A DOUBLE-SIDED CAUSER PAYS IMPLEMENTATION OF FREQUENCY DEVIATION PRICING

An ARENA-Supported Project Sponsored by the Australian Energy Council

CONTROL AND PRICING THEORY REPORT

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Executive Summary

This is the second of a set of four reports to be prepared under an AEC/ARENA supported project to study the theoretical and practical bases for a specific implementation of Frequency Deviation Pricing (FDP), known as Double-Side Causer Pays (DSCP).

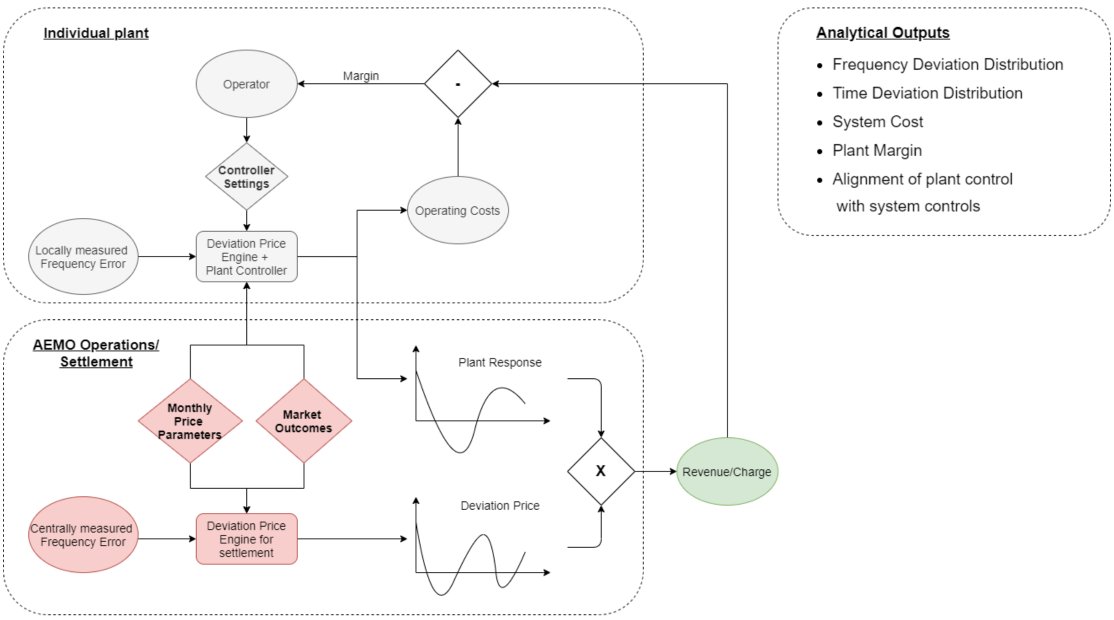
The Inception Report set out how the project team intends to approach the project, setting out the intended steps in detail.

The current report outlines the theoretical basis for FDP and how it could be implemented as DSCP. Specifically, we also examine some critical implementation issues with a view to resolving or at least clarifying and quantifying them in the set of analytical studies to be covered in the analysis report.

This report outlines a model, the Linear-Quadratic Regulator (LQR) Model of the electricity system which, when extended to support inputs from available measurements, provides a robust foundation for FDP and the DSCP analysis. Computer code has been developed which, when further enhanced with additional reporting and realistic data, will be used for the studies in the next phase of the project.

The report also considers a set of implementation issues some of which will require the modelling studies to address fully. This leads to an indicative DSCP market design which will form the basis for study in the next phase of the project. The main elements of the system including the general flow of control and data are illustrated in the figure below.

Proposed DSCP Implementation



Note that the system has decentralised control but centralised settlement. Inputs to the decentralised control are:

- FDP components easily calculated from local measurements of frequency and time error;
- dispatch interval weightings based on energy market dispatch local price outcomes, available in advance; and
- additional global weightings applied by AEMO also known in advance, usually at the start of a settlement period.

More implementation details are set out below.

- The DSCP system will target PFR and AGC regulation, as two distinct but closely related services.
- The system will use AGC metering for settlement. Participants can track their own performance locally.
- The FDP components will be:
  - Raw 4 second frequency deviation, or frequency deviation filtered with a 6 second (say) time constant, supporting PFR; and
  - A frequency deviation signal filtered through a 35 second (say) time constant, supporting performance under AGC regulation.
- With a dispatch interval (DI), FDP signals would be weighted by a ramp between the previous local energy price (including loss factors) and the next local energy price.
- The FDPs within each DI should be accumulated and averaged into 5-minute factors. Because of the ramping there will be two factors per interval.
- A global weighting will be set to target some fraction of a corresponding or neighbouring enablement income stream.
- As not all participants are metered, there will be a residual to be allocated on some basis, likely in proportion to energy.
- Some additional rules may assist confidence, especially initially and during a transition.
  - One such rule might be to restrict DSCP payment receivers to those providing enablement services or registered for mandatory PFR. However, the long-term goal should be to extend participation as widely as possible.
- Initially, all existing or proposed services could be kept in place.
  - However, the regulation causer pays cost stream should reduce in size over time and support a simplified cost recovery option in line with that used for contingency.

This design and variations on it will be stress tested with an LQR-type model in the next phase of the project.

Appendix A in this report sets out the LQR model and its extension in more detail, illustrated with a simple example.

Appendix B is a summary of the comments and queries made by industry participants at the knowledge sharing workshop held on 27 May 2021, together with the responses of the project team.

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1 Introduction

1.1 Project and Report Objective

The Australian Energy Council (AEC) with ARENA support has sponsored this project to examine a specific option for pricing and promoting a market for Primary Frequency Response (PFR). The work is motivated by a desire to see a market for PFR maintain good frequency control in normal conditions in the National Electricity Market (NEM) when the current mandatory approach to provision sunsets in 2023.

In its Frequency Control Frameworks Review and subsequent discussion papers, AEMC has identified some modification of the existing causer pays system for regulation as a candidate for pricing PFR[1]. Subsequently, CS Energy commissioned a small project of IES to demonstrate how such an approach might work; the approach was called Double sided Causer Pays (DSCP).[2]

The aim of this project is to outline the basis for Frequency Deviation Pricing (FDP) specifically applied to PFR and to study a range of implementation issues. DSCP is a specific implementation of FDP applied to PFR but potentially also covering AGC regulation as well faster services such as FFR and inertia and even slower services such as ramping. AEC sponsorship does not imply a commitment to the approach by itself or its members; only a desire to see the option fully examined.

This report aims to outline the control and pricing theory and to lay out the key design before the modelling stage begins. The context of these stages and reports are explained in the previously published Inception Report[3].

Readers are strongly advised to review the Inception Report before tackling this Theory and Pricing Report.

1.2 Outline of this Report

In essence PFR is a service that responds directly to frequency deviations, traditionally delivered by governors to help stabilise the system when subject to disturbances. PFR works in conjunction with a slower moving service, AGC regulation, to keep frequency and time deviations within required bounds. We will therefore consider the broader control problem and associated Frequency Deviation Pricing (FDP) before narrowing down on specific issues around the implementation of DSCP.

This report is structured as follows:

- Section 2 outlines the general models used for modelling and controlling the system and how pricing information can be extracted. We can derive from that the form of a pricing function which is simple and practical enough to measure and act on locally, as well as be used for settlement.

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[1] AEMC, Frequency control frameworks review, Final report, 26 July 2018 and AEMC, Primary frequency response rule changes, Consultation paper, 19 September 2019

2 Intelligent Energy Systems (IES), A Package of Improvements for the NEM Auction, April 2017

[3] Intelligent Energy Systems (IES), A double-sided causer pays implementation of Frequency Deviation Pricing, Inception Report, April 2021

- In Section 3 we use this background to consider a set of policy questions that would arise when considering a possible implementation of DSCP. While the theoretical background does not provide unambiguous answers in all cases, it does serve to inform any discussion. We conclude at 3.4 with an overview of the intended design to be modelled and stress tested in the next stage of the project.
- In Section 4 we draw the key conclusions from this work. This work supports the modelling and performance analysis be carried out in the next stage of the project.
- Appendix A contains more detail and examples on the LQR model and its extensions that were outlined in Section 2.
- A knowledge-sharing workshop based on the current report was held on 27 May 2021. Appendix B contains a summary of the comments made and questions asked, together with a response from the project team. The workshop was useful in highlighting areas of industry concern and interest that require more work in the next project phase.

2 The Basis for FDP and a DSCP Implementation

2.1 Overview

The goal of frequency control is to match supply and demand at all times within the dispatch interval, given the initial schedule set by the energy market. The control problem is to marshal the resources, including inherent system inertia, to achieve that goal. It should balance the actions needed to achieve the frequency and time error performance standards against the cost of moving away from target trajectories and the cost of control. A typical control is ramp rate. PFR is one important resource and DSCP is one means of marshalling that resource with a financial incentive. Financial incentives where practical are likely to encourage better performance and deliver lower costs than technical rules such as the current mandatory approach to PFR.

We outline the DSCP concept in the following Section 2.2. However, there are many questions to be resolved about this concept, some of the main ones being:

- Would implementation of the concept tend to stabilise or destabilise the system, especially in the presence of rapid ramping technologies such as batteries? DSCP is a closed loop system which may need tuning or additional rules to prevent over-reaction to frequency deviations.
- How should the deviation price be determined, especially to be fully accessible to participants in real time so that can manage their opportunities and exposures?
- What is the relationship of FDP and DSCP to existing and proposed frequency control services? Are DSCP and FDP more generally mutually exclusive to these services, or complementary? For example, could the DSCP concept potentially extend beyond PFR to include pricing of AGC regulation performance?

There are also implementation issues to address, many of which will be discussed in Chapter 3.

To inform a resolution of these questions, Appendix A outlines a Linear Quadratic Regulation (LQR) model and some extensions of that model. Such a model provides the foundation of computer modelling of some key topics and informs what an efficient and stabilising FDP should look like. It confirms the proposed simple DSCP pricing structure but provides some confidence in its stabilising properties. The results of this analysis are presented in Section 2.3. The analysis stage of this project will present a more fully developed computer models and a more detailed analytical justification for the structure of the FDP.

In section 2.4 we consider options for scaling the basic FDP structure, including DSCP, for integration into the into NEM.

2.2 An Introduction to DSCP[4]

Double-sided Causer Pays borrows a concept from the existing "causer-pays" technique that is used to determine how to allocate the cost of the FCAS Regulation services. In this system participants are assessed every four seconds to see how they are deviating from dispatch target trajectories as shown in Figure 1 on the next page.

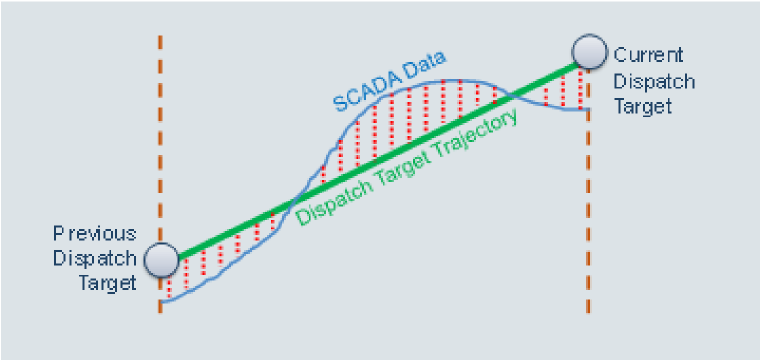
[4] This section is based on AEC's summary description of DSCP and this project, as it appears on its website.

THE BASIS FOR FDP AND A DSCP IMPLEMENTATION

In the existing Causer Pays approach, if participants deviate from their dispatch trajectory in a way that makes the frequency worse (i.e., they are below target when the frequency is low, or vice versa), then a penalty is determined for the participant. The penalty is the product of the volume of the deviation and the size of the frequency error measured during that four second interval.

These penalties are then accumulated over four weeks. Participants then must fund AEMO's FCAS regulation costs in the following four weeks in proportion to the size of the penalty they previously accrued.

Figure 1 Causer Pays Deviation Quantities



$$\textit{Scheduled Deviation Gen} = \textit{ActualGeneration} - \textit{TargetTrajectory}$$

Source: AEMO Causer Pays Procedure[5]

The logic of this allocation is that it charges those who "caused" the deviations that created the need for the FCAS regulation service in the first place. There are obvious limitations to that existing arrangement, such as:

- The four-week lag means that participants are not paying in proportion to their current performance, but rather based on an assumption that historical performance will continue; and
- Only penalties are recorded, i.e., deviations from target that *assist* in correcting the frequency are not rewarded.

Double-sided Causer Pays

This approach uses the causer pays concept, but without the two limitations above. It expressly detects all deviations from dispatch target every four seconds. Those participants who are making the frequency worse (i.e., the penalty described above) pay those participants who are making the frequency better. Again, the quantities are a product of the deviation and frequency error, but the transaction is resolved in the four second interval, i.e., there is no 4-week delay.

This way, generators mandated by the new rule to provide PFR can be rewarded in accordance with their actual observed performance, thereby creating an incentive to perform.

Note that unscheduled demand, forecast by AEMO, also contributes to the frequency error. AEMO's demand forecast is effectively a "dispatch target" and to the extent actual demand varies

[5] 5 AEMO, Regulation FCAS Contribution Factor Procedure, December 2018

from it, this affects frequency in the same way as a generator missing its target. In both the existing process and IES' approach, demand is treated the same way as a generator. Demand causer-pays costs (or possibly rewards) are passed on to customers as a class.

But having worked out the volume of causer pays or causer support, there is the key question of what price to apply to these volumes – there is no obvious value to draw upon. IES has previously studied using a centrally determined estimate of the opportunity costs of supporting frequency from a standard thermal generator. Another approach is to use the price of the FCAS Regulation market as a proxy of the value of frequency correction.

2.3 Control and Pricing Theory

In Appendix A we outline a model of an electricity system from which is possible to derive:

- the theoretical basis for a stable, efficient and simple control strategies for each element of the modelled system
- the structure of the prices (FDP) corresponding to those strategies; and
- the basis for a computer model that can be used to study some key questions on the feasibility and desirability of the FDP approach including the DSCP concept.

The general result is that an FDP consists of a set of separable price components which can readily be calculated recursively from frequency measurements at the resolution of the available metering.

The key formulae are summarised below in the box following.

The FDP can be calculated from the simple recursion:

$$q(i) = qold(i)*(1 - dt/TC(i)) - (dt/TC(i))*fe \qquad i = 1, 2, 3, ...n \qquad (1)$$

where

fe is the frequency error

q(i) is the current intermediate price component factor and qold(i) the previous one.

dt is the measurement interval.

TC(i) are time constants that are characteristics of the system.

We can apply a gain (weighting) to each component to get its price:

$$p(i) = G(i)*qold(i) \qquad (2)$$

Where the G(i) are gains (weightings) that are to be determined by some external process.

Participants would see all price components to get a single price:

A large and comprehensive model could in theory allow calculation of the weightings G as we can in smaller models, but limited data and other system considerations suggest that a pragmatic approach is required. We address this issue in the following Section 2.4.

The recursion formula suggests the metering interval dt places a firm lower limit on what can be achieved with a given metering resolution. For example, with 4-second SCADA metering the smallest practical time constant would be 4 seconds. With this time constant the recursion becomes simply the raw 4-second measured frequency deviation scaled by some factor. Applying this price components to the participant deviation leads to the proposed PFR pricing formula for one interval:

FDP Factor = Generator/load deviation * Frequency deviation (4)

This formula ensues that:

a) a generator/load that maintains its nominated ramp will have a nil price exposure, regardless of the frequency deviation; and

b) if it deviates from its ramp in a way that helps frequency, it will achieve a positive deviation and therefore a positive financial incentive.

However, for PFR it may be that a slightly longer time constant would be more suitable – say 6 seconds, to bring it into line with AEMO's 6 second service. This should be reviewed.

The lag used in AEMO's AGC regulation is about 35 seconds so this time constant may be suitable for pricing AGC regulation as an extension to DSCP for PFR. Longer time constants may support other services under consideration for the NEM such as ramping. Shorter time constants down to fast frequency response (FFR) or even Inertia (with some addition to the formula) fit within this framework but would require high resolution metering. Such metering would be like current meters but with updated firmware.

2.4 Scaling the FDP formula

2.4.1 The need to weight the pricing formula

The theoretical model outlined in this report assumes all system parameters are constant, even though load and generation may be tracking along different system conditions over the day or when some major incident such as network separation occurs. Required is a robust basis for scaling the pricing factors in a way that is efficient as well as useful and transparent to participants. If weightings are to change each 5 minutes, it should be done on a stable and easily understood basis.

The LQR model has useful scaling properties which can help. If all costs, state variables and control variables are consistently scaled, for example by splitting the system into two smaller but identically structured parts, the system optimal operating policies and prices remain unchanged. This useful result from the LQR model suggests that, to a first order at least, a similar pricing regime could apply under a range of scaled but otherwise similar system scenarios, even including separation. The plant mix will change but the approximation suggests pricing may be robust against modestly changing conditions, or even drastic ones in many cases. However, scale is not the only relevant factor determining how to weight the FDP, as outlined in the following subsection.

Our focus is on the PFR component of the FDP, although elements of these proposals may have wider applicability.

2.4.2 Options for weighting deviation prices

We can define our control and pricing task as:

- Minimise total costs subject to reliability standards set for frequency and time error being met.

We note that FDP would not be the only mechanism working towards this goal, at least initially.

We need a methodology to weight the FDP signal to achieve the above result. This methodology will likely need to reflect conditions at different times and in different locations, or perhaps satisfy a broader criterion such as promoting a wide geographic spread of service providers.

Some options (not necessarily mutually exclusive) for weighting the FDP price are:

1. Set the provider component of the FDP price to satisfy to some benchmark such as an estimated of the cost of supply of the currently marginal unit. This was the initial approach taken in the CS Energy-sponsored work on DSCP.
2. Weight the FDP price relative to the energy price (including loss factors)
3. Weight the price relative to some fraction of FCAS enablement price or cost stream – PFR or regulation

Approach 1 is not practical because the marginal unit is likely to change l over time (e.g., towards batteries rather than thermal units and such costs would be difficult to determine. It also ignores the basic aim of achieving technical targets.

Option 2 has some attractions while not be complete, as it still needs a mechanism to weight technical targets with the costs of achieving them. The attractions are:

- We can show for LQR logic that, under certain reasonable assumptions about cost structures, scaling by energy price would require no additional adjustments to maintain interest in providing PFR.
- Weighting by energy price would encourage a wider geographic interest in providing the service, whether it be by DSCP alone or by DSCP combined with enablement. Achieving such geographic spread is a stated AEMO goal. That spread would come at some cost to a strictly least cost outcome but may better satisfy AEMO robustness criteria.
- Given that a participant performs reasonably consistently, we can show that PFR costs and income can easily be hedged in the energy market. This contrasts with other FCAS mechanisms which are difficult to hedge.

These reasons appear compelling so weighting by energy is a preferred approach. However, we still need to determine a suitable overall weighting designed to achieve the required technical goal; to lie within the frequency limits determined by the Reliability Panel.

For an initial implementation we propose some variant of Option 3. That is, we set a weighting factor to achieve some fraction of the corresponding enablement income stream, if such a stream exists. The justification is that the enablement quantity set by AEMO and the prices that result ensure that the frequency standard will be met. Setting the weighting on FDP that keeps a non-negative price and income stream puts more weight on performance while maintaining the apparent assurance offered by enablement. What is that fraction? Best that it be set initially low and ramped up as confidence is gained.

If there is no enablement service for PFR, then a suitable proxy might be some fraction of the AGC regulation income stream. However, performance would need to be monitored and the fraction adjusted in this case. We note that it is more important for this factor to be known in advance by participants (but adjusted from time to time) than to achieve a precise funding fraction ex post.

In summary to convert the LQR pricing logic into a workable approach, we propose that:

- the 4 second factors within a dispatch interval be weighted by the energy price;
- an overall weighting be determined in advance which approximately achieves some fraction of the corresponding enablement income stream;
- the fraction should start low and be ramped up gradually; and
- the parameter that is estimated to achieve that fraction over a settlement period should be published and known by participants in advance of its application, even though it may achieve a slightly different outcome than initially calculated.

3 Implementation Issues

3.1 Overview

In this chapter we review a set of practical implementation issues for DSCP, building on the basic FDP logic of the previous chapter and summarised. in the final section of the chapter, we note that the next phase of this project will provide more detailed modelling and analysis.

3.2 DSCP as a Pragmatic Implementation of FDP for PFR

The FDP logic set out earlier in this report would, with additional adjustment, potentially create efficient prices for "instantaneous" energy at different timescales, such that frequency and time error are efficiently controlled. Our initial focus is primary frequency response for small deviation control, which we assume can captured with 4 second measurements from SCADA metering. We choose SCADA as a metering option initially because it:

- is already operating for scheduled participants;
- is likely to be sufficient for the purpose (but subject to further analysis in a later stage of this project); and
- is already used and accepted for regulation causer pays.

More accurate metering capable of measuring FDP performance right down to the level of FFR and inertia would require some further development.

Regardless of the metering method, implementation would follow the following logic. This logic in no way varies the basic FDP linear pricing logic set out earlier in this report.

- In each 5_minute dispatch interval, the product of frequency deviation and generation/load deviation is calculated, averaged and stored.
- At settlement time, each 5-minute value is weighted according to some rule and the resulting sum determined for payment purposes.
- Note that parties who are not 4-second metered or otherwise not participating are excluded from this calculation, so that there will be a residual balancing amount that will need to be paid or charged in some other way e.g., in proportion to energy.
- Note also that the 5-minute weightings, however determined, would be made available to participants as part of the 5-minute dispatch. Combined with local frequency metering and measurements from their own plant, participants would have complete information to guide their responses.

How to determine the 5-minute weightings is a significant element of the current project.

Note the similarity to the current causer pays procedure. One key difference is that all quantities can easily be measured and understood locally. Another difference is the scope for the market to be two sided, although metering limitations may limit the scope to do this in the short term.

3.3 Some Practical Issues to be Addressed

3.3.1 Adequacy of Metering

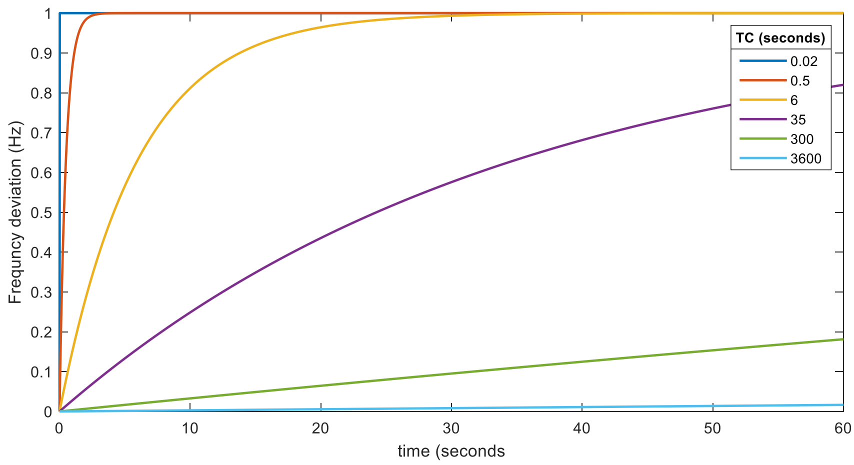
SCADA metering at 4 seconds has been deemed adequate for regulation causer pays. PFR is a faster service so the applicability of 4 second SCADA measurements is not so clear. As foreshadowed in the inception report, we will in the next phase of work perform extensive studies based on historical data to understand the sources of error or incompleteness from using SCADA metering for PFR and to assess its suitability to support DSCP.

3.3.2 Determining Time Constants

FDP theory outlined in Appendix A highlights the relevance to pricing of a set of time constants that characterise the system being modelled. Mathematically, these emerge naturally from the convergence properties of the pricing recursion formula. Physically, these prices track and provide incentives for control action to manage different speeds of response and, importantly, remove the frequency offset that PFR alone cannot eliminate[6]. We can calculate these precisely in a model and it is helpful to do so to understand better the factors that determine them.

The chart below shows responses to a step change in frequency for different time constants. Each response would also be scaled by a weighting factor to give a component of price. In this chart the measurement length is assumed to be one cycle and the minimum time constant is therefore 0.02 seconds (20 milliseconds)[7], showing an immediate step change following the frequency change. The 3600 second time constant would be appropriate for time deviation correction. Such a large time constant has only a very small impact on frequency deviation price and frequency responses which operate in a range of less than 60 seconds. This is adequate for time error correction because time error does not tend to destabilise the system. A time constant of 3600 seconds for time error correction has been used for the current AGC control system for regulation.

Figure 2: Step response PFR price factors for different Time Constants



For a real system, direct calculation from a model appears impractical. An alternative approach is to recognise that the physical parameters determining these time constants are likely to be the same as those driving AEMO's definition of frequency control services, both current and future. The immediate requirement is to deal with PFR, whose time constant is likely to be in the 4-6 second range. However, in the analytical studies in the next phase of this project we will also consider the possibility of longer time constants such as the approximately 35 seconds used by AGC regulation.

[6] See https://en.wikipedia.org/wiki/Proportional_control for an explanation. The inability of PFR alone to eliminate frequency offset is also demonstrable by the computer model developed to test DSCP under this project.
[7] Using SCADA this minimum would be 4 seconds on the mainland.

3.3.3 Dealing with system non-linearities

Non-linearities can take for the form of hard limits or discontinuities or be of a continuous nature. Examples are:

1. lower and upper capacity limits of generation as well as internal equipment;
2. transitions from positive to negative net output;
3. discontinuities such as rough running zones; and
4. mild non-linearities in some system dynamics.

Capacity Limits

On Example 1, a unit operating at capacity cannot take part in half of a symmetric PFR price. However, if motivated with a sufficient PFR price, participants may be prepared to make their own headroom or footroom if and when the PFR price is right relative to the energy price. The issue is moot if there is to be an enablement service for PFR. In that case the enablement process provides the necessary head and footroom, assuming FDP and enablement can operate together, while FDP could provide the financial incentive to perform and perhaps to drive down enablement prices (to be discussed later).

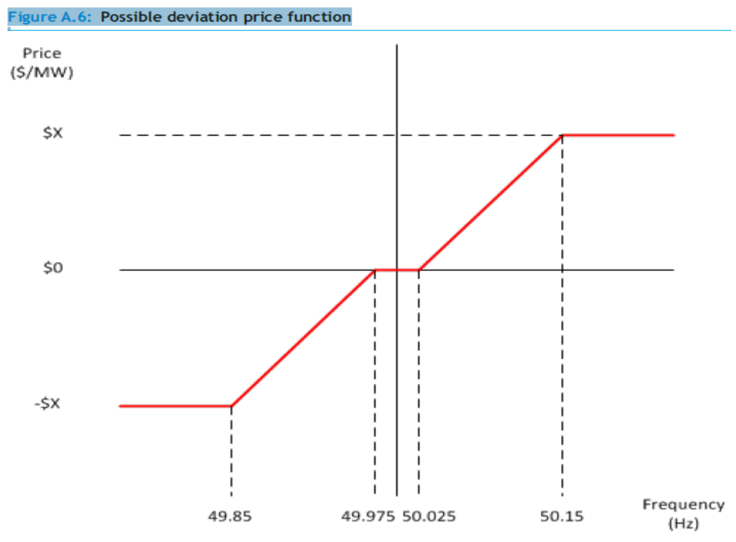
Transitions from positive to negative

The case of Example 2 is a variation on Example 1. Non-or partial (one-sided) participation is always an option.

Dead Bands and Rough Running Zones

On Example 3 and more generally, participants can avoid operating in rough running zones, capacity limits or deadbands through their operating procedures, irrespective of the pricing rule. Attempting to allow for deadbands and other non-linearities in the pricing function fails the test of technology neutrality. For example, consider the non-linear pricing function in Figure 3 below.

Figure 3: Illustrative Non-linear Pricing Function



Source: AEMC, Frequency control frameworks review, Final report, 26 July 2018, p93.

The function is flattened in a band either side of zero try to "remove" deadband operation and is capped to try to restrict pricing to the NOFB. The appropriate width of the deadband is technology specific. For example, a thermal unit may benefit for a specific deadband to reduce wear and tear, whereas a battery could operate satisfactorily with no dead band at all. They could make those decisions with a simple linear pricing function. AEMO could still attempt to model operations if large units are required to advise AEMO of their preferred settings.

Mild non-linearities

On Example 4, once the hard limits are removed or softened, any remaining nonlinearities are likely to be second order in the case of regulation because the plant will be operating with small deviations in a linear operating region. Some indirect evidence for that is the symmetric, normally distributed frequency behaviour that is typical of a well-functioning control of system and predicted by the LQR model and its extensions. Because of this, a linear control and pricing rule for small deviation control is not only adequate but also efficient.

In summary:

- under a linear pricing rule, participants can generally deal with their own limits and non-linearities by not or partially participating, avoiding deadbands and rough running zones and by making their own headroom and footroom. Headroom and footroom may in any case be provided by enablement markets (but see next sub-section);
- The linear pricing rule for small deviation control need not and should not be adjusted to account for deadbands or for any other reason unless performance under a linear rule is demonstrated to be unsatisfactory.

3.3.4 Interface with other frequency control services

PFR is defined as a frequency control service directly proportional to frequency deviation. However, it operates in close conjunction with AGC regulation, which consists of an enablement process for procurement, direct control of units through the system AGC and payment through regulation causer pays approach. AGC regulation is a delayed service that is controlled to drive frequency deviations toward zero.

In addition, there is currently a mandatory rule for generation units to provide primary frequency response capability where practical. Enablement markets for wide band as well as narrow band PFR are options under consideration by AEMC. Pricing of PFR for regulation would inevitably interact with contingency services at this level.

Taken an even broader view, the FDP logic extends readily to the pricing of fast-acting services such as FFR and inertia, subject to the development a promulgation of suitable metering. AGC 4-second metering is insufficient for measuring contingency performance.

PFR pricing and settlement can complement a mandatory requirement in the short term, although it would be best if the mandatory rule could then be relaxed somewhat, based on accumulated experience, to improve efficiency. PFR could also complement an enablement arrangement if introduced. Concerns about "double dipping" can be overstated, especially if PFR payments were to be limited to participants enabled for regulation FCAS in the first instance. In that case, competition to gain access to the performance payments should drive the price of enablement down.

PFR complements the slower-moving AGC service. While PFR partially arrests deviations, AGC regulation drives the deviation towards zero. PFR operates on raw 4 second frequency deviation data or (equivalent to a time constant of 4-6 seconds, say), while the time constant for AGC regulation is an order of magnitude greater – around 35 seconds. The operation of PFR and AGC regulation overlap but that does not mean one takes over from the other. It follows that, consistent the LQR model, all price components should operate together and simultaneously. Specifically, that includes PFR pricing with regulation pricing. There should be no concerns about double counting between the pricing of these two services.

Consider the merits of an FDP pricing component lagged with a time constant of 35 seconds, approximating the AGC operating lag. If this payment stream were to be restricted initially to parties enabled for AGC regulation, competition for access to it should drive FCAS regulation enablement prices down, reducing the costs going through the current AGC regulation causer pays mechanism. Such an outcome would allow the current cost recovery mechanism to be scrapped and replaced by a simpler charge, perhaps by bundling it with contingency cost recovery. On the other hand, if the DCP pricing were not too aggressive, participant interest in enablement would remain and DSCP could be made universal to all with SCADA metering. This would likely be a superior approach.

On the interaction between small deviation and contingency services, the default position should be that small deviation pricing (i.e., pricing within the NOFB) should always apply; that is, it should not be suspended in the case of a contingency. Subject to further study, allowing the small deviation service to assist the large is a simple and efficient approach. However, lags in SCDA metering might limit DSCP to the NOFB until faster acting metering is used.

In summary

- DSCP for PFR can operate comfortably with either a mandatory requirement or an enablement service, acting as a performance incentive which can also drive down enablement costs (if there are any).
- There is scope to simplify and improve the AGC regulation arrangements by adding a lagged price component to the DSCP system.

3.3.5 Stability of the system with more renewables as well as lower inertia.

More renewables in the system implies a wider range of potential forecasting errors and need for more FCAS to manage them[8]. System inertia will also decline. All these factors can be modelled with LQR and its extensions. Such modelling may suggest merit in services and corresponding FDP components with time constants at sub-second levels (i.e., FFR) or even longer time constants to assist with ramping. We can extend the set of measurements available to include system acceleration (RoCoF). This would lead to a price component based on acceleration which might be attractive batteries able to provide synthetic inertia.

While we can and will model these cases, implementation of the fast-moving ones would require dedicated metering programmed to capture performance down to the level of a few cycles[9]. This

[8] AEMO has determined this relationship. See Figure 32 in the 2018 ISP. https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/isp/2018/integrated-system-plan-2018_final.pdf?la=en&hash=40A09040B912C8DE0298FDF4D2C02C6C

[9] The MASS specifies 50ms for compliant metering.

important scenario therefore falls outside the scope of DSCP as we have defined it. However, services with time constants of more than 4 seconds could be included in a DSCP logic.

3.3.6 Stability of the system with more batteries

Batteries are current and likely future dominant providers of frequency control services. Even when operating to arbitrage energy, there is usually scope for them to also provide the full range of frequency control services, for both small and large deviations. This is due to their ability to ramp almost instantaneously (through their inverters) and to sustain that change for minutes, or even 5-10 minutes in most cases.

We can model optimal battery behaviour in the LQR by examining what happens when we set their ramping and deviation costs approach zero. There may be an issue with saturation – approaching limits which will have to be resolved. Assuming a stable and optimal solution exists based on a linear control within its operating range, we need to examine whether a battery operator would be incentivised to follow and strategy that is optimal for the system. These are potentially challenging issues which will be addressed in the modelling in a later stage of this project.

As with the case of low inertia requiring FFR, we cannot expect DSCP using SCADA to address the issue of fast response of batteries; that would require dedicated metering. However, we do need to examine the likely response of batteries to a PFR price signal under DSCP.

3.3.7 Impact of potential “rogue behaviour”

We can produce an instantaneous energy price from the LQR model and show that providers paid under this price would generate a profit by varying the timing and extent of provision. However, we have yet to show that the FDP pricing formula as proposed encourages stabilising behaviour, even though the pricing formula is consistent with stable operation of the system.

To study this, we propose to run an Optimised LQR simulation, but take one participant and examine what happens when its output is varied from the system wide optimal. This could be easily done by changing the weight given to their local linear control. We would expect to the system to remain stable and the participants to lose margin. We would then see what happens with a larger participant or a group of participants acting in concert. Depending on the outcome, it may be prudent to consider some additional (not too tight) rules or implementation strategy that provide greater assurance about stability.

We note that existing enablement markets provide some assurances that sufficient capability is in place, while a policy to target some fraction of the enablement income stream is a mechanism that would keep DSCP pricing well away from any instability concerns.

3.3.8 Fixing DSCP pricing discontinuities between dispatch intervals

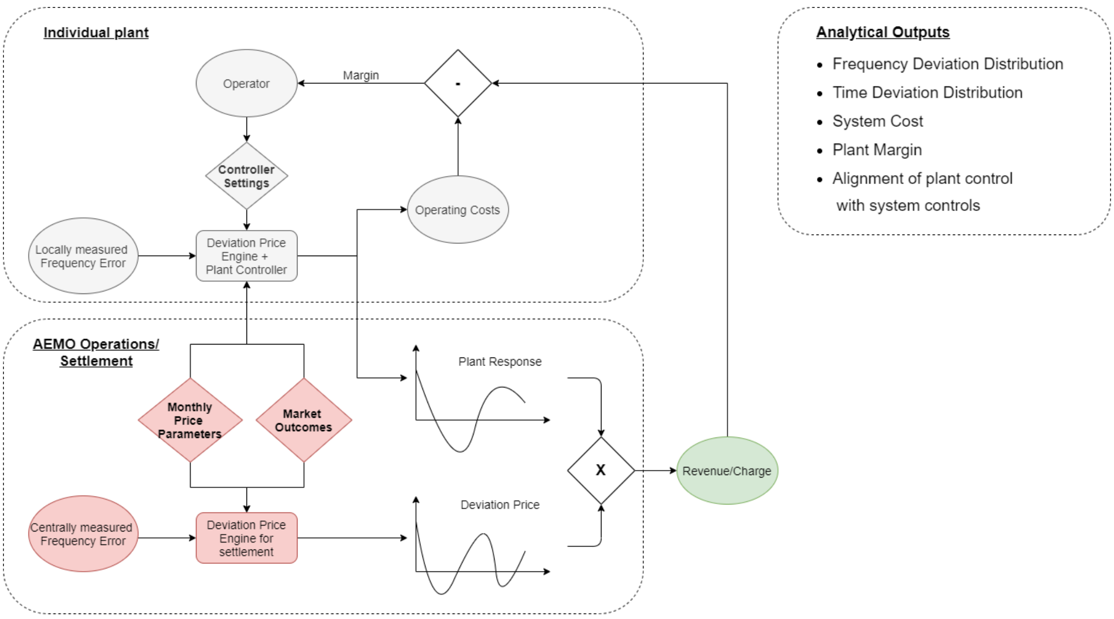
If FDP is applied within each dispatch interval weighted by energy price (or weighted by some other means), there will be a price discontinuity at the boundary between dispatch intervals. This is undesirable as smooth pricing and control should be the aim.

We can fix this by noting that the energy dispatch price is calculated at a point 5 minutes distant, so it is reasonable to take the FDP as varying around a price ramp between the current dispatch energy price and the next, even though market energy is treated differently. This is a simple adjustment that still allows participants to track their own performance in real time.

3.4 Overview of a Possible DSCP Design and Implementation Strategy

Bearing in mind the above discussion, our "straw man" design for a DSCP system is outlined below. It is a slightly more detailed and extended version of the basic DSCP system outlined at the start of this section. The main elements of the system including the general flow of control and data are illustrated in the figure below.

Figure 4: Proposed DSCP Implementation



Note that the system has decentralised control but centralised settlement. Inputs to the decentralised control are:

- FDP components easily calculated from local measurements of frequency and time error;
- dispatch interval weightings based on energy market dispatch local pricing outcomes, available in advance; and
- additional global weightings applied by AEMO, also known in advance, usually at the start of a settlement period.

More details are set out below.

- The DSCP system will target PFR and AGC regulation, as two distinct but closely related services.
- The system will use AGC metering for settlement. Participants can track their own performance locally.
- The FDP components will be:
  - Raw 4 second frequency deviation, or frequency deviation filtered with a 6 second (say) time constant, supporting PFR; and
  - A frequency deviation signal filtered through a 35 second (say) time constant, supporting performance under AGC regulation.

IMPLEMENTATION ISSUES

- With a dispatch interval (DI), FDP signals would be weighted by a ramp between the previous local energy price (including loss factors) and the next local energy price.
- The FDPs within each DI should be accumulated and averaged into 5-minute factors. Because of the ramping there will be two factors per interval.
- A global weighting will be set to target some fraction of a corresponding or neighbouring enablement income stream.
- As not all participants are metered, there will be a residual to be allocated on some basis, likely in proportion to energy.
- Some additional rules may assist confidence, especially initially and during a transition.
  - One such rule might be to restrict receivers of DSC payments to those providing enablement services or registered for mandatory PFR. However, the long-term goal should be to extend participation as widely as possible.
  - Another might be to make the arrangement opt-in for all participants. SCADA- metered parties could choose to abstain from DSCP (but be charged a share of residual costs based on energy), while embedded and non-SCADA metered parties could choose to opt-in with suitable metering, not necessarily SCADA.
- Initially, all existing or proposed services could be kept in place.
  - However, the regulation causer pays cost stream should reduce in size over time and support a simplified cost recovery option in line with that used for contingency.

This design and variations on it will be stress tested with an LQR-type model in the next phase of the project.

4 Conclusions

The AEC/ARENA Double-Sided Causer Pays project has been split into four major parts:

1. An inception phase, where the proposed scope and approach for the project has been laid out. This report has been completed and published on the AEC website.
2. A phase to lay a theoretical foundation for later work and to pose and analyse some Implementation issues further study. This phase is the subject of the current report.
3. An analysis phase, where a range of analyses and modelling studies will be carried out to firm up some of these concepts and their possible merit.
4. A concluding phase in which the results and recommendations are summarised into a Final Report.

This report is intended to cover the second phase.

The second and last stages will include knowledge sharing workshops which may in turn guide later work. The project intended to inform industry consideration of the evolving requirements of frequency control and does not imply any commitment by AEC.

In this report we have outlined in Chapter 2 and the Appendix the following:

- the Linear-Quadratic Regulator (LQR) model which, with practical extensions allowing system states to be estimated from available measurements, is suitable for modelling the real power in an electricity system including when subject to disturbances;
- how a frequency deviation price can be derived from marginal cost information in the extended LQR model that is suitable for valuing frequency control energy;
- how the pricing formula can be condensed and simplified into a relatively small set of separable components easily calculated directly from frequency measurements, each with a distinct time constant and gain; and
- how a raw pricing formula based on frequency with various lags can be scaled to give a potentially practical FDP/DSCP arrangement.

This work leads to an indictive FDP/DSCP arrangement along the following lines:

- Deviations (the traded quantity) would be measured relative to a straight-line trajectory between successive dispatch interval energy targets. An alternative is to use deviations from the AGC trajectory if a unit is enabled for AGC service, although this is not our base proposal. SCADA metering would be used where available; otherwise, costs would be pro-rated according to energy within the dispatch interval.
- The deviation price would have one or more components, each lagged with a low pass filter with a specific time constant and gain (weighting). The weighting would consist of two factors;
  - a time and location of use factor, which we propose be the local energy price for each trading unit, intended to ensure interest in providing PFR/regulation at all times and circumstances, including network separation; and
  - a constant or rarely changed parameter (set in advance of each settlement period) aiming to achieve a specific ratio of FDP/DSCP market turnover relative to a corresponding FCAS enablement market turnover.

CONCLUSIONS

- So, we have:
  - FDP/DSCP_Price_Component (k)= - Constant*Local_Energy_Price*FDP_Factor(k)

  Where FDP_Factor is set recursively as follows:

  FDP_Factor(k, t+1) = FDP_Factor(k,t)*(1 – dt/TC(k)) + dt/TC(k))*Frequency_Deviation(t)

  where

  k = the FDP/DSCP component

  t = the measurement time period

  dt = the measurement interval

  TC(k) = the time constant for component k

  Constant is a constant set by AEMO prior to each settlement period to target a market turnover as some fraction of the corresponding FCAS enablement market turnover.

  Note the negative sign on the right-hand side.
- Subject to further study, the FDP/DSCP components might be characterised by:
  - a component to support PFR with a Time Constant TC of 4-6 seconds. For SCADA metering on the mainland, a TC of 4 seconds is the raw frequency measurement; and/or
  - a component to support AGC regulation with a TC of 35 seconds (say), which is indicative of current AGC settings.
- There are variations on the indicative design above that are worthy of investigation. Some of these have been identified in this report and in ensuing discussions; they will be considered in later project stages.

We have developed a computer model to demonstrate these concepts, but the reporting will be greatly enhanced, and a more realistic model structure built to support the next analysis phase of this project.

As outlined in Chapter 3, the model supplemented with an analysis of historical data will be used to study topics relevant to implementation such as:

- the suitability of SCADA metering for an initial implementation of DSCP;
- the parameters of the pricing components that may be applicable in the real system, and how they relate to the specification of existing frequency control services;
- the role of batteries and how they would or should behave to achieve efficient and stable control under FDP;
- the impact of reducing inertia and more variability from renewables;
- whether the proposed pricing would ensure stability in the presence of non-optimal behaviour and what extra measures may be necessary if not;
- how different options for weighting the pricing formula would operate quantitatively;
- the potential financial impact on various parties.
- the scope for combining PFR pricing with AGC regulation in some way.
- whether FDP could assist with the likely increased ramping needs of the future system; and
- the elements of a preferred DSCP implementation, with possible variations, for industry consideration

The analysis phase of this project to follow will also include analysis of historical data to evaluate how frequency control performance by participants has changed over time and the scope there might be for improvement under DSCP. The suitability of SCADA metering of PFR will also be examined in more detail.

Appendix A Control and Pricing Theory

A.1 Overview

Frequency control of an electricity systems is a specific example of a more general control problem known as the Linear Quadratic Regulator (LQR) and its many variations and extensions. A particular extension of the LQR, called Liner Quadratic Gaussian Control (Gaussian Control) has proved to be particularly powerful for dealing with real world problems, because it accepts the reality of what can be practically measured[10]. In the case of a market-oriented electricity system, for example, basing at least some control and associated pricing on local measurements such as frequency has some intuitive appeal.

LQR problems can be formulated as very large optimisation problems, having quadratic objective and linear constraints. While LQR offers a far more efficient solution method and additional insights, they share common properties which are useful to recognise. For example, in a linear programming dispatch model of an electricity system such as used in the NEM, the shadow price (sometimes called dual variable) of the energy balance equation serves as the market price for energy in that location. A system to control frequency based on LQR also has a corresponding instantaneous price based on the so-called swing equation, which describes the power (and therefore energy) balance in a dynamic electricity system.

We will demonstrate in this chapter how this price can be calculated recursively based on practical measurements of frequency and time deviation as well as, potentially, system acceleration (RoCoF). Such a price can serve as price to assess and reward frequency control performance, subject to suitable metering being available and a supporting set of market rules.

A.2 The Linear Quadratic Regulator

A.2.1 The LQR model and example

Model description

The LQR model can be described as follows:

- Our system can be characterised with a set of states and associated variables. Examples of states are:
  - The deviation from target of a generator (in MW)
  - The deviation from forecast of a load
  - The frequency deviation, expressed as a deviation in spinning energy (inertia)
  - The time deviation, which is the time integral of frequency deviation, as expressed.

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[10] There are many articles and texts on Linear Quadratic Gaussian Control. e.g., T. Söderström, 'Linear Quadratic Gaussian Control', obtainable from SpringerLink *https://link.springer.com/chapter/10.1007/978-1-4471-0101-7_11.* For a straightforward statement of the LQR and solution see *https://en.wikipedia.org/wiki/Linear%E2%80%93quadratic_regulator* For a similar statement of the Linear Quadratic Gaussian problem see *https://en.wikipedia.org/wiki/Linear%E2%80%93quadratic%E2%80%93Gaussian_control*

The states have associated variables that assume different value at different times. A real system may have many thousands of states as each unit of a participant may have a range of control settings at hand and complex system dynamics.

A typical control might be a generator ramp rate and its associated variable will have a value which the plant operator can change over time according to some strategy based on available information.

- The system evolves over time according to a set of linear relationships where a new state is a linear function of the previous state variables and control variables.
- We aim to minimise an objective which is the sum over time of quadratic cost incurred by changes from schedule or forecast of states and controls. We usually assume an infinite horizon so that the objective is then an expected cost per unit time.
- We assume that states and controls are measured relative to some base situation which as arrived at by the energy market scheduling process.
- The system may be subject to disturbance by noise impacting the state variables, according to a noise process with a specific covariance matrix.
- The system may be regarded as continuous or operate at discrete (usually small) time steps. The discrete approach is the more robust.

This model does not directly support hard limits; plant is assumed to operate within a linear operating range.

A Simple Example

To give the LQR model some substance, consider a system with a single load and a single generator that is subject to a step change in load.

The states in this simple model are:

- Power deviation from schedule
- Load Deviation from forecast
- Frequency deviation expressed as spinning energy deviation
- Time error expressed also in terms of spinning energy

The single control is the controllable energy inputted to the generator.

PFR is an automatic and spontaneous response and is treated as a damping term based on load frequency sensitivity and assumed droop setting for the generator.

The core of the model is the swing equation which is:

Rate of change of spinning energy = Controlled generation + Load + Damping (PFR) + Disturbance

(5)

All terms are deviations from some base point, so we assume a consistent sign convention – all deviation injections are positive. The disturbance is a fixed step change in load in our initial; run.

> This swing equation is analogous to the energy balance equation defined in the NEM scheduling algorithm. Just as with the 5-minute energy balance, the swing equation can also produce a price of frequency control energy.

Other relationships are described as:

Rate of change of power output = ramp rate (control) (6)

Rate of change of time deviation = Frequency deviation (7)

Damping/PFR = Factor * Spinning energy deviation (related to frequency deviation) (8)

Finally, we need a workable cost objective. The following objective term is an appropriate trade-off between frequency and time deviation correction.

[(Frequency deviation expressed as energy) + (Time deviation as integral of energy)/TI]^2

The time constant TI can be set large enough, say 1 hour, so as not to interfere with good frequency performance. This squared term also needs to be weighted by some tuning factor, set to achieve the desired frequency performance standard. This is an unavoidable tuning parameter.

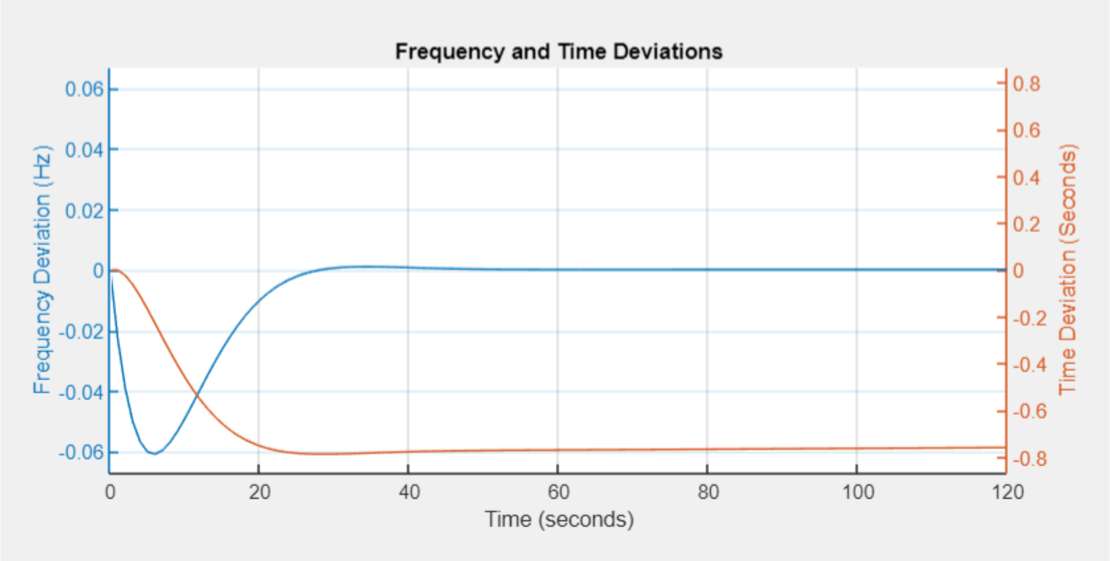
There are additional squared costs for deviations away from power trajectories and control settings.

We assume some parameters in the model which are not particularly realistic but illustrate the nature of the system operation. We will build more realistic models I the next stage of the project.

Indicative Results

When the step change in load is the only disturbance the following Figure 1 shows indictive frequency deviation and time deviation trajectories when the optimising strategy is followed. The frequency is quickly stabilised while the time error from the disturbance appears to persist. Time error correction has a one-hour time constant so its track towards zero has barely begun on this 2-minute chart. The long time constant however, means that frequency is little affected by the time deviation correction. There is a small frequency offset that drives the time deviation correction which is not visible on the chart.

Figure 5: Frequency and Time Deviation Trajectories - Single Initial Disturbance

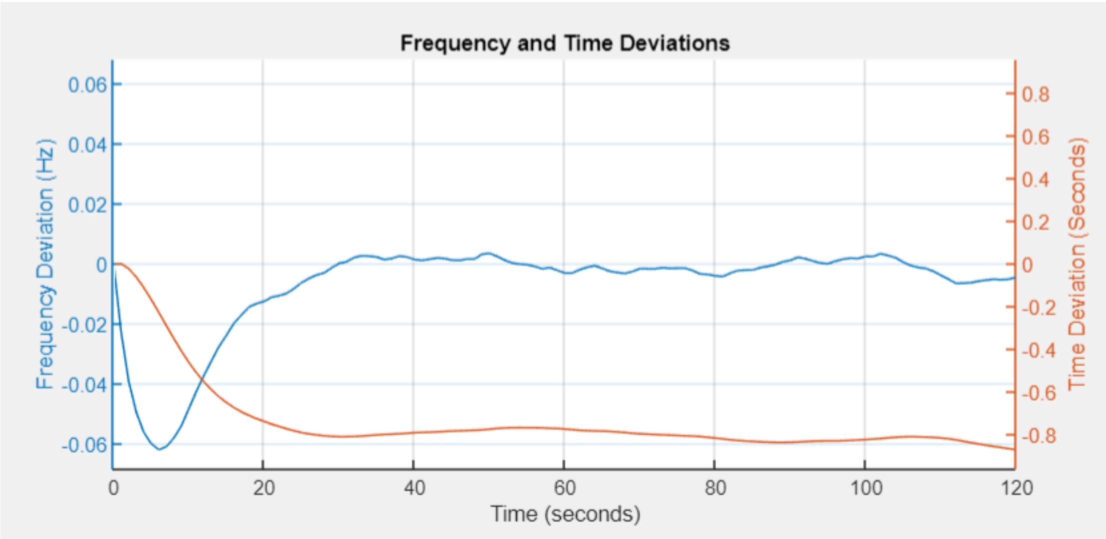


LQR with disturbances

When the disturbances are random and centred on zero, the LQR optimal control policy is unchanged. This is a standard result of the LQR model with disturbances. The outcome will be driven by more volatility in the value of the disturbed state variables, typically load but also. generation.

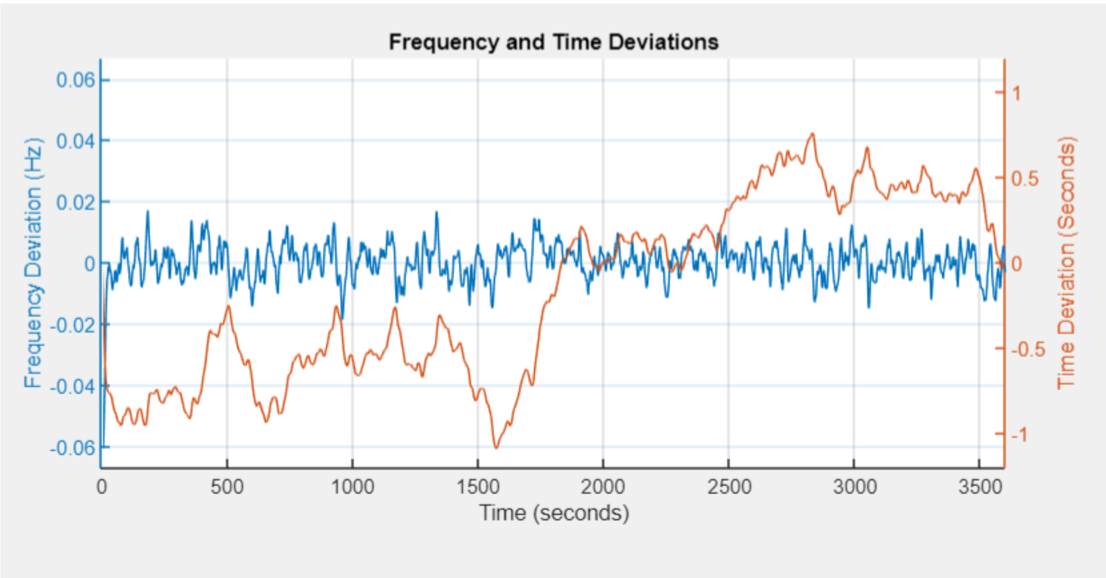
Following is a chart of showing frequency and time error when the load is subject to a disturbance partially correlated with another disturbance on the output of the generator.

Figure 6: Frequency and Time Deviation Trajectories with Random Disturbances



Under these random disturbances the system remains stable and has a similar response, with the effect of noise evident. A snapshot over an hour gives a broader picture as shown in Figure 3 below.

Figure 7 : Frequency and Time Deviation Trajectories over a One-hour Period



From the LQR theory we can calculate both directly and by simulation:

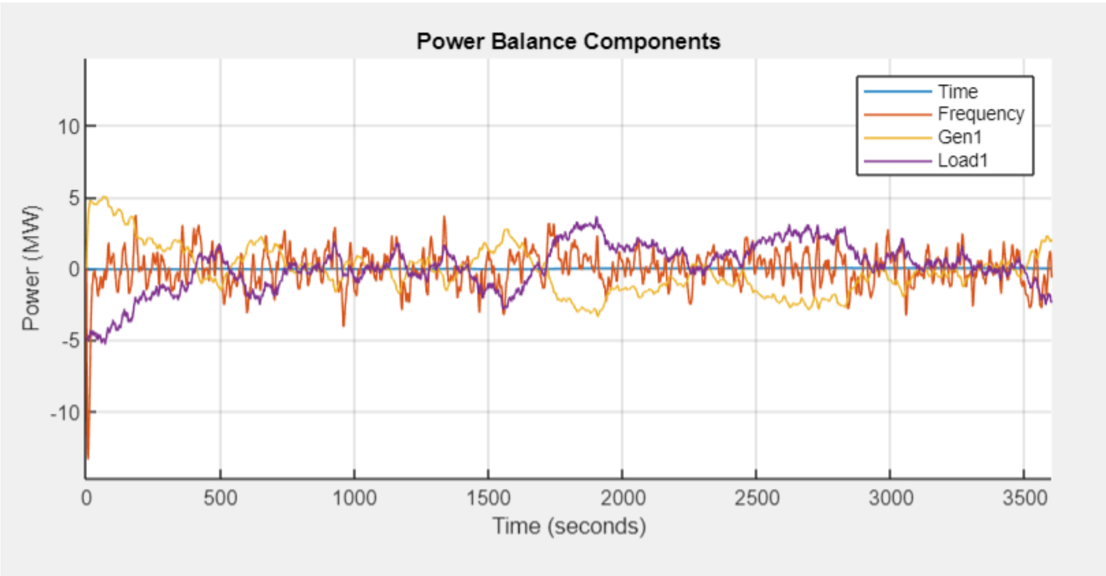
- the expected cost per unit time to operate and control the system; and
- the standard deviations and correlations of the state variables, particularly the frequency and time variables shown above.

LQR theory also shows that under the zero-centred noise and linear model assumptions and under optimal control, the state variables are multivariate normally distributed. Normality is often observed with frequency plots.

The time deviation in the plots appears to wander aimlessly but it is controlled, and it is normally distributed (under the assumptions of the model) when sampled over a sufficiently long period such as a month. However, if the centred noise assumption is not met, the distribution may be skewed. For example, while frequency will always be zero centred, if there is a bias toward under-forecasting the system will have more negative time deviations than positive and the time deviation distribution will be skewed, with a longer tail on the negative side. Such nuances do not detract from the validity of the LQR model.

Figure 4 shows a plot of the variables defined in our simple model, expressed as power. Note that the generator approximately follows the slow drift of the load; this is the equivalent of regulation AGC in the NEM. The much faster moving noise is mostly handled by damping (PFR) and system inertia. As represented by the orange line. Note that these do not equate exactly to the components of the swing equation. We will carry out a more detailed analysis of how this balance is achieved in studies planned for later in the project. Note also that the time deviation has little influence on short term system dynamics due to the large time constant assumed.

Figure 8: Power Balance

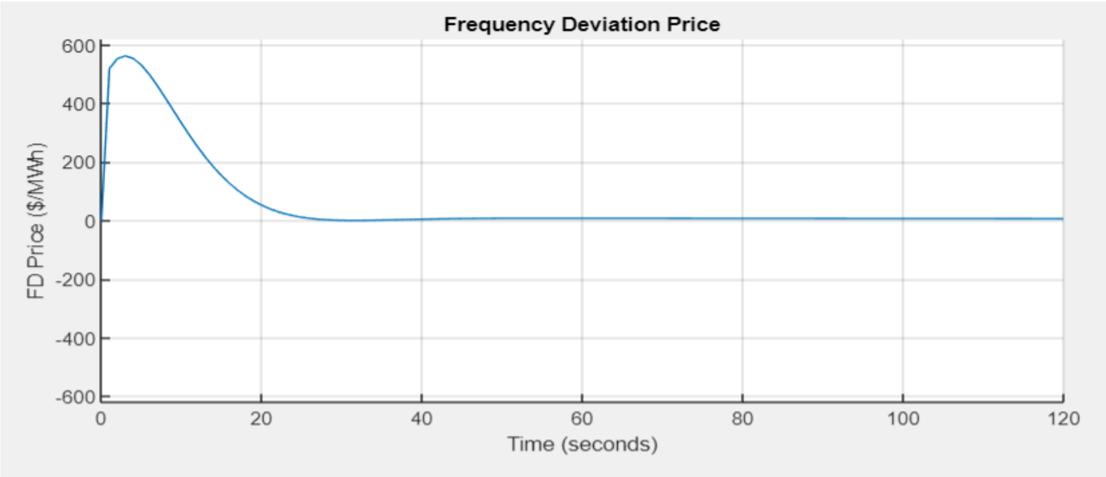


A.2.2 Extracting prices from the LQR Model

The optimised system cost at any time is a quadratic function of the system states. This is one of the core outputs of the solution of an LQR model. The function is defined by a square matrix whose dimension is the number of states. It follows that the marginal cost, interpreted as a price, is a linear function of the system state. Below is a plot, for the example above without noise, of the marginal cost corresponding to the spinning energy variable associated with the swing equation. This is the change in the cost to the system of an increment of energy at that moment. It is conceptually identical to the energy price as calculated in the NEM energy market.

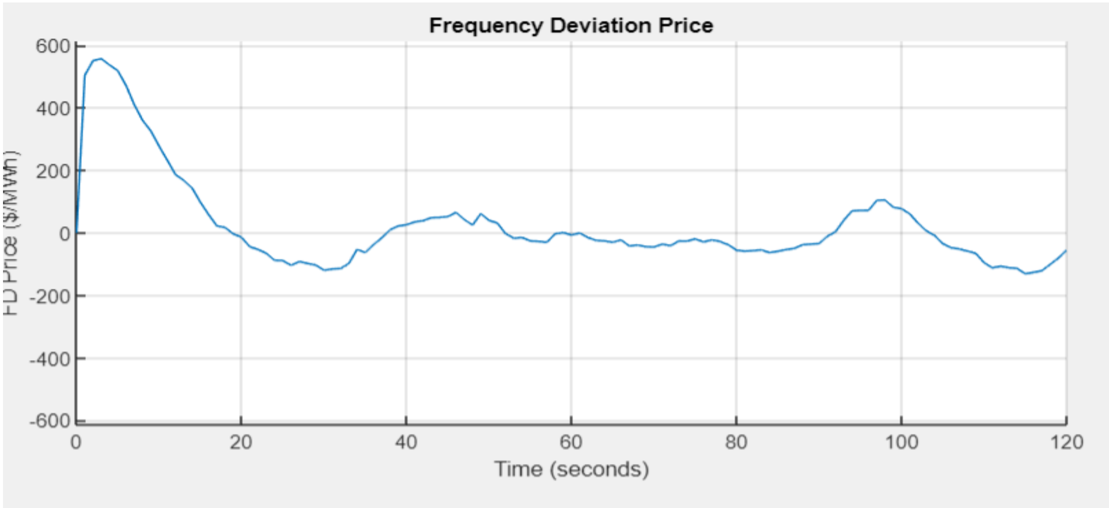
Figure 5 following shows the profile of the instantaneous spinning energy price in our example where there is an initial step change in load only. As expected, the price increases as a negative step load is imposed. It generally follows a similar profile as frequency (but inverted), although it appears to peak a little earlier. With a mix of technologies in the system, one cannot expect a direct relationship between price and raw frequency; there will be a mix of price components present. Note that the prices shown in the example are intended to indicate only the general shape of an efficient FDP.

Figure 9: Price Profile under a Step Change with No Other Noise



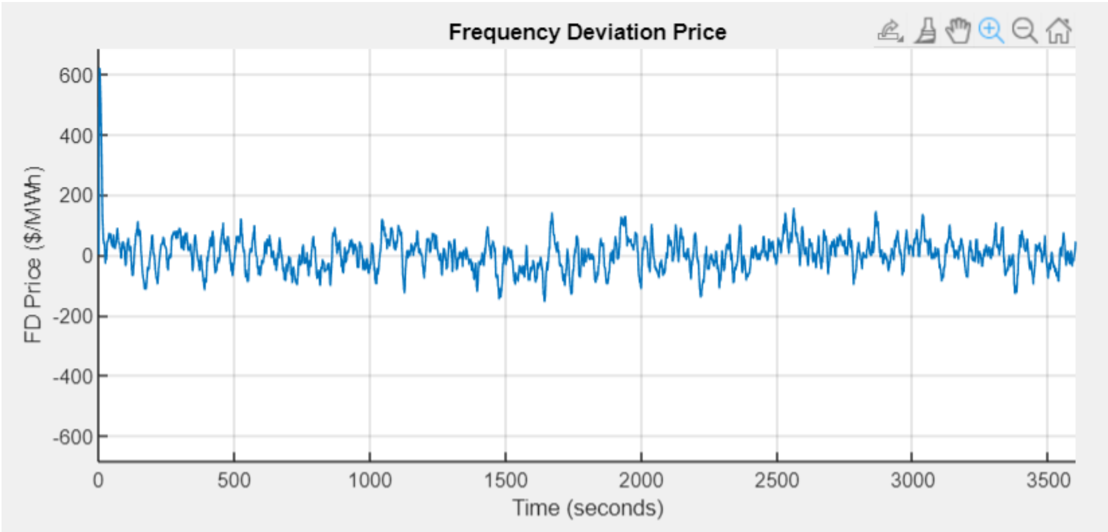
We can add noise as before and the price will show the same sort of variation as frequency, but not identical; see Figure 6 below.

Figure 10: Price Profile with Step Change in load and Additional Noise



Finally, looking at the longer one-hour block in Figure 7 following, one can see the general pattern of prices in the system as it is subjected to ongoing disturbances and correction. As with frequency and time deviations as well as other state variables, prices tend to follow normal distributions as they are a calculated as a simple linear transformation of the system states.

Figure 11: Price Profile with Noise over One Hour



A.2.3 Conclusions on the utility of the LQR

The LQR solution can be characterised as follows, for the case with or without noise.

- The controls are linear functions of the evolving system states. That is, a control such as a ramp rate for a plant is the weighted sum of the current values of the system states. The weights for each plant are a characteristic of the system.
- The linear control obtained is the optimal control for the system and is stabilising under normal conditions.
- The LQR control is an optimal linear control even for non-Gaussian noise (such as one-sided contingencies), although there may be a better non-linear control.

In addition, we note the following on prices from the model:

- All state variables have a corresponding shadow price, which, like controls, are linear functions of the current system state.
- An important shadow price corresponds to the swing equation which, in essence, values an increment of spinning energy (Inertia) in the system. This price is shared by all parties hooked to the grid and can serve to value energy for frequency control. Note that this price is directly derived from the optimal control, which is stabilising.
- As with states, the pattern of optimal prices tends to be normally distributed.

Finally, we note the difficulty of applying this model directly to a real situation:

- The number of states can be very large and corresponding data difficult or impossible to assemble.

- The system state can be difficult to measure and be made available in time for use at the local level. AEMO does have access to many state measurements through SCADA metering and uses it for AGC regulation, but such measurements are not helpful for PFR and faster services such as FFR and Inertia.

A.3 Gaussian Control and Pricing

A.3.1 Overview

There is an extension to LQR which makes it a practical tool in many more situations than the basic LQR model. It combines the power of a Kalman filter with LQR to give a control logic driven not by the system state, but by any measurements which may be practically available. Furthermore, the measurements may themselves suffer from random noise.

A.3.2 The Kalman Filter and LQR

To use the LQR model without measuring the system state in real time, we need some way to estimate the system state from a limited set of measurements. In the case of an electricity system for example, there are only limited measurements available locally to a participant - frequency deviation, time deviation and the state of one's own plant. Can we estimate the state of the system simply from frequency measurements? In principle we can, by using a Kalman filter. In practice we need to simplify things, but the principle is the same.

A Kaman filter applied to electricity would work follows:

- We use an identical system model as the LQR.
- We have set of measurements which we know are determined by some linear function of the system state, perhaps subjected to random noise.
- We wish to drive the system forward and progressively update our estimate of the system state. The Kalman filter provides the tool to do that.

In practice, the Kalman filter has some difficulty separating out similar technologies, so it works best when they are grouped into similar classes, which is probably sufficient for control and most modelling purposes.

An LQR when combined with a Kalman filter is called Gaussian control and would operate as follows:

1. A new estimate of the system state is obtained by passing the previous estimate (from the previous period) through the system state and control equations and adding a Kalman filter term designed to progressively improve the estimate.
2. The Kalman filter takes the errors between the actual measurements and an estimate of those measurements to calculate adjustments to the system states.
3. The estimate of the system state is used to form the control strategy using standard LQR logic.
4. That real control strategy combined with real system dynamics operate to create a new frequency and time deviation outcome which can be measured.
5. One can now estimate a new system state and continue, by returning to step 1.

It is evident from the above description that the estimated system state evolves step by step driven by the evolving measurements. It follows that system prices, and the price of spinning energy, also follow a recursive trajectory driven by available measurements. In fact, it is possible to express system state in terms spinning energy price components through an inversion process. By doing this, we can show that the spinning energy price components are governed by a recursive formula taking the following form:

p = M*pold + E*fe (9)

where

fe is the measured frequency deviation

p is a vector of price components and pold is the previous value

M is a square matrix whose dimension is the number of states (potentially large)

E is a vector of weights converting the measured fe to price component adjustments

A similar, separate formula applies to time deviation with the weighting vector E replaced by a different vector H. However, the Matrix M remains the same.

A.4 Deriving a Workable FDP Structure

We note for the previous section that a set of FDP components can be recursively calculated directly from frequency measurements on the assumption that most parties are behaving rationally in response to their price signals or constrained to do so by other processes or rules.

In essence, the matrix M tends to drive prices toward an equilibrium, but this is constantly disturbed by a newly measured frequency error operating through the gain vector, E.

A relatively small and simple system is readily modelled under this logic. Such modelling is useful to test ideas. However, for a real system, the maintenance of a square matrix M and a vector of gains E when there are hundreds or even thousands of states becomes problematic.

There is a range of possible solutions to this problem, such as state reduction techniques. The aim is to represent a complex, large system as simply as possible with a system with a much smaller set of states. We can approach this outcome relatively simply by:

- performing an eigenvalue factorisation of the matrix M;
- dropping the imaginary parts of that transformation (these drive the oscillatory parts of the solution, which we do not need.
- dropping the small eigenvalues which contribute little to the matrix and therefor the evolution of the FDPs state. An 80-20 rule typically applies here; and
- Using the resulting condensed matrix form transforming the price components into a much smaller set of price components, capturing most of the original information.

This process leads to M being reduced to a simple diagonal matrix whose entries are all less than 1, so that the FDP evolution tends to convergence. The evolution of each FDP component, p(i), then takes the form:

pnew(i) = (p(i)*(1 – dt/TC(i)) + (dt/TC(i))*G(i)*fe[11] (10)

where

pnew(i) is the updated price component

[11] G(i) will be negative for stable operation.

dt is the measurement time interval

TC(i) is a time constant for component price component i

fe is the measured frequency deviation in the interval

G(i) is the gain (weighting) which converts a measured fe into a price component adjustment. It will have a negative value.

Note that the price components are separable and easily calculated. Participants should see all FDP components as their optimal strategy while be based on some combination of them. GC is a vector of modified gains to be applied to the much smaller set of price states.

If we perform the recursion (11) many times, we can see that the initial state becomes irrelevant.

The FDP can be calculated from the simple recursion:

q(i) = qold(i)*(1 – dt/TC(i)) + (dt/TC(i)) *fe i = 1, 2, 3, ….n (11)

where

q(i) and qold(i) are intermediate price component factors

TC(i) are time constants

From this recursion we can apply a gain (weighting) to each component to get its price:

p(i) = G(i)*q(i) (12)

Participants would see all price components to get a single price:

p = sum(p(i) (13)

In the LQR model the controls (e.g. ramp rates) are simple weighted sum of these price components. However, participants could finesse that approach as they see fit.

Equation (12) describes filters with various time constants applied to raw frequency. What are these time constants? We can model relatively simple cases and will do so in the next stage of this project, but the turn out to be characteristic time constants in the system, closely resembling the service definitions (4-6 seconds for PFR and around 35 seconds for AGC regulation (based on AEMO current practice) in the existing FCAS markets. Longer time constant may also be worth considering; for example, to support an emerging ramping requirement. Very short time constants are also covered, even though not yet supported by metering. So, we choose time constants which span the period of interest of about one order of magnitude apart and matching existing services when available. We would expect these time constants to remain stable over long periods, as they are characteristic of the physical nature of the system.

The vector of gains G are likely to be much more variable. It would likely reflect the current state of the system and may evolve over time as responses become more widely tuned. Options for determining these gains or weightings are a major part of the current project and will considered in this report.

The equation (12) can be programmed into a meter and accumulated into 5-minute averages and later uploaded and applied to settlement, where gains (weightings) can be applied to each-5-

minute set. These gains should be determined and made available to active participants at the start of each dispatch interval.

The focus of the previous discussion has been on managing frequency deviations. For time deviations, LQR theory indicates a similar approach to frequency which, when simplified, gives a separable pricing formula for time error of the same form. However, the case of time deviation there is likely only a need for a single, large time constant of, say, one hour. This would avoid incurring too much of a frequency hit while correcting time deviations a task, which is not central to system security. The time deviation price would appear as a very small, slow-moving price of offset.

Where does PFR fit into this framework? We will study the matter further in the next stage of the project, but we are limited in the first instance by the metering available, which is 4 seconds. We can see from the price component formula above that for a 4 second measurement interval the smallest time constant possible is 4 seconds, which corresponds to a raw 4 second frequency measurement. However, it may be that PFR corresponds to a slightly longer time constant, say 6 seconds. This can be accommodated. The component pricing formula does provide a specific lower limit on the services that can be supported by current SCADA metering.

Optimal control does require services in addition to PFR and the Gaussian control and pricing model accommodates that. So, the current AGC regulation service evidently corresponds to a pricing component lagged by about 35 seconds (the approximate time constant used by the AEMO AGC). In fact, the AGC may be able to accommodate many different time constants clustered around such a value, but pricing need not be so precise.

Appendix B Responses to Workshop Queries and Comments

B.1 Introduction

This note aims to address queries raised and comments made during the workshop on this report held on 27 May 2021. We have attempted to group the queries, comments and our responses by topic to avoid repetition.

B.2 General Comment

There seemed to be some uncertainty as to why we presented in the following order:

- an outline of the linear Quadratic Regulator (LQR) model application to a simple system;
- the extension of LQR to include noise and, using the Kalman Filter, to base decisions on local measurements of frequency and time error rather than the complete system state;
- how price components for spinning energy can be derived from local measurements, simple and robust enough to use in practice; leading to:
- a review of implementation issues leading to an indicative implementation for later study and debate.

This order follows the sequence outlined in our Inception Report.

Some general lines of questioning were: What is the point of all this algebra? Where are the numbers? How does the theory lead to these numbers?

The purpose of the algebra is to develop understanding. Frequency deviation pricing (FDP) is an idea that has appeal (to some, at least) as it appears to make intuitive sense, but there are many questions to answer:

- Is it stable, and if so, under what conditions?
- Is it efficient and, if, so, under what conditions?
- Should the pricing formula be linear or non-linear?
- Should it be based on raw frequency alone, or perhaps several components with various lags? If there is more than one component, do they overlap in time or are they separated?
- How can the pricing be made robust under different system conditions?
- What 'levers' would AEMO have to achieve desirable technical outcomes?
- Does the DSCP implementation give participants the information and control thy need to manage their plants?

We think the answers to these questions need a solid basis beyond intuition.

Having made that point, quantitative studies are needed to firm up the parameters of a good implementation. Those will follow in the next project phase.

B.3 Response to Specific Issues Raised

B.3.1 Primary, Secondary and Tertiary Response

Query and Comment

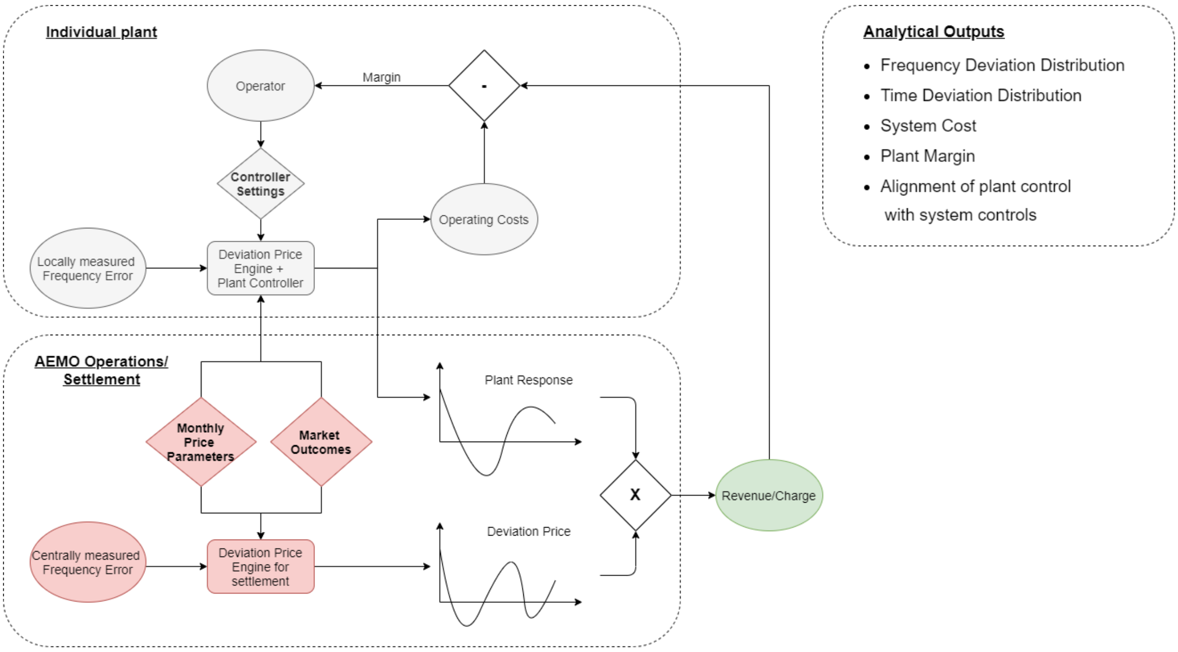
There was some animated discussion or whether the proposal was directed at primary secondary or tertiary control, whether it was centralised or decentralised and whether the whole logic is out of date because it's based on the characteristics of thermal generators.

Response

The intention is for a largely decentralised system, but it cannot be entirely 'libertarian' as some central hand (AEMO) needs to strike the balance between the cost of control and the achievement of technical outcomes. AEMO need only tune for the technical outcome. With a good design this intrusiveness should be minimal.

In the figure below we have reproduced a presentation slide with a few adjustments made for clarity. The settlement will be centralised but control will be local, based on measurements made locally, market inputs locally available (such as 5-minute energy or regulation enablement price) and a weighting for each price component set in advance by AEMO according to some rule, hopefully no more often than each month.

Figure 12: Proposed DSCP Implementation



In the report and presentation, we referred to price components being part of the theoretical outcome, each with its own time constant and weighting. Where do these elements come from?

The time constants come from an analysis of the convergence properties of the optimal control solution – an algebraic task but one which can be understood. Broadly, they will tend to reflect the time lags in the system relating to time error control, inertia and governor action, lagged response of plant and load behaviour. One might expect these time constants to be driven by the same issues that drive AEMO's implementations of PFR and AGC as well as its consideration of faster-acting services. We would expect them to change over time as the plant mix changes. Similarly, the weights are a function of the optimal solution. We intend to produce a working paper to show how these weights are calculated in a modelling environment. We will be studying how these different components evolve in the next project stage. However, for a practical implementation we propose an initial weighting based on local energy price, further weighted by a parameter set according to a monthly cash flow measure relative to that of any corresponding FCAS services.

Some confusion may have arisen because the LQR model by itself implied a centralised approach. However, our FDP/DSCP proposal is based on the version of LQR extend to support state estimation from local measurements. This model supports a decentralised approach.

Decentralised elements in FCAS markets do not necessarily supplant centralised ones, although they may make them less dominant.

B.3.2 Metering

Query and Comment

There was a discussion noting that FCAS metering had a resolution of 50ms for 6 second FCAS and that a faster, narrow band (small deviation) response could be considered as part of the PFR incentive/DSCP work.

Response

The FDP theory outlined is independent of metering resolution and could apply to services requiring high resolution measurement, including inertia. However, the initial implementation of DSCP proposes to use SCADA metering which has a resolution of 4 seconds on the mainland. The next project phase will review the adequacy of SCADA for small deviation metering duty.

Longer term, FDP should be supported by high resolution metering. Such metering would need to have revised firmware to be able to calculate and accumulate not only energy but the product of energy and frequency-based functions at high resolution. The project team may be able to demonstrate a simple prototype with this functionality later in the project.

B.3.3 Price Function and Weighting

Query and Comment

There was a good deal of discussion on where the price function and its parameters come from. Some of the discussion seemed to assume that the four-state toy example presented was the full extent of the proposed model (it is not) and whether the whole approach is outdated because the unextended LQR is a full state model and therefore centralised.

Response

The four-state model presented was the simplest example we could come up with that illustrates how the LQR and its decentralised extension would work. We will develop a larger, more diverse and more realistic model in the next project phase. It will use similar logic and software code but have more and diverse data elements driving it.

The pricing formula *structure* comes from the theoretical analysis for an efficient, stable control system, namely:

- one or potentially more price components linked to a frequency-based function, each with an associated time constant and weighting/gain;
- the frequency function in each case is a linear, low pass filter with an individua time constant and weighting/gain; and
- the different pricing components can and will overlap.

We can and will use models based on this theory to undertake studies, including calculating suitable time constants and weightings/gains. However, in a practical implementation, relying on a detailed model of huge scale and complexity seems neither practical viable nor necessary. Instead, in this project we will study and propose how these parameters can be determined pragmatically, albeit with some basis in theory. We have suggested a few avenues for exploration, including weighting by the local energy price and linking dollar turnover to FCAS enablement turnover.

Some have expressed a strong distaste for any system with a lagged pricing element. A range of factors seem to be in play here, including bad experience with the current causer pays (lagged) mechanism, references to the distortions cause by 5-minute dispatch and half-hour settlement, and a belief that everything will be instantaneous when batteries become dominant. To these concerns, we say that analysis will suggest whether lagged elements in an FDP/DSCP design make sense or not. Regulation causer pays and half-hour settlement are rife with nasty but known compromises.

B.3.4 Feedback to the Energy Market

Query and Comment

What would be the feedbacks to the energy and/or FCAS enablement markets?

Response

Our basic model takes the base trajectory as a given from the energy market. However, in practice many things will change over time – plants online and load, as well as the degree of variability. This affects inertia, damping and the control options available.

We can envisage a more comprehensive LQR-type model that takes these issues into account. However, we can instead recognise that the basic model has useful scaling properties, suggesting that weighting by energy price or perhaps a nearby enablement price would deal with most circumstances. We argue in favour of an energy price weighting, not least because it offers favourable hedging opportunities. Energy prices are available in advance of dispatch.

There was comment on whether weighting would affect behaviour. This is to be studied further.

B.3.5 Application, Participation and Controls

Query and Comment

How would DSCP apply to the NEM? How would participants operate – as now or with new or modified controls?

Response

The immediate scope for DSCP (using SCADA metering) appears to be to support PFR and regulation. Our report envisaged retaining existing mandatory and AGC causer pays during a transition phase, with scope to loosen the mandatory requirement and replace current AGC causer pays with an alternative, simpler arrangement to recover enablement costs. Of course, such a transition phase could be bypassed completely and perhaps with less confusion. This is a policy decision.

Longer term, we could have DSCP supporting ramping and even an operational reserve market. Indeed, if implemented for regulation, DSCP would provide some support to ramping as a matter of course, perhaps to the extent that an additional ramping service may not be required.

How would plant operate under DSCP? We can envisage several situations. For PFR support many generators need to do no more than what they are already required to do under the mandatory rule; some may be prompted to do a little more. If the mandatory rule could be relaxed a little, for example by widening the maximum deadband, some of the more expensive options might then drop out with no adverse effect and lower costs. Some rule to minimise geographical over-concentration of provision may be needed, although weighting by local energy price should help diversify supply. We don't envisage any new control systems would be required for thermal generators with governors. For participating wind and solar, frequency following controls would be required, but no different to those required under a mandatory arrangement.

In the case of regulation, a participant could choose to become enabled and get the DSCP price, i.e. get paid for both; this should attract more competition and lower costs in enablement. Enablement for regulation may be the simplest way to respond to a lagged DSCP price component. Others might prefer to stay outside the system because they have no SCADA metering or simply to remain independent. However, a cost-effective high-resolution meter that supports FDP could expand participation greatly.

If operating independently according to the FDP price signal, one would focus on the different price components. These components are easily determined from frequency and time error measurements, weighted by a market price available 5 minutes in advance. Such a system together with a control strategy could easily be implemented on a laptop. A fast-acting plant would respond to the PFR component, slower acting plant to the lagged component. Batteries and similar plant could respond to both.

B.3.6 Contingency Events and Network Interaction

Query and Comment

There was an extended discussion on how DSCP would interact with contingencies and the network, either as contingencies or as transporters of regulation in the case of MNSPs.

Response

Would DSCP apply in the case of a generator or load contingency? Our preference would be yes, largely for simplicity and consistency but also because it helps rather than hinders contingency management. DSCP should be regarded as a support service wherever it applies. As the pricing formula is linear, there would be some wealth transfer from the contingent party, but certainly a lot less than a cubic formula and not likely to supplant enablement. In the next phase we will study such a situation to confirm this assertion or otherwise. If some cost of contingency were to be paid by the contingent party, the cost of enablement would be likely to decline. More efficient scheduling and cost recovery mechanisms through the energy market could then be considered.

Apart from Basslink, which would be left to operate as now, we don't envisage any network participation in DSCP. The current causer pays logic separate out regional forecasts as useful information, but that and losses is eventually allocated to non-SCADA-metered parties in each region. We envisage a similar approach for DSCP, without some of the intermediate allocation to network elements.

We will study further what would happen under DCSP in the event of network islanding. With the FDP weighted by local energy price we expect each region would maintain some level of PFR and regulation internally. Further, from scaling arguments we hypothesise that the FDP/DSCP parameters would likely remain suitable during and after the continency, noting that contingency services would be in play in the immediate aftermath of the separation.

B.3.7 Battery Cycling

Query and Comment

We noted comment that batteries incur no penalty for rapid ramping, but the number of cycles affects battery life, implying a larger burden of DSCP on short duration batteries.

Response

We will review these cost and lifetime issues for our modelling in the next phase of the project. Rapid ramping of batteries is a useful capability for managing contingencies but is also potentially destabilising.

B.3.8 Conformance Rules

Query and Comment

The workshop noted that rapid ramping from batteries could occur now without conformance rules constraining such behaviour. What would be the conformance rules under DSCP?

Response

FDP and DSCP are designed to achieve efficient and stable outcomes with fewer conformance rules than apply under the current pricing regimes. Nevertheless, studies to be carried out in the next phase of this project may suggest areas of vulnerability where specific conformance rules would provide additional comfort to AEMO without jeopardising the potential efficiency gains too much.

For example, while our proposal to weight the FDP formula by the local energy market price should encourage diverse geographic provision of PFR and regulation, an additional constraint limiting the level of concentration in provision could also be applied. This could be quite simple such as limiting payments to some proportion of the energy market trading payments.

B.4 Conclusions

The workshop discussion has highlighted issues that can and should be addressed in the next phase of the project. Many are already foreshadowed in our inception report. However, others identified include:

- operation with contingencies;
- treatment of the network;
- conformance rules;
- description of how plant would operate including control system requirements; and
- costs and effects of battery cycling.