COSTING OF PRIMARY FREQUENCY CONTROL

Report to CS Energy

6 August 2019

FINAL REPORT

IES ●●●
Intelligent Energy Systems

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Executive Summary

CS Energy has commissioned IES to design and publish reports that would demonstrate the efficient cost of frequency control. The aim of this costing is to provide the basis for an incentive for participants to provide primary frequency control (PFC). CS Energy has provided all the specifications of the reports including layout and calculations. PFC costs are calculated separately for raise and lower control. Reports have been implemented in 2 formats: 5-minute ex post reports as well as a real-time monitor.

The 5-minute ex post reports are accessible by NEOpoint customers and allow the user to view historical costs. The quantities reported in the historical reports include PFC costs (both raise and lower), regulation enabled, regulation costs (as they are now) area control error, frequency deviation and others to expose the state of frequency control in the NEM.

The real-time monitor is a live monitor available on the NEOmobile platform, this allows the user to see the cost of primary frequency control as it evolves in real time. Other quantities presented are regulation enablement, regulation costs and area control error.

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Table 1: Definitions

Term	Definition
IES	Intelligent Energy Systems
ACE	Area Control Error
ACEreg/RR	Regulation requirement (ACEreg = -ACE)
PFC	Primary Frequency Control/Primary Frequency Response
NEM	National Electricity Market
AEMO	Australian Energy Market Operator
RRP	Regional Reference Price
FI	Frequency Indicator

Note: variables are defined in the text as required.

1   Introduction

C S Energy wishes to promote an efficient approach to the pricing of primary frequency control (PFC) in the Australian National Electricity Market (NEM). To do this, C S Energy believes that a good way forward is to publish, in real time if possible, an estimate of the total cost of primary frequency control if it were to be efficiently priced. It has commissioned Intelligent Energy Systems (IES) to implement and support publication of this costing procedure ex post as well as in real time.

CS Energy has provided a formulation for the cost as well as an Excel file demonstrating a worked example of how the cost formula works. Upon further inspection and discussion with C S Energy some modifications were made; the final version of the costing formula is given in Section 2.1.

Costs can be calculated after the event (ex post) or in real time. AEMO publishes the required 4 second causer pays data each day, which makes PFC costs available a day late. We can calculate a real time PFC cost by using IES's real time frequency and time error measurements to compute a real-time ACE value. The method and relationship is detailed in 4Appendix A.

In summary, the primary data sources for the costing formula are:

- Regional Reference Prices (RRP) available in real time from AEMO's market database

- 4 second Area Control Error (ACE) values obtainable from:

  o AEMO sources a day after the event, for ex post calculations

  o IES's frequency and time error measurements, for real time or within-day calculations

- Parameter values required by the PFC costing formula which are manually input.

2   Method

2.1   5 minute ex post

PFC costs are calculated separately for raise and lower, in each 5-minute dispatch interval (DI). This section describes the formula used to compute cost values for a DI after the interval has passed. (ex post).

Given Data:

- 4 second ACE values (either AEMO published or computed)

- 5 minute Dispatch Data for mainland regions (NSW1, SA1, VIC1, QLD1)

- Static parameters

  o Marginal Price (MC): Cost of generating 1MWh of electricity, initially set at $55/MWh.

  o Throttle Percentage (throttle): Ratio quantifying the inefficiencies created by throttling the generator, initially set at 90%.

Method:

1. Compute opportunity cost (*OppC*) for a dispatch interval based on the regional reference price of the region with the maximum "scheduled reserve". (See Appendix B for SQL query)

2. For every given dispatch interval compute the following 4 grouped values

a. $ACEmin$: Minimum of the 4sec ace values below zero within the DI

b. $ACEmax$: Maximum of the 4 sec ace values above zero within the DI

c. $nACEAvg$: Average of the 4 sec ace values below zero within the DI

d. $pACEAvg$: Average of the 4 sec ace values above zero within the DI

Note: If in a DI there were no positive or no negative values, the associated grouped value is set to zero.

3. Compute capacity and utilisation prices

a. $HeadroomCP = MAX(OppC, 0)$

b. $FootroomCP = MAX(-OppC, 0)$

c. $HeadroomUP = -OppC$

d. $FootroomUP = OppC$

4. Compute capacity and utilisation costs

a. $HeadroomCC = ACEmin \times HeadroomCP/-12$

b. $FootroomCC = ACEmax \times FootroomCP/12$

c. $HeadroomUC = nACEAvg \times HeadroomUP/-12$

d. $FootroomUC = pACEAvg \times FootroomUP/12^*$

*The 12 scales the units from an hourly basis to that within 5 minutes

5. Compute ultimate cost for a lower or raise service

a. $Total\ Cost\ (Raise) = HeadroomCC + HeadroomUC$

b. $Total\ Cost\ (Lower) = FootroomCC + FootroomUC$

2.2 Real time

The real-time implementation of the costing formula is similar to that described in section 2.1. However, since the values of ACEmin, ACEmax, nACEAvg and pACEAvg over a DI are not known within the interval (future values of ACE cannot be known), an approximation will need to be made. Currently a sliding 5-minute window of the most recent 4-second ACE values is used to compute an instantaneous estimate of the grouped values. A beneficial property of this approach is that the approximated value will equal the ex post value at the end of the dispatch interval. This approach applies to Step 2 in the method described above; all other steps remain unchanged.

3 Presentation

3.1 5-minute ex post reports/charts

The aim of IES is to make the historical reports available through NEOpoint. This would allow the user to view different periods. The following reports have been implemented:

- **Primary Frequency Control**

  This report plots the estimated cost of PFC with ACE, FI, regulation enablement (including additional amounts to correct time error) and regulation costs. The data series plotted on the chart are:

Table 2: Data displayed in the Primary Frequency Control Costs chart

Name (Legend Entry)	Units	Summary
Mainland.ACEreg[AEMO.Hz]	MW	The ACEreg as calculated using frequency deviation provided by AEMO without time error adjustment. (obtained half hourly)
Mainland.ACEreg[IES.Hz]	MW	The ACEreg as calculated using frequency deviation measured by IES without time error adjustment. (obtained instantaneously)
Mainland.ACEreg[IES.Hz, IES.Te]	MW	The ACEreg as calculated using frequency deviation and time error measured by IES. (obtained instantaneously)
F_MAIN+NIL_DYN_RREG	MW	The FCAS lower regulation requirement when the time error constraint (F_MAIN+NIL_DYN_LREG) is binding
F_MAIN+NIL_DYN_LREG	MW	The FCAS raise regulation requirement when the time error constraint (F_MAIN+NIL_DYN_RREG) is binding
Mainland.ACEreg[AEMO.ACE]	MW	The ACEreg as obtained from AEMO. (obtained 1-2 days after the event)
LowerPFC[IES.Hz]	$	The cost of lower PFC computed using IES' instantaneous frequency measurements.
RaisePFC[IES.Hz]	$	The cost of raise PFC computed using IES' instantaneous frequency measurements.
LREG.Cost	$	The cost of lower regulation. (See Appendix C)
RREG.Cost	$	The cost of lower regulation. (See Appendix C)
Mainland.FI	MW	Frequency Indicator (obtained half hourly)
RREG_MAIN	MW	Raise regulation enablement
LREG_MAIN	MW	Lower regulation enablement

There is a region selector used to choose which region to obtain the FCAS regulation price from when computing LREG.Cost and RREG.Cost.

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Figure 1: Screenshot of Primary Frequency Control Costs chart

- **LowerPFC**

  This report plots the cost of lower PFC with the cost of lower regulation. The data plotted on the chart are:

Table 3: Data displayed in the LowerPFC chart

Name (Legend Entry)	Units	Summary
LowerPFC[AEMO.ACE]	$	The cost of lower PFC, computed using AEMO's ACE values
LowerPFC[IES.Hz, IES.Te]	$	The cost of lower PFC, computed using an approximation of ACE from IES' measurements of frequency and time error.
LowerPFC[IES.Hz]	$	The cost of lower PFC, computed using an approximation of ACE from IES' measurements of frequency. No time error adjustment is done.
LREG.Cost	$	The cost of lower regulation from the FCAS markets. Computed as a product of enablement and dispatch price of regulation (See Appendix C for SQL Query)

There is also a region selector (top right) used to choose the region from which to obtain the FCAS regulation price for computing LREG.Cost and RREG.Cost (See Appendix C).

Figure 2: Screenshot of LowerPFC chart
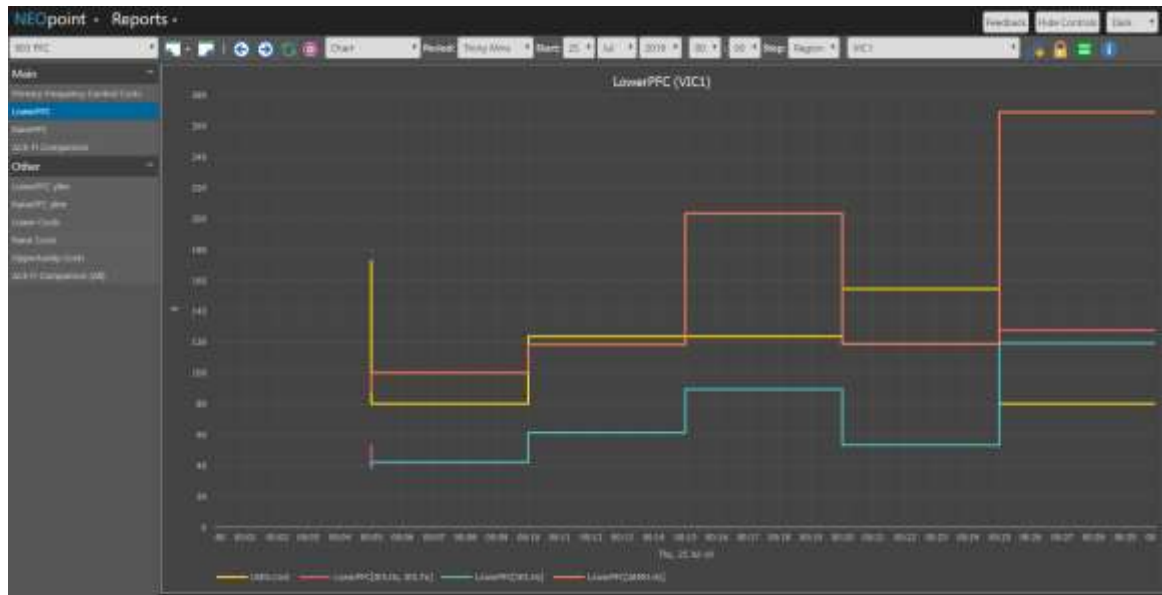
- **RaisePFC**

   This report plots the cost of raise PFC with the cost of raise regulation. The variables in this report are the raise counterparts of the previous report.

- **ACE-FI Comparison**

Table 4: Data displayed in the ACE-FI Comparison chart

Name (Legend Entry)	Units	Summary
Mainland.ACEreg[IES.Hz]	MW	The ACEreg as calculated using frequency deviation measured by IES without time error adjustment. (obtained instantaneously)
F_MAIN+NIL_DYN_RREG	MW	The FCAS lower regulation requirement when the time error constraint (F_MAIN+NIL_DYN_LREG) is binding
F_MAIN+NIL_DYN_LREG	MW	The FCAS raise regulation requirement when the time error constraint (F_MAIN+NIL_DYN_RREG) is binding
Mainland.Hzdev[IES.Hz]	Hz	Frequency deviation as measured by IES (obtained instantaneously)
Mainland.FI	MW	Frequency Indicator (obtained half hourly)
RREG_MAIN	MW	Raise regulation enablement
LREG_MAIN	MW	Lower regulation enablement

Figure 3: Screenshot of ACE-FI Comparison chart

- **LowerPFC2 ylim, RaisePFC2 ylim**

  These are variants of the above plots that truncate very high values to make the remainder more readable. The y-axis has been fixed such that the chart reveals the general trend but hides any excessively large peaks.

- **Lower Costs**

  This chart shows the intermediate values for computing the lower frequency control costs. See Section 2.1 for calculation steps.

Table 5: Data displayed in the Lower Costs chart

Name (Legend Entry)	Units	Summary
FootroomUC[IES.Hz]	$	The utilisation costs of lower PFC
FootroomCC[IES.Hz]	$	The capacity costs of lower PFC
FootroomUP[IES.Hz]	$/MWh	The utilisation price of lower PFC
FootroomCP[IES.Hz]	$/MWh	The capacity price of lower PFC

Figure 4: Screenshot of Lower Costs chart
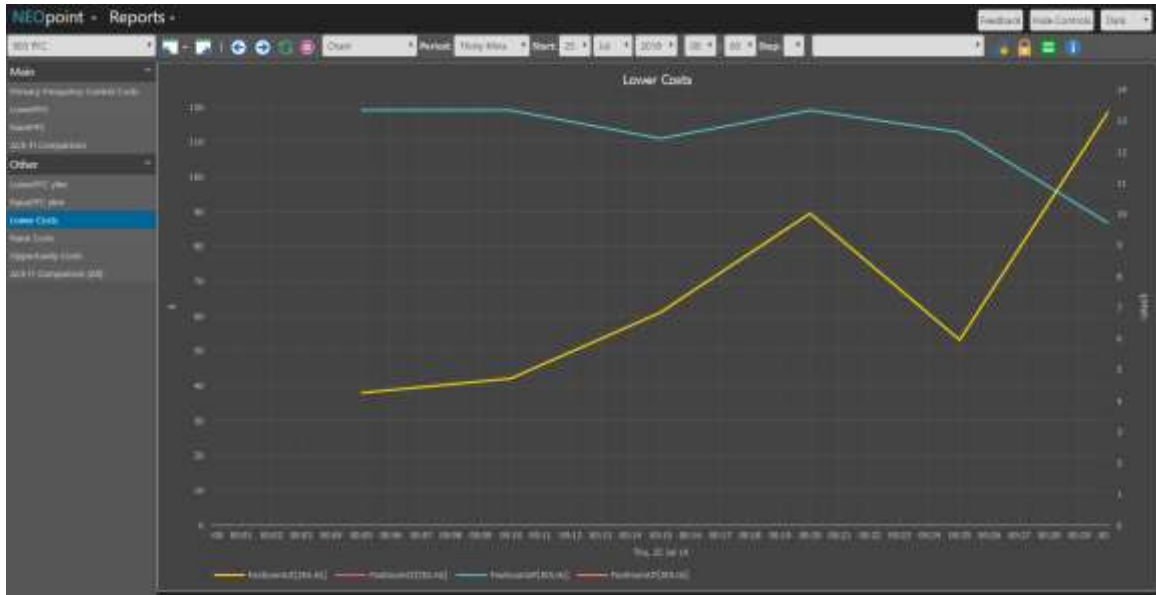
- **Raise Costs**

  This chart shows the intermediate values for computing the raise frequency control costs. The data in this chart are the raise counterparts of the above chart.

- **Opportunity Costs**

  This chart shows the opportunity costs used to compute the lower and raise PFC costs. See Appendix B for the formulation and SQL query.

Table 6: Data displayed in the Opportunity Costs chart

Name (Legend Entry)	Units	Summary
Opportunity Cost (min rrp)	$/MWh	The opportunity cost based on the region with the minimum RRP
Opportunity Cost (max reserve)	$/MWh	The opportunity cost based on the region with the maximum scheduled reserve. This variation is the one used to calculate PFC costs.

Figure 5: Screenshot of Opportunity Costs chart
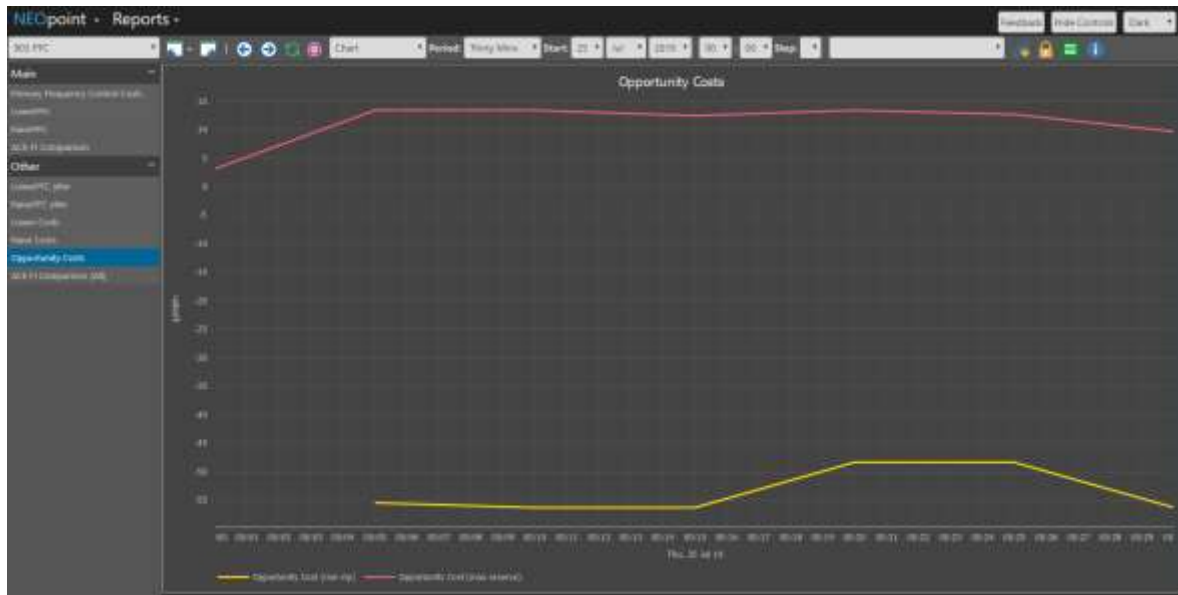
- **ACE FI Comparison (All)**

  This chart is very similar to "ACE FI Comparison". However, it contains more data series. The additional series plotted are

Table 7: Data displayed in the ACE-FI Comparison (All) chart

Name (Legend Entry)	Units	Summary
Mainland.ACEreg[AEMO.Hz]	MW	The ACEreg as calculated using frequency deviation provided by AEMO without time error adjustment. (obtained half hourly)
Mainland.ACEreg[IES.Hz, IES.Te]	MW	The ACEreg as calculated using frequency deviation and time error measured by IES. (obtained instantaneously)

Figure 6: Screenshot of ACE-FI Comparison (All) chart
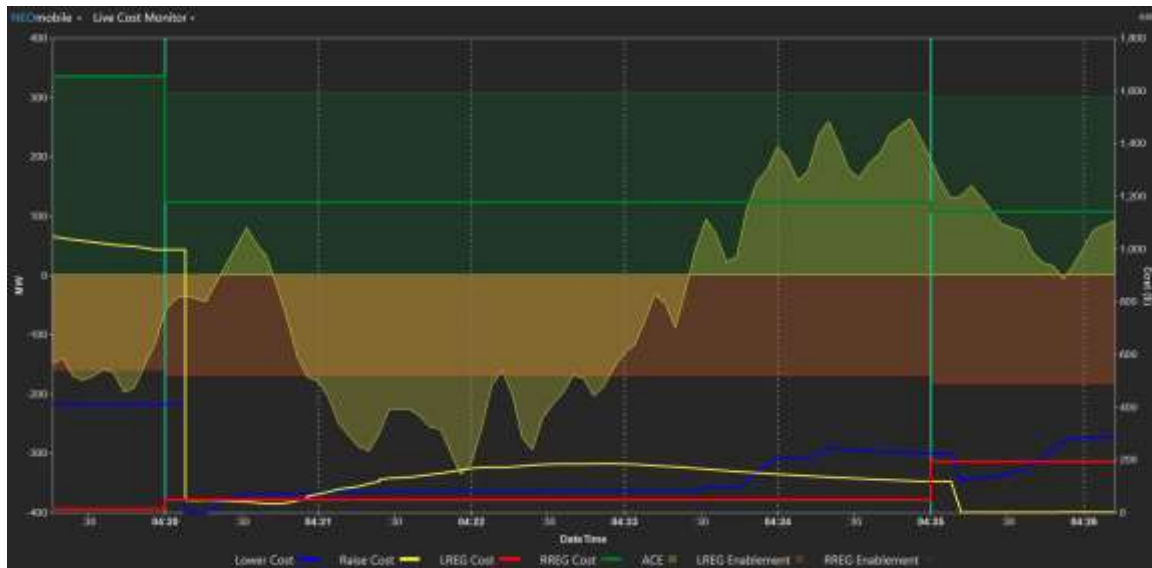

3.2 Real time monitor

The real-time is similar to the implementation of the frequency monitor on IES's NEOmobile platform. It would be on a separate page on NEOmobile and would cover a period of 5 minutes. The chart would be updated every 4 seconds as new data is made available. Due to IES' development practices to maintain the integrity of the NEOmobile platform, the real-time cost monitor would first be published to the NEOmobile test server. Once it is certain that there aren't any unforeseen problems, the monitor will be published to the production NEOmobile server. The test server can be accessed at http://test.neomobile.com.au. The data plotted on the monitor are:

Table 8: Data presented on the real-time cost monitor

Name (Legend Entry)	Units	Summary
Mainland ACEreg	MW	The ACEreg as calculated using frequency deviation measured by IES without time error adjustment. (obtained instantaneously)
Lower PFC	$	The cost of lower PFC computed using IES' instantaneous frequency measurements.
Raise PFC	$	The cost of raise PFC computed using IES' instantaneous frequency measurements.
RREG Enablement	MW	Raise regulation enablement
LREG Enablement	MW	Lower regulation enablement
LREG.Cost	$	The cost of lower regulation. (See Appendix C)
RREG.Cost	$	The cost of lower regulation. (See Appendix C)

Figure 7: Screenshot of real-time monitor on NEOmobile

4   Conclusion

The reports as per CS Energy's specifications and calculations have been completed and made available to CS Energy. This includes the historical reports available through NEOpoint as well as the live real-time cost monitor available through the NEOmobile test server, contingent on the fact that the monitor would be published to the production server when it is suitable.

The real time monitor is a useful tool to visualise the evolution of costs. For market participants, also of interest would be a real time monitor of how much and to whom costs would be incurred and allocated. This could be done though an adjustment to the causer pays logic which would be better targeted than the exemption approach currently proposed by AEMO. While there may not be a simple relationship between a workable pricing arrangement and the efficient costs calculated under this project, these efficient costs provide guidance as to how that pricing should be tuned.

Appendix A   Relationship between ACE, Frequency Error & Time Error

A.1   Relationship between ACE, frequency and frequency offset

It has been documented by AEMO[1] that ACE is computed as:

$$ACE = 10 \times BIAS \times (F - FO - 50)$$

Where:

- BIAS is a tuning parameter, it was found empirically as 280 Hz/MW
- F is the measured system frequency
- FO is frequency offset which is a function of accumulated time error

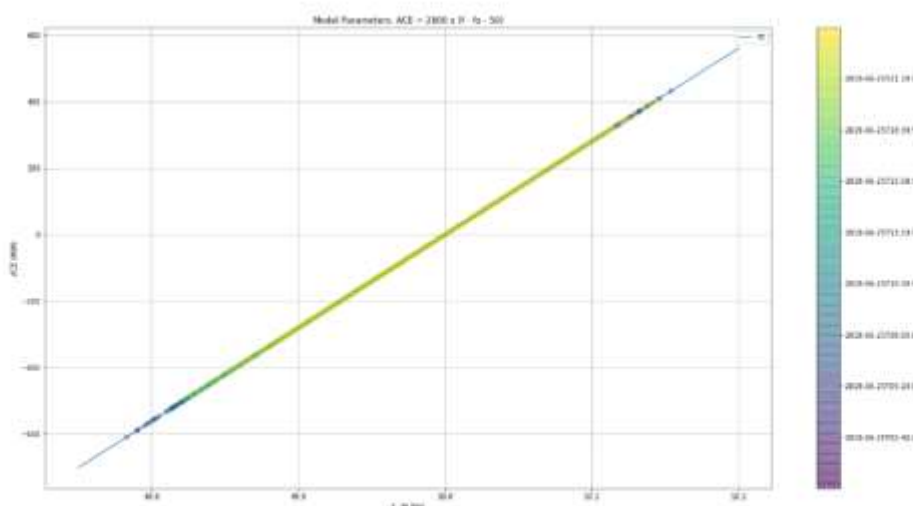**Figure 8: Time varying plot of ACE and (frequency-offset)**

Figure 8 demonstrates this behaviour, a fitted linear model is superimposed over the data. Note: this data is taken from causer pays data of 25 June 2019.

The value of FO is relatively small (~0.03Hz), so a reasonable assumption could be to assume FO = 0 and use a simplified formula:

$$ACE = 2800 \times (F - 50)$$

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[1] Regulation FCAS contribution factor procedure, https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Ancillary_Services/Regulation-FCAS-Contribution-Factors-Procedure.pdf
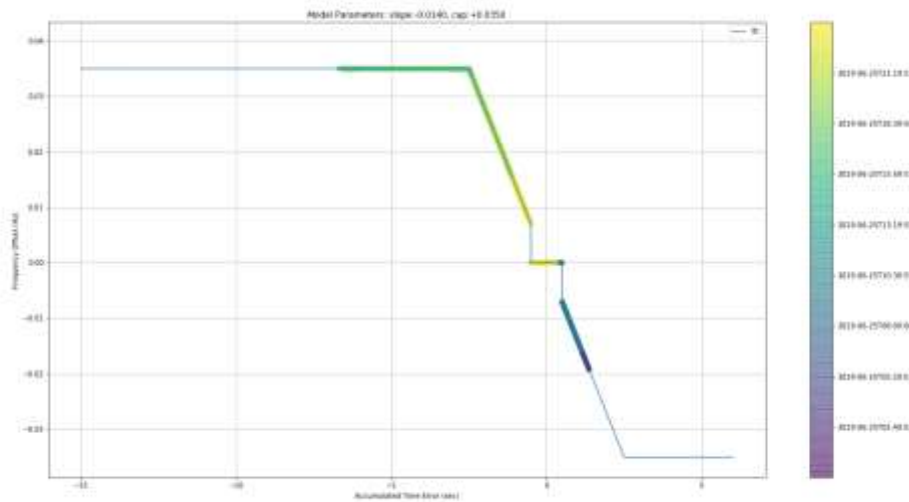
A.2 Relationship between frequency offset and time error

This relationship is more complicated and no AEMO document was found decrying t. Consider Figure 9 which plots the frequency offset vs accumulated time error. This data is from 25 June 2019.

Figure 9: Time varying plot of frequency offset and accumulated time error (25 Jun)

There is a piecewise linear relationship between the two. Specifically:

$$FO(Te = \begin{cases} cap & Te < -2.5 \\ m \times Te & -2.5 \leq Te < -0.5 \\ 0 & -0.5 \leq Te < 0.5 \\ m \times Te & 0.5 \leq Te < 2.5 \\ -cap & 2.5 < Te \end{cases}$$

In Figure 9 a fitted model of this piecewise function is superimposed over the acquired data.

The values of m and cap are -0.01 and 0.035 for the data shown in. However, these values do not always remain constant. On March 8 (), for example, the relationship changed to what it is now. There does not seem to be any documentation regarding this change or this relationship. If this relationship is used in the computation of ACE, the model may need to be tweaked every few months (when a change is noticed). The only parameters to change are 'm' and 'cap' the other values (the points of inflexion) remain constant.

Figure 10: Time varying plot of frequency offset and accumulated time error (08 Mar)
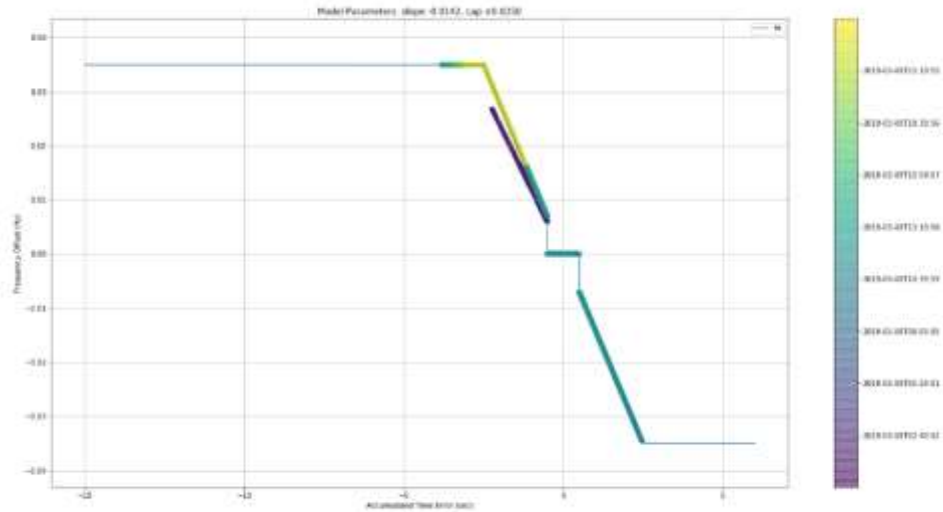
As mentioned earlier, the value of the offset is relatively small. It may suffice to ignore the effect of time error on ACE for the purpose of this project. However, both implementations (one using time error and one without) have been added to the historical reports for the sake of comparison.

Appendix B   Opportunity Costs

The computation of opportunity cost is the one of the first steps in computing PFC costs. 2 methods have been proposed. The first is based on the RRP of the region with minimum RRP and the second is based on the region with maximum scheduled reserve.

The second method is the chosen method and has been incorporated into all reports described in this report. Formulation of both is given in the SQL queries below. A comparison is provided in the opportunity costs report described in section 3.1.

Table 9: SQL query for computing opportunity cost from region with minimum RRP

```sql
select
 SETTLEMENTDATE,
 min(RRP)-50/0.9 "Opportunity Cost (min rrp)"
from
 DISPATCHPRICE
where
 SETTLEMENTDATE > %f and SETTLEMENTDATE <= %t
group by SETTLEMENTDATE
```

Table 10: SQL query for computing opportunity cost from region with maximum scheduled reserve

```sql
select dp.settlementdate, dp.rrp- 50/0.9 as "Opportunity Cost (max
reserve)"
from DISPATCHPRICE DP, DISPATCHREGIONSUM DRS,
(
    select DR.settlementdate, max(AVAILABLEGENERATION -
DISPATCHABLEGENERATION - TOTALINTERMITTENTGENERATION - UIGF) as
Scheduled_Reserve, intervention
    from DISPATCHREGIONSUM DR,
    (
        select settlementdate, max(INTERVENTION) as maxint
        from DISPATCHREGIONSUM
        WHERE settlementdate between %f and %t
        GROUP BY settlementdate
    ) maxi
    WHERE DR.settlementdate between %f and %t
    and DR.settlementdate = maxi.settlementdate
    and DR.INTERVENTION = maxi.maxint
    GROUP BY settlementdate
) maxsr
where dp.settlementdate = maxsr.settlementdate and
DP.Settlementdate = DRS.settlementdate and
DP.REGIONID = DRS.REGIONID and
DRS.INTERVENTION = maxsr.intervention and
DP.INTERVENTION = 0 and
AVAILABLEGENERATION-DISPATCHABLEGENERATION-TOTALINTERMITTENTGENERATION-UIGF
= maxsr.Scheduled_Reserve
order by 1
```

Appendix C   Regulation Costs

The regulation costs are computed as the product of the enabled regulation and the price of regulation and a factor to convert the units to 5min. Thus, the calculation is given as

$$Cost = \frac{Enablement \times Price}{12}$$

This calculation is incorporated into the following queries for lower and raise costs. The price of regulation is usually the same among the 4 mainland regions; however, there are rare circumstances where the price is different. To account for this there is a region selector in all reports that have the regulation cost as a series on the chart, the user can choose which region the price is to be obtained from.

Table 11: SQL query to compute lower regulation costs

```sql
select
TRS.SETTLEMENTDATE,
TRS.LREG_Main*TP.LOWERREGRRP/12 as "LREG.Cost"
from
%o.DISPATCHPRICE TP,
(
select
drs.SETTLEMENTDATE,
sum(drs.LOWERREGLOCALDISPATCH) as "LREG_Main"
from
mms.DISPATCHREGIONSUM drs,
(
 select SETTLEMENTDATE, max(intervention) as INTERVENTION
 from mms.DISPATCHREGIONSUM
 where SETTLEMENTDATE between %f and %t
 group by SETTLEMENTDATE
) maxint
where drs.SETTLEMENTDATE between %f and %t
and drs.REGIONID in ('NSW1','QLD1','SA1','VIC1')
and drs.SETTLEMENTDATE=maxint.SETTLEMENTDATE
and drs.INTERVENTION=maxint.INTERVENTION
group by drs.settlementdate
order by drs.SETTLEMENTDATE asc
) TRS
where
TP.SETTLEMENTDATE between %f and %t
and TRS.SETTLEMENTDATE = TP.SETTLEMENTDATE
and TP.INTERVENTION = 0
and TP.REGIONID = '%i'
```

Table 12: SQL query to compute raise regulation costs

```sql
select
TRS.SETTLEMENTDATE,
TRS.RREG_Main*TP.RAISEREGRRP/12 as "RREG.Cost"
from
%o.DISPATCHPRICE TP,
(
select
drs.SETTLEMENTDATE,
sum(drs.RAISEREGLOCALDISPATCH) as "RREG_Main"
from
mms.DISPATCHREGIONSUM drs,
(
 select SETTLEMENTDATE, max(intervention) as INTERVENTION
 from mms.DISPATCHREGIONSUM
 where SETTLEMENTDATE between %f and %t
 group by SETTLEMENTDATE
) maxint
where drs.SETTLEMENTDATE between %f and %t
and drs.REGIONID in ('NSW1','QLD1','SA1','VIC1')
and drs.SETTLEMENTDATE=maxint.SETTLEMENTDATE
and drs.INTERVENTION=maxint.INTERVENTION
group by drs.settlementdate
order by drs.SETTLEMENTDATE asc
) TRS
where
TP.SETTLEMENTDATE between %f and %t
and TRS.SETTLEMENTDATE = TP.SETTLEMENTDATE
and TP.INTERVENTION = 0
and TP.REGIONID = '%i'
```