AEC/ARENA DOUBLE-SIDED CAUSER PAYS PROJECT

CONTROL & PRICING THEORY AND APPLICATION

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SESSION 1: FDP/DSCP CONTROL AND PRICING CONCEPTS

- Definitions:
  - FDP => Frequency Deviation Pricing – the concept of pricing energy within a dispatch interval based on frequency deviations
  - DSCP => Double Sided Causer Pays – a specific implementation of FDP that looks a bit like the Regulation Causer Pays system.
- Session 1 Agenda
  - Lay the groundwork for later implementation studies + basis for computer code
  - Where does FDP/DSCP fit?
  - The basics – the Linear Quadratic Regulator (LQR)
  - Gaussian Control – LQR based on practical measurements
  - Deriving a workable FDP/DSCP pricing formula
- Session 2 after the break will outline our proposed approaches to some key implementation issues e.g.
  - Can FDP/DSCP deliver stable and efficient operation in practice, now and in future?
  - Is SCADA metering sufficient for an initial implementation?
  - What are the key elements of a possible DSCP initial implementation?

THE 'JAMES WATT' GOVERNOR

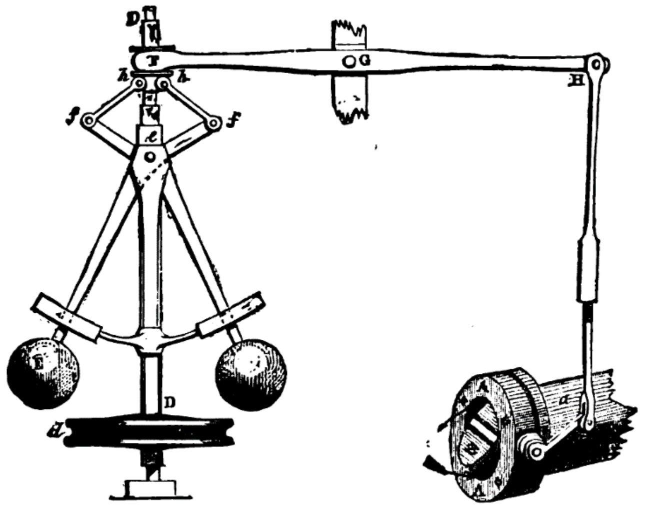
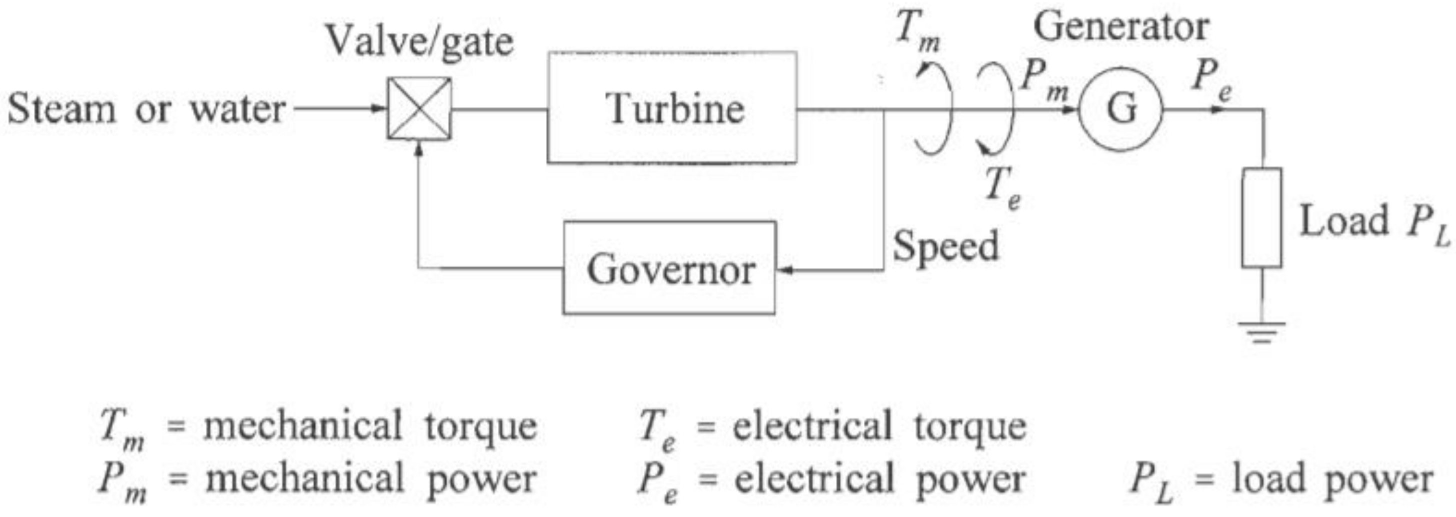
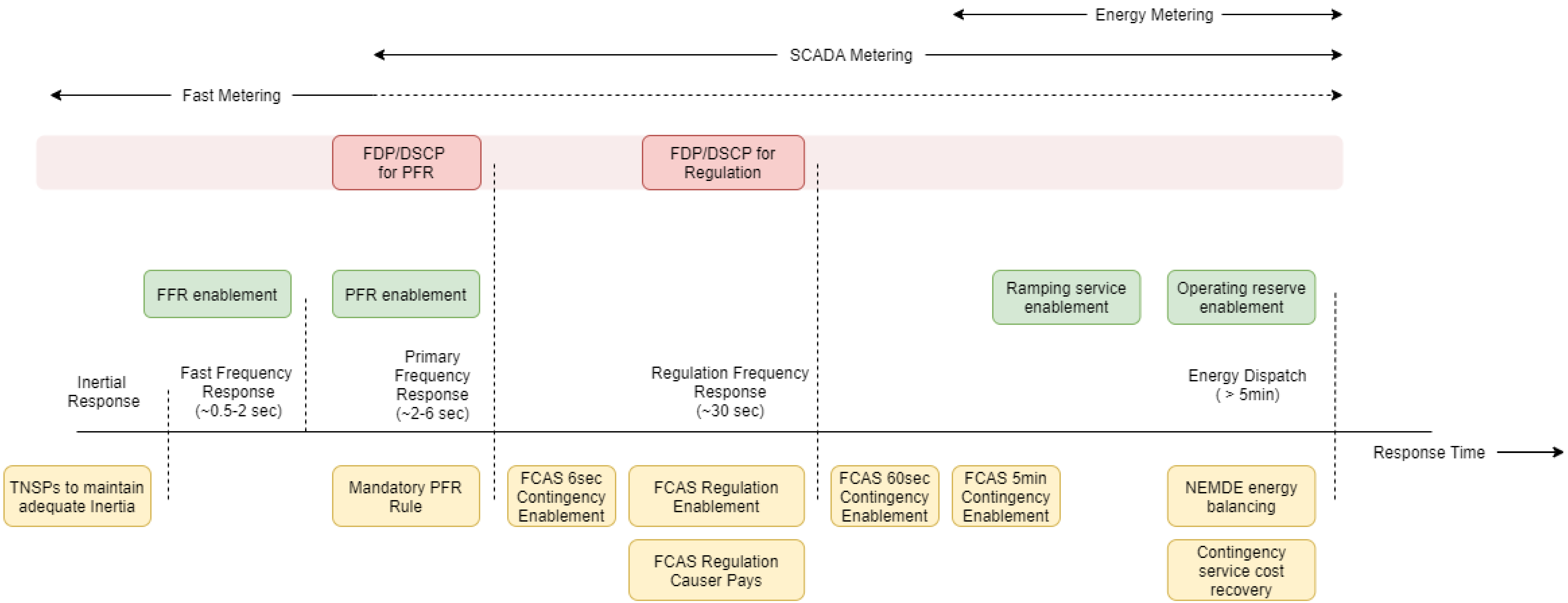


FIG. 4.—*Governor and Throttle-Valve.*



Analogous controllers available for wind, solar and battery (through inverters)

ENERGY AND FREQUENCY CONTROL SERVICES IN THE NEM



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EXAMPLES OF FREQUENCY AND TIME ERROR DISTRIBUTIONS

Figure 8 Mainland frequency distribution

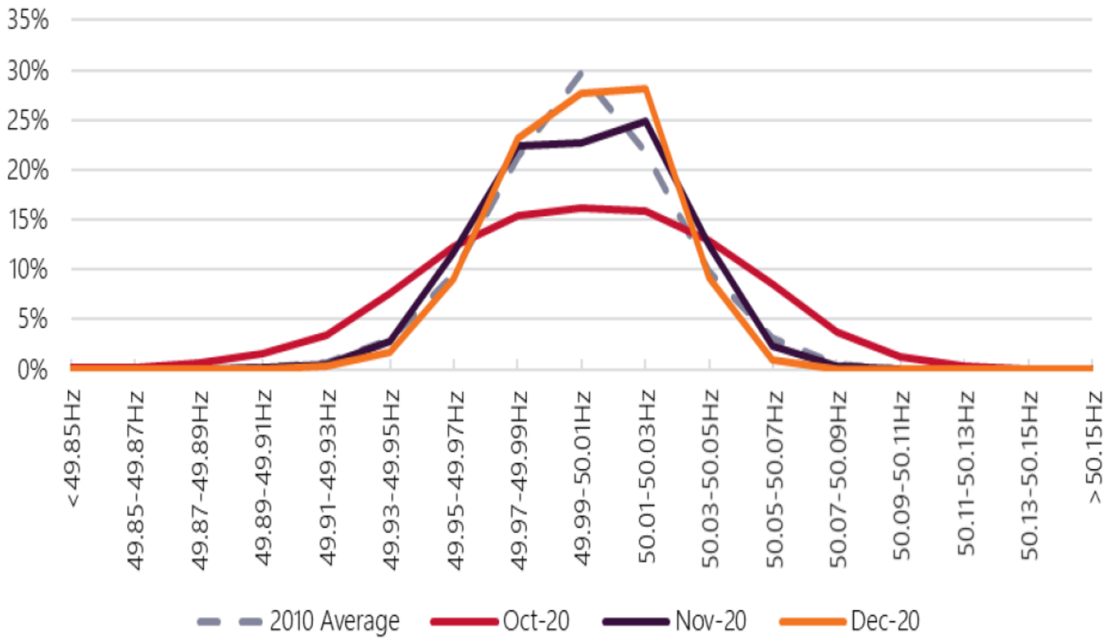
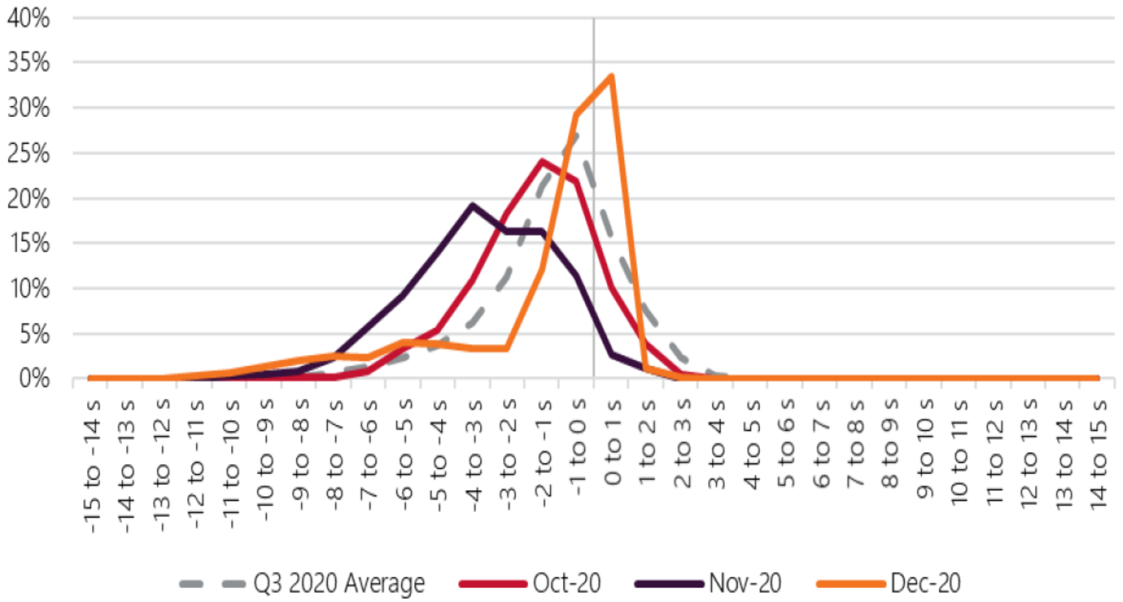


Figure 4 Mainland time error distribution



Source: AEMO - Frequency and Time Error Monitoring –Quarter 4 2020

MARKETS SUPPORTED IN THE NEM

	Capacity	Energy
NEM Energy Market	✓	✓
NEM Frequency Control Markets	✓	✗

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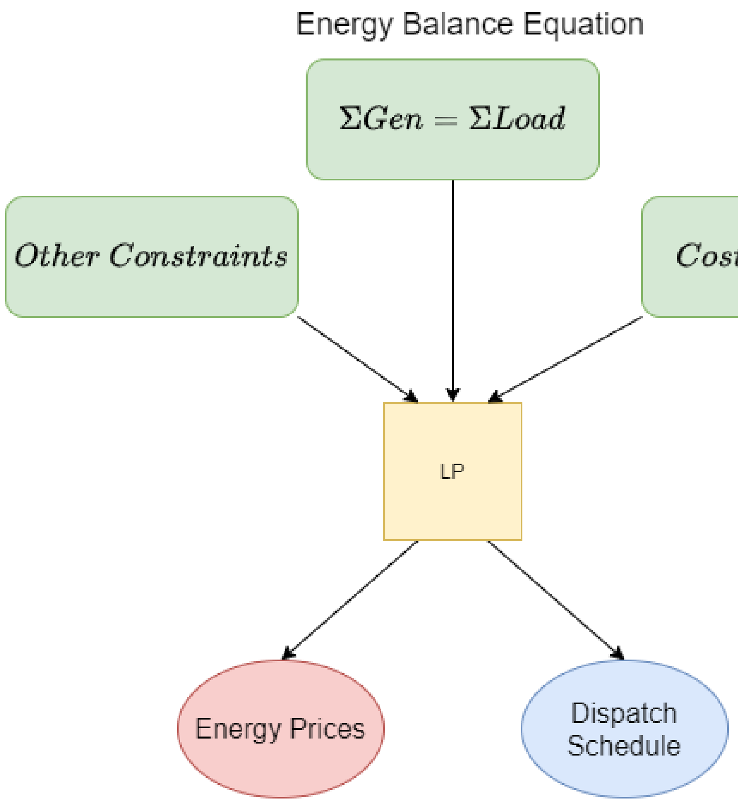
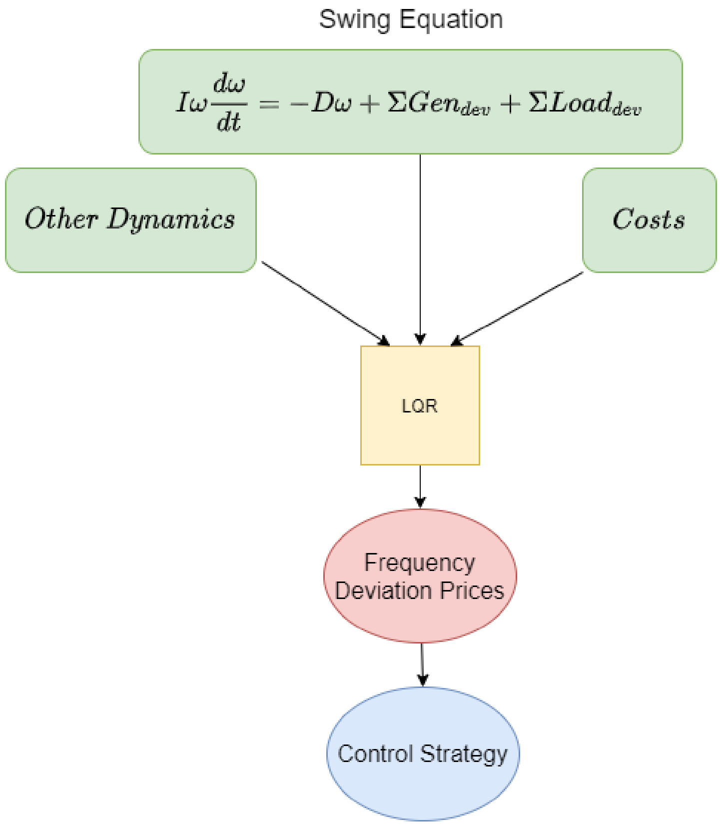
ENERGY DISPATCH PRICING COMPARED WITH FREQUENCY DEVIATION PRICING

Energy Market



Frequency Control



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SESSION 1: REMAINING AGENDA

- We aim to lay the theoretical foundation for a pragmatic evaluation of DSCP options
- The Linear-Quadratic Regulator (LQR) - “full state” feedback control
  - And how to extract a frequency deviation price from it
  - Limitations
- Linear-Quadratic Gaussian Control
  - An extension to LQR that supports control from (limited) available measurements
    - e.g. frequency and time deviation, RoCoF?
  - Evolution of frequency deviation price can be determined from local measurements
- Making the frequency deviation pricing formula practical
  - Determining system time constants
  - Scaling the pricing formula
  - Weighting strategy
- Final pricing form

THE LINEAR QUADRATIC REGULATOR (LQR)

Definition of the LQR

- The LQR is a “full state controller where:
  - The state equations/evolution are linear
  - The objective function is quadratic
  - Usually, the state and control variables are cantered on some base level, usually taken to be zero
- The system can be solved using a dynamic programming type approach and delivers:
  - a feedback control linear in the system states
  - an optimised quadratic objective function

States and Controls for our Simple Model

- What are the system states/variables?
  - Frequency deviation
  - Time deviation
  - Load deviation (forecast error, load volatility load relief from frequency deviation)
  - Generator deviation (inc. drift, PFR and inertia)
- What are the controls/variables?
  - Ramp rate for generator
  - Generator droop settings (not optimized, but they affect damping)
  - Inertia?

MODELLING (LINEAR) SYSTEM DYNAMICS

$$x = \begin{bmatrix} T_{dev} \\ Hz_{dev} \\ Gen_{dev} \\ Load_{dev} \end{bmatrix}$$

Discrete Dynamics

$$x_{new} = A_d x_{old} + B_d u$$

$$A_d = I + A_c dt \qquad B_d = B_c dt$$

Continous Dynamics

$$A_c = \begin{bmatrix} 0 & \frac{1}{TI} & 0 & 0 \\ 0 & \frac{-1}{DTC} & 1 & 1 \\ 0 & 0 & \frac{-1}{Grev_{TI}} & 0 \\ 0 & 0 & 0 & \frac{-1}{Lrev_{TI}} \end{bmatrix} \qquad B_c = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

Gen_RampRate

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MODELLING COSTS

$$x = \begin{bmatrix} T_{dev} \\ Hz_{dev} \\ Gen_{dev} \\ Load_{dev} \end{bmatrix}$$

$$Min \sum (x^T Q x + u^T R u) dt$$

$$Q = \begin{bmatrix} Wt & \frac{Wt}{TI} & 0 & 0 \\ \frac{Wt}{TI} & \frac{Wt}{TI^2} & 0 & 0 \\ 0 & 0 & Gen_{cost} & 0 \\ 0 & 0 & 0 & Load_{cost} \end{bmatrix}$$

$$R = \begin{bmatrix} Gen_{rampcost} \end{bmatrix}$$

LQR SOLUTION

Linear Control

$$u = -Kx$$

$$Gen_{ramp} = k_1 T_{dev} + k_2 Hz_{dev} + k_3 Gen_{dev} + k_4 Load_{dev}$$

$$ObjectiveCost = x^T P x$$

This is a single value
e.g. $10,000

$$Marginal\ Cost = 2Px$$

There is a single marginal cost
for each state variable

Marginal cost of spinning energy $= 2P_2 x$

System Evolution

$$x_{new} = (A - BK) x_{old}$$

$(A - BK)$ is a stabilising matrix

TOY SYSTEM DATA SET

	Value	Description
SysType	1	System type
dt	1	Measurement Interval
TDurn	300	Run Duration
DI	300	Dispatch interval
Seed	0	Random seed
fe0	0	Frequency error initial value
te0	0	Time error initial value
Macc	100	Target control matrix accuracy
TD	0	RoCoF Time Constant
TI	3600	Time Error Time Constant
Wt	1.00...	Controlled Function Weight
f0	50	Reference Frequency
feSD	1.00...	Frequency Measurement No...
TeSD	1.00...	Time Error Measurement No...
eps	1.00...	Tiny value
VFlag	1	Flag to include/exclude syst...
Inertia	11000	
Damping	1400	
DTC	7.8571	

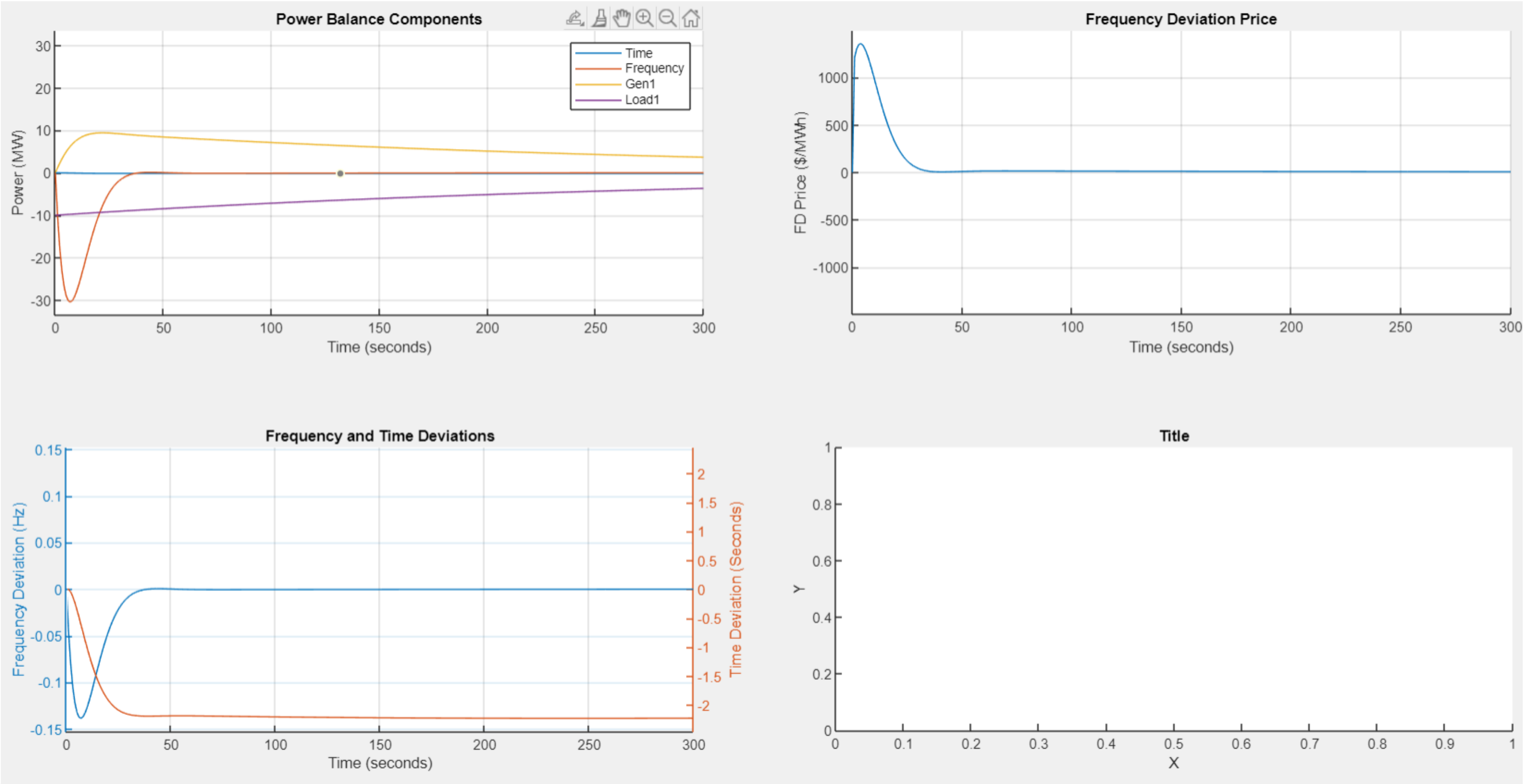
Name	Type	Rating	PFactor	RevTC	Inertia	Droop	QCostF...	RCostFac	SysNoise	MW0
Gen1	Gen	500	7	1000000	8	5	1	2	0.2000	0
Load1	Load	500	7	300	3	5	0	0	1.0000	-10

	ISE	SE	Gen1	Load1
ISE	1	0	0	0
SE	0	1	0	0
Gen1	0	0	1.0000	0.5000
Load1	0	0	0.5000	1.0000

Select Data File

Restore Defaults

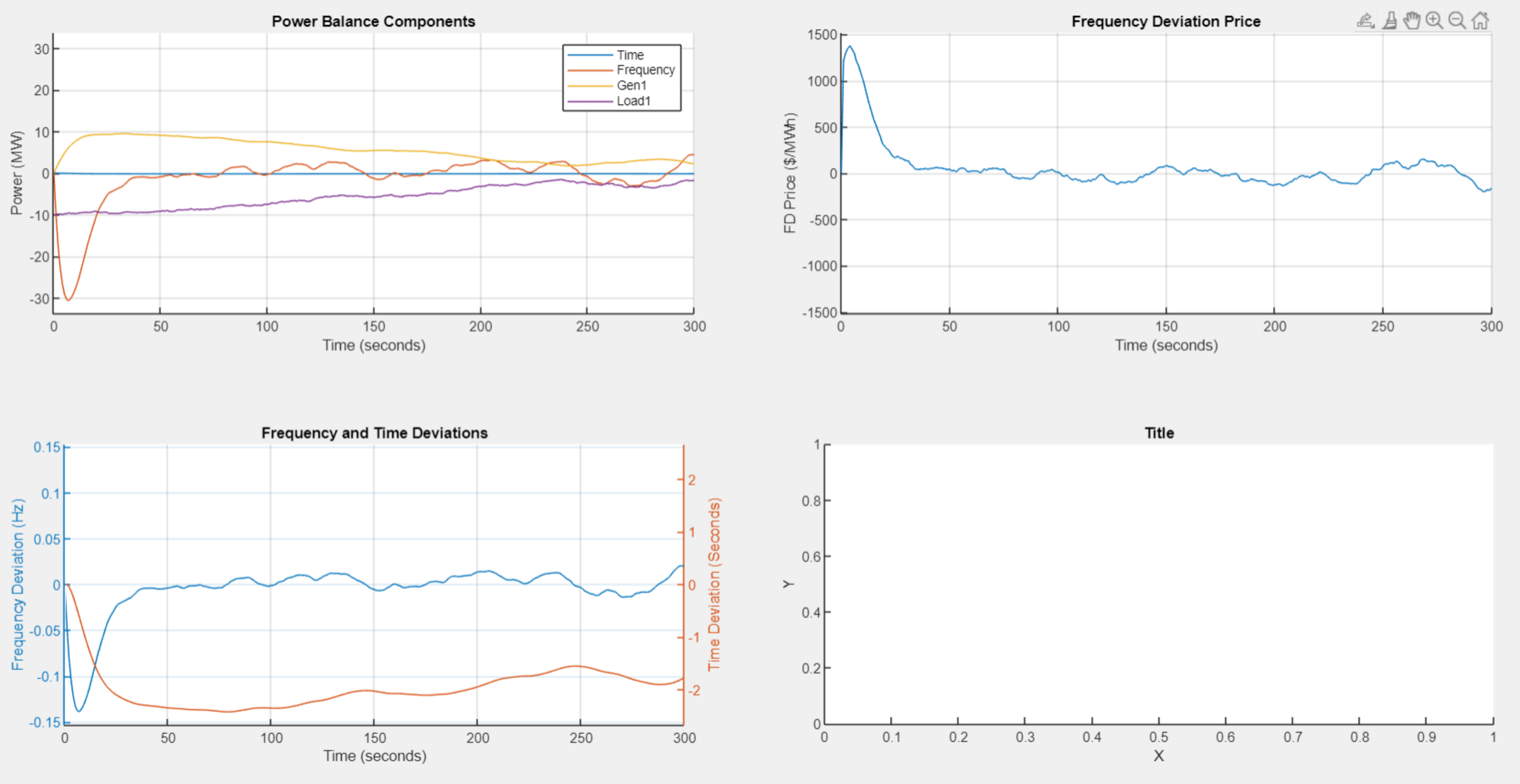
LQR SOLUTION CONVERGENCE (NO NOISE)



ADDING SYSTEM DISTURBANCES (NOISE)

- A real system will tend to be disturbed from its base trajectory
  - 5-minute forecasting errors
  - Load deviations
  - Generator deviations including semi-dispatched units
  - Disturbances may be correlated
- The LQR controller remains unchanged!
- The objective cost is increased by a fixed (and calculable) amount per unit time, so:
- Marginal costs and pricing also remain unchanged!
- System evolution becomes: *xnew* = (A-BK)*xold* + noise term

LQR EXAMPLE WITH DISTURBANCES



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CONCLUSIONS ON THE UTILITY OF THE LQR

- The LQR model delivers and optimal controller under the assumptions of the model. i.e. linear dynamics, quadratic costs, Gaussian disturbances
  - Delivers stable, least cost control
- Even with arbitrary disturbances it is an optimal linear controller.
  - There may be a better non-linear one.
- The marginal value of spinning energy (price) is easily calculated from the system state
  - Like the controller, frequency deviation price is also linear in the values of the state variables.
- Disadvantage – required knowledge of full system state in real time
  - We seek an approach with the similar advantages but based on available (local) measurements

LINEAR QUADRATIC GAUSSIAN (GAUSSIAN) CONTROL AND PRICING

- In practice, we seldom know the full system state for LQR control, but only data from a limited set of measurements.
  - Local measurements are required for rapid response
- Those measurements may also be imperfect (subject to noise) to different degrees
- We can complement LQR with a system to estimate the system state from a limited set of measurements
  - e.g. local measurements of frequency and time error
- The Kalman Filter is such an efficient estimator
  - LQR combined with a Kalman filter is known as Linear Quadratic Gaussian control
    - Examples: moon landing; small drone control; current NEM AGC?

OPERATION OF GAUSSIAN CONTROL

- Assume some initial operating state (our estimate of it may have large errors)
- From the currently estimated system state, determine a control using LQR logic.
  - This real control interacts with the real system, together with disturbances, to drive a new set of real states and real measurements
- From frequency and time error measurements, a Kalman filter updates its estimate of the current system state
  - Initially very rough, but it improves (normally quite quickly) over time.
- System dynamics are now described by:

xnew = GX*xold + WX*measurements

- GX is a stabilising matrix, WX is a weighting matrix, measurements are e.g. frequency deviation and time deviation. States x are all estimated.

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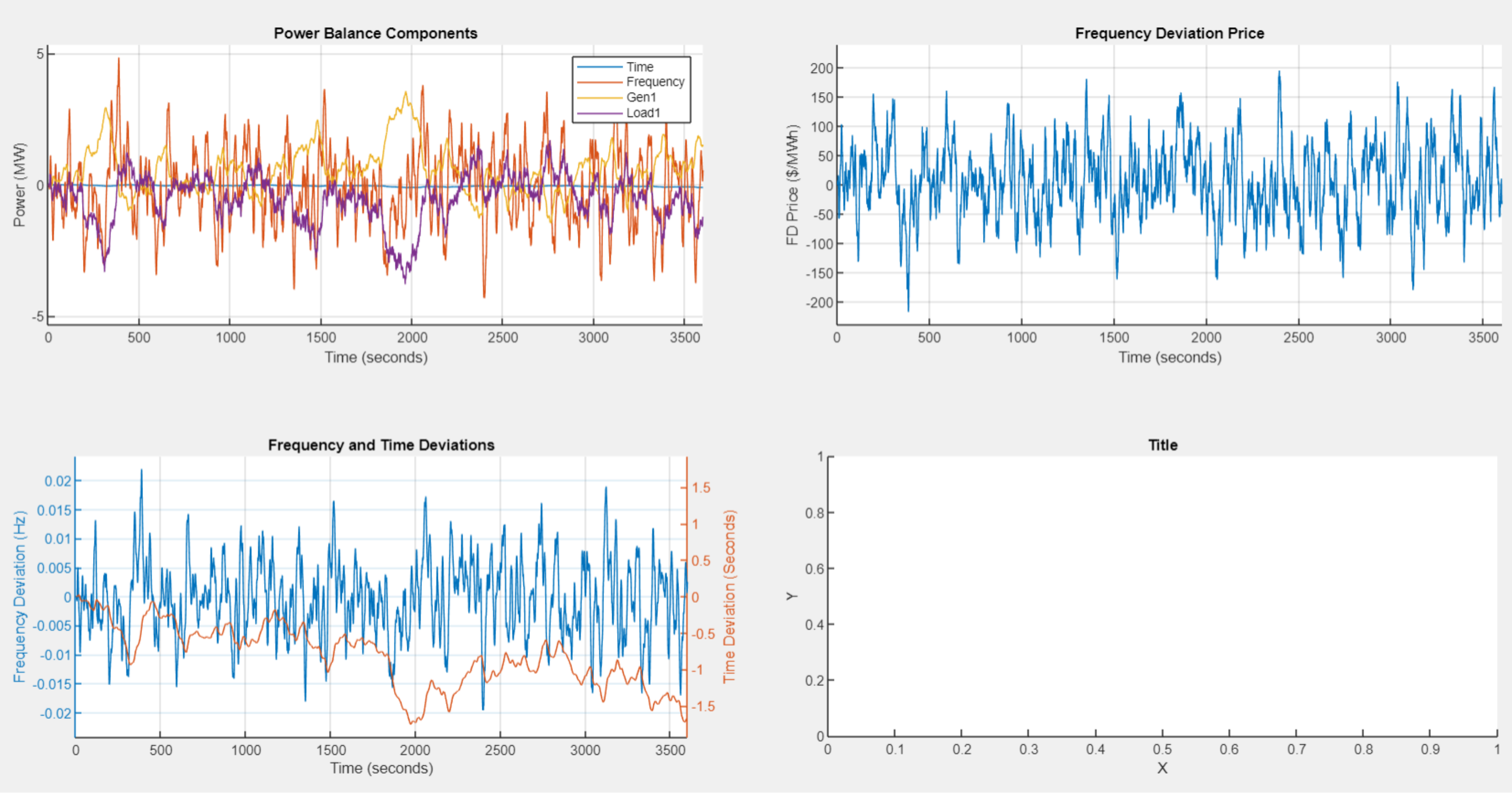
EXAMPLE OF GAUSSIAN CONTROL OUTPUT



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DERIVING A WORKABLE FDP/DSCP PRICING STRUCTURE

- System dynamics under Gaussian control

xnew = GX*xold + WX*measurements

- Practical challenges in real electricity system world…..
  - Dimension of x (number of states) is very large
  - GX is very large, square and dense
  - WX is also large (but only 2 dimensions wide)
  - GX and WX are hard to calculate in the real world, although quite easy when there is good data and system is of modest size
- We need a way to compress, simplify and link to other market systems
- And to drive or motivate the system by price

HOW CAN WE DERIVE AN EVOLVING SYSTEM PRICE?

- Given system state (x) evolution and our price of spinning energy:
  - price = P2*x = p(2,1)*Tdev + p(2,2)*Hzdev + p(2,3)*Gendev + p(2,4) Loaddev
    - P2 is second row of "Cost to Go" from LQR solution
  - price = price1 + price2 + price3 + price4 where pricei are components that align with the state terms
- We can write this in vector and matrix form as
  - price = diag(P2)*x where diag(P2) is a diagonal matrix with P2 on the diagonal
- And then invert (almost always possible) to get state as a function of price components:
  - x = inv(diag(P2))*price
- So, in LQR we can plug in price components wherever we see state variables
  - **Specifically, the optimal control is a linear function of price components; and also**

pricenew = G*priceold + W*measurements

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SIMPLIFYING THE PRICING WHILE MAINTAINING ITS GOOD PROPERTIES

- We will outline how the price components can be made separable and reduced in number, To simplify things, let's assume time is already separated out, so we have:

$$\boxed{\text{pricenew} = G*\text{priceold} + w*\text{Hzdev}}$$

  - where w is a column vector of weights, to be determined (note that each w will be negative).

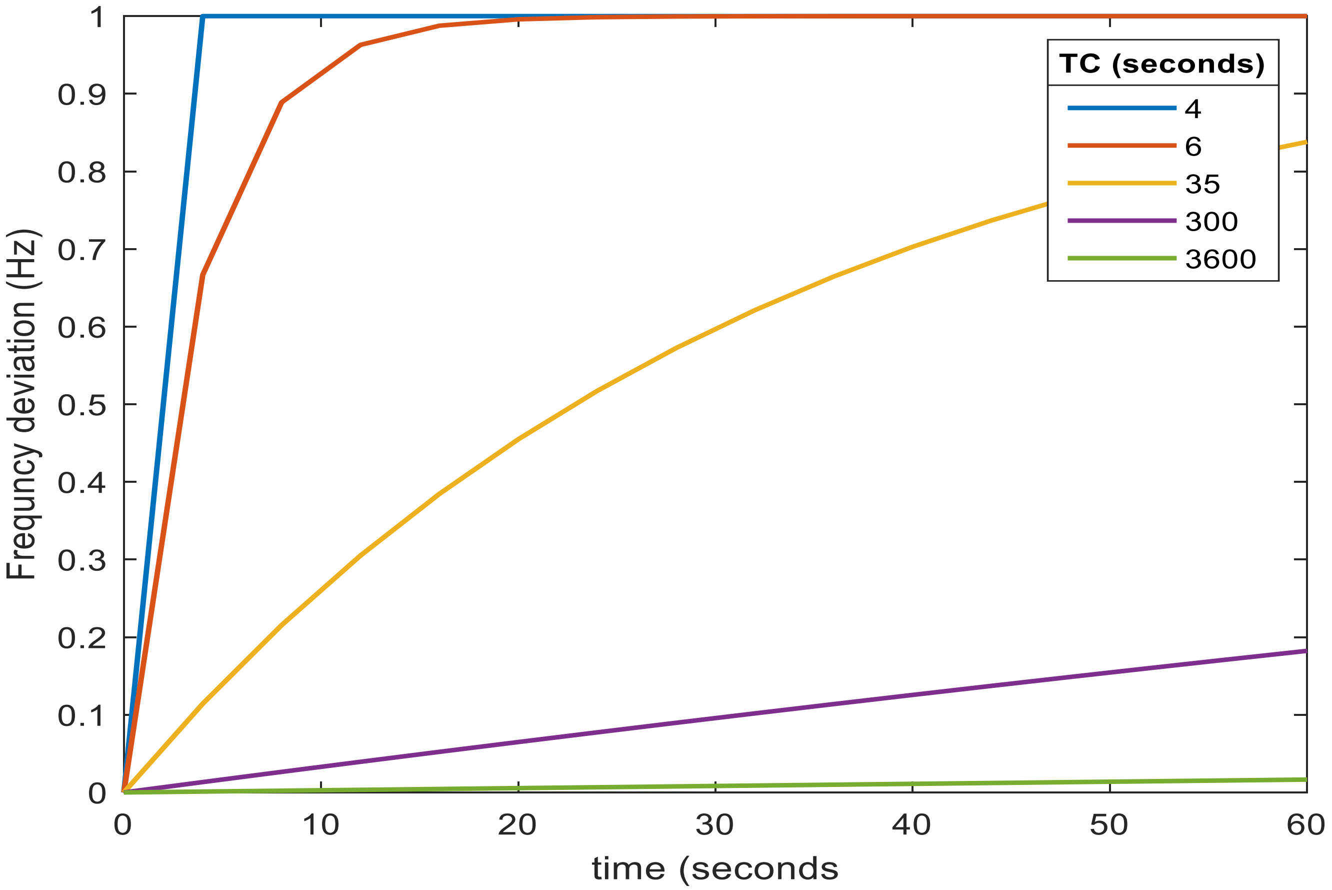
- The behaviour of systems like this is well studied in maths and engineering. By changing the variables, the terms can be made separable. If we drop terms that might cause oscillations we find that each component of price evolves in the following way (low pass filter):

$$q(i) = (1 - \text{delt}/TC(i)) - (\text{delt}/TC(i))*\text{Hzdev}(i)$$

$$\text{price}(i) = \text{weight}(i)*q(i) \qquad \text{and price} = \text{sum}(\text{price}(i))$$

  - delt is measurement interval
  - TC(i) is the time constant of component I
  - Hzdev(i) is the measured frequency deviation
  - weight(i) is a weighting on component I
  - q(i) is an intermediate calculated value

UNWEIGHTED PRICE COMPONENT RESPONSE TO A STEP CHANGE



SHRINKING THE NUMBER OF PRICE COMPONENTS

- We can review separable components and shrink their number:
  - Discard small time constants (<4 seconds – can't measure yet)
  - Discard large time constants >5-10 minutes – market will take care??? Time error – retain.
  - Amalgamate 'close' values
  - There are advanced techniques, but judgement required in practice.
- For the NEM
  - Case 1 - Single component: 4 sec. TC –> raw frequency – this is base assumption for DCSCP
  - Case 2 - Two components: add 35 sec. TC to support/simplify regulation FCAS with extended DSCP
  - Case 3 - ????
- Note that price components are additive; they work together.
  - In 4 second TC case, payment in one measurement period is proportional to HzDev*MW – Causer Pays!
  - In 35 second (?) case HzDev is lagged with a known and simple low pass filter formula.

WEIGHTING THE PRICE COMPONENTS (1)

- Note the important parameter Wt used to weight the frequency/time deviations relative to the deviation and control dollar costs in the system:
  - We aim to minimize costs subject to the distribution of frequency/time deviations staying within specified bounds, so Wt will be adjusted to chive that goal
- We also need a practical away to deal with system changes over time (e.g. over a daily cycle) in the event of a rapid and major change e.g. network separation, but noting that contingency services would kick in)
- Good News for LQR!
  - If a system is scaled the same everywhere, pricing and control strategies remain unchanged.
  - While uniform scaling is never achieved, this result nevertheless suggests that a pricing formula can remain ‘fixed’ in different situations

WEIGHTING THE PRICE COMPONENTS (2)

- Can we weight the FDP to maintain a stable and efficient operation?
- Some Options
  - Weight by matching regulation enablement price with an estimate of the marginal cost of supply from a thermal generator (indicative method from CS Energy/IES Report)
    - Unsatisfactory, mainly because a thermal generator may not remain a suitable benchmark
  - Weight to achieve a cash turnover through SCP bearing some relationship to that through enablement (regulation or even PFR if present.
    - Ensures that DSCP does not take over from enablement, at least at (possible) launch.
    - A measurable basis, but only applicable over a settlement period.
  - Weight by some other method ???

WEIGHTING PRICE COMPONENTS (3)

- We also recognize that:
  - The system changes over the course of the day and at times of stress, especially the energy price.
  - AEMO seeks a wide geographic spread of the service, not all lumped into one region
- Weighting each component each 5 minutes by the (local) Energy Market Price is a robust possible solution for the following reasons:
  - Under certain assumptions about cost functions (exponential within some range), the LQR model scales in a way that maintains the same control strategy for frequency. i.e. energy prices do not influence DSCP participation
  - The FDP/DSCP cash flow stream is easy to hedge through the energy market
    - Payment(i) = Weight(i) * Energy_Market_Price * FDP_Covariance(i), where
    - Payment(i) is the payment relating to price component (service) i
    - Weight(i) is determined in advance no more than each settlement period, by assessing against enablement cash
    - Energy_Market_Price is the local energy market price (including MLFs!)
    - FDP_Covariance(i) is the DSCP factor for price component i for that 5 minutes.

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SESSION 2: MOVING TO IMPLEMENTATION

SESSION 2 AGENDA

- DSCP as a pragmatic implementation of FDP for PFR
- Implementation issues
  - Adequacy of metering
  - Dealing with system non-linearities
  - Interface with other frequency control services
  - Stability of the system with more renewables and lower inertia
  - Stability of the system with more batteries
  - Stability of the system with too-high pricing
  - Impact of potential “rogue behaviour”
  - Fixing DSCP pricing discontinuities between dispatch intervals
- Overview of a possible DSCP design and implementation strategy
- Software demonstration?

DSCP AS A PRAGMATIC IMPLEMENTATION OF FDP FOR PFR

- 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.

DSCP AS A PRAGMATIC IMPLEMENTATION OF FDP FOR PFR (2)

- Regardless of the metering method, the following logic would apply for each price component to be implemented (one or possibly two). This logic is consistent with the FDP concepts already described.
  - In each 5_minute dispatch interval, the product of frequency deviation (lagged if required) and generation/load deviation is calculated for each measurement interval, averaged and stored.
  - At settlement time, each 5-minute value is weighted according to some rule and the resulting sum determined for payment purposes.
  - 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, as well as participation in any enablement market, participants would have complete information to guide their responses.
  - Note also the similarity to the current causer pays procedure. A 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.

ADEQUACY OF SCADA METERING

- SCADA metering is at 4 second intervals (on the mainland) and less reliable than energy settlement metering in several respects:
  - Our Inception Report outlines how we will analyze the adequacy of SCADA metering at the PFR level
  - Note that ‘narrow band’ PFR is deigned to support the ‘small deviation’ (regulation) service to deal with frequency changes that are relatively slow and smooth (to be demonstrated).
- We also need to examine how potentially fast acting participants might react when metered at 4 seconds e. g. by investigating the commercial incentives expected to apply because the metering can’t keep up.
  - This is a specific analysis topic to follow.

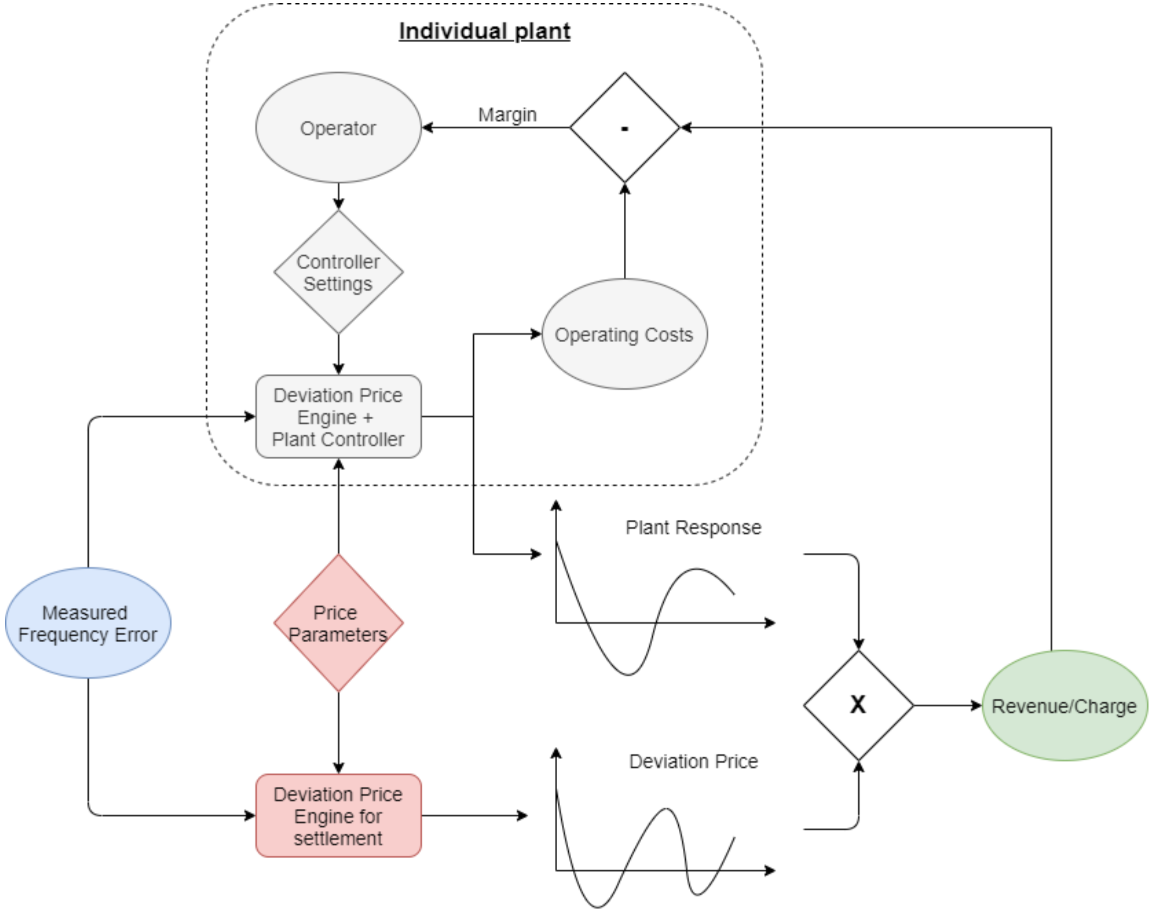
DEALING WITH SYSTEM NON-LINEARITIES

- A key assumption of our model and pricing is that the system is linear within the region of operation
  - ‘hard’ limits such as capacity would be handled by existing enablement markets – effectively ensuring sufficient headroom
  - Absent an enablement market, participants could make their own headroom if sufficiently motivated
    - Hence the importance of weighting the factors by energy or some near proxy when capacity is strained.
  - Other ‘non go’ areas such as rough running areas or dead bands can also be managed by participants
- Given these conditions, there is no basis to for a non-linear or capped pricing function, or one which implements pricing dead bands; linear is simplest and most efficient.
  - Linear control and Gaussian noise produces normally distributed outputs, which is generally observed.

INTERFACE WITH OTHER FREQUENCY CONTROL SERVICES

- DSCP for PFR and possibly to support regulation would work with or possibly replace existing and proposed frequency control services including
  - Mandatory PFR (existing but subject to review and possible replacement)
  - Existing regulation enablement and Causer Pays cost recovery
  - Potential PFR enablement
  - Indirectly, contingency services
  - Indirectly and possibly, ramping and even operational reserve markets (ESB).
- 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.
  - Mandatory provision could be wound down over time of deemed appropriate – more efficient?
- There is scope to simplify and improve the AGC regulation arrangements by adding a second, lagged price component to the DSCP system:
  - This could drive down enablement costs and allow the existing causer pays system eventually to be scrapped and replaced with a simpler way to recover costs.

METHODOLOGY FOR FINANCIAL INCENTIVES/STABILITY STUDIES



Analytical Outputs

- Frequency Deviation Distribution
- Time Deviation Distribution
- System Cost
- Plant Margin
- Alignment of plant control with system controls

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STABILITY OF THE SYSTEM WITH MORE RENEWABLES AND LOWER INERTIA

- 10 years hence we expect to see more renewable plant and less ‘spinning’ plant with in-built inertia:
  - Leading to greater variability within the DI and lower inertia
- We can model these conditions and check for
  - What volume and type of delivery capability will be warranted
  - Response and stability of the system operating under FDP as inertia declines
  - At what point would CADA metering limitations become unacceptable, prompting a move to higher resolution metering
- This work will intersect with another study issue concerning batteries
  - As well as studies concerning profit-seeking and possibly careless behaviour

STABILITY OF THE SYSTEM WITH MORE BATTERIES

- Battery technology is well suited to frequency control and will likely be available in volume by 2030 or before:
  - Batteries can ramp almost instantaneously and normally sustain an output for 5 to minutes without interrupting its daily energy cycle.
  - This ability provides opportunity as well as a possible challenge to stability under FDP/DSCP
- We will study this as follows
  - Establish a baseline with and historical plant mix
  - Taking one unit to be a battery, see what happens to an optimized LQR solution as ramping cost is reduced
    - Check for policy change, stability, metering issue, profitability and system performance
  - Check what happens when there is saturation – limit reached
  - Check point of battery maximum profit and consistency with good outcome
  - Check metering issue if optimal response is very fast
- Demonstration?

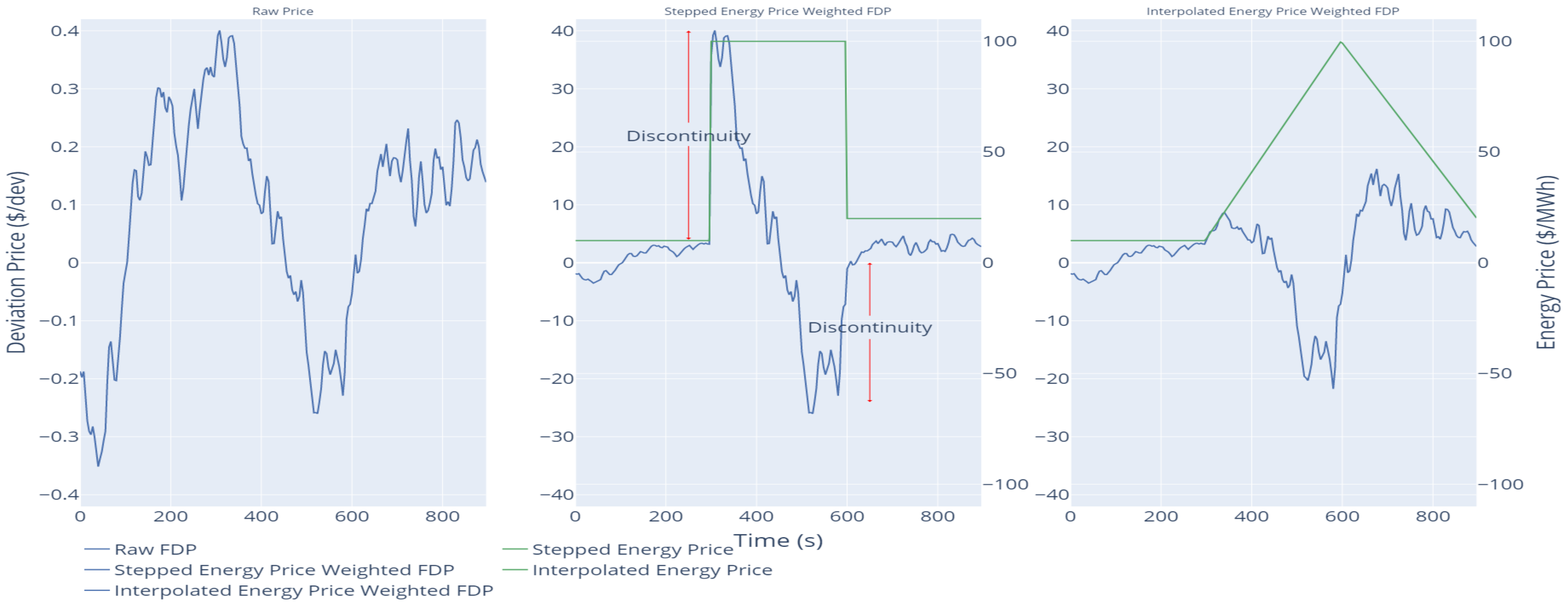
STABILITY OF SYSTEM WITH GAIN TOO HIGH ON SOME FDP COMPONENTS

- The proposed weighting strategy for the FDP components would seek to ensure non-negative residual prices on the corresponding enablement.
  - Signaling that enablement is still setting the requirement even though FDP might be doing some or most of the work
- However, there may be no exactly corresponding enablement market at the time
  - In which case it may be possible to inadvertently weight the FDP to be ‘too high’ (i.e. higher than an optimal value for stability and efficiency)
  - For example, a modest FDP might elicit far more response tan expected
- To be tested by modelling:
  - If the gain is too high, are participants motivated to respond in proportion, risking instability?
  - Or are they financially motivated to wind back to adjust to a more stable outcome?
  - Does a modest level of mispricing affect stability, costs, some combination or not much at all?

IMPACT OF POTENTIAL “ROGUE BEHAVIOUR”

- Rogue behaviour is defined as behaviour that is non-optimal both for the system as a whole and also for a participant’s finances.
  - Such behaviour might result from a lack of attention to strategy, perhaps from a group of similar participants
  - We note the such behaviour is already ubiquitous within the system load
- We will study what might happen when a large participant acts erratically, if given the license to make their own decisions to respond to FDP
  - How would the rest of the system be likely to respond?
  - Does this behaviour pose any risk to system stability or costs?

FIXING DSCP PRICING DISCONTINUITIES BETWEEN DISPATCH INTERVALS



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OVERVIEW OF POSSIBLE DSCP DESIGN AND IMPLEMENTATION STRATEGY (1)

- The DSCP system will target PFR and AGC regulation, 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 service (two services proposed here) per interval.

OVERVIEW OF POSSIBLE DSCP DESIGN AND IMPLEMENTATION STRATEGY (2)

- 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: restrict receivers of payment 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 shrink over time and so support a simplified cost recovery option like that used for contingency.

CONCLUSIONS – PROJECT ANALYSIS PHASE

- We will perform further analyses relating to ‘Size of the Prize’
  - Historical PFR performance
  - Improvement under mandatory PFR capability
  - Scope for further improvement
- Assessment of potential SCADA metering performance under DSCP
- System modelling will:
  - be based on a fully-developed LQR/Gaussian model and detailed reporting, integrated with a simple energy market;
  - model enablement markets at some level; e.g. assume MW and enabled and price of FCAS services;
  - stress test for stability based on variations on the optimal LQR operating policies;
  - focus on likely system status 10 years hence; and
  - investigate financial winners and losers (if any!) in each scenario