.74 MW
	2	No change				

(i) Tie-breaking formulation resolves tied scenarios that were not identified in section 2.4

With the proposed formulation, the number of periods in which ties were resolved is higher than that identified under re-runs conducted in section 2.4. For example, only 16 periods of ties were found for energy in the 2 MCE re-runs conducted as compared to 19 periods of ties resolved with the application of this formulation. This observation suggests that the formulation can resolve other tied scenarios beyond those identified in the re-runs.

Non-marginal units that were tied were found to contribute to this higher number of ties resolved. For example, of the 70 tied periods that were resolved under contingency reserve, 11 were periods with non-marginal ties. These tied situations generally stem from the existence of binding constraints such as the ReserveGenerationMax constraint, which restricts total energy, regulation and reserve that can be scheduled from a GRF to its maximum generation capacity. There may be instances in which the MCE randomly schedules tied units that are bounded by these constraints. The formulation thus resolves such scenarios as well.

(ii) Tie-breaking formulation achieves consistent results

Scenario 2 is conducted to ensure that the tie-breaking formulation produces consistent results. The simulation shows that this formulation produces consistent dispatch schedules that do not vary with the re-shuffling of offers.

Reallocation of Revenue

Table 11 summarises the reallocation of revenue arising from the proposed formulation. The results of this impact closely align with that derived from the re-runs conducted under section 2.3.

[6] This number is based on dispatch periods with tied scenarios. In this instance, the sum of marginal ties and non-marginal ties exceeds the total number of dispatch periods with ties as some of these periods include both marginal and non-marginal ties.

Table 11: Revenue reallocation arising from tied situations following the application of the tie-breaking formulation

Product	Average Rev Reallocation ($/MWh)	Min Rev Reallocation ($/MWh)			Max Rev Reallocation ($/MWh)		
		Price ($/MW)	Tied MW	Revenue	Price	Tied MW	Revenue
Energy	$916.50	$181.19	0.463	$84.66	$175.59	9.69	$1702.44
Regulation	$59.65	$0.01	0.30	$0.0030	$259.91	1.09	$283.30
Pri. Reserve	$1.56	$0.01	0.049	$0.00035	$6.31	1.19	$7.51
Sec. Reserve	$2.86	$0.01	4.42	$0.044	$10.45	1.18	$12.33
Cont. Reserve	$5.77	$0.01	0.38	$0.0038	$273.59	1.03	$281.80

Impact on Interruptible Load

As discussed in section 2.5, it is entirely plausible for ties to affect LRFs even though none were observed during this study period. Further simulation was conducted to verify that the proposed tie-breaking formulation does resolve ties between LRFs.

To simulate such a scenario, reserve provision limits imposed on LRFs were deliberately reduced from between 10% to 30% to 0.5% to 2%, as reflected in Table 12 overleaf. These values were selected such that the total reserve offered by LRFs will be more than the reserve requirement for each class of reserve, and as a result, will necessitate tie-breaking. Further re-runs were then conducted on LRFs dispatch schedules with these revised limits.

Table 12: Reserve limits imposed on LRFs in simulation

	Class of Reserve	Average Reserve Requirement During Study Period	Limit (% of Reserve Requirement)	Average reserve that can be provided by LRFs (in MW)
1	Primary Reserve	200.00 MW	2%	4 MW
2	Secondary Reserve	253.71 MW	1%	2.53 MW
3	Contingency Reserve	504.49 MW	0.5%	2.52 MW

Table 13 compares the ratio delta of tied LRFs before and after imposing the tie-breaking constraints with the revised reserve limits. As discussed in section 4.1, ratio delta represents the difference between a pair of tied units' scheduled quantity-to-offer tranche ratio. A non-zero ratio delta indicates that tied units are disproportionately allocated, either due to binding constraints (if tie-breaking is imposed) or due to random allocations (without tie breaking). A ratio delta of 0 indicates that units are proportionately allocated to their offer tranche quantities.

With the proposed limits, ties were observed between 2 LRFs that belong to different MPs. Similar to GRFs, Table 13 shows that primary and secondary reserve had the most number of tied situations. Without tie-breaking, ratio delta for LRFs averaged 0.499 for primary reserve, 0.75 for secondary reserve and 0.59 for contingency reserve. With the proposed tie-breaking constraints, the ratio delta for all tied LRFs across all products reduced to 0, indicating that the tied quantities were proportionately reallocated based on their individual offer tranches.

Table 13: Results of ratio delta pre and post tie-breaking

	No of periods with tied LRFS (out of 144)	No of tied LRFs	Without Tie Breaking			With Tie Breaking
			Max of Ratio Delta	Average of Ratio Delta	Min of Ratio Delta	Max of Ratio Delta
Primary	140	2	0.99	0.499	0.17	0
Secondary	141		0.96	0.75	0.23	
Contingency	42		0.81	0.59	0.35	

An example of the impact of this simulation on 1 January 2012, Period 8 is described below. Table 14 shows 2 tied units, LRFs 1 and 2, with their respective offer tranche quantities. With reduced reserve limits, these 2 units are competing to be scheduled for a total of 4.12 MW, 2.53 MW and 2.37 MW of primary, secondary and contingency reserve respectively.

Without the proposed tie-breaking constraints, Table 14 shows that the MCE scheduled the entire available quantity for each reserve class to 1 of the 2 tied LRFs, instead of proportionately allocating this quantity to each tied unit in proportion to their offer tranches. For example, LRF 2 was scheduled for 4.12 MW of primary and 2.53 MW of secondary reserve, while LRF 1 was not scheduled for any reserves under these categories. This disproportionate allocation resulted in a positive ratio delta of 0.46 for primary reserve and 0.28 for secondary reserve.

With the proposed tie-breaking constraints, the MCE scheduled the 2 tied units in proportion to their individual offer quantities. As such, the ratio delta between the tied pairs was reduced to 0 across all products.

Table 14: Impact of Reducing Reserve Provision Limits on LRFs (1 January 2012, Period 8)

Product	LRF	Offer Tranche Quantity	Pre Tie-Breaking		Post Tie-Breaking	
			Scheduled Quantity	Ratio Delta	Scheduled Quantity	Ratio Delta
Primary	LRF 1	3.2 MW	0 MW	0.46	1.08 MW	0
	LRF 2	9 MW	4.12 MW		3.04 MW	
Secondary	LRF 1	3.2 MW	0 MW	0.28	0.66 MW	0
	LRF 2	9 MW	2.53 MW		1.86 MW	
Contingency	LRF 1	3.2 MW	2.37 MW	-0.74	0.82 MW	0
	LRF 2	6 MW	0 MW		1.55 MW	

Impact of Tie-breaking Constraints in High-priced Periods

It is likely for there to be a higher number of offer tranches that coincide with a product's price ceiling in high-priced dispatch periods, giving rise to the possibility of ties. These ties are also more likely to occur between different MPs. Further simulation was thus conducted to evaluate the effect of tie-breaking in such periods.

14 high-priced periods[7] that occurred between 15 August 2011 and 30 May 2012 were selected to analyse this effect. Results from introducing the tie-breaking constraints in these periods are shown in Table 15 below.

Table 15: Impact of Tie-breaking Constraints on Selected High-Priced Periods

Product	Price Range	No of Periods with Ties	Between Different MPs	Marginal Ties	Non-marginal Ties	Max. Rev Reallocation ($/MWh)		
						Price	Tied MW	Revenue
Energy	$583.63 - $4500	0	N.A.					
Reg.	$204.91- $300	3	1	2	1	$204.94	3.4	$696.80*
Pri Res	$0.03 - $210.51	6	0	6	0	$11.66	2	$33.32
Sec Res	$5.26- $2422.01	2	1	2	0	$210.45	1	$210.45
Cont. Res	$394.33 - $3500	3	1	1	2	$215.72	3.4	$733.448*

*****denotes ties between different MPs

The results in Table 15 largely follow that derived in the earlier simulation. Although primary reserve had the highest number of periods with ties, all these tied scenarios occurred between facilities under the same MP. In contrast, while there were fewer periods with ties in regulation, secondary reserve and contingency reserve, these products had ties that occurred between different MPs.

From a revenue reallocation perspective, contingency reserve had the highest maximum revenue reallocation due to a relatively high contingency reserve price of $215.72. Incidentally, this reallocation occurred between facilities under different MPs. A similar instance was found in regulation, where there was a revenue reallocation of $696.80 from one MP to another.

The results above runs contrary to our postulation that more ties may be found in high-priced periods. It follows that such high prices usually occur due to shortfall in one or more products. As such, the MCE will schedule all facilities that offered into the SWEM for these periods and still face a shortage of supply, resulting in the absence of ties at the marginal level.

4.3 Impact on Net Benefit and Market Prices

An insignificant reduction in the objective value (net benefit) of between $\$1x10^{-4}$ to $\$1x10^{-6}$ was observed in the simulation. These values are attributed to ties that could not be resolved in order to meet the primary objective function.

There were also no observed changes in the prices of all products (energy, regulation, primary reserve, secondary reserve and contingency reserve).

[7] A high-priced period refers to one with any product that reached its price ceiling.

4.4 Case Analysis

This section provides detailed case analysis of 3 distinct dispatch periods in the simulation with the following characteristics.

(i) Case 1 – Tie-breaking on tied marginal units (1 January 2012, Period 6)

Case 1 illustrates a situation in which tied marginal units were found across all products. Scheduled quantities were fairly reallocated in proportion to these units' respective offered quantities following the application of the tie-breaking constraints.

(ii) Case 2 - Tie-breaking on tied non-marginal units (2 January 2012, Period 40)

Case 2 identifies a scenario where ties were resolved between non-marginal units. In the simulation, these scenarios were found to occur in dispatch periods with binding constraints on non-marginal units.

(iii) Case 3 – Tie-breaking with changes in reserve requirements (1 January 2012, Period 41)

Case 3 discusses a situation where contingency requirement increased with the proposed tie-breaking constraints. These observations were found in 8 of the 144 dispatch periods in the simulation.

4.4.1 Case 1- Tie-breaking on Tied Marginal Units

Table 16 reflects all GRFs that displayed changes in scheduled quantities after the application of tie-breaking constraints in this dispatch period. These changes are compared using the GRFs total offered amount for the tied offer tranche ("Offer Tranche"), scheduled MW from that offer tranche ("Sch") and remaining MW in that tranche ("Block Spare). The ratio of a unit's scheduled quantity to its offered quantity in a tranche ("Scheduled Qty to Offer Tranche Ratio") is also represented in Table 16. An equal ratio across tied units implies that these units have been fairly allocated with scheduled quantities that are proportionate to their offered quantities.

2 observations were made and are discussed overleaf.

<u>Proportionate reallocation of scheduled quantities between 2 or more price-tied pairs in all products</u>

Case 1 displays a situation where tied marginal units were found in energy, regulation and all classes of reserve. To achieve a proportionate allocation methodology, the constraints are formulated such that tied units with higher offered quantities should be allocated higher amounts and vice versa. This attribute can be observed in this scenario.

For example, G6 and G7 were price-tied for the offer tranche of $179 prior to the application of the constraint. This is because the MCE co-optimises resources based on the cost of procuring an additional MW from a unit. It would thus cost $179 to schedule an additional MW of energy from G6 given that it was fully scheduled for its previous offer trance of 10 MW at $170. However, Table 16 shows that G7 was allocated 8.54 MW of its 10 MW offered quantity as compared to G6 with 0 MW at an equal offer tranche. This random allocation in favour of G7 can be inferred from the units' respective Scheduled Quantity to Offer Tranche ratios with G7 at 0.854 and G6 at 0. Following the tie-breaking constraints, the MCE reallocated 4.27 MW of energy from G7 to G6, equalising the scheduled quantity to offer tranche ratio between these 2 units to 0.57.

Proportionate reallocations of scheduled amounts were also seen in other products following the addition of the proposed constraints in the MCE. In regulation, G8 and G10 should ideally be scheduled equal amounts of regulation given their identical offer tranches of 5 MW at $0.01. These 2 units' scheduled quantities should also exceed that of G11's given their larger offer tranches. However, prior to tie-breaking, the MCE fully cleared G10 and G11 for 5 MW and 4 MW respectively, but only partially scheduled G8 for 4.02 MW of regulation. This distribution of scheduled regulation resulted in an outcome, whereby the scheduled quantity-to-offer tranche ratios of G10 and G11 at 1 were marginally higher than the ratio of G8 at 0.98. With tie-breaking, Table 16 shows that G8 and G10 were proportionately allocated quantities of 4.65MW each while G11's scheduled regulation was decreased from 4MW to 3.72MW. This reallocation thus equalised the 3 units' scheduled quantity-to-offer tranche ratio from a range of 0.804 to 1 prior to tie breaking to 0.93 following the addition of the proposed constraints.

Under primary reserve, price-tied units G4, G5 and G8 submitted offer tranches of 15 MW, 12.3 MW and 15 MW respectively. Given their equal-sized offer tranches, both G4 and G8 should be scheduled for an equal amount of primary reserve that is more than that of G5. However, prior to tie-breaking, while G5 and G8 were fully cleared for primary reserve at their offer tranches, G4 was only partially cleared for primary reserve at 14.64MW. With the proposed formulation, G4 was allocated an additional 0.23 MW of primary reserve from G8 (0.11MW) and G5 (0.12MW). This result indicates a proportionate allocation as reflected in the balanced scheduled quantity-to-offer ratio of 0.99 between the 2 units.

Other classes of reserve also displayed similar tie-breaking solutions. For example, the MCE re-allocated 0.016MW of secondary reserve from G3 to G1 with tie-breaking. This is because G3 had a larger offer band of 5MW as compared to G1's 2MW. In the case of contingency reserve, the MCE increased G6's and G7's scheduled quantities by 21.4MW and 0.78MW respectively. These additional quantities were reallocated by reducing scheduled quantities from G1, G2, G8 and G9.

<u>System-wide net benefit overrides tie-breaking constraints</u>

Although G9 was tied with G4, G5 and G8 at $0.01, the MCE did not increase its primary reserve contribution following tie-breaking. This is because G9 was constrained by its reserve envelope. As such, increasing this unit's scheduled primary reserve would have resulted in a substantially higher cost of procuring energy and in turn, led to a decrease in system-wide net benefit.

<u>Implications</u>

The observations described above indicate that while the tie-breaking formulation is able to adequately reallocate tied marginal units with scheduled quantities that are proportional to their offered quantities, it also ensures that the MCE places a greater emphasis on the primary objective of maximising net benefit than on the secondary objective of resolving tied situations.

Table 16: Case 1 (1 January 2012, Period 6) - Tie-breaking on marginal units

USEP: $180.016
Primary reserve price: $0.01
Secondary Reserve Price: $0.01
Contingency reserve price: $0.01
Regulation Price: $0.01
Objective Value (Net Benefit): 203751999.92

Type of Product	GRF	Offer Tranche	Pre			Post			Change in sch. MW
			Sch. (MW)	Block spare (MW)	Scheduled Qty to Offer Tranche Ratio	Sch. (MW)	Block spare (MW)	Scheduled Qty to Offer Tranche Ratio	
Energy	G6	10 MW at $170	10	0 at $170	0/10 =0 (for offer tranche 10MW @ $179)	4.27	5.73 at $179	5.73/10 = 0.57	4.27
		10 MW at $179	0	10 at $179					
	G7	10 MW at $179	8.54	1.45 at $179	8.54/10=0.854	4.27	5.73 at $179	5.73/10 = 0.57	- 4.27
Regulation	G8	5 MW at $0.01	4.02	0.98	4.02/5 = 0.804	4.65	0.35	4.65/5 = 0.93	0.63*
	G10	5 MW at $0.01	5	0	5/5 = 1	4.65	0.35	4.65/5 = 0.93	-0.35
	G11	4 MW at $0.01	4	0	4/4 =1	3.72	0.28	3.72/4 = 0.93	-0.28
Primary Reserve	G4	15 MW at $0.01	14.64	0.36	14.64/15 = 0.976	14.88	0.13	14.88/15 = 0.99	0.23*
	G5	12.3 MW at $0.01	12.3	0	12.3/12.3 = 1	12.19	0.11	12.19/12.3=0.99	-0.11
	G8	15 MW at $0.01	15	0	15/15 = 1	14.88	0.12	14.88/15 = 0.99	0
	G9	35MW at $0.01	28.42	6.58	28.42/35 = 0.812	28.42	6.58	28.42/35 = 0.812	0
Secondary Reserve	G1	5MW at $0.01	4.96	0.056	4.96/5 =0.992	4.976	0.04	4.976/5 = 0.99	0.016
	G3	2MW at $0.01	2	0	2/2 = 1	1.984	0.016	1.984/2 = 0.99	-0.016
Contingency Reserve	G1	26.5MW at $0.01	26.5	0	26.5/26.5 = 1	22.68	3.82	22.68/26.5 =0.86	-3.82
	G2	20MW at $0.01	20	0	20/20 =1	17.12	2.88	17.12/20 =086	-2.88
	G3	25MW at $0.01	0	25	25/25 =1	21.40	3.60	21.40/25 = 0.86	21.40
	G5	25 MW at $0.01	20.62	4.38	20.62/25=0.825	21.40	3.60	21.40/25 = 0.86	0.78*
	G8	85MW at $0.01	85	0	85/85=1	72.76	12.24	72.76/85 =0.86	-12.24
	G9	70MW at $0.01	63.16	6.84	63.16/70=0.902	59.92	10.08	59.92/70 = 0.86	-3.24

*marginal unit prior to tie-breaking

4.4.2 Case 2 – Application of Tie-breaking on Non-marginal Tied Units

While most ties occurred between marginal units in the simulation, tie-breaking was also found to occur between non-marginal units. One such case (2 January 2012, Period 4) is described in detail below.

Table 17 overleaf identifies non-marginal GRFs that displayed changes in scheduled quantities with the proposed tie-breaking constraints. Specifically, changes were observed in both regulation and contingency reserve even though both G1 and G2's tied offer tranches were priced below the clearing prices of these 2 products as described below.

Observations

In terms of regulation, both G2 and G1 each submitted offer tranches of $0, resulting in a tied scenario. The MCE thus reduced G2's scheduled regulation by 0.2MW and reallocated this amount to G1. This reallocation took place even though both GRFs' offers of $0 were significantly below the clearing price of $127.99.

A similar situation was observed in contingency reserve where both units submitted regulation offers of $0. Following the tie-breaking formulation, the MCE reduced G1's scheduled contingency reserve by 0.2MW and reallocated this amount to G2. This reallocation occurred though both GRF's offer prices were at $0, which is significantly below the clearing price of $134.73

These observations indicate that the formulation impacted tied non-marginal units in the simulation.

Reason

The situation described above occurred because G1 and G2 were each bounded by their respective Reserve Generation Maximum constraint. Under this constraint, the sum of a GRF's scheduled energy, scheduled regulation and the highest scheduled quantity of any class of reserve (primary, secondary or contingency reserve) cannot exceed its Reserve Generation Maximum Capacity. In this instance, both GRFs were scheduled for quantities that reached their Reserve Generation Max constraint of 360MW, restricting additional amounts of energy, regulation of reserve that can be scheduled from both units. The results thus indicate that the formulation also identifies ties at such constraints and respects these constraints when resolving tied situations.

Table 17 also compares the difference in ratios between each tied pair, for both products. This indicator reflects the extent to which the proposed constraints resolved the random allocations between these tied units. The differences in ratio between G1 and G2 were reduced from 0.04 to 0.03 for regulation and 0.06 to 0.04 for contingency reserve. These decreases imply that the formulation does attempt to schedule tied units' quantities that are proportionate to their offered quantities as much as possible, even on constrained units.

Implications

Case 2 thus shows that the proposed formulation is also able to resolve ties between constrained non-marginal units that may arise from a unit's generation capability or may be attributed to reserve limits imposed on ILs.

Table 17: Case 2 (2 January 2012, Period 4) – Changes in scheduled quantities on non-marginal units

<table>
<tr><th colspan="21">USEP: $341.00
Primary reserve price: $1.04
Secondary Reserve Price: $1.04
Contingency reserve price: $134.73
Regulation Price: $127.99
Objective Value (Net Benefit): 200789829.27</th></tr>
<tr><th rowspan="3">GRF</th><th rowspan="3">Res Gen Max</th><th rowspan="3">Energy Sch</th><th rowspan="3">Pri. Res Sch.</th><th rowspan="3">Sec. Res Sch.</th><th colspan="8">Regulation</th><th colspan="8">Contingency Reserve</th></tr>
<tr><th rowspan="2">Offer Tranche</th><th colspan="2">Pre</th><th colspan="2">Post</th><th rowspan="2">Change</th><th colspan="2">Reg. Ratio Delta</th><th rowspan="2">Offer Tranche</th><th colspan="2">Pre</th><th colspan="2">Post</th><th rowspan="2">Change</th><th colspan="2">Cont. Ratio Delta</th></tr>
<tr><th>Sch</th><th>Spare</th><th>Sch</th><th>Spare</th><th>Pre</th><th>Post</th><th>Sch</th><th>Spare</th><th>Sch</th><th>Spare</th><th>Pre</th><th>Post</th></tr>
<tr><td>G1</td><td>360</td><td>340</td><td>7.5</td><td>11</td><td>5 MW at $0</td><td>4.80</td><td>0.2</td><td>5.00</td><td>0</td><td>0.2</td><td rowspan="2">0.04</td><td rowspan="2">0.03</td><td>30 MW at $0</td><td>15.2</td><td>14.8</td><td>15</td><td>15.0</td><td>-0.2</td><td rowspan="2">0.06</td><td rowspan="2">0.04</td></tr>
<tr><td>G2</td><td>360</td><td>340</td><td>7.5</td><td>11</td><td>6.5 MW at $0</td><td>6.50</td><td>0</td><td>6.30</td><td>0.2</td><td>-0.2</td><td>30 MW at $0</td><td>13.5</td><td>16.5</td><td>13.7</td><td>16.3</td><td>0.2</td></tr>
</table>

4.4.3 Case 3 – Tie-breaking with Changes in Reserve Requirements

Changes in the contingency reserve requirement were also observed in selected periods. One such instance (1 January, Period 41) is described in detail below.

Observation

Table 18 reflects GRFs with changes in scheduled contingency reserve following the introduction of the tie-breaking constraints. These changes can be segregated into 2 main groups, where GRFs in Group A (G1-G4) each submitted offer tranches of 40MW at $0.04 while both GRFs in Group B (G5-G6) each submitted 20MW at $0.01.

In an ideal scenario with proportionate allocation, all GRFs in Group A should be scheduled for equal amounts of contingency reserve. However, prior to the proposed formulation, it can be seen that the MCE allocated G1 relatively more contingency reserve of 40MW as compared to a range of between 30MW to 36.33MW for the other 3 GRFs. Following the proposed constraints, the MCE balanced out this allocation by reducing G1's and G4's scheduled contingency reserve quantities, while increasing G2's and G3's scheduled quantities. This re-distribution resulted in an equal allocation of 33.81MW to each tied unit in Group A.

However, it was also observed that the MCE increased G5's and G6's scheduled contingency reserve quantity by 5.78MW each. This increase occurred despite the observation that both units were proportionately allocated 0.22MW of contingency reserve prior to the tie-breaking formulation. As a result, the MCE imposed an additional 8.23 MW of contingency reserve requirement for this dispatch period following tie-breaking. Nevertheless, this increase in requirement did not lead to any change in the net benefit of 228870099.72.

Reason

To evaluate the rationale for this increase in contingency reserve requirement, there is a need to analyse each GRFs' changes in ratio delta, as reflected in Table 19. The table shows the ratio delta of each tied pair in this dispatch period, with 6 pairs in Group A and 1 in Group B. The tie-breaking formulation reduced all ratio deltas in Group A from a range of -0.16 to 0.25 to 0 across the group. This indicates that ties were evenly reallocated across all 4 units.

Table 18 shows that this tie-breaking reallocation in Group A resulted in a net shortfall of 2.89 MW of contingency reserve with a reduced cost of $0.1156 to the MCE. As such, the MCE had to search for a solution to meet this reserve shortfall without imposing additional cost to the objective function, resulting in an increase in contingency reserve contribution from G5 and G6 of 11.56MW at a cost of $0.1156. This increase in contributions from both GRFs resulted in a higher contingency reserve requirement as both G5 and G6 were coincidentally the risk setters for this dispatch period.

This observation of an unchanged net benefit despite the increase in contingency reserve requirement indicates the occasional existence of multiple solutions in the co-optimisation process. Under such a scenario, the MCE is able to select from a variety of different dispatch schedules to arrive at the same objective value. Without the proposed tie-breaking constraints, the MCE may have opted for the outcome in the original RTDS. With the proposed tie-breaking constraints, the MCE found it more optimal to select the dispatch schedule that would result in a proportionate allocation of tied units, while retaining the same system-wide net benefit.

Implications

This case shows that the MCE may choose to adjust reserve requirements for a given dispatch period in its search for a tie-breaking solution. However, despite this increase, the MCE still ensures that the solution retains the primary objective function of maximising net benefit.

Table 18: Case 3 (1 January 2012, Period 41) – Tie-breaking with changes in contingency reserve requirement

USEP: $181.18
Primary reserve price: $1.04
Secondary Reserve Price: $1.04
Contingency reserve price: $0.04
Regulation Price: $76.56
Objective Value: 231578918.51

GRF		Res Gen Max	Contingency Reserve										
			Offer band	Pre				Post				Change in Sch. MW	Change in Cont. Res. Req
				Sch.	Block Spare	Value of scheduled quantity	Reserve Req.	Sch.	Block Spare	Value of Scheduled Quantity	Reserve Req		
Tied Group A	G1	368	40 MW at $0.04	40	0	40 x $0.04 =$1.6		33.81	6.19	33.81 x $0.04 =$1.3524		-6.19	
	G2	364	40MW at $0.04	30	10	30 x $0.04 =$1.2		33.81	6.19	33.81 x $0.04 =$1.3524		3.81	
	G3	370	40 MW at $0.04	31.80	8.2	40 x $0.04 =$1.272		33.81	6.19	33.81 x $0.04 =$1.3524		2.01	
	G4	370	40MW at $0.04	36.33	3.67	40 x $0.04 =$1.4532		33.81	6.19	33.81 x $0.04 =$1.3524		-2.52	
Tied Group B	G5	354	20 MW at $0.01	0.22	19.78	20 x $0.01 =$0.0022		6	14	6 x $0.01 =$0.06		5.78	
	G6	365	20MW at $0.01	0.22	19.78	20 x $0.01 =$0.0022		6	14	6 x $0.01 =$0.06		5.78	
Total			-			**$5.5296**	**510.31 MW**	-		**$5.5296**	**518.55 MW**	**8.67 MW x 0.95 = 8.23 MW**	**8.23 MW**

Table 19: Case 3 (1 January 2012, Period 41) – Comparison of Contingency Ratio Deltas in 2 tied groups

Tied Group	Tied Pairs	Pre Tie-breaking			Post Tie-breaking			Net Change in Sch. MW	Net Change in Cost
		Scheduled Qty/Offer Band Tranche (1st Unit)	Sch. Qty/Offer Band Tranche (2nd Unit)	Pre Ratio Delta	Scheduled Qty/Offer Band Tranche (1st Unit)	Sch. Qty/Offer Band Tranche (2nd Unit)	Post Ratio Delta		
Tied Group $0.04	G1-G2	40/40 = 1	30/40=0.75	0.25	33.81/40 = 0845	33.81/40 = 0845	0	-2.89	-2.89MW x $0.04= -$0.1156
	G2-G3	30/40 = 0.75	31.80/40 =0.795	-0.04	33.81/40 = 0845	33.81/40 = 0845	0		
	G3-G4	31.80/40 =0.795	36.33/40= 0.9083	-0.11	33.81/40 = 0845	33.81/40 = 0845	0		
	G1-G3	40/40 = 1	31.80/40 =0.795	0.21	33.81/40 = 0845	33.81/40 = 0845	0		
	G1-G4	40/40 = 1	36.33/40= 0.9083	0.09	33.81/40 = 0845	33.81/40 = 0845	0		
	G2-G4	30/40 = 0.75	36.33/40= 0.9083	-0.16	33.81/40 = 0845	33.81/40 = 0845	0		
	G1-G2	40/40 = 1	30/40 = 0.75	0.25	33.81/40 = 0845	33.81/40 = 0845	0		
Tied Group $0.01	G5-G6	0.22/20=0.01	0.22/20=0.01	0	0.22/20=0.01	0.22/20=0.01	0	11.56	11.56 x $0.01 = $0.1156

5 Impact on System Performance

The introduction of the proposed tie-breaking constraints will increase the CPLEX solve time. However, this increase is still well within the recommended CPLEX threshold time.

Table 20: A Comparison of CPLEX Performance

Run Type	Recommended CPLEX Threshold Time	Clearing Time Before Changes	Expected Clearing Time with Tie-Breaking Constraints	% Increase
Real-time Dispatch	30 seconds	25 seconds	25.2 seconds	0.80%
Short-term Schedule	240 seconds	120 seconds	122.6 seconds	2.17%
Pre-dispatch Schedule	900 seconds	800 seconds	815.2 seconds	1.90%
Market Outlook Scenario	7200 seconds	3100 seconds	3157.6 seconds	1.86%

6. Implementation Considerations

6.1 Implementation Process

Code changes were made to the test environment to conduct the simulations described in section 4. The same code applies for all products and all facilities. As such, more effort will be required to apply the constraints only to a single product and/or to one type of facility.

If the constraints are applied to only some products and/or some facilities at this juncture, more effort and costs will be incurred in the future to extend the application of these constraints to more products and/or facilities. Thus, it makes sense to introduce these constraints across all products and facilities now, if the decision is to implement tie-breaking.

6. 2 Implementation Cost

The breakdown of the estimated implementation time and costs are:

Table 21: Estimated Implementation Time and Costs

Time Estimates		
MCE Development (**60% completed)**	4 man-weeks	5 calendar-weeks
System Tests and Performance	2 man-weeks	3 calendar-weeks
User Acceptance Testing (UAT)	4 man-weeks	6 calendar-weeks
Audit	2 man-weeks	4 calendar-weeks
Total Time Required	12 man-weeks	18 calendar-weeks
Cost		
Power Systems Consultant Resource/EMC Manpower	Within EMC's Budget	
Audit	$20,000	

Total Additional Cost Required	$20,000 (To be funded from the RCP Contingency Budget)

7. Conclusion

The MCE currently schedules GRFs/LRFs with equal-priced offers in a random manner, which may result in dispatch instability. In practice, these random allocations were found to mainly impact reserve providers.

The proposed tie-breaking formulation presented above is able to deal with these random allocations by accurately apportioning tied GRFs/LRFs' scheduled quantities based on their individual offered quantities, without compromising the primary objective of maximising net benefit. The solution is also able to adequately address tied scenarios across all products. In addition, the formulation is capable of breaking ties amongst units tied at marginal and non-marginal offer tranches, resulting in a more robust solution.

Thus, it is advantageous to implement this proposed formulation to energy, regulation and reserve across all GRFs and LRFs in the SWEM.

8. Consultation

We published the rule modification proposal for comments on 14 May 2012, and comments were received from Tuas Power. Their comments and EMC's response are provided below:

<u>Comments from Tuas Power</u>

a. *As raised in the clarification meeting, we request EMC to clarify on the objectives of applying the tie-breaking formula to ALL products if the benefit is mainly for the IL accounts and from the start of the paper it is stated that the objective is not for fairness but rather for dispatch stability.*

<u>EMC's Response</u>

There two aspects to the comments above, the objective of introducing tie-breaking constraints in the MCE and the products and type of facility that these constraints should extend to.

(i) Objective of addressing ties

As discussed, ties result in random allocations between units. The paper established that for marginal units, dispatch stability precedes fairness as the primary objective for exploring a potential tie-breaking solution. This is especially so for energy and LRFs where random allocations may result in dispatch uncertainty for a facility.

(ii) Application of tie-breaking constraints

While the proposal to look at tie-breaking solutions stemmed from observed random allocations between LRFs (which only provide reserve), the re-runs concluded that ties do affect GRFs as well. The re-runs also showed that ties can occur across all products. As such, the paper explored a tie-breaking solution that caters to both types of facility and all products.

As discussed in section 7.1, it makes sense to apply tie-breaking to all products and all types of facilities if the decision is to implement tie-breaking.

Comments from Tuas Power Supply

b. *From the simulation, there is no case of tie between different gencos; this may be attributed to nodal pricing structure, which makes our context quite different from AEMO. Also it is good if EMC can check with AEMO from their experience what problems they have encountered with such tie-breaking formula and to ensure that there is no compromise on the maximization of net benefit in the system.*

EMC's Response

While no ties were found between different MPs for energy in the simulation, ties between different MPs were observed for all other products. We agree that price-ties for energy will be more significant in AEMO since AEMO uses zonal pricing while the SWEM uses nodal pricing.

AEMO also reverted on their experience with tie-breaking. They conveyed that the starting point of these constraints was to address ties within a zone, but mainly from a dispatch stability perspective. They did not indicate any major issues with these constraints and added that generators generally consider the outcome to be fair and predictable.

9. Technical Working Group (TWG)'s Deliberations at the 17th TWG Meeting

The above proposal was tabled at the 17th TWG Meeting held on 25 June 2012. This section summarises the TWG's comments and EMC's responses for the RCP's consideration.

a. Query on Sample Size

Mr Tan Cheng Teck queried on the use of a sample size of 144 periods. Specifically, he commented that it might be insufficient to draw any conclusions on dispatch instability although he did not have a specific suitable sample size in mind.

EMC advised that a sample size of 30 is usually large enough to approximate a normal distribution. In the study, EMC had chosen a larger sample size of 144 periods.

b. Query on Dispatch Stability

Mr. Tan also questioned EMC's objective of addressing the issue of tied offers. He opined that while EMC had stated its objective to be achieving dispatch stability, the results of this study did not show that tie-breaking addressed dispatch stability for GRFs. He referred to Case 3 where the scheduled quantities of 40MW, 30 MW, 31.80MW and 36.33MW for Tied Group A became 33.81MW each following tie-breaking. These small changes in MW did not seem to demonstrate addressing dispatch instability. Mr. Chua Gwen Heng and Ms. Tini Mulyawati concurred on Mr Tan's views.

On this query, EMC reiterated that there is insufficient reason to introduce tie-breaking for fairness, but a tie-breaking mechanism may be considered for the purpose of achieving dispatch stability. However, EMC added that, ultimately, it was for the industry to decide on whether tie-breaking will sufficiently improve dispatch stability to warrant implementation.

EMC's Comments

To address the some TWG's members concerns on whether tie-breaking address dispatch stability and to facilitate the RCP's decision process, an additional column has also been included in Table 10 to reflect the maximum change in scheduled quantities (in MW) after introducing the proposed tie-breaking constraints. These values give an indication of potential fluctuations that can be addressed with the proposed constraints. For example, contingency reserve had the highest reallocation quantity of 31.74 MW, while other products' maximum reallocation ranged from 3.47MW to 9.29MW. It is thus for the RCP to decide, based on these indicative values, on whether dispatch stability is a cause for concern.

c. TWG's Votes

The members who **supported** the proposal were:

1) Mr. Tony Tan Kia Shuan (Tuas Power)
2) Mr. Mr Yong Kong Kiong (SP PowerGrid)
3) Mr. Loh Poh Soon (Power System Operation)
4) Mr. Chen Jian Hong (EMC)

The members who **did not support** the proposal were:

1) Mr. Tan Cheng Teck (Senoko Energy)
2) Mr. Chua Gwen Heng (Sembcorp Cogen)
3) Ms. Tini Mulyawati (Keppel Energy)

Ms. Tini Mulyawati said that she would support the proposal only if it could clearly be seen to address the objectives of the paper, fairness and dispatch stability. However, based on the results of the study, she was not convinced of its benefits in addressing all objectives.

Mr. Chua Gwen Heng said that if the proposal for tie-breaking was to address fairness issues, he would support it. However, he would not support it for addressing dispatch stability issues.

10. RCP's Deliberation at 62nd RCP Meeting

Following consideration at the 62nd RCP Meeting, the RCP unanimously **supported** the proposed methodology and **tasked** EMC to draft the relevant Market Rules.

11. Proposed Rule Changes

Arising from the RCP's decision, EMC has drafted the proposed Market Rules changes to implement the tie-breaking methodology in the SWEM. Figure 4 describes the approach used to introduce these Market Rules changes while Table 22 summarises the proposed rule changes.

Figure 4: Approach Used in Proposed Market Rules Changes

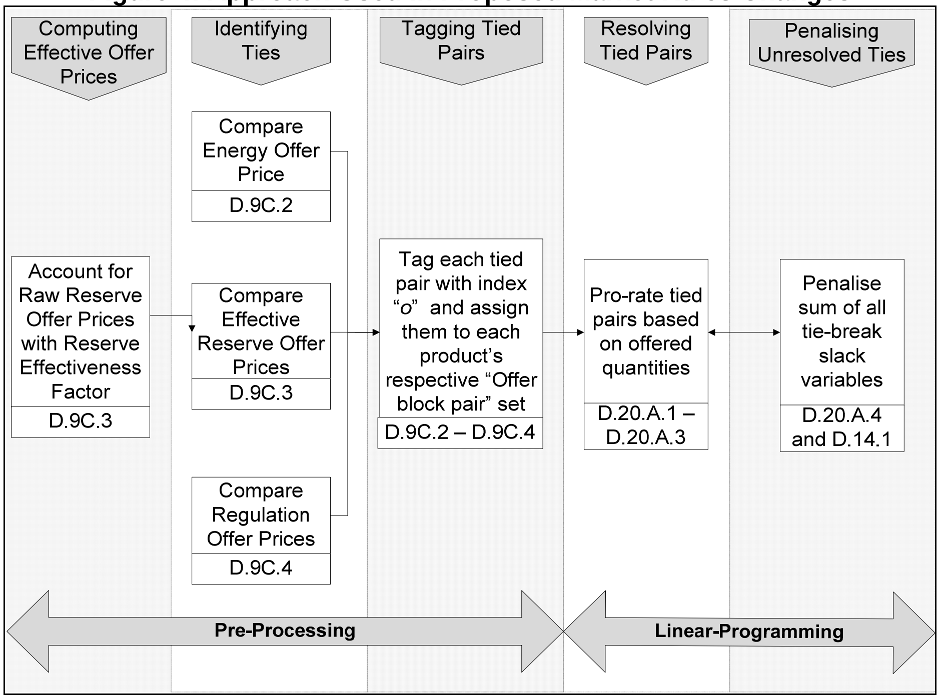


Table 22: Proposed Rule Changes

Section	Proposed Change	Reason for Change
Chapter 6 Appendix 6D.2	Addition of 6 new sets "TIEDENERGYOFFERBLOCKPAIRS", "TIEDENERGYOFFERBLOCKPAIR$_o$" "TIEDRESERVEOFFERBLOCKPAIRS" "TIEDRESERVEOFFERBLOCKPAIR$_o$" "TIEDREGULATIONOFFERBLOCKPAIRS' "TIEDREGULATIONOFFERBLOCKPAIR$_o$"	To introduce sets for price- tied pairs for all products
Chapter 6 Appendix 6D.3	Addition of parameter, "TieBreakingPenaltyFactor"	To introduce a new parameter for the purposes of computing the tie-breaking penalty constraint.
Chapter 6 Appendix 6D.4	Addition of 6 new slack variables "EnergyTieBreakSlack1$_o$", "EnergyTieBreakSlack2$_o$", "RegulationTieBreakSlack1$_o$", "RegulationTieBreakSlack2$_o$", "ReserveTieBreakSlack1$_o$" and "ReserveTieBreakSlack2$_o$"	To define new variables to be used in section D.20A of Appendix 6D for the purpose of resolving the tie between price-tied price-quantity pairs.

Section	Proposed Change	Reason for Change
Chapter 6 Appendix 6D.4	Addition of "TiebreakingPenalties"	To introduce a tie-breaking penalty variable representing the sum of all tie-breaking penalties for energy, reserve and regulation to be included as a penalty cost to the objective function in D.14 of Appendix 6D.
Chapter 6 Appendix 6D.5	Addition of 6 new functions *(g(o),j(o)), (g'(o),j'(o)), (r(o),j(o)), (r'(o),j'(o)), (l(o),j(o)), (l'(o),j'(o))*	To identify each respective price-quantity pairs of energy, reserve and regulation offers.
Chapter 6 Appendix 6D.9C.1	Addition of description of section	To state that sets derived in this new section are to be used for the purpose of tie-breaking constraints in the new D.20A.
Chapter 6 Appendix 6D.9C.2-6D.9C.4	Introduce 3 new pre-processing conditions that each assigns tied pairs to their respective sets	To identify price-tied energy, reserve or regulation pairs, following which these pairs will be assigned to their respective sets.
Chapter 6 Appendix 6D.14	Introduce the "TieBreakingPenalties" variable in the objective function	To include the tie-breaking penalty for unresolved ties as a cost to the existing objective function.
Chapter 6 Appendix 6D.14, 6D.16.1.2	Include the word "ENERGY" to set under "BIDS"	To correct for a typographical error
Chapter 6 Appendix 6D.20A.1-6D.20A.3	Introduce a tie-breaking constraint for each product	To introduce tie-breaking constraints that resolve the ties between price-tied pairs for each product.
Chapter 6 Appendix 6D.20A.4	Introduce a constraint that sums the slack variables of all unresolved tied price-quantity pairs	To sum all unresolved tied price-quantity pairs for all products to be included as a cost in the objective function.

12. Consultation for Market Rules

The proposed rule modifications were published for industry comments on 3 October 2012 and no comments were received.

13. TWG's Deliberation at the 18th TWG Meeting

The proposed rule changes were presented at the 18th TWG Meeting held on 19 October 2012. The TWG unanimously supports the proposed rule modifications set out in Annex 3.

14. Legal Sign-off

EMC's legal counsel has indicated that because of the technical nature of the rule modification proposal he is not able to provide a legal signoff

15. Recommendation

The RCP unanimously **recommends** that the EMC Board:

a. **adopt** the rule modification proposal as set out in Annex 3;

b. **seek** EMA's approval of the rule modification proposal as set out in Annex 3

c. **recommend** that the proposed rule modification come into force **18 weeks** after the date on which the approval of the Authority is published by the EMC.

Annex 1: Tie-breaking methods used in other jurisdictions

Jurisdiction		Description	Applicable to SWEM?
Australian Energy Market Operator[8]	**Type of Market**	Real-Time (5 min)	Yes. AEMO uses a Linear Programming solver, which is similar to that used in SWEM's MCE.
	Product that Tie-Breaking is Applied on	Energy & Demand Bids	
	Identification of Ties	2 marginal or non-marginal equal-priced offer/bid bands (with a $\$1X10^{-6}$ penalty) of the same product type in the same region	
	Tie-breaking Method	Pro-rata between two units and co-optimised	
	Formulation	AEMO employs a cost minimisation objective function, where tie-breaking is allocated as part of the violation penalty cost. This penalty cost is represented by the following constraint: $\text{tbslack1-tbslack2} = \frac{\text{Band Dispatch}_i}{\text{Band Size}_i} - \frac{\text{Band Dispatch}_j}{\text{Band Size}_j}$ In the constraint above, Band Dispatch refers to the pro-rated dispatch quantities of each pair of price-tied energy offers, i and j. These pro-rated quantities are then represented as a ratio of their respective Band Size, which are the offered quantities for the corresponding price band. Tbslack1 and tbslack2 are non-negative slack variables. The example below exemplifies how this constraint works. Suppose there are 2 price-tied offers of $10 as follows: Bandsize1=20MW, Bandsize2=30MW, Required quantity= 10MW The Band Dispatch for each of these 2 offers are given by:	

[8] 1 July 2010, "Publication of Price Setter Data – Business Specification" Section 4.4

Jurisdiction		Description	Applicable to SWEM?
		Band Dispatch$_1$= $\frac{20}{(20+30)} \times 10MW = 4MW$ Band Dispatch$_2$ = $\frac{30}{(20+30)} \times 10MW = 6MW$ The constraint is thus given by: tbslack1-tbslack2 = $\frac{4}{20} - \frac{6}{30} = 0$ (No violation) The tie-breaking cost in the solver is represented by: $\sum(tbslack_i \times 10^{-6})$ The solver attempts to minimise the tie-breaking cost and attaches a small penalty factor of $\$1x10^{-6}$ such that it will not significantly affect the primary objective function. In the ideal scenario (as reflected in the example above), a pair of price-tied offers can be evenly apportioned such that this cost is minimised to zero. There are occasions where dispatch quantities may be constrained at certain MWs. Under such circumstances, a pair of tied-offers cannot be evenly apportioned, i.e. tbslack1-tbslack2>0, resulting in a positive tie-breaking cost. The solver separates a group of tied offers into pairs, and compares these pairs individually, but simultaneously. This pair-wise approach ensures that if one of the tied band size cannot be optimally pro-rated without violating a constraint or compromising the primary objective function, the solver can proceed with breaking ties using other unconstrained band sizes. Thus, there are n(n-1)/2 number of comparisons if there are n tied bids.	
Independent Electricity System Operator[9]	**Type of Market**	Real-Time (5 min)	No. IESO uses a non-linear solver, as reflected by the quadratic tie-breaking function. Although the MCE's CPLEX solver
	Product that Tie-Breaking is Applied on	Energy, Demand & Reserve	
	Identification of Ties	2 or more equal-priced offers without considering trade-offs	

[9] 12 October 2011, "Chapter 7 System Operations and Physical Markets – Appendices" Section 2.8 and Section 5

Jurisdiction		Description	Applicable to SWEM?
	Tie-breaking Method	Pro-rata across all tied units (Adjusted to reflect current capability of facility) and co-optimised	can resolve non-linear problems, the solutions are often inconsistent. Also, introducing non-linear programming may reduce the MCE's performance.
	Formulation	IESO's solver aims to maximise the benefit in its objective function. Tie-breaking is assigned as a penalty cost and is represented by the constraint below: $$\text{Tiebreaking} = \sum\left[(0.0005)\frac{(\text{Demand Scheduled from Bid Block}_i)^2}{\text{Maximum MW of Bid Block}_i}\right] + \sum\left[(0.0005)\frac{(\text{Energy Scheduled From Energy Offer Block}_i)^2}{\text{Maximum MW of Energy Offer Block}_i}\right] + \sum\left[(0.0005)\frac{(\text{Energy Scheduled From Reserve Offer Block}_i)^2}{\text{Maximum MW of Reserve Offer Block}_i}\right]$$ The constraint above represents the quadratic of the amount scheduled from a block over the maximum MW that can be scheduled from that block. This implies that tie-breaking costs will increase regardless of whether the amount scheduled for a given band as a result of prorating increases or decreases. The solver attaches a relatively small penalty cost of $\$5\text{x}10^{-4}$ to the constraint.	
Midwest ISO[10]	**Type of Market**	Real-Time (5 min), Day-ahead Market	Yes. Formulation is similar to that applied by AEMO.
	Product that Tie-Breaking is Applied on	Energy & Operating Reserves	
	Identification of Ties	Equal-priced tied offers	
	Tie-breaking Method	Tied offers are dispatched based on pro-rated quantities (Adjusted for losses) and co-optimised	
	Formulation	MISO employs a cost minimisation algorithm similar to that of AEMO's in its solver's objective function. Tie-breaking is allocated as a penalty cost[11] as reflected in the constraint below	

[10] 29 June 2011, "Business Practices Manual (BPM) Energy and Operating Reserve Markets Attachment A Market Optmization Techniques", Section 3.8, "BPM Attachments B and D"

Jurisdiction		Description	Applicable to SWEM?
		$\frac{\text{Proportional Dispatch}_m}{\text{Offered Quantity}_m} - \frac{\text{Proportional Dispatch}_n}{\text{Offered Quantity}_n} = \text{EnergyTieBreak1}_{mn} - \text{EnergyTieBreak2}_{mn}$ The solver minimises the difference of 2 pro-rated dispatch quantities, m and n, where pro-rated dispatch quantities are represented in proportion to their respective offered quantities. EnergyTieBreak1 and EnergyTieBreak2 are slack variables. The solver then attaches a low penalty price of about $\$1 \times 10^{-6}$ to the slack variables as follows: Energy Tie Breaking Penalty Costs = $\sum_{e1}\sum_{e2} 0.000001 \times \text{EnergyTieBreak1}(e1, e2)$ + $\sum_{e1}\sum_{e2} 0.000001 \times \text{EnergyTieBreak2}(e1, e2)$ A low penalty price of about $\$1 \times 10^{-6}$ ensures that the Linear Programming Solver will override this constraint in the presence of a more economic solution and/or in the event of other constraints with higher penalty prices. Similar tie-breaking rules apply for Operating Reserves.	

[11] Ma, X, Song H, Hong M, Chen Y and Zak E (2009) "The Security-Constrained Commitment and Dispatch for Midwest ISO Day-ahead Co-optimised Energy and Ancillary Service Market"

Annex 2

Power Systems Consultants

Energy Market Company

Reference: J2115-REP-074 Rev02

Date: 06 Mar 2012

To: Nerine Teo

Market Administration, EMC

From: Tri Huu Le

PSC Consulting NZ

Tie Breaking for Reserves

Introduction

Purpose

This paper introduces tie breaking concepts and discusses tie breaking solutions incorporating some suggestions from EGR Consulting Ltd following its review on the issue.

Background

In most MCE solutions there will one or more offers made that are only partially cleared for each of the products that are scheduled (Energy, Primary Reserve, Secondary Reserve, Contingency Reserve and Regulation). Most often this is at the marginal offer where the total quantity required has been met but not all the last offer quantity has been used up. Other causes of partial clearance of offers can be due to other constraints that are binding. These situations of partial clearing of an offer are expected and generally no issues result from this.

However, while there is no issue with one participants offer being partially cleared there can be when more than one participant's offers are made at the same price with some being only partially cleared. In these instances there may be no way to differentiate the offers or order to decide how much of each are cleared by the solver. When this occurs the MCE may not come up with what would be considered an equitable schedule and instead it essentially randomly schedules quantities from each (often it will fully clear one participant and partially clear another).

This means there is a "tie" in the offers and ways to deal with this are described as "tie-breaking".

Interruptible Load reserve

There are many situations under which tie breaking can occur, but one that was previously found common is for Interruptible Load (IL) reserve.

The reason that it is common for IL is that it has a cap on the total quantity that can be cleared in any given period and IL participants often offer at the same price of $0/MW. When the cap is reached no more IL can be scheduled and partial clearance of IL offers result and as the IL participants often all offer at the same price of $0/MW then a tie occurs.

In such cases IL offers that tie will be cleared on an arbitrary basis by the CPLEX solver. Under the RCP work plan, a pro-rata approach was suggested such that quantities of *marginal* offers are to be cleared in proportion to their offered quantities at the *marginal* price. Such suggestion would potentially enable more certainty of clear quantities for IL participants.

For example market participants A and B both offer reserve at $X/MWh at 5MW and 10MW respectively. $X/MWh is the marginal price and the requirement at the marginal price is only 3MW i.e. less than the total of 15 MW available. Currently the quantity of reserve A and B that is cleared for is arbitrarily determined; it could be 0 MW of A and 3 MW of B, or 0 MW of A and 3 MW of B, or any random combination of A and B quantity to make up to 3 MW. However with respect to the RCP suggestion, cleared quantity of A and B should be $\frac{5\,MW}{5\,MW+10\,MW} * 3MW = 1MW$, and $\frac{10\,MW}{5\,MW+10\,MW} * 3MW = 2MW$ respectively.

Other Reserves & Regulation

Our preliminary investigation finds that out of 144 clearing reruns in study, more than 24% having ties for all three reserve classes and around 3% for regulation. This study shows that tie breaking would very likely occur to reserves and regulation in general. And so if at all available, a tie breaking methodology should be made available to all types of Reserve classes and Regulation.

Key considerations for a tie breaking methodology for reserves

Firstly to deal with not only IL but reserves and regulation, a tie breaking methodology should be made generic whenever possible while maintaining market clearing solution feasibility and optimality. Secondly it should also consider both the complexity level of identifying ties and the likelihood of such occurrences in order to have a more pragmatic approach for the market.

Breaking ties while maintaining solution feasibility and optimality

The key objective for the MCE is to clear the market for a feasible dispatch schedule with the maximum benefit. This objective will need to be preserved for any available tie breaking methodology suggested.

Without considering optimality and feasibility, a simplistic pro-rata method could result in an infeasible and sub-optimal dispatch schedule. For example, after pro-rata, a primary reserve provider might be scheduled such that its energy + reserve + regulation could be more than its maximum rating. Or possibly its reserve schedule could be outside its reserve envelope. Hence, the tie break solution is deemed infeasible. In another example, maybe due to co-optimisation effect it might not be possible for the MCE to schedule a regulation provider at higher and lower than the actual target itself for optimal solution. In other words, breaking ties that result in changes to the schedule target could result in a sub-optimality.

Identifying ties

When there is no trade-off between energy and reserves, ties can be easily identified because effective reserve price offer would be the reserve price offer. However the complexity lies in the determination of tied offers when there is a trade-off due to co-optimisation. Typically effective reserve price offer in this case would not only be the **reserve** price offer but also an opportunity cost component determined by the energy price. And since this opportunity cost depends on both transmission losses and congestion, so does the effective reserve price. Thus given the very low likelihood of energy offer ties, it seems even more unlikely that reserve offers will be tied, in this situation.

Should the tie breaking formulation be non-linear?

Currently the NEMS MCE clears the market using IBM Cplex (LP/MIP) solver. Although Cplex is capable of solving a non-linear problem, its solution quality and performance are inconsistent, vary and unpredictable. And so in general it is not recommended that non-linear formulation be introduced or if need be a linear approximation should be applied to linearize the formulation.

Tie breaking options

General assumptions in identifying ties

Given the low likelihood of having offer ties with trade-offs and the high level of complexity in identifying ties, it is assumed that reserve/regulation offers are in a tie group when their effective reserve price offers are identical; and that the effective reserve price offers are derived solely from the expected reserve group effectiveness component. And this means tie identification can be done ex-ante.

It is also assumed that whenever there is an opportunity cost involved for co-optimisation, the solution should consider preserving the primary objective value as the top priority before any tie break can be done.

Option 1: Heuristic post-processing

In principle this approach identifies a group of identical-price offer blocks that could be in tie-breaking situation and pro-rating their schedules accordingly based on the total cleared quantity of the group and individual offer proportions.

Such approach could be incorporated in the "post processing" in a series of steps

- Step 1. Group the offer blocks that tie into different price groups
- Step 2. Calculate the offer quantity proportion for each block of a price group for all groups
- Step 3. Calculate the total cleared quantity of all blocks in a price group for all groups
- Step 4. Identify which price group is subject to tie breaking
- Step 5. Pro-rate the cleared quantity based on individual offer proportion and the total cleared quantity.

Limitations

With no losses, congestion or generation trade-offs to consider, tie breaking for IL would be a suitable candidate for this approach. However for other reserve types it is possible that heuristic adjustment will produce a sub-optimal or infeasible solution which is not desirable.

Option 2: Linear programming (LP)

Tie breaking in groups

Key principles

a. All tied offers will be grouped in for potential tie breaking
b. By minimizing the disproportion inferring quantity, which is the largest of all normalized quantities in the tie group, the MCE would generally attempt to equalize all the normalized quantities and consequentially schedule all the cleared quantities in proportion and would result in the proportionate tie breaking solution. This principle has some shortcoming that will be explained later on in the following section.
c. The tie breaking objective terms and constraints are linear

How are the normalized and disproportion inferring quantity formulated?

For a given offer A, the normalized quantity can be calculated as follows:

$$NormalizedQty_A = \frac{TotalGroupRawReserveBlockMax_p}{RawReserveBlockMax_A} RawReserveBlock_A$$

And the disproportion inferring quantity is the maximum value of all normalized quantities in the tie group: $DisproportionInferringQty = Max(NormalizedQty_i)$

What is an example of normalized cleared quantities?

Assuming that we have 3 tied offers, A, B and C offered at marginal price of $1/MW for 5, 10 and 5 MW respectively and that 4 MW of required quantity is to be met. Under the perfect tie breaking, schedules for A, B and C should be 1 MW (5/20 x 4), 2 MW and 1 MW respectively. This also means that the normalized quantity for A is $\frac{20}{5} * 1 = 4$; likewise for B is $\frac{20}{10} * 2 = 4$ and for C is $\frac{20}{5} * 1 = 4$

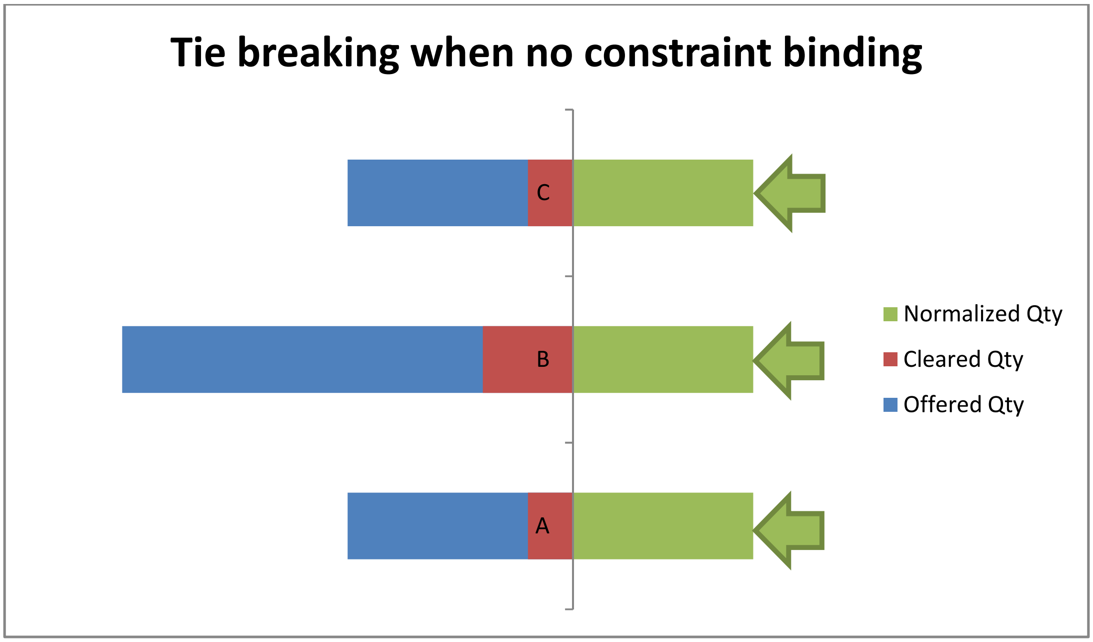


Figure 1 Cleared Qty and Normalized Qty in the perfect tie breaking solution

What is the issue when there is some binding constraint?

In the same example, now let's further assume that due to some binding constraint, A cannot be cleared below 2 MW without breaking some constraint or compromising the primary objective value, and that it's cleared at 2 MW. This means that cleared quantity for B and C must be less than or equal to 2 MW and that the tie breaking is only valid between B and C.

<u>What would the normalized quantities be if only B and C were in the tie break for 2 MW?</u>

$ClearedQty_B = \frac{10}{15} * 2 = {}^4/_3$	$ClearedQty_C \leq \frac{5}{15} * 2 = {}^2/_3$
$NormalizedQty_B = \frac{15}{10} * \frac{4}{3} = 2$	$NormalizedQty_C = \frac{15}{5} * \frac{2}{3} = 2$
$DisproportionInferringQty = Max(NormalizedQty_i) = 2$	

Now let's look at the range of the normalized quantities for all 3 offers as a result of such binding constraint.

$ClearedQty_A = 2$	$ClearedQty_B \leq 2$	$ClearedQty_C \leq 2$
$NormalizedQty_A = \frac{20}{5} * 2 = 8$	$NormalizedQty_B \leq \frac{20}{10} * 2 = 4$	$NormalizedQty_C \leq \frac{20}{5} * 2 = 8$
$DisproportionInferringQty = Max(NormalizedQty_i) = 8$		

It can be seen from the two tables above that it is impossible for the MCE to reduce the disproportion inferring quantity, which is fixed at 8, down to value of 2 to balance out proportionately schedule of B and C when A is bound at 2 MW. In other words when A is constrained on, B and C would be randomly scheduled by the MCE; either B or C could be at 2 MW or 0 MW, or any value in between. This is a limitation of the method which could be addressed by the pair tie breaking method described later on. The figure below illustrates such limitation.

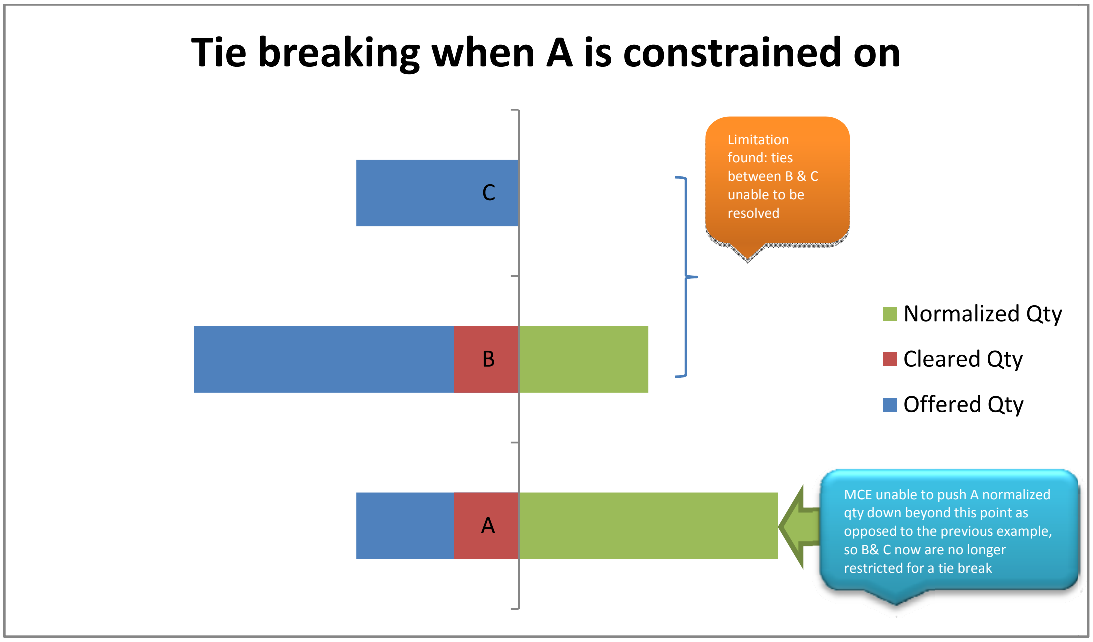


Figure 2 Cleared Qty and Normalized Qty in the binding scenario

Tie breaking in pairs

Key principles

This method is being applied in AEMO and MISO market. Generally it is based on the following principles:

a. All potentially-tied offers should be paired up for tie breaking

b. Any pair that could not have perfect pro-rata solution due to other constraints or co-optimization trade-offs will result in a very small tie breaking penalty. This penalty will incentivize the MCE to search for a solution with best possible pro-rata for all marginal offer ties, while not compromising the primary objective function.

c. The tie breaking objective terms and constraints are linear

What are the pairs for tie breaking from the previous example?

In contrast with tie breaking in the whole group, this method pairs up all the potentially-tied offers. From the previous example, the following tie breaking pairs will be formed:

– Between A and B

– Between A and C

– Between B and C

Example of what a perfect pro-rata solution should be for a pair of tied reserve offers?

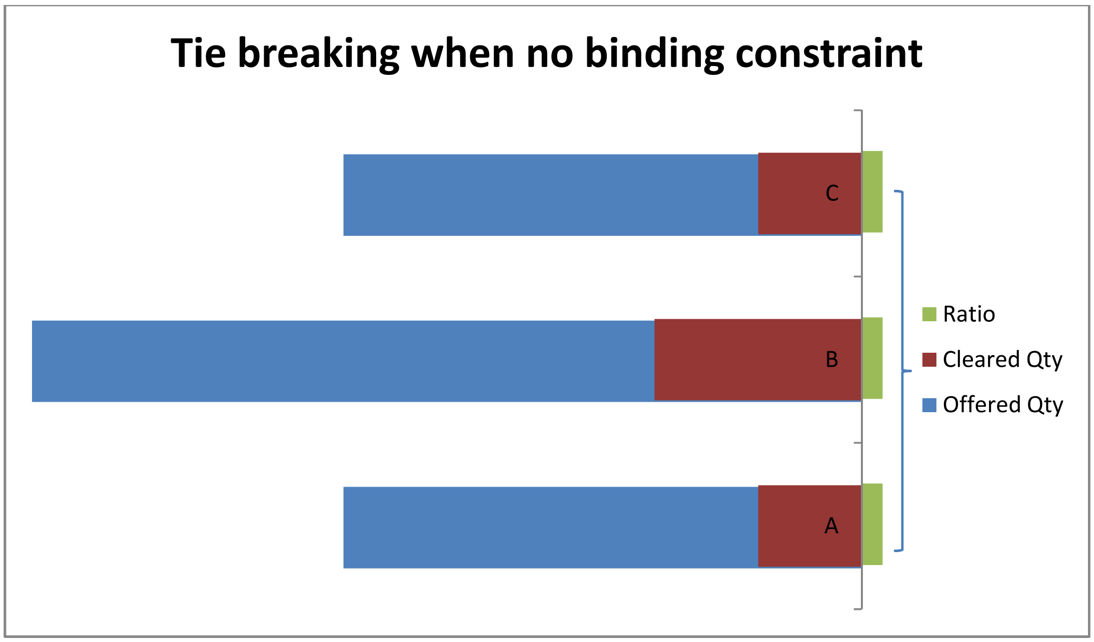
Primary Reserve Provider A offers 5MW @ marginal price of $1.00/MW (effective price)

Primary Reserve Provider B offers 10MW @ marginal price of $1.00/MW (effective price)

The total required quantity is 3 MW. Usually without tie breaking, 3 MW would be totally cleared for either A or B by the MCE and result in zero schedule for one of them.

However since offer A represents 1/3 of the total offer and B represents 2/3, a perfect and proportionate dispatch schedule would be (5/15) x 3 = 1 MW for A and likewise (10/15) x 3 = 2 MW for B. This also means that the cleared to offer quantity ratio for two offers are equal. That is: $\frac{ClearedQtyA}{OfferQtyA} = \frac{1}{5} = \frac{ClearedQtyB}{OfferQtyB} = \frac{2}{10}$ and $RatioDelta = \frac{ClearedQtyA}{OfferQtyA} - \frac{ClearedQtyB}{OfferQtyB} = 0$

The following diagram illustrates the perfect tie breaking solution between A, B and C with equal ratios (cleared/offered qty) as the result:

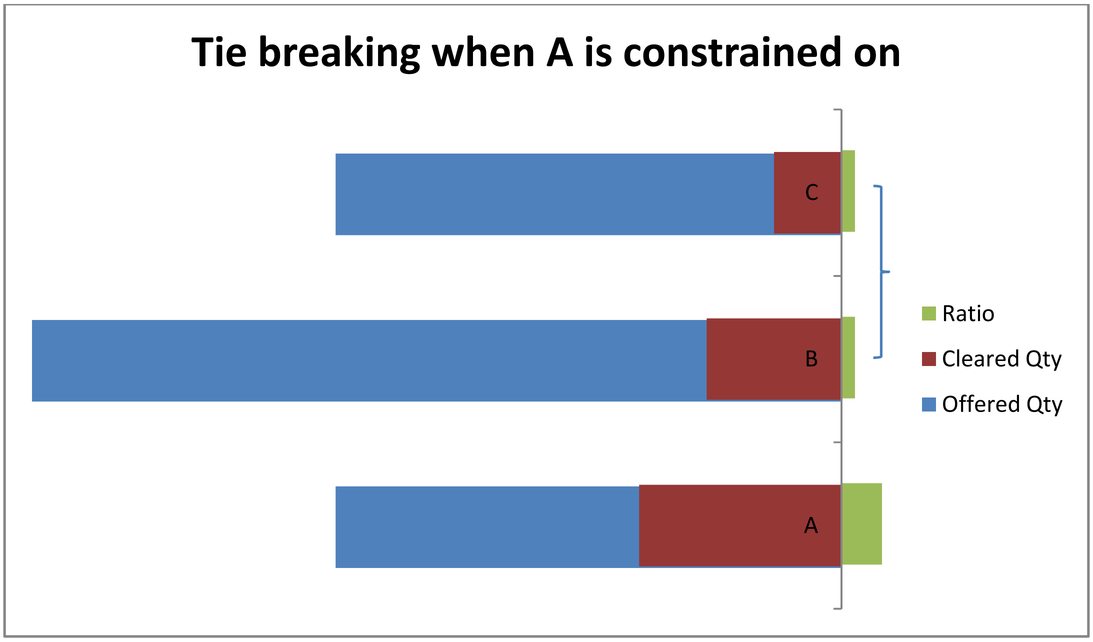


What if a perfect pro-rata solution cannot be achieved due to some binding constraint?

If there were some binding constraints that restrict the cleared to offer quantity ratio for two offers from being equal, or $RatioDelta$ cannot be zero, having a perfect tie break solution is impossible without compromising the primary objective (the maximum market benefits). Instead since this $RatioDelta$ component can always be mathematically represented by two non-negative variables or $RatioDelta = s1 - s2$, in order to achieve as close to perfect tie breaking solution as possible, the MCE could be incentivised to minimize $s1$ and $s2$ by having a small penalty for having non-zero ratio delta in its objective function.

And so for each tie break pair there will be a pair of slack variables, $s1$ and $s2$, which will be used to allow the MCE to break ties independently of other pairs. This means that even if A is on binding constraint, the MCE will still break ties between B and C.

The following diagram illustrates the results of tie breaking between A, B and C based on the previous example when some binding constraint on A exists.



As can be seen in the diagram above, the ratio for B and C are now the same even though A is constrained on.

Tie breaking formula

The following table illustrates the suggested tie breaking formulation for all products, reserves, regulation and energy:

Tie breaking term in the objective function: $$TieBreakingPenalty = \varepsilon \sum_{i,j} (TieBreakSlack1_{i,j} + TieBreakSlack2_{i,j})$$ (i, j): *indexes to tied offer i and j respectively* for all products and ε *is a small penalty factor*
Tie breaking for each pair of tied reserve offer block (i, j) of the same reserve class: $$\frac{RawReserveBlock_{r,i}}{RawReserveBlockMax_{r,i}} - \frac{RawReserveBlock_{r',j}}{RawReserveBlockMax_{r',j}} = TieBreakSlack1_{i,j} - TieBreakSlack2_{i,j}$$ Where, $$\frac{ReserveOfferPrice_{r,i}}{EstReserveEffectiveness_{r(g,c)}} = \frac{ReserveOfferPrice_{r',j}}{EstReserveEffectiveness_{r'(g,c)}}$$ (In the simulation, the effective prices are rounded to <u>4 decimal places</u> when being compared)
Tie breaking for each pair of tied regulation offer block (i, j): $$\frac{RegulationBlock_i}{RegulationBlockMax_i} - \frac{RegulationBlock_j}{RegulationBlockMax_j} = TieBreakSlack1_{i,j} - TieBreakSlack2_{i,j}$$
Tie breaking for each pair of tied energy offer block (i, j): $$\frac{GenerationBlock_i}{GenerationBlockMax_i} - \frac{GenerationBlock_j}{GenerationBlockMax_j} = TieBreakSlack1_{i,j} - TieBreakSlack2_{i,j}$$

Non Linear Programming (NLP)

In some markets such as WESM Philippines or IESO Ontario, a non-linear programming method is applied to tie breaking. In principle, in this method the solver pro-rates schedules for cases where two or more schedules are optimal. The pro-rating rules will be based on the size of the MW or quantity block of the price curves containing the non-unique schedules. Only that part of the price curve within the bid/offer's availability region will be used. This feature is implemented by adding a quadratic term for each price curve segment in the solver engine. This quadratic term is: $\varepsilon * \frac{ClearedQty^2}{OfferQty}$, where ε is a very small parameter, such that the addition of the term will not change the schedule (or primary objective function) if there is not a tie (can be set to 0.001 or lower). The additional term is so small that it doesn't affect scheduling, nor does it impact the price.

Limitation

As mentioned previously non-linear problems might cause issues related to Cplex solution quality and performance consistency. This method should not be considered at this point in time.

Summary and recommendations to go forward

This report re-introduces the tie breaking concepts and summarises some key considerations for a tie breaking solution. Subsequently it describes some available options for tie breaking. Option 1 is using heuristics-based manual approach. The key limitation of this approach is feasibility and optimality might be compromised when the method applies generically to reserve and regulation classes other than IL. Option 2 attempts to break ties using linear programming based on two methods, namely breaking ties in groups and in pairs. While the former method is simple in formulation, at times it might be unable to balance schedules without breaking a constraint or compromising the primary objective value. And this is its key limitation going forward. In contrast the latter method of breaking ties in pairs addresses such limitation while maintaining the formulation in a fairly simple form. Last but not least Option 3 applies non-linear method in its tie breaking formulation. Due to limitation in Cplex solver Option 3 is deemed unsuitable for the time being. Going forward PSC suggests Market Administration team evaluate further this pair-wise LP method taking into account key considerations mentioned above.

The following section presents some findings for the tie breaking simulation based on the pair-wise tie breaking method for further considerations.

Appendix - Simulation results for pair-wise tie breaking method

Methodology

A sample set of 144 dispatch periods, representing 1 holiday and 2 weekdays, is selected for simulation in EMSTAT. The reruns are simulated under three scenarios. In scenario 1, offers are shuffles and reruns are carried out without tie breaking formulae. In scenario 2, EMSTAT applies tie breaking with no shuffles of the offers. And in scenario 3, offers are shuffled prior to reruns with tie breaking. Details of these scenarios can be found in the following table.

Scenario	Setup	Result observations
Scenario 1 – Shuffles of offer ordering – No tie breaking formulation	Before the rerun in EMSTAT, the orders of energy, regulation and reserve offers are shuffled to simulate the randomness of data ordering when reading from Oracle database. In case multi clearing solutions exist, the shuffles might be able to induce a different set of schedules. In this stage no tie breaking formulation is applied	The rerun results will be compared with the original production results to identify the percentage of changes in schedule which indicates the level of tie cases.
Scenario 2 – No shuffles of offer ordering – Apply of tie breaking formulation to all 5 products, energy, regulation and 3 classes of reserves	While the inputs are kept intact to preserve the originality of the production cases, the EMSTAT will apply the tie breaking formulae in the reruns of these cases in an attempt to break ties across all 5 products	The rerun results will be compared with the original production results to identify actual level of tie cases. The primary objective values are also of interests to ensure there is no significant compromise of market benefits if not zero due to tie breaking
Scenario 3 – Shuffles of offer ordering – Apply of tie breaking formulation to all 5 products, energy, regulation and 3 classes of reserves	Similar to stage 1, stage 3 have the orders of offers shuffled before the reruns in EMSTAT. However in this stage EMSTAT will still apply the tie breaking formulae in the reruns	The rerun results will be compared with those of stage 2 to determine the consistency of the tie breaking schedules. Primary objective values are also monitored for optimality check.

Assumptions

The simulation assumes the value of 10^{-6} for ε. Primary objective value will be observed throughout the simulation to ensure this value is significant enough to break ties whenever possible while it does not compromise the primary optimality.

The simulation also assumes that tie offers are identified based on the effective prices for all products. For energy and regulation the effective prices are merely the offer price whereas for reserves the effective prices are ${OfferPrice}/{GroupEffectiveness_0}$

Summary of the results

	Scenario 1					Scenario 2					Scenario 3				
Key consideration aspects	**Eng**	**Reg**	**Pri**	**Sec**	**Con**	**Eng**	**Reg**	**Pri**	**Sec**	**Con**	**Eng**	**Reg**	**Pri**	**Sec**	**Con**
Feasibility	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Primary objective optimality $\varepsilon = 10^{-6}$	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Observed tie case percentage (Avg.)	9%	1%	37%	24%	36%	13%	3%	76%	50%	49%	13%	3%	76%	50%	49%
Tie break at marginal tie groups (out of all the tie cases)	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*100%*	*40%*	*100%*	*100%*	*90%*	*100%*	*40%*	*100%*	*100%*	*90%*
Tie break at non-marginal tie groups, possibly due to binding constraints such as res gen max or IL limit, etc. (out of all the tie cases)	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*0%*	*60% (*)*	*0%*	*0%*	*16% (**)*	*0%*	*60%*	*0%*	*0%*	*16%*
Tie break at non-marginal tie groups due to IL limit only	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*	*0%*
Tie break solution consistency rate (After 3 rounds of shuffles)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100%	100%	100%	100%	100%

(*) (**):Illustrations for this tie breaking type will be shown below. Note that the total of the two figures exceed 100%. This is a normal observation since within a period, a dispatch schedule could inherently have ties at marginal and non-marginal groups for a particular product.

With the use of $\varepsilon = 10^{-6}$ the feasibility and optimality is 100% observed in the simulation. Without tie breaking, reshuffles of offering data order result in some degree of changes in schedules in all products. This means there are some potential tie cases that need tie breaking. And after tie breaking, as expected we can see a significant increase in the number of tie cases, most of which would not be determined beforehand.

We also find that a majority of tie breaking happens at the marginal tie groups as expected. Interestingly enough there are some cases where the MCE balances solutions at non marginal tie group, mostly for binding Reserve Generation Max constraint.

Tie breaking for regulation at non-marginal tie group

A typical case for this is period 40 in which tie breaking is observed at non-marginal tie groups in both regulation and contingency and prices for these two products are $127.99 and $134.73 respectively. Tie breaking is observed between G1 and G2. Below is summary of their schedules before and after applying tie breaking:

Facility	Gen cleared	Reg cleared	Reg block price	Reg block spare	Con cleared	Con block price	Con block spare	Gen + Reg + Con (ResGenMax)	Reg Cleared/Offer Ratio	Reg Ratio Delta (absolute value)	Con Cleared/Offer Ratio	Con Ratio Delta (absolute value)
PRE												
G1	340	4.80	$0.00	0.20	15.20	$0.00	14.80	360.00	0.96	0.04	0.51	0.06
G2	340	6.50	$0.00	0.00	13.50	$0.00	16.50	360.00	1.00		0.45	
POST												
G1	340	5.00	$0.00	0.00	15.00	$0.00	15.00	360.00	1.00	0.03	0.50	0.04
G2	340	6.30	$0.00	0.20	13.70	$0.00	16.30	360.00	0.97		0.46	

Three areas are observed from the above table:

- Firstly, as seen on the table, the offer price for both contingency reserve and regulation by the two tie providers are at $0.00 which is well below their respective marginal prices.
- Secondly, the ratio delta, which is an indication of how well the solution is proportionately balanced, shows that after the tie breaking the ratio delta is brought down to smaller levels.
- Thirdly, Reserve Generation Max constraint is binding for both units and applying tie breaking does not break this constraint hence feasible tie breaking solution.

How relevant is this for IL tie breaking?

This type of scenarios show that the tie breaking formulation can balance schedules even the tie groups are not at the marginal. Typically this could happen when units are constrained on for some reason. Aside from the co-optimisation reason due to the binding of Reserve Generation Max constraint, IL limit would also likely to constrain IL providers on. When this occurs applying tie breaking would help balance the IL schedule accordingly.

Existing Rules (Release 1 Jan 2012)	**Proposed Rules** (Deletions represented by strikethrough text and addition underlined)		**Reason for Modification**
	APPENDIX 6D – MARKET CLEARING FORMULATION		
	SECTION A: DEFINITIONS		
[New Sets]	**D.2 SETS**		
	TIEDENERGYOFFERBLOCKPAIR$_o$	The o^{th} pair of *price-quantity pairs* identified under section D.9C.2.	To introduce a new set representing each pair (each such pair hereafter referred to as a "price-tied energy pair") of price-quantity pairs of energy offers which have the same price.
	TIEDENERGYOFFERBLOCKPAIRS	The set of all pairs of *price-quantity pairs* identified under section D.9C.2. Indexed by *o*.	To introduce a new set representing all price-tied energy pairs for the purpose of computing the tie-breaking penalty constraint.
	TIEDREGULATIONOFFERBLOCKPAIR$_o$	The o^{th} pair of *price-quantity pairs* identified under section D.9C.4.	To introduce a new set representing each pair (each such pair hereafter referred to as a "price-tied regulation pair") of price-quantity pairs of regulation offers which have the same price.
	TIEDREGULATIONOFFERBLOCKPAIRS	The set of all pairs of *price-quantity pairs* identified under section D.9C.4. Indexed by *o*.	To introduce a new set representing all price-tied regulation pairs for the purpose of computing the tie-breaking penalty constraint.
	TIEDRESERVEOFFERBLOCKPAIR$_o$	The o^{th} pair of *price-quantity pairs* identified under section D.9C.3.	To introduce a new set representing each pair (each such pair hereafter referred to as a "price-tied reserve pair") of price-quantity pairs of reserve offers [of the same reserve class] which have the same price.

<table>
<tr><th>Existing Rules (Release 1 Jan 2012)</th><th>Proposed Rules (Deletions represented by strikethrough text and addition underlined)</th><th>Reason for Modification</th></tr>
<tr><td></td><td><table><tr><td></td><td></td></tr><tr><td>TIEDRESERVEOFFERBLOCKPAIRS</td><td>The set of all pairs of price-quantity pairs identified under section D.9C.3. Indexed by o.</td></tr></table></td><td>To introduce a new set representing all price-tied reserve pairs for the purpose of computing the tie-breaking penalty constraint.</td></tr>
<tr><td>[New Parameter]</td><td>D.3 PARAMETERS<table><tr><td>TieBreakingPenaltyFactor</td><td>A factor having the value of 10^{-6}, or such other value as may be determined by the EMC.</td></tr></table></td><td>To introduce a new parameter, having a value of 10^{-6} or such other value as may be determined by the EMC, for the purposes of computing the tie-breaking penalty constraint.</td></tr>
<tr><td>[New Variables]</td><td>D.4 VARIABLES<table><tr><td>$EnergyTieBreakSlack1_o$
$EnergyTieBreakSlack2_o$</td><td>The variables representing the extent to which the energy tie-breaking constraint associated with $TIEDENERGYOFFERBLOCKPAIR_o$ in section D.20A.1 is violated.</td></tr><tr><td>$RegulationTieBreakSlack1_o$
$RegulationTieBreakSlack2_o$</td><td>The variables representing the extent to which the regulation tie-breaking constraint associated with $TIEDREGULATIONOFFERBLOCKPAIR_o$ in section D.20A.3 is violated.</td></tr><tr><td>$ReserveTieBreakSlack1_o$
$ReserveTieBreakSlack2_o$</td><td>The variables representing the extent to which the reserve tie-breaking constraint associated with $TIEDRESERVEOFFERBLOCKPAIR_o$ in section D.20A.2 is violated.</td></tr><tr><td>TieBreakingPenalties</td><td>The sum of all tie-breaking penalties arising from the violation of any tie-breaking constraints set out in section D.20A.</td></tr></table></td><td>To define new variables to be used in section D.20A of Appendix 6D for the purpose of resolving the tie between price-tied price-quantity pairs.

To introduce a tie-breaking penalty variable representing the sum of all tie-breaking penalties for energy, reserve and regulation to be included as a penalty cost to the objective function in D.14</td></tr>
</table>

Existing Rules (Release 1 Jan 2012)	Proposed Rules (Deletions represented by strikethrough text and addition underlined)	Reason for Modification
		of Appendix 6D.
[New Functions]	**D.5 FUNCTIONS** *(g(o),j(o)), (g'(o),j'(o))* — References respectively each of the *price-quantity pairs* identified under section D.9C.2 belonging to TIEDENERGYOFFERBLOCKPAIR$_o$. *(l(o),j(o)), (l'(o),j'(o))* — References respectively each of the *price-quantity pairs* identified under section D.9C.4 belonging to TIEDREGULATIONOFFERBLOCKPAIR$_o$ *(r(o),j(o)), (r'(o),j'(o))* — References respectively each of the *price-quantity pairs* identified under section D.9C.3 belonging to TIEDRESERVEOFFERBLOCKPAIR$_o$	New functions introduced to identify each respective price-quantity pairs of energy, reserve and regulation offers.
	SECTION B: PRE-PROCESSING	
[New Section]	**D.9C TIED OFFERS** D.9C.1 The sets derived in this section D.9C shall be used for the purpose of tie-breaking constraints under D.20A.	To state that the sets derived in this new section are to be used for the purpose of tie-breaking constraints in the new D.20A.
	D.9C.2 If a *price-quantity pair (g,j)* of GENERATIONOFFERBLOCKS$_g$ and a *price-quantity pair (g',j')* of GENERATIONOFFERBLOCKS$_{g'}$ meet the following condition, they shall be assigned to a set, TIEDENERGYOFFERBLOCKPAIR$_o$: $GenerationOfferPrice_{(g(o),j(o))} = GenerationOfferPrice_{(g'(o),j'(o))}$ $\{g(o)=g, \in$ ENERGYOFFERS $g'(o)=g' \neq g, \in$ ENERGYOFFERS $j(o)=j, \in$ GENERATIONOFFERBLOCKS$_{g(o)}$ and $j'(o)=j', \in$ GENERATIONOFFERBLOCKS$_{g'(o)}\}$	To identify price-tied energy pairs, following which these price-tied offer pairs will be assigned to the set "TIEDENERGYOFFERBLOCKPAIR$_o$".
	D.9C.3 If a *price-quantity pair (r,j)* of RAWRESERVEBLOCKS$_r$ and a *price-quantity pair (r',j')* of RAWRESERVEBLOCKS$_{r'}$ meet the following condition, they shall be assigned to a set, TIEDRESERVEOFFERBLOCKPAIR$_o$:	To identify price-tied reserve pairs taking into account estimated reserve effectiveness. These price-tied offer pairs are then assigned to the set "TIEDRESERVEOFFER

Existing Rules (Release 1 Jan 2012)	Proposed Rules (Deletions represented by strikethrough text and addition underlined)	Reason for Modification
	$\dfrac{\text{ReserveOfferPrice}_{(r(o),\, j(o))}}{\text{EstReserveEffectiveness}_{r(o)}} = \dfrac{\text{ReserveOfferPrice}_{(r'(o),\, j'(o))}}{\text{EstReserveEffectiveness}_{r'(o)}}$ $\{r(o)=r, \in$ RAWRESERVEOFFERS $r'(o)=r' \neq r, \in$ RAWRESERVEOFFERS $c(r) = c(r'), \in$ RESERVECLASSES $j(o) = j, \in \text{RAWRESERVEBLOCKS}_{r(o)}$ $j'(o) = j', \in \text{RAWRESERVEBLOCKS}_{r'(o)}$ $\text{EstReserveEffectiveness}_{r(o)} \neq 0$ and $\text{EstReserveEffectivness}_{r'(o)} \neq 0\}$	BLOCKPAIR$_o$".
	D.9C.4 If a *price-quantity pair (l,j)* of REGULATIONOFFERBLOCKS$_l$ and a *price-quantity pair (l',j')* of REGULATIONOFFERBLOCKS$_{l'}$ meet the following condition, they shall be assigned to a set, TIEDREGULATIONOFFERBLOCKPAIR$_o$: $\text{RegulationOfferPrice}_{(l(o),j(o))} = \text{RegulationOfferPrice}_{(l'(o),\, j'(o))}$ $\{l(o)= l, \in$ REGULATIONOFFERS $l'(o)= l' \neq l, \in$REGULATIONOFFERS $j(o) = j, \in \text{REGULATIONOFFERBLOCKS}_{l(o)}$ $j'(o) = j', \in \text{REGULATIONOFFERBLOCKS}_{l'(o)}\}$	To identify price-tied regulation offer blocks, following which these price-tied offer pairs will be assigned to the set "TIEDREGULATIONOFFERBLOCKPAIR$_o$".
	SECTION C: LINEAR PROGRAM	
D.14 OBJECTIVE FUNCTION 14.1 The NetBenefit is maximised, where: D.14.1.1 $\text{NetBenefit} = \sum_{\{j,p \mid j \in \text{PURCHASEBIDBLOCKS}_p, \text{where } p \in \text{BIDS}\}} \text{PurchaseBidPrice}_{p,j} \times \text{PurchaseBlock}_{p,j}$ $- \sum_{\{j,g \mid j \in \text{GENERATIONOFFERBLOCKS}_g, \text{where } g \in \text{ENERGYOFFERS}\}} \text{GenerationOfferPric}e_{g,j} \times \text{GenerationBlock}_{g,j}$ $- \sum_{\{j,r \mid j \in \text{RAWRESERVEBLOCKS}_r, \text{where } r \in \text{RAWRESERVEOFFERS}\}} \text{ReserveOfferPrice}_{r,j} \times \text{RawReserveBlock}_{r,j}$ $- \sum_{\{j,l \mid j \in \text{REGULATIONOFFERBLOCKS}_l, \text{where } l \in \text{REGULATIONOFFERS}\}} \text{RegulationOfferPrice}_{l,j} \times \text{RegulationBlock}_{l,j}$ $- \sum_{\{j,n \mid j \in \text{EXCESSGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}} \text{ExcessGenerationPenalty}_{n,j} \times \text{ExcessGenerationBlock}_{n,j}$ $- \sum_{\{j,n \mid j \in \text{DEFICITGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}} \text{DeficitGenerationPenalty}_{n,j} \times \text{DeficitGenerationBlock}_{n,j}$ $- \text{ViolationPenalties}$	**D.14 OBJECTIVE FUNCTION** 14.1 The NetBenefit is maximised, where: D.14.1.1 $\text{NetBenefit} = \sum_{\{j,p \mid j \in \text{PURCHASEBIDBLOCKS}_p, \text{where } p \in \text{ENERGYBIDS}\}} \text{PurchaseBidPrice}_{p,j} \times \text{PurchaseBlock}_{p,j}$ $- \sum_{\{j,g \mid j \in \text{GENERATIONOFFERBLOCKS}_g, \text{where } g \in \text{ENERGYOFFERS}\}} \text{GenerationOfferPrice}_{g,j} \times \text{GenerationBlock}_{g,j}$ $- \sum_{\{j,r \mid j \in \text{RAWRESERVEBLOCKS}_r, \text{where } r \in \text{RAWRESERVEOFFERS}\}} \text{ReserveOfferPrice}_{r,j} \times \text{RawReserveBlock}_{r,j}$ $- \sum_{\{j,l \mid j \in \text{REGULATIONOFFERBLOCKS}_l, \text{where } l \in \text{REGULATIONOFFERS}\}} \text{RegulationOfferPrice}_{l,j} \times \text{RegulationBlock}_{l,j}$ $- \sum_{\{j,n \mid j \in \text{EXCESSGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}} \text{ExcessGenerationPenalty}_{n,j} \times \text{ExcessGenerationBlock}_{n,j}$ $- \sum_{\{j,n \mid j \in \text{DEFICITGENERATIONBLOCKS}_n, \text{where } n \in \text{NODES}\}} \text{DeficitGenerationPenalty}_{n,j} \times \text{DeficitGenerationBlock}_{n,j}$ $- \text{ViolationPenalties}$	To correct a typographical error in the existing Market Rules. To introduce unresolved ties as a tie-breaking penalty in the existing objective function.

Existing Rules (Release 1 Jan 2012)	Proposed Rules (Deletions represented by strikethrough text and addition underlined)	Reason for Modification
	– TieBreakingPenalties	
D.16 TRANSMISSION D.16.1.2 Node Balance Generation Constraint: $$NodeNetInjection_n = \sum_{g \in OFFERS_n} Generation_g - \sum_{p \in BIDS_n} Purchase_p + \sum_{j \in DEFICITGENERATIONBLOCKS_n} DeficitGenerationBlock_{n,j} - \sum_{j \in EXCESSGENERATIONBLOCKS_n} ExcessGenerationBlock_{n,j}$$	**D.16 TRANSMISSION** D.16.1.2 Node Balance Generation Constraint: $$NodeNetInjection_n = \sum_{g \in OFFERS_n} Generation_g - \sum_{p \in ENERGYBIDS_n} Purchase_p + \sum_{j \in DEFICITGENERATIONBLOCKS_n} DeficitGenerationBlock_{n,j} - \sum_{j \in EXCESSGENERATIONBLOCKS_n} ExcessGenerationBlock_{n,j}$$	To correct a typographical error in the existing Market Rules.
[New Section]	**D.20A TIE-BREAKING CONSTRAINTS** D.20A.1 Energy Tie-Breaking Constraint: $$\frac{GenerationBlock_{(g(o),\,j(o))}}{GenerationBlockMax_{(g(o),\,j(o))}} - \frac{GenerationBlock_{(g'(o),j'(o))}}{GenerationBlockMax_{(g'(o),j'(o))}} = EnergyTieBreakSlack1_o - EnergyTieBreakSlack2_o$$ {o ϵ TIEDENERGYOFFERBLOCKPAIRS}	To introduce tie-breaking constraints that resolve the tie between price-tied energy pairs.
	D.20A.2 Reserve Tie-Breaking Constraint: $$\frac{RawReserveBlock_{(r(o),\,j(o))}}{RawReserveBlockMax_{(r(o),\,j(o))}} - \frac{RawReserveBlock_{(r'(o),\,j'(o))}}{RawReserveBlockMax_{(r'(o),\,j'(o))}} = ReserveTieBreakSlack1_o - ReserveTieBreakSlack2_o$$ {o ϵTIEDRESERVEOFFERBLOCKPAIRS}	To introduce tie-breaking constraints that resolve the tie between price-tied reserve pairs.
	D.20A.3 Regulation Tie-Breaking Constraint:	To introduce tie-breaking constraints that resolve the tie between price-tied

Existing Rules (Release 1 Jan 2012)	Proposed Rules (Deletions represented by strikethrough text and addition underlined)	Reason for Modification
	$\frac{\text{RegulationBlock}_{(l(o),\, j(o))}}{\text{RegulationBlockMax}_{(l(o),\, j(o))}} - \frac{\text{RegulationBlock}_{(l'(o), j'(o))}}{\text{RegulationBlockMax}_{(l'(o),\, j'(o))}}$ $= \text{RegulationTieBreakSlack1}_o - \text{RegulationTieBreakSlack2}_o$ $\{ o \in \text{TIEDREGULATIONOFFERBLOCKPAIRS} \}$	regulation pairs.
	D.20A.4 Tie-breaking Penalty Constraint: $\text{TieBreakingPenalties} = \text{TiebreakingPenaltyFactor} \times [\sum_{o \in \text{TIEDENERGYOFFERBLOCKPAIRS}} (\text{EnergyTieBreakSlack1}_o + \text{EnergyTieBreakSlack2}_o) + \sum_{o \in \text{TIEDRESERVEOFFERBLOCKPAIRS}} (\text{ReserveTieBreakSlack1}_o + \text{ReserveTieBreakSlack2}_o) + \sum_{o \in \text{TIEDREGULATIONOFFERBLOCKPAIRS}} (\text{RegulationTieBreakSlack1}_o + \text{RegulationTieBreakSlack2}_o)]$	To introduce a tie-breaking penalty constraint that sums up all unresolved price-tied price-quantity pairs for energy, reserve and regulation to be included as a penalty cost to the objective function in Section D.14 of Appendix 6D.