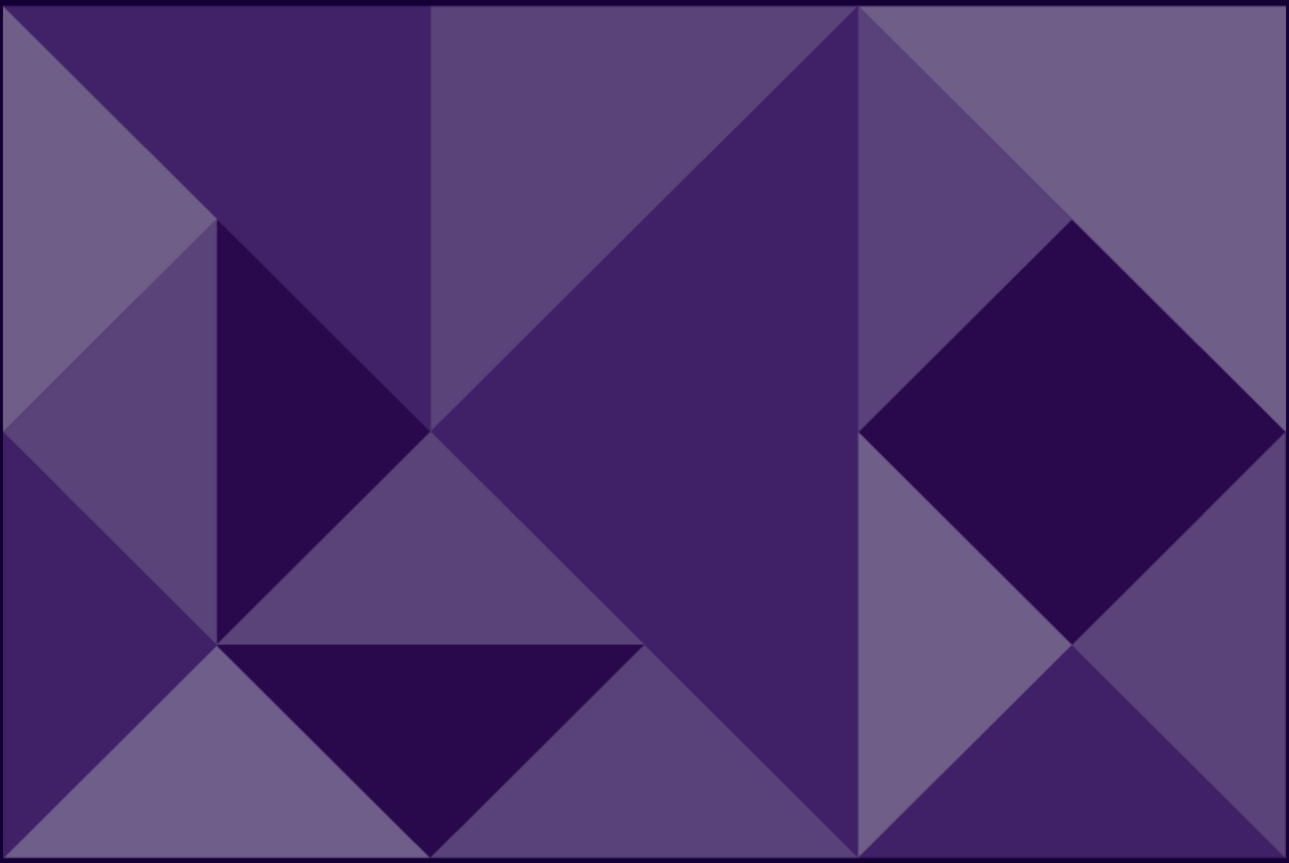
13 July 2023

Report to AEMO

Modelling the settlement effects of Project Energy Connect

Final Report



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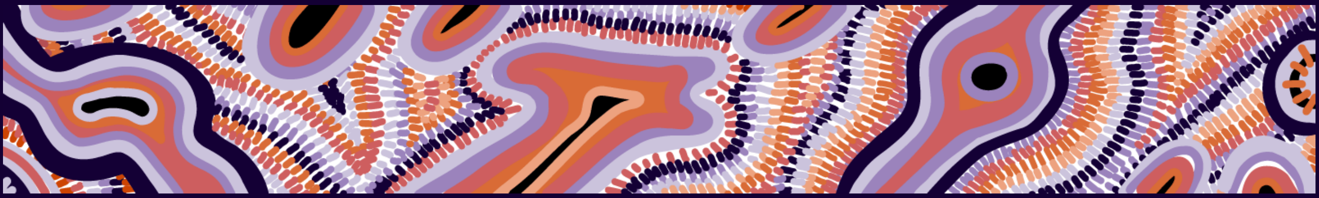

Goomup, by Jarni McGuire

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Executive summary

The expected commencement of Project Energy Connect (PEC) in 2024 will introduce an inter-regional transmission loop connecting South Australia, New South Wales and Victoria. This report sets out the key findings and analysis from the modelling undertaken to understand potential settlement residue issues which may occur as a result of the loop:

Box ES 1 Problem Statements

How will negative inter-regional settlement residues accrue in the loop and what are the key drivers?

How does the phase shift transformer (PST) impact inter-regional settlement residues?

What methods are available to distribute negative inter-regional settlement residues between the three regions?

Summary of key findings

The table below summarises of the key findings from our analysis:

Table ES 1 Summary of key findings

Issue	Key Finding
Positive inter-regional settlement residues	The modelling indicates that the loop will have positive inter-regional settlement residues on all three interconnectors only 7 to 11% of the time. Today's normal may become abnormal with PEC and the introduction of the transmission loop so there is a clear need for changes to dispatch and regulations to ensure reasonable settlement outcomes. Positive inter-regional settlement residues do not necessitate any change in regulations.
Negative inter-regional settlement residues	The modelling shows the PEC loop will commonly result in negative inter-regional settlement residues on inter-connectors, and this is expected as part of efficient dispatch. This usually occurs when overall settlement around the loop is in surplus – this is called 'net positive residue'. However, at times settlement is modelled to be in deficit, with the negative inter-regional settlement residues exceeding those positive, so settlement is in deficit – this is called net negative residue. This occurs due to mispricing of generator nodes in the presence of intra-regional constraints. Negative inter-regional settlement residues are expected to increase into the future due to increased periods of congestion.
Net positive (non-negative) residue (settlement in surplus)	The combination of the loop constraint and intra-regional constraints is expected to often result in negative residues on one (or two) directional interconnector(s) in the loop, and yet inter-regional settlement is in surplus overall.

Issue	Key Finding
	The frequency and value of net positive (non-negative) residue is expected to be commonplace, around 94 to 98% of total periods across the PST scenarios. Out of these, roughly 40% of periods had zero residue. Net positive residues are expected to occur regularly and indicate a need to reallocate settlement residues around the loop.
Net negative residue (settlement in deficit)	The combination of the loop constraint and intra-regional constraints is expected to result in net negative residues on the loop. The frequency and value of net negative residue is expected to be small but increase over time. It ranges from one to five per cent across all years and PST scenarios. The value is also expected to be very low compared to the positive settlement residue, around one per cent. In summary, net negative residues are expected to occur and could be managed through: • Do nothing • Constrain flows on negative IRSR lines • Disconnect a line to remove the loop constraint (however we found that net negative IRSR can still occur without the loop constraint and only intra-regional constraints) • Both options two and three above
Impact of PST on settlement residues	The PST setting is expected to have a material impact on settlement outcomes because it is an equality constraint and binds every period. It often prevents NSW-SA and VIC-SA interconnectors from reaching their physical limits. This results in much higher occurrences of positive and negative settlement residues on the loop. The VIC-NSW interconnector has the highest capacity and lowest coefficient on the loop which means it has the highest range of dispatch outcomes. As a result, it is expected to have much higher positive residues than the other interconnectors.
Reallocation of settlement residues	We looked at different methods to reallocate negative settlement residues on the loop for the periods where there is net positive settlement residue. Scaling back the positive legs by the negative leg and zeroing out the negative leg appears to be the most efficient method. This is because it results in relatively minor changes and is simple to implement.

Recommendations

- Due to the loop constraint, PEC is going to be underutilised most of the time which is inconsistent with the proposed operational strategy of the PST. The PST control strategy should primarily focus on maximising the value of trade and not maximising flows to ratings, because the loop constraint does not allow both PEC and Heywood to flow at their ratings. A different strategy such as optimisation (for example, through NEMDE, or PreDispatch) to provide a more economical dispatch outcome could be considered.
- AEMO’s current loop constraint approximation needs to be improved to include the impact of intra-regional flows through generator terms. Otherwise, it creates inaccurate nodal prices which may mislead generator bidding, with the potential to produce sub-optimal dispatch. This may have further implications for the proposed Congestion Relief Market (CRM) design because it uses local prices for settlement of Congestion Relief. The loop flow constraint is also an input for upcoming 2024-25 MLFs so needs to be finalised by the end of the year.
- The loop flow constraint can be improved by completing the loop flow model via incorporating generator and dispatchable load terms that in effect model the intra-regional lines that are part of the inter-regional loop. Further since VNI is composed of four inter-regional lines there would need to be four loop flow constraints, one for each line, and an additional constraint that sets VNI to be equal to the sum of the four physical lines.

Introduction

1

The expected commencement of Project Energy Connect (PEC) in 2024 will introduce an inter-regional transmission loop connecting the South Australia, New South Wales and Victoria regions. PEC is likely to interact with the NEM's current hub and spoke pricing model in these areas:

- Allocation of the inter-regional settlement residues (IRSRs) and clamping of interconnector flows when there is net negative residue on the loop.
- Operation of the phase shifting transformers (PST) in NSW to impact the flows on the South Australia to NSW interconnector (PEC). This will influence regional prices and the IRSRs.
- Calculation of locational marginal prices (LMPs or nodal prices).

AEMO has engaged ACIL Allen to advise on the impact of PEC on these areas. This report sets out the key findings from our analysis.

The following box summarises the problem statements which the project aims to address.

Box 1.1 Problem Statements

How will negative inter-regional settlement residues accrue in the loop and what are the key drivers?

How does the PST impact inter-regional settlement residues?

What methods are available to distribute negative inter-regional settlement residues between the three regions?

Extrapolating from the problem statement, the following project objectives were undertaken in three stages:

1. Develop a simple prototype model to gain insight into the problem and enable AEMO staff and external stakeholders to get a feel for what could happen with an inter-regional loop constraint.
2. Run a full NEM market model with intra-regional constraints and the loop constraint to simulate the impact of the loop constraint over the first few years of operation.
3. Explore how to reallocate the negative settlement residue on the loop under different methods.

The following chapters describe the process undertaken to achieve these objectives:

Chapter 2 sets out the findings from the first stage of the analysis.

Chapter 3 sets out the findings from the second stage of the analysis.

Chapter 4 looks at methods to reallocate settlement residues on the loop.

1.1 Background

Loop flow constraint

AEMO has modelled a loop flow constraint equation which shows the interrelationship between the flows on the NSW-SA, VIC-SA and VIC-NSW interconnectors. The loop flow constraint is an approximation that has not yet been proven in NEMDE. Further engineering assessments will consider the effectiveness of the constraint in representing loop flows and the effect of the PST.

Further detail on the development of loop flow constraints is provided in Appendix A.

PEC includes phase-shifting transformers (PST) which act to balance flow on the AC interconnectors, via changing the flow along the NSW-SA interconnector. The PST changes tap position to balance flows around the loop by effectively changing the impedance of the PEC interconnector, rebalancing flows between NSW-SA and VIC-SA.

The loop flow constraint is an 'equality' equation using an '=' rather than an inequality limit equation ("<=" or ">="). As such, it applies at all times, and will affect prices around the loop when other limit constraints apply in dispatch.

Loop flow constraint:

PEC + c(1) x VNI + c(2) Heywood = PST(ɸ)   where:

c(i)   is a constant (constraint coefficient)

PST(ɸ) is a MW offset based on the PST's tap change voltage phase shift of ɸ

Coefficients and PST(ɸ) are set out below:

Table 1.1 PST Loop Flow Constraint Coefficients

Scenario	c(1) - VNI	c(2) - Heywood	PST(ɸ)
1) No outage, PST -6.73°	0.1413	0.8084	-20.9260
2) No outage, PST 0°	0.1410	0.8073	73.7164
3) No outage, PST 8°	0.1408	0.8090	186.6568

Increasing the PST angle increases the PST(ɸ) MW offset on PEC in the direction of flow towards SA. This balances flow around the loop and allows more power to be dispatched to flow on PEC towards SA.

Negative Settlement Residues

Inter-Regional Settlement Residues (IRSRs) accrue from the transfer of electricity through regulated interconnectors between adjacent regions with different prices. Typically, in the NEM IRSR will be positive when electricity flows from a lower-priced region to a higher priced region. The differences in regional reference prices can be caused by constraints and transmission losses as power flows across an interconnector. For this analysis, losses have not been included to focus on the impact of the loop and intra-regional constraints. IRSRs are purchased by market participants to manage price separation risks when trading power in two different priced regions.

Negative IRSR result from periods of power flow from higher priced regions to lower priced regions. In the NEM currently, these counter-priced flows are typically driven by:

- Dispatch process issues that require a counter-priced flow in response to operational requirements including, intra-regional network constraints, market ancillary service requirements and inter-network tests.
- Errors or problems arising from failed SCADA data input, telemetered ratings, or other dispatch issues
- Pricing and metering issues where AEMO might intervene in the dispatch process or set intervention pricing or regional reference node pricing to the market price cap. Issues may also result from generators not conforming to their dispatch target.

AEMO processes manage negative IRSR by allowing negative IRSR to accrue on an interconnector up to the $100,000 threshold[1]. If accumulation of negative IRSR over the period of counter price flows is forecast or estimated to reach the threshold, AEMO intervenes to apply a “clamp” by invoking constraint equations that limit the flow over the directional interconnector. This condition reduces counter price flows and stays in place until AEMO decides that the conditions causing the counter-price flows no longer persist.

The integration of PEC and the first inter-regional transmission loop in the NEM will give rise to negative settlement residues becoming an increasingly common feature of dispatch as the power flows are balanced around the loop and dispatch optimised to maximise economic value. Negative IRSR may occur on one, two or three “legs” (interconnectors) around the loop. IRSR around the loop in aggregate may then be either net positive (a settlement surplus) or net negative (a settlement deficit).

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[1] https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Dispatch/Policy_and_Process/2018/Brief-on-Automation-of-Negative-Residue-Management.pdf

Stage One: Prototype model

2

2.1 Spreadsheet model

With the introduction of PEC and how the PST is operated, the inter-regional loop could impact the NEM in the areas of: dispatch, regional reference pricing, IRSRs, and how LMPs would be calculated in the CRM.

To get some insight into PEC's impact on NEM's IRSRs and the calculation of LMPs and inter- and intra-regional surpluses in the CRM and to enable AEMO staff to get a feel for what could happen with an inter-regional loop, two simple spreadsheet models were developed. One uses a NEM style regional model and an inter-regional loop flow constraint and the other uses a DC power flow model. The DC power flow model was developed to check the NEM style regional model and facilitate comparing results between the two models.

The spreadsheet models showed that:

- Net negative inter-regional settlement residues around the inter-regional loop can readily occur when there are binding intra-regional constraints and incentives for the constrained generators to bid at the market floor price (MFP), this is the case even when the PST's operation is optimised
- The use of a loop flow equality constraint that only uses interconnector flows does not produce optimal dispatches nor correct LMPs
- The optimisation of the PST settings can substantially impact the efficiency of the dispatch, amount of the net negative inter-regional settlement residues and prices
- There are a number of possible ways to manage negative inter-regional settlement residues on the inter-regional loop including:
  - constrain flows on negative IRSR lines
  - disconnect a line, say Heywood or PEC,
  - constrain flows on a negative IRSR line, say PEC, and disconnect a line, say Heywood
  - ignore net negative settlement residues

The spreadsheet models can enable the quick exploration a number of possible ways to allocate the settlement residues around the inter-regional loop such as:

- when the IRSRs are positive on each interconnector just allocate according to each interconnectors IRSR
- when there is one negative IRSR around the loop but there is a net positive total IRSR use a formula to allocate the total IRSR
- when there is a total negative settlement residue use a formula to allocate the total to each interconnector.

The formulae used for allocations of the IRSRs could be functions of flows, shadow prices of interconnector capacity constraints, shadow prices of loop flow constraints, inter-connector IRSRs etc.

2.1.1 Overview of models

The spreadsheet models consist of:

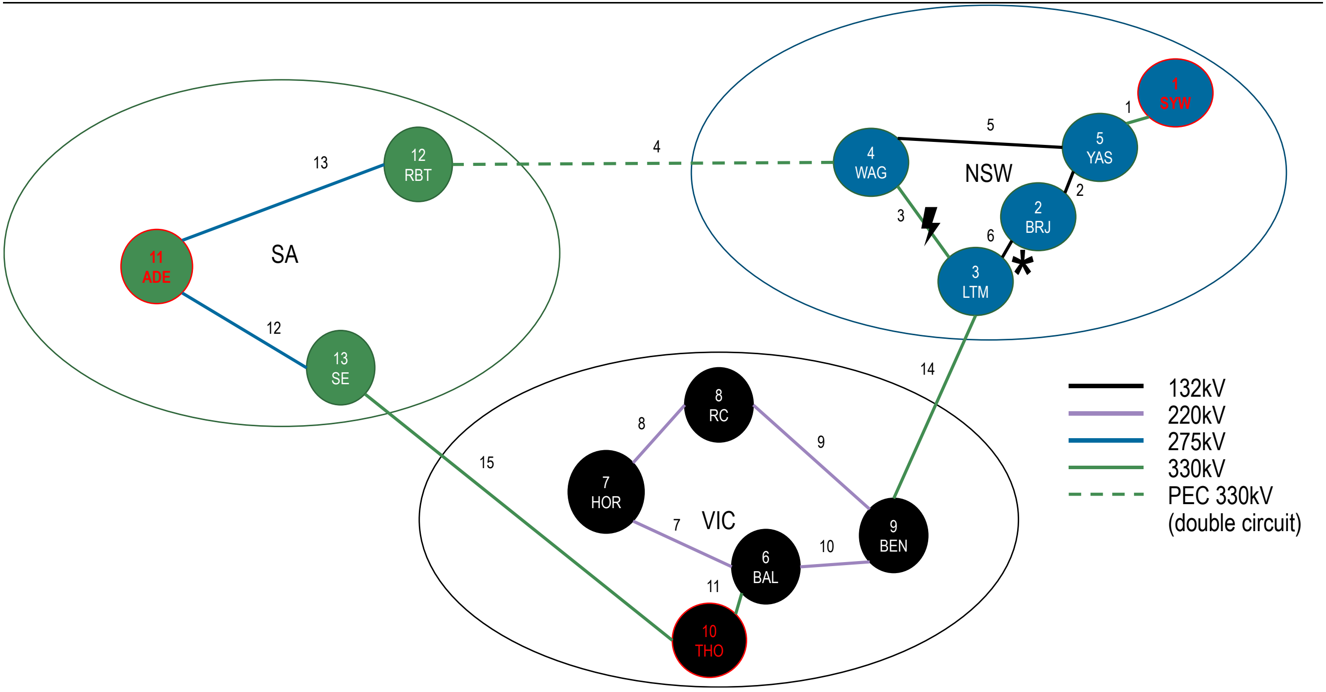
1. a NEM regional model with the options of
    a. a full loop flow constraint and
    b. an approximate loop flow constraint which only uses interconnector flows and
2. a DC power flow model.

The spreadsheet models used steady state thermal constraints, not N-1 constraints. However, this should be adequate to get a feel for the issues.

Network and branch information

The models used a stylised network configuration with key elements of the NSW, Victorian and SA regions and the interconnectors, see Figure 2.1. The network models used the branch ratings, resistances (Rs), reactances (Xs) and network topology to directly model the power flows in the DC power flow model or indirectly model the power flows via NEM like generic constraints based on power injection shift factors.

Figure 2.1 Network Configuration



Load and bus information

The bus input comprised the nodal load forecasts. The regional load forecasts and the network constraint RHSs were calculated from the nodal load forecasts and branch ratings. The NEM loop dispatch model also included regional load violation variables and penalties.

Generators and dispatchable loads/batteries

In the model, there were 16 generators and two dispatchable loads/batteries. The generator and dispatchable load/battery input data consisted of:

- Node/bus connection point
- Type of generating unit
- Minimum power (Pmin) which could be negative for a battery or load
- Maximum power output (Pmax)

- Two quantity and price bid/offer bands for energy

The NEM loop dispatch optimisation

The formulation of the NEM loop optimisation was:

Minimise the total energy and violation penalty costs

Subject to the following constraints:

- Dispatch of energy price bands >= 0
- Dispatch of energy price bands <= offered capacity
- Dispatch of energy >= operational Pmin
- Dispatch of energy <= operational Pmax
- Regional energy violations >= 0
- Energy power flows are within line limits based on shift factors
- Inter-regional loop flow constraints:
  - Power flows around regional loop = 0 (or offset) if no PST operation
  - Power flows around regional loop = constant if PST phase angle is set
  - Power flows around regional loop are between upper and lower bounds if PST operation is a decision variable
- Regional energy balance

Management of network constraints in NEMDE

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

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

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

$F_i = \sum a_i P(i)$

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

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

Or

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

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

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

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

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

This leads to the post contingent thermal constraint on power flows

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

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

Calculation of RRPs and LMPs

NEM RRPs

The NER 3.9.2 (d) states that

> *The spot price at a regional reference node represents the marginal value of supply at that location and time, which is determined as the price of meeting an incremental change in load at that location and time as per clause 3.8.1(b).*

This is just the marginal price at the RRN, that is, it is just the LMP at the RRN.

DC power flow model calculation of RRPs and LMPs

The DC power flow model calculates the LMPs for all buses (nodes) from the shadow prices of the nodal energy balance equations. It calculates the RRPs as the LMPs for the RRNs.

NEM loop flow model calculation of RRPs

In NEMDE the spot price at the RRN is determined from the shadow price of the regional energy balance equation. Because this approach has been used to determine the RRPs, all network constraints have to be 'oriented' such that they do not include any terms for dispatchable resources located at the RRN or on the RRN side of a network constraint, otherwise the correct RRP could not be determined from the shadow price of the energy balance equation.

NEM loop flow model calculation of LMPs

The calculation of LMPs for the current situation in the NEM where there are no inter-regional loop flows is as follows.

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

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

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

Impact of loop flow constraints on LMPs

With the addition of an inter-regional loop flow constraint the formula above no longer correctly calculates LMPs. The shadow price of the loop flow constraint and the coefficients of the lines involved in the constraint now need to be included. In effect the loop flow constraint adds to the shadow prices of the network constraints.

If the shadow price of the loop flow constraint is μ and the coefficient of line k in this constraint is d_k then if we just model simple thermal steady state constraints the LMP of bus n is

$$LMP_n = RRP + \sum_{k\ in\ network\ constraints} (\lambda_k + d_k \times \mu) \times c_{k,n}$$

Note that if generator terms are added to the loop flow constraint instead of the coefficients of the lines then the formula for the LMP is

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

Settlement Surpluses and LMPs

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

The energy settlements surplus for an LMP model is

Surplus

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

Where L_j is the load at bus j and G_k is the generation at bus k.

This surplus is also equal to the network constraint costs

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

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

This is also equal to the congestion rents on the transmission lines where F_k is the flow

$$= \sum_{k\ in\ Lines} (LMP_{end} - LMP_{start}) \times F_k$$

2.1.2 Two models for the inter-regional loop flow constraint

The spreadsheet model allows for choosing a full loop flow constraint or an approximate loop flow constraint that only uses the inter-regional lines and has an offset term. The approximate loop flow constraint does not produce optimal dispatches nor correct LMPs because it is missing intra-regional flow terms or equivalently generator terms, see discussion in section A.4.

The comparison and analysis in the spreadsheet model identified the inter-regional loop flow constraint and its impact on intra-regional constraints as an additional area for refinement with or following the implementation of PEC. The continued application of the approximate loop flow constraint will not produce the optimal dispatches and correct LMPs, which could mislead generators regarding network congestion and investment decisions because a generator would not have accurate marginal pricing information. Further, this can lead to sub-optimal outcomes with the introduction of the CRM.

2.1.3 Test cases

The spreadsheet test cases were set up such that the bids were logically consistent, to a reasonable extent, with each generating unit's short run marginal cost (including opportunity costs), RRP and its underlying locational marginal price based on the marginal costs (shadow prices) of binding constraints. Where binding network constraints and the RRP constrained a unit's output was above its SRMC then it would bid at below its own LMP, probably down to the market floor price (MFP) of -$1000/MWh.

A range of test cases were set up with some resulting in overall inter-regional settlement surpluses (net positive around the loop) and some ending up with overall negative settlement surpluses (net negative around the loop) even when the PST's voltage phase shifting tap settings were optimised.

2.1.4 Example of net negative settlement residue

An example of a dispatch which results in a negative total inter-regional settlement surplus is in spreadsheet workbook *Inter-regional loop model v2.4.xlsx.* The basic setup of this model was as follows:

Loads

BUS	Name	Description	Region	Regional reference node	Nodal load forecast
1	SYW	Sydney West	NSW	1	1000
2	BRJ	Burrinjuck	NSW	0	60
3	LTM	Lower Tumut	NSW	0	60
4	WAG	Wagga	NSW	0	60
5	YAS	Yass	NSW	0	60
6	BAL	Ballarat	VIC	0	90
7	HOR	Horsham	VIC	0	90
8	RC	Red Cliffs	VIC	0	90
9	BEN	Bendigo	VIC	0	90
10	THO	Thomastown	VIC	1	800
11	ADE	Adelaide	SA	1	250
12	RBT	Robertstown	SA	0	30
13	SE	South East	SA	0	30
Total					**2,710**

Construction of Bids and Offers

Generators bids will respond to the RRPs and the presence of network constraints. Where binding network constraints and the RRP constrained a unit's output was above its SRMC then it would bid at below its own LMP, probably down to the market floor price (MFP) of -$1000/MWh. An iterative process of rebidding and pre-dispatch price projection would continue until the offer prices, local LMPs and RRPs were in an approximate equilibrium. The bids and offers were determined to approximate this equilibrium.

RRPs

The RRPs were as follows.

Region	RRN	Load	Generation	RRP
NSW	1	1,240	1,833	1,600.90
VIC	10	1,160	620	110.00
SA	11	310	257	-56.00
Total		**2,710**	**2,710**	

Underlying LMPs

The underlying LMPs were as follows.

BUS	Name	Description	Region	Regional reference node	Nodal load forecast	LMP (nodal shadow price)	RRP
1	SYW	Sydney West	NSW	1	1000	1,600.90	1,600.90
2	BRJ	Burrinjuck	NSW	0	60	-1,000.00	1,600.90
3	LTM	Lower Tumut	NSW	0	60	-359.93	1,600.90
4	WAG	Wagga	NSW	0	60	-179.37	1,600.90

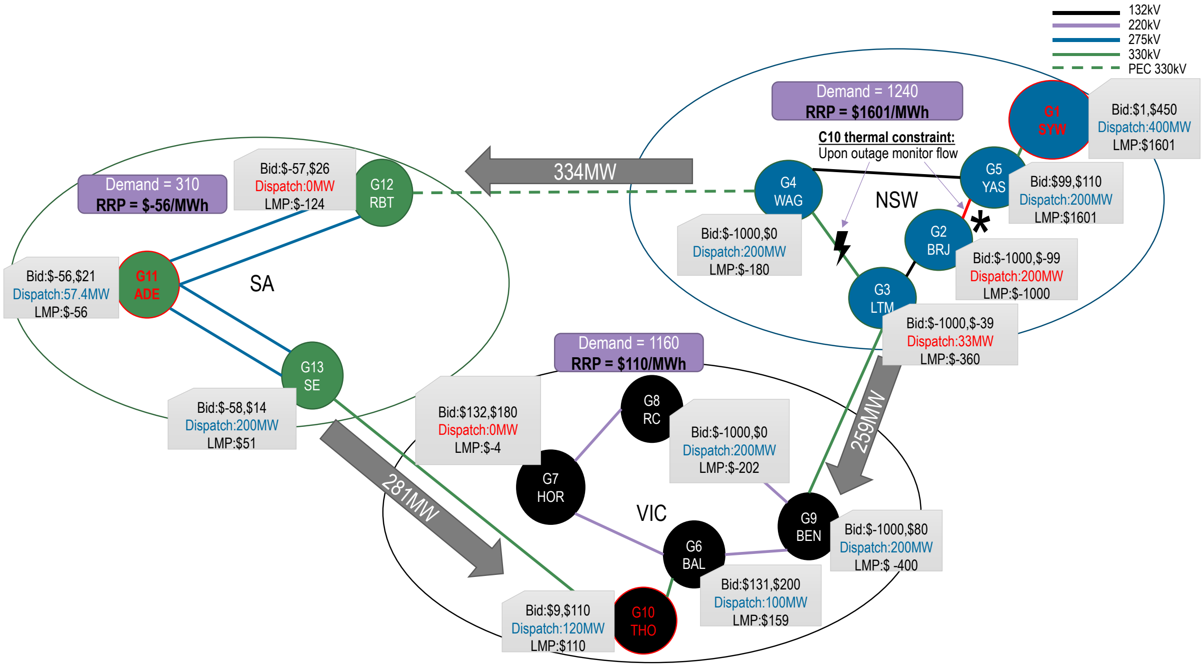
BUS	Name	Description	Region	Regional reference node	Nodal load forecast	LMP (nodal shadow price)	RRP
5	YAS	Yass	NSW	0	60	1,600.90	1,600.90
6	BAL	Ballarat	VIC	0	90	158.15	110.00
7	HOR	Horsham	VIC	0	90	-4.02	110.00
8	RC	Red Cliffs	VIC	0	90	-202.01	110.00
9	BEN	Bendigo	VIC	0	90	-400.00	110.00
10	THO	Thomastown	VIC	1	800	110.00	110.00
11	ADE	Adelaide	SA	1	250	-56.00	-56.00
12	RBT	Robertstown	SA	0	30	-124.08	-56.00
13	SE	South East	SA	0	30	50.52	-56.00
					2,710		

Units, Bids and Offers

Because the prices were very high in NSW and the Yass to Burrinjuck line was constrained NSW generators located at nodes 2, 3 and 4 bid at the MFP. Similarly, Vic generators at node 8 and 9 bid at the MFP.

Gen	Node	Region	Capacity	Pmin	Pmax	SRMC	Energy MW 1	Energy MW 2	Energy Price 1	Energy Price 2	Dispatch MW
G1	1	NSW	200	0	400	76	200	200	1	450	400.0
G2	2	NSW	200	0	200	77	200	0	-1,000	-99	32.6
G3	3	NSW	200	0	200	78	200	0	-1,000	-39	200.0
G4	4	NSW	200	0	200	79	200	0	-1,000	0	200.0
G5	5	NSW	200	0	200	130	100	100	99	110	200.0
G6	6	VIC	200	0	200	131	100	100	131	200	100.0
G7	7	VIC	200	0	200	132	100	100	132	180	0.0
G8	8	VIC	200	0	200	80	200	0	-1,000	0	200.0
G9	9	VIC	200	0	200	81	200	0	-1,000	80	200.0
G10	10	VIC	200	0	200	-55	100	100	9	110	120.0
G11	11	SA	200	0	200	-56	100	100	-56	21	57.4
G12	12	SA	200	0	200	-57	100	100	-57	26	0.0
G13	13	SA	200	0	200	-58	100	100	-58	14	200.0
G14	1	NSW	200	0	200	-59	100	100	14	101	200.0
G15	2	NSW	200	0	200	-60	200	0	-1,000	0	200.0
G16	3	NSW	200	0	200	-61	200	0	-1,000	0	200.0
G17	4	NSW	100	-100	100	101	100	100	-1,000	-1,000	100.0
G18	5	NSW	100	-100	100	102	100	100	100	119	100.0
			3,400	-200	3,600						2,710.0

2.1.5 Test Case Results



The main results were as follows.

Inter-regional settlement residues

The generator bidding in the presence of intra-regional binding constraints between Burrinjuck and Yass and Ballarat and Bendigo resulted in a large net negative IRSR around the loop.

Interconnector (line)	4	14	15	
Start region	NSW	NSW	VIC	
End region	SA	VIC	SA	
Flow	334.00	258.62	-281.39	
RRP_start	1,600.90	1,600.90	110.00	
RRP_end	-56.00	110.00	-56.00	**Total**
Inter-regional settlement residues	-553,412.16	-385,571.32	46,710.65	**-892,272.83**

Constraint costs and line rentals

The constraint costs and line rentals are below.

LINE	From BUS	To BUS	Comments	Flow	Flow min	Flow max	Shadow price flow min	Shadow price flow max	LMP start	LMP end	Network congestion (shadow price x RHS)	Network congestion (flow x LMP end – LMP start)
1	1	5	SYW to Yass	-400	-960	960	0.00	0.00	1,600.90	1,600.90	0.00	0.00
2	2	5	Yass to BRJ	143	-143	143	0.00	-3056.88	-1,000.00	1,600.90	437,133.35	371,929.04
3	3	4	Lower Tumut to Wagga	111	-1,020	1,020	0.00	0.00	-359.93	-179.37	0.00	20,042.62
4	4	12	Part of Energy	334	-800	800	0.00	0.00	-179.37	-124.08	0.00	18,467.90

LINE	From BUS	To BUS	Comments	Flow	Flow min	Flow max	Shadow price flow min	Shadow price flow max	LMP start	LMP end	Network congestion (shadow price x RHS)	Network congestion (flow x LMP end – LMP start)
			connect Upgrade									
5	4	5	Wag to Yass 132	17	-137	137	0.00	0.00	-179.37	1,600.90	0.00	30,264.66
6	2	3	BRJ to Lower Tumut 132	30	-143	143	0.00	0.00	-1,000.00	-359.93	0.00	18,958.96
7	6	7	Ballarat to Horsham	-28	-361	361	0.00	0.00	158.15	-4.02	0.00	4,478.69
8	7	8	Horsham to RC	-118	-361	361	0.00	0.00	-4.02	-202.01	0.00	23,286.37
9	8	9	RC to Bendigo	-8	-324	324	0.00	0.00	-202.01	-400.00	0.00	1,507.87
10	9	6	Bendigo to Ballarat	361	-361	361	0.00	-733.86	-400.00	158.15	264,922.77	201,492.08
11	6	10	Ballarat to Ref node	399	-700	700	0.00	0.00	158.15	110.00	0.00	-19,194.97
12	11	13	Adelaide to South East	111	-1,400	1,400	0.00	0.00	-56.00	50.52	0.00	11,864.80
13	11	12	Adelaide to Robertstown	-304	-1,100	1,100	0.00	0.00	-56.00	-124.08	0.00	20,696.44
14	3	9	Lower Tumut to Bendigo	259	-1,500	1,500	0.00	0.00	-359.93	-400.00	0.00	-10,361.78
15	10	13	Thomastown to South East	-281	-1,200	1,200	0.00	0.00	110.00	50.52	0.00	16,738.07
										Total	**702,056.12**	**710,170.76**
										PST constraint cost	**8114.63**	
										Total network constraint costs	**710,170.75**	

Note that the total network congestion costs calculated as -RHS x shadow price = - flow x shadow price plus the loop flow constraint cost of RHS x loop flow constraint shadow price are equal to the total of the line rentals which equal flow x (end LMP – start LMP).

What is interesting to note is the line rentals when LMPs are used results in the total line rentals being positive and matching the total network constraint costs. Also, the total line rental equals the settlement surplus ($710,170.75) if generators and loads were settled at their LMPs.

Based on an economic dispatch (albeit with generator offers that only occur with regional pricing), if we compare only the line rentals for the three interconnectors, and extend the earlier table, the difference in settlement residues as calculated under the NEM's regional pricing model (-$892,272.83) and the line rental generated by the three interconnector circuits using LMPs ($24,844.18) is significant.

Interconnector (line)	4	14	15	
Start region	NSW	NSW	VIC	
End region	SA	VIC	SA	
Flow	334.00	258.62	-281.39	
RRP_start	1,600.90	1,600.90	110.00	
RRP_end	-56.00	110.00	-56.00	**Total**
Inter-regional settlement residues	-553,412.16	-385,571.32	46,710.65	**-892,272.83**
LMP surplus (or line rental)	18,467.90	-10,361.78	16,738.07	**24,844.18**

This is a good example of the problem presented by the NEM's regional settlement. The 'mispricing' of generator nodes in settlement, by paying the RRP, encourages a generator to bid at very low prices to preserve dispatch when the generator's nodal price drops in the presence of an intra-regional constraint. The underlying dispatch remains economic, as is shown in this case, with net positive line rentals around the loop, yet using the NEM's regional settlement it is in deficit, with net negative interregional settlement residues. This example implies a requirement to retain negative residue management constraints after the connection of PEC. It also shows the effect of the loop constraint, with the spring washer effect resulting in negative line rentals for NSW to VIC, but positive in aggregate across the three lines.

If the generators and loads were settled at the LMP, they would only be paid $925,912, and loads would pay $1,636,083, leaving the LMP surplus of $710,170.25. The difference in settlements is shown in the following table:

Customer and generator payments

Because of the large negative IRSR there was a matching shortfall of customer revenues relative to generator payments.

Region	NSW	VIC	SA	Total
RRN	1	10	11	
Load	1,240	1,160	310	**2,710**
Generation	1,833	620	257	**2,710**
Export	593	-281	0	
Import	0	259	53	
Net supply	1,240	1,160	310	
RRP	1,600.90	110.00	-56.00	
Customer payments	1,985,119.10	127,600.00	-17,360.00	**2,095,359.10**
Payments to generators	2,933,846.10	68,199.40	-14,413.58	**2,987,631.92**
Regional surplus	-948,727.00	59,400.60	-2,946.42	**-892,272.82**
Settling at nodal price				
Customer payments	$1,604,509	$47,691	-$16,207	**$1,636,083**
Payments to generators	-$1,010,409	-$6,890	$91,386	**$925,912**
Surplus				**$710,171**

2.2 Python model

A simple three region NEM style model with intra-regional network constraints was developed in python and scenarios were generated to illustrate occurrences of negative settlement residue. The model includes three regions, with 3-5 generators in each region. Intra-regional constraints are only applied in NSW. 256 scenarios were modelled: four PST scenarios, 8 bid scenarios and 8 demand scenarios.

Table 2.1 PST Scenarios

PST Scenario	PST loop constraint
1: NO PST	None
2: PST -6.73°	NSW-SA – 0.14*VIC-NSW-0.81*VIC-SA = -21
3: PST 0°	NSW-SA – 0.14*VIC-NSW-0.81*VIC-SA = 74
4: PST 8°	NSW-SA – 0.14*VIC-NSW-0.81*VIC-SA = 187

8 different bid scenarios were generated to cover different combinations of negative and positive generator bidding in each region. 8 different demand scenarios were generated to cover different combinations of high and low demand in each region.

2.2.1 Summary results

256 scenarios (combinations of negative bids and demand) were simulated. Out of these 48 scenarios did not solve due to an infeasible solution so these were excluded from the analysis. From the remaining 208 scenarios there were 8 scenarios with net negative IRSR on the loop.

Net negative IRSR on the loop occurred:

- 0% of the time in PST scenario 1 (no loop constraint)
- 3% of the time in PST scenario 2
- 4% of the time in PST scenario 3.
- 13% of the time in PST scenario 4.

This shows that the tap setting has a relatively high impact on settlement results

Net negative IRSR tends to occur when:

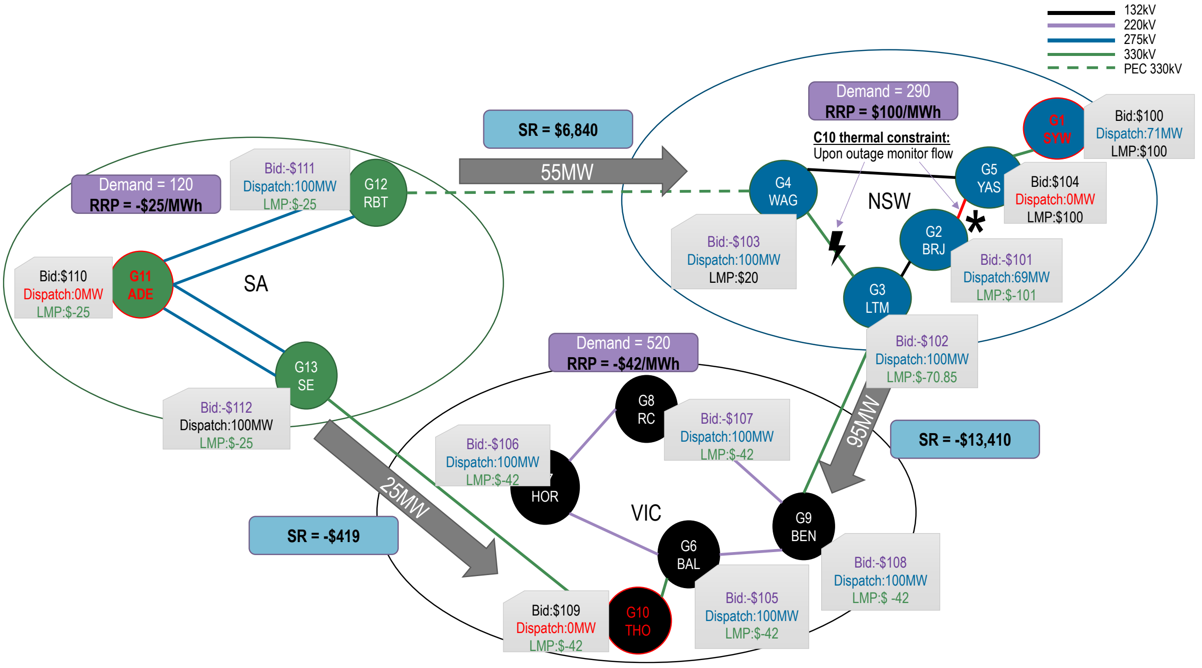
- The loop constraint and intra-regional constraints with an interconnector term are binding.
- Low-cost regional generators are constrained off due to binding intra-regional constraints and the price is set by a relatively high cost generator.

The diagram below shows an example of when net negative settlement residue occurs in a scenario.

2.2.2 Example of net negative settlement residue

In the scenario shown in Figure 2.2, the C10 constraint is binding (“on outage of Wagga to Lower Tumut, avoid overload of Lower Tumut to Burrinjuck”) which causes LMP separation between G5, G2, G3 and G4. This is known as the “spring washer effect” where prices spiral in the NSW intra-regional loop due to a transmission constraint. We also have a “spring washer effect” in the inter-regional loop where prices spiral due the loop constraint and binding C10 constraint. There is a high level of negative IRSR between VIC and NSW caused by the negative bid of G3 which is dispatched to minimise the total system cost even though it does not supply the local NSW load on the other side of the constraint. The power is exported to VIC, creating a high negative IRSR level. The C10 intra-regional constraint is the main driver of negative IRSR. If we disable it, the IRSR is zero and there are no binding constraints.

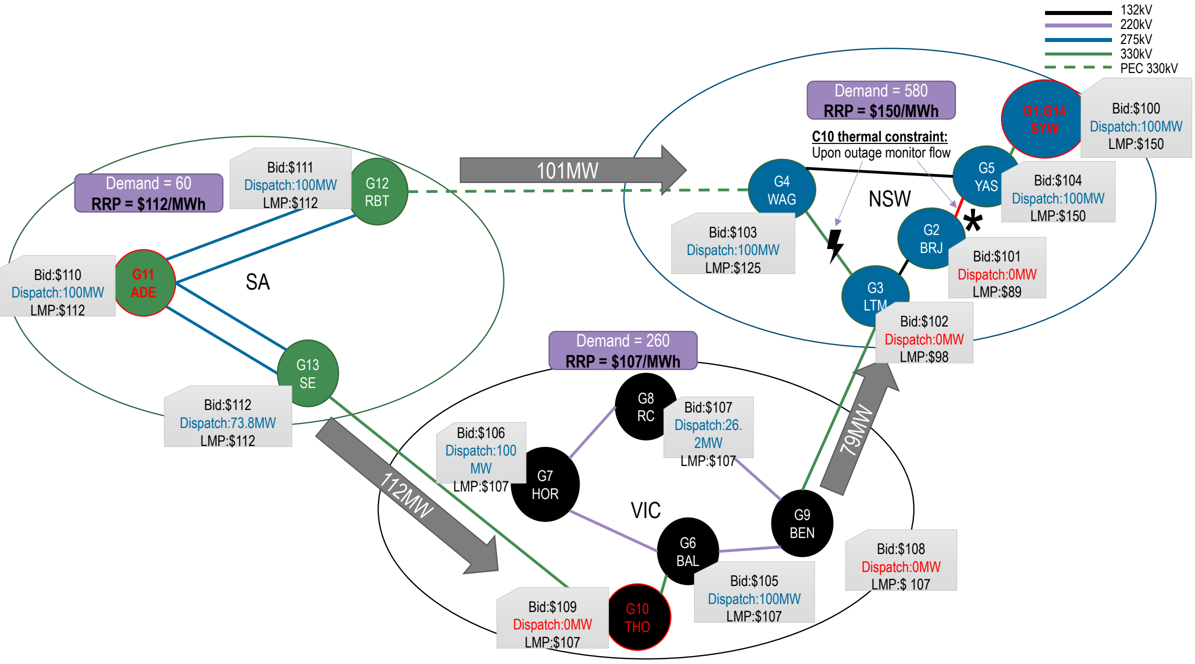
Figure 2.2 Example of net negative IRSR – negative bidding scenario and binding constraints



2.2.3 Example of net positive residue

The scenario in Figure 2.3 shows an example outcome where there was negative IRSR on a single leg between SA and VIC due to the C10 constraint, but the net IRSR is positive due to low demand in VIC. The price in SA and VIC is being set by the marginal generator in each region but there is price separation between all regions due the PST loop constraint and C10 constraint. NSW has a spring washer effect due to the C10 constraint but overall net positive IRSR. This is because flows are going from VIC to NSW due to low demand in VIC, constrained generators in NSW and no NSW generators bidding negative.

Figure 2.3 Example of negative IRSR on VIC-SA leg – positive bidding and binding constraints



2.3 Summary of Stage 1 Models and Findings

Table 2.2 Summary of prototype models and findings

Model	Design	Key purpose	Findings
Excel	Includes three regions, with 3-5 generators in each Intra-regional constraints are applied based on basic line limits Optimises to minimise the total energy costs subject to energy power flows within line limits based on shift factors (calculates power injection shift factors) Manages constraints based on nodal input/output and power factors The loop flow constraint is calculated dynamically based on interregional flows and adds the generator impact on loop flow LMPs are calculated based on the coefficient term and the shadow price. This also includes the impact of the loop flow constraint. Coefficients are set before hand by flows. Can be reformulated in terms of net injections. NEMDE does not have nodal loads but instead uses feedback constraints.	Somewhat more reflective of physical system than Python model Calculates LMPs directly and includes the impact of loop flow constraint on LMPs due to having the full loop constraint (not AEMO approximation) Calculates loop flow constraint coefficients directly including the generator impact rather than using AEMO approximation	Reveals the differences between the settlement residue or surplus generated by transmission lines (including ICs) under the LMP approach, and how this can be compared to settlement under NEM's regional pricing model and interregional settlement residues. Highlighted that generators within a region can bid to the floor, that these offers can affect the RRP, and the LMP for these generators may remain >-$1,000, because other generators in adjacent regions can't bid to floor. Evidence of a possible need for negative residue management (NRM) constraint equations to remain even with PEC
Python	Three regions, with 3-5 generators in each region Intra-regional constraints for N-1 (single line contingency) are applied in NSW only. Four PST scenarios as per AEMO's loop flow model (including no PST) 256 scenarios.	Provides example scenarios of drivers of negative IRSR and shows impact of the PST – demonstrating the key drivers are intra-regional constraints and generator bidding.	Shows how the equality loop constraint works and that it binds all the time due to the equality Intra-regional constraints and mispricing of regional generators could lead to rebidding causing counter price flows and the loop to run a settlement deficit Demonstrates "intra-regional loop within inter-regional loop" Suggested need for NRM constraint equations to remain even with PEC

Stage Two: NEM Model

3

3.1 Model Assumptions

The starting point for the NEM model is ACIL Allen's March 2023 Reference case projection of the NEM. This was updated to include thermal constraints from the 2020 ISP ESOO thermal constraints workbook and additional constraints not included the ISP dataset which bind frequently historically. ACIL Allen develops an updated market outlook – a Reference case projection – every quarter. The updated Reference case reflects current market conditions including any recent changes such as (but not limited to):

- new supply
- change in fuel costs
- change in demand
- government policy
- interconnector upgrades.

The Reference case incorporates the best information available to ACIL Allen when the case is developed. All assumptions used in the modelling are taken from publicly available or in-house information and databases ACIL Allen maintains.

Interconnector losses were assumed to be zero in the scenarios to focus on the impact of the loop and intra-regional constraints on settlement outcomes without additional "noise" from relatively small inter-regional price differences due to losses. When interconnector losses are included net negative settlement residues do not change significantly and net positive residues are moderately higher due to the accumulation of periods with mildly higher positive residues due to higher occurrence of regional price differences.

3.1.1 Scenarios

To understand the impact of the loop constraint and PST settings on settlement residues the following scenarios were run:

1. No intra-regional (IR) constraints, only the loop constraint.
2. No loop constraint, only intra-regional constraints.
3. Loop constraint where solver can select the optimal PST setting for each dispatch period. The model includes the following constraints to allow the solver to optimise the PST for the least cost solution.
   a) PST1: NSW-SA-0.14*VIC-NSW-0.81*VIC-SA >-21.01
   b) PST2: NSW-SA-0.14*VIC-NSW-0.81*VIC-SA <187.01
4. Loop constraint with a fixed tap setting. We understand that the PST will manually be adjusted to the most appropriate tap setting once or twice a day and NEMDE will not optimise it. AEMO has advised the following different tap settings to understand their impact:
   a) PST1: NSW-SA-0.14*VIC-NSW-0.81*VIC-SA = -21
   b) PST2: NSW-SA-0.14*VIC-NSW-0.81*VIC-SA = 74
   c) PST3: NSW-SA-0.14*VIC-NSW-0.81*VIC-SA = 187

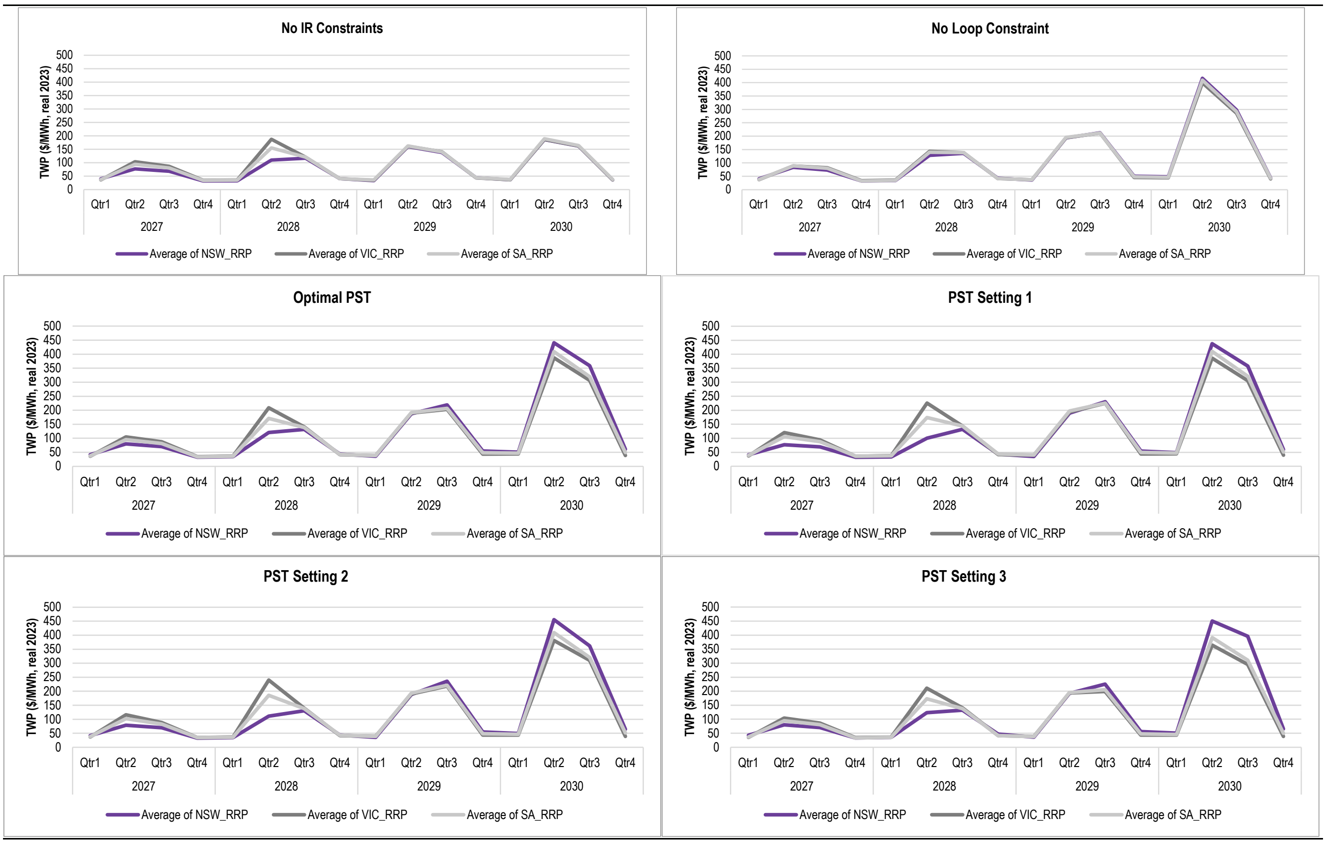
Table 3.1 Scenario design

Scenario	Designed to prove, or investigate
1) No intra-regional constraints	Shows how flows on parallel lines are balanced as represented by loop constraint – manifesting in the spring washer pricing effect (prevalence of net positive residues)
2) No loop constraint	Shows how, on their own, intra-regional constraints do not result in the spring washer effect (net positive residues
3) Loop constraint with PST as linear variable	Shows possible opportunity to optimise the PST
4) Loop constraint with PST as fixed input (PST1-3)	Shows the range of settlement residue outcomes under close to "set and forget" operating approaches of the PST. This is the current implementation approach.

3.2 Quarterly price projections for NSW, VIC, SA

Figure 3.1 shows quarterly price projections for each of the six scenarios. In this Reference case, the new generation capacity assumed to enter the market in response to the various state energy policies is the most important driver for wholesale price outcomes in the period to 2030. Another driver is the retirement of Eraring and Bayswater in 2029 and 2030 which results in significantly higher prices in the scenarios with intra-regional constraints assuming no planting changes. This is due to higher levels of congestion which results in increased gas generation at higher price bands. Note that the constraint set only includes publicly announced network upgrades and does not include intra-regional upgrades likely to be installed as part of the NSW Roadmap which may change constraint formulations and affect prices.

Figure 3.1 Quarterly price projections for each scenario



No IR Constraints

No Loop Constraint

Optimal PST

PST Setting 1

PST Setting 2

PST Setting 3

3.3 Settlement residue results

3.3.1 Summary results

The following figures show the projected frequency of negative IRSR on each leg of the loop under each scenario. The model was run at hourly resolution (8760 periods in each year) from 2027 to 2030 to capture expected changes in capacity due to thermal retirements and the government roll out of renewables and long duration storage.

Figure 3.2 shows the frequency of negative IRSR on a single leg only. There is a significantly higher occurrence of negative IRSR in scenarios where the loop constraint is enabled compared to the “No loop constraint” scenario, and when intra-regional constraints are applied in 2029 - 2030.

Figure 3.2 Frequency of negative IRSR on a single leg

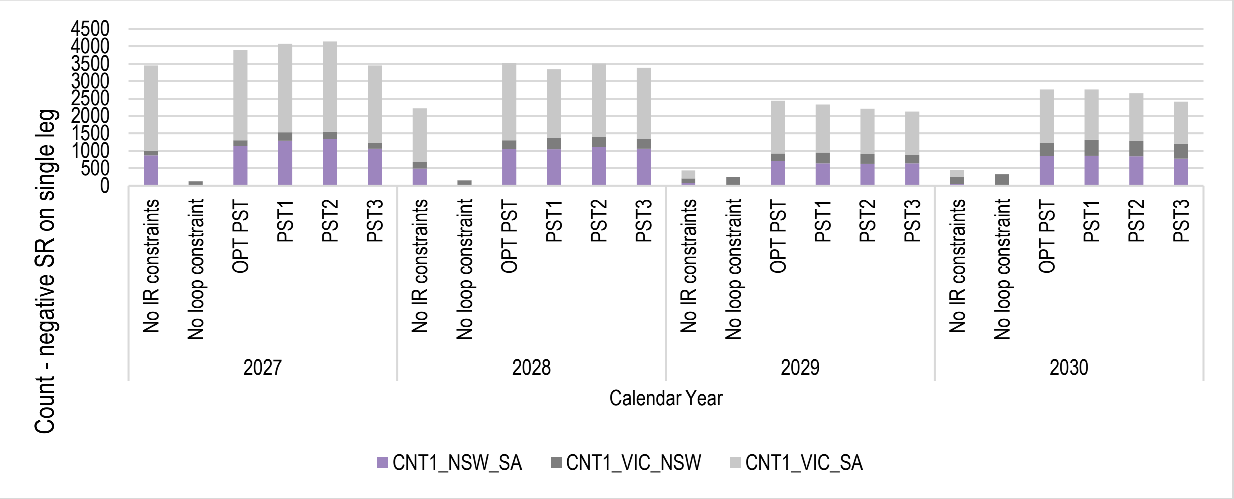


Figure 3.3 shows higher negative IRSR on two legs where both IR and the loop constraints are enabled compared to the first two scenarios where only one is. The PST 1,2 and 3 scenarios show that different PST tap settings have a high impact on settlement outcomes. This is because the tap setting directly impacts NSW-SA flows, indirectly impacting flows on the other legs, which impacts IR constraints and regional and nodal prices.

Figure 3.3 Frequency of negative IRSR on two legs

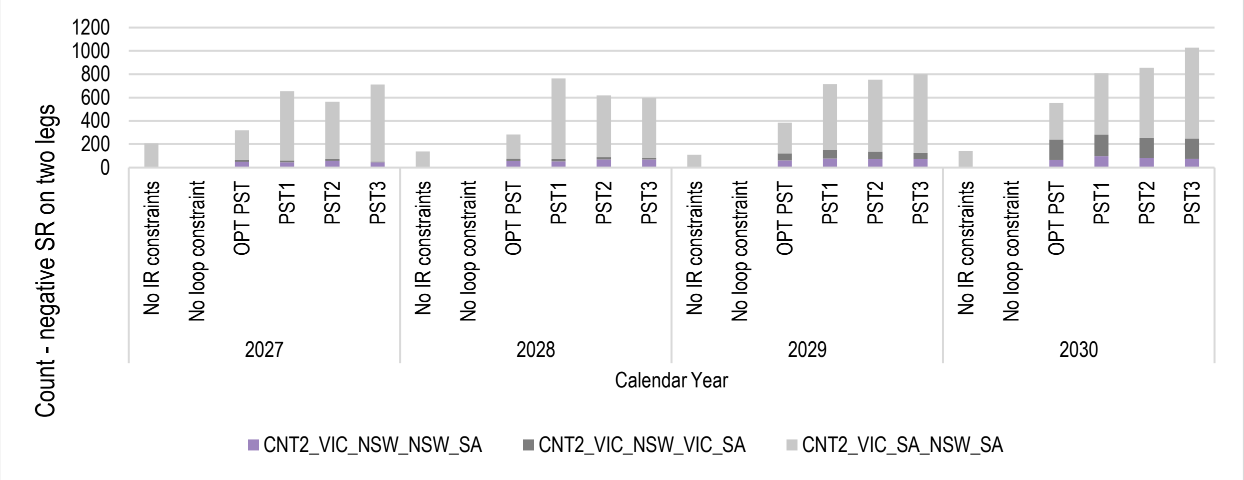
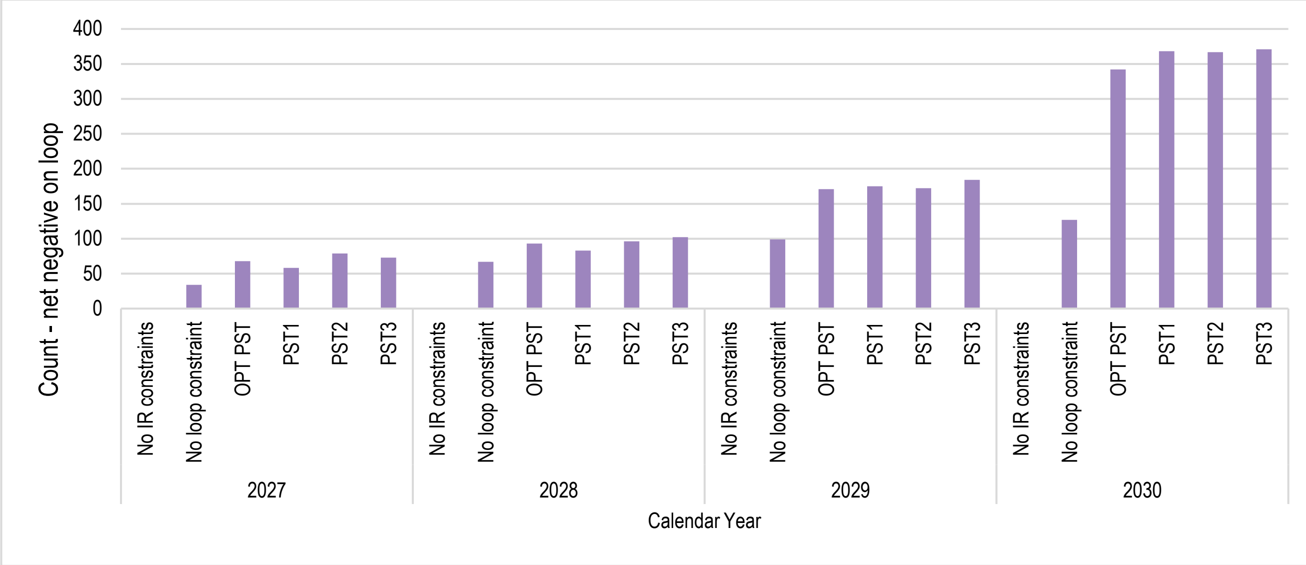


Figure 3.4 shows that there are no instances of net negative IRSR in the “No IR constraints” scenario and lower instances in the “No loop constraint” scenario than in the other scenarios where they are combined. The frequency of negative IRSR is projected to increase in 2029 and 2030 due to the assumed retirement of Bayswater and Eraring units which increases the binding frequency of constraints related to transmission limits near those stations.

Figure 3.4 Frequency of net negative residue



3.3.2 Impact of intra-regional constraints and loop constraint on negative settlement residues

We compared the hypothetical scenarios: “no loop constraint” and “Optimal PST” to assess the impact of intra-regional constraints and the loop constraint on negative IRSR. The “Optimal PST” scenario is used for comparison but would represent similar relative outcomes in PST 1, 2 and 3 scenarios.

The following results show summary statistics from the top ten binding constraints with the highest marginal values. The marginal value indicates how much the total system cost decreases when the constraint's right hand side is relaxed by 1MW. So a high marginal value suggests a high impact on the regional reference price, nodal prices and settlement residues. We determined from the summary statistics whether any relationships existed between constraints with a high marginal value and negative settlement residue.

Negative settlement residue on a single leg

Figure 3.5 shows the sum of the marginal values and frequency of binding constraints where there was negative IRSR on a single leg of the loop and no loop constraint enabled. There is a high correlation between the binding frequency of “Q>>N_NIL_2B2L1_2B2L2_11_ISP” and “N>>N_NIL_29_20_ISP” and negative IRSR. The table below shows that these constraints have the VIC-NSW term on the left side, which explains why they impact IRSR. For example, when a constraint forces flows from VIC to NSW to relieve congestion in NSW, this can result in counter-price flows on a single leg.

Table 3.2 Top binding constraints which include interconnector term on left hand side

Constraint Name	Interconnector	Description
N>>N-NIL_1A_ISP	VIC1-NSW1	Out= Nil; avoid O/L (BAYSWATER PS to LIDDELL PS) 330kV line 1 for loss of (BAYSWATER PS to LIDDELL PS) 330kV line 2
N>>N-NIL_HE_1_R_ISP	VIC1-NSW1	Out= Nil; avoid O/L (SNOWY2_ to LOWER TUMUT) 330kV line 1 for loss of (MURRAY to UPPER TUMUT) 330kV line 1
N>>V-NIL_O_R_ISP	VIC1-NSW1	Out= Nil; avoid O/L (UPPER TUMUT to MURRAY) 330kV line 1 for loss of (LOWER TUMUT to WAGGA) 330kV line 1
N>>N_NIL_29_20_ISP	VIC1-NSW1	Out= Nil; avoid O/L (SYDNEY WEST to SYDNEY NORTH) 330kV line 1 for loss of (SYDNEY WEST to VINEYARD) 330kV line 1
Q>>N_NIL_2B2L1_2B2L2_11_ISP	VIC1-NSW1	Out= Nil; avoid O/L (BAYSWATER PS to LIDDELL PS) 330kV line 2 for loss of (BAYSWATER PS to LIDDELL PS) 330kV line 1

Constraint Name	Interconnector	Description
S>>NIL_RBTU_WEWT_ISP	V-SA	Out= Nil; avoid O/L (WATERLOO EAST to WATERLOO) 132kV line 1 for loss of (ROBERTSTOWN to TUNKILLO) 275kV line 1
V>>N-NIL_HA_ISP	VIC1-NSW1	Out= Nil; avoid O/L (MURRAY to UPPER TUMUT) 330kV line 1 for loss of (MURRAY to LOWER TUMUT) 330kV line 1

Figure 3.5 Frequency and sum of marginal values of binding constraints when there is negative residue on a single leg – no loop constraint, only intra-regional constraints

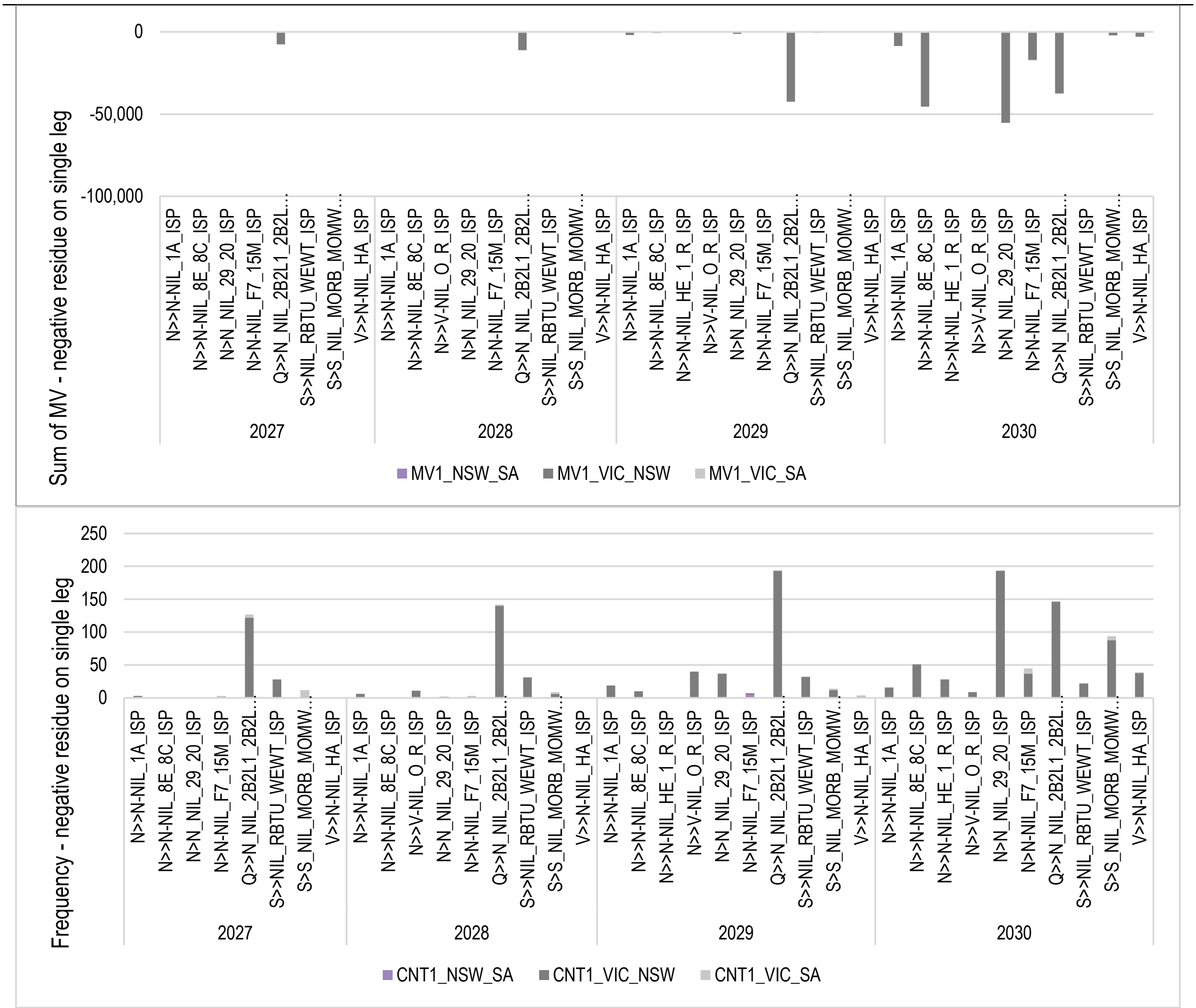
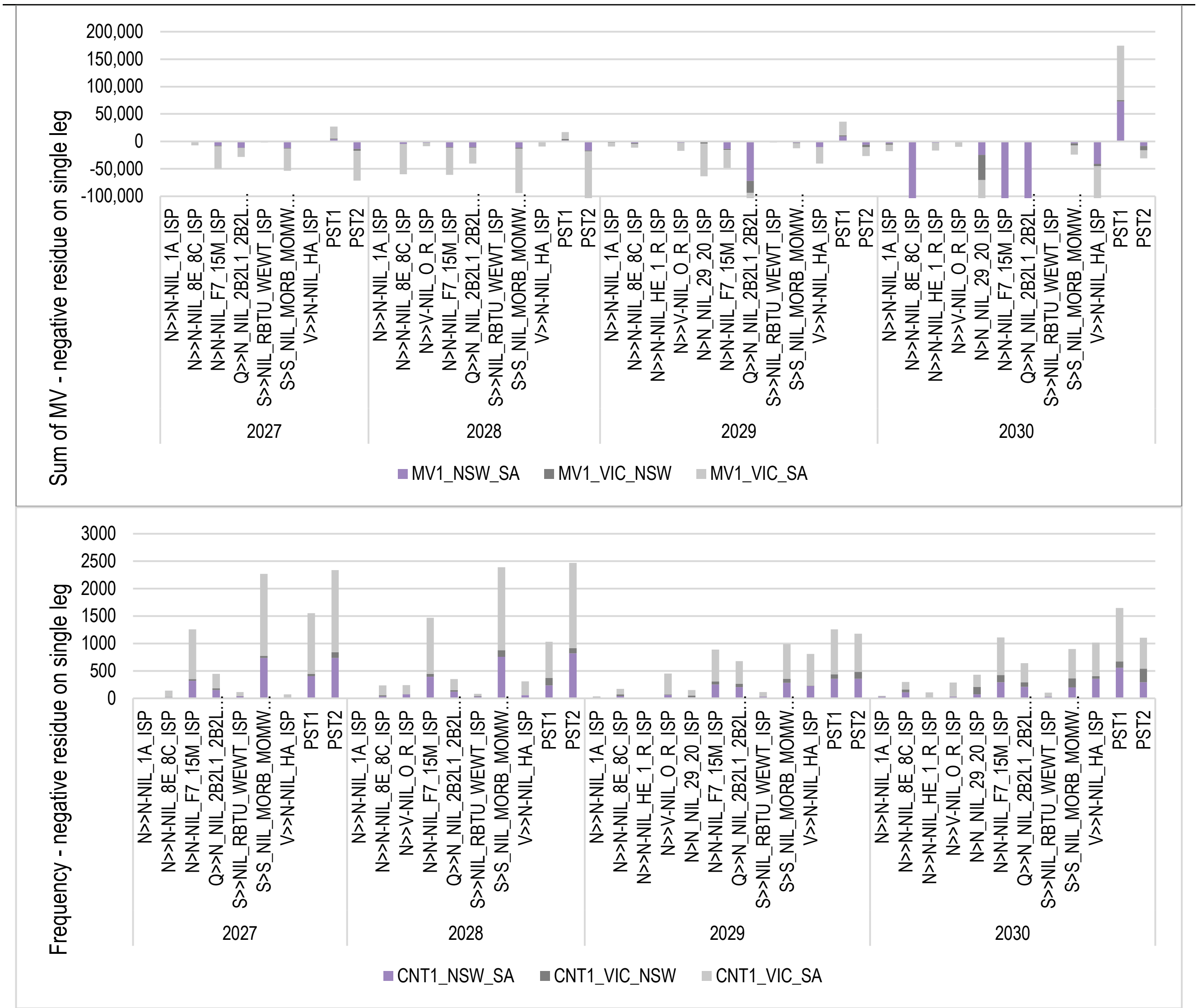


Figure 3.6 shows that when the loop constraint is included the binding frequency and marginal values increase significantly. Negative residues appear also on the VIC-SA and NSW-SA legs as shown by the light grey and purple bars. The loop constraint further restricts the freedom of interconnector flows on the loop which otherwise would be able to balance regional prices and produce zero IRSR. Also shown are the loop constraints: PST1 which is a ">" constraint so has a positive marginal value and PST2 which is a "<" constraint and has a negative marginal value similar to the intra-regional constraints.

Figure 3.6 Frequency and sum of marginal values of binding constraints when there is negative residue on a single leg –loop constraint and intra-regional constraints



Negative settlement residue on two legs

Figure 3.7 shows a very low frequency of binding constraints when there is negative IRSR on two legs of the loop and no loop constraint included in the model. Intra-regional constraints on their own may cause negative settlement residue on a single leg but it is less frequent on two legs simultaneously. However, once the loop constraint is added as shown in Figure 3.8, negative IRSR starts to appear on multiple loops because there is a coupling between loop flow terms in intra-regional constraints and loop flow terms on all legs of the loop.

Figure 3.7 Frequency and sum of marginal values of binding constraints when there is negative residue on two legs – no loop constraint, only intra-regional constraints

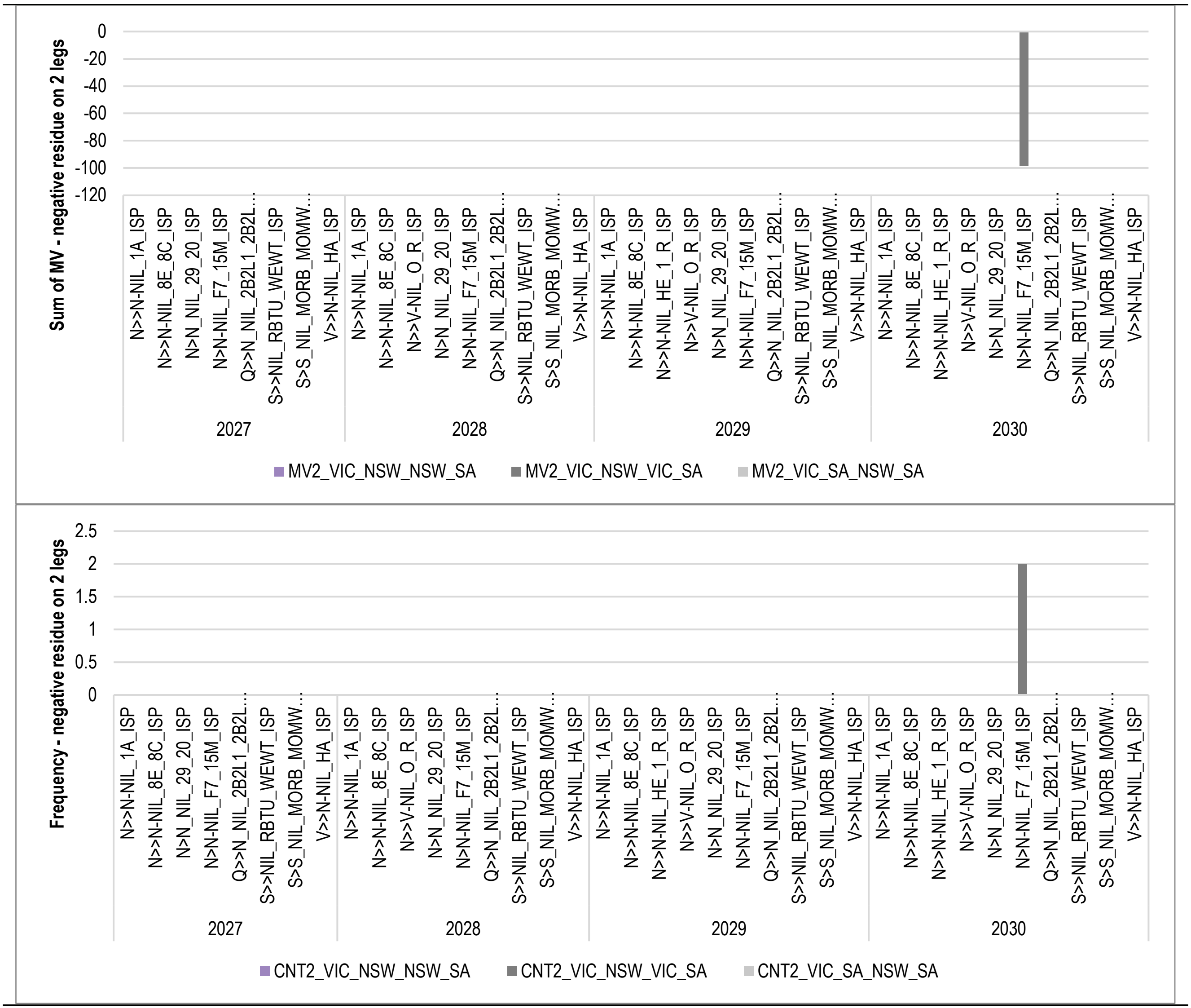
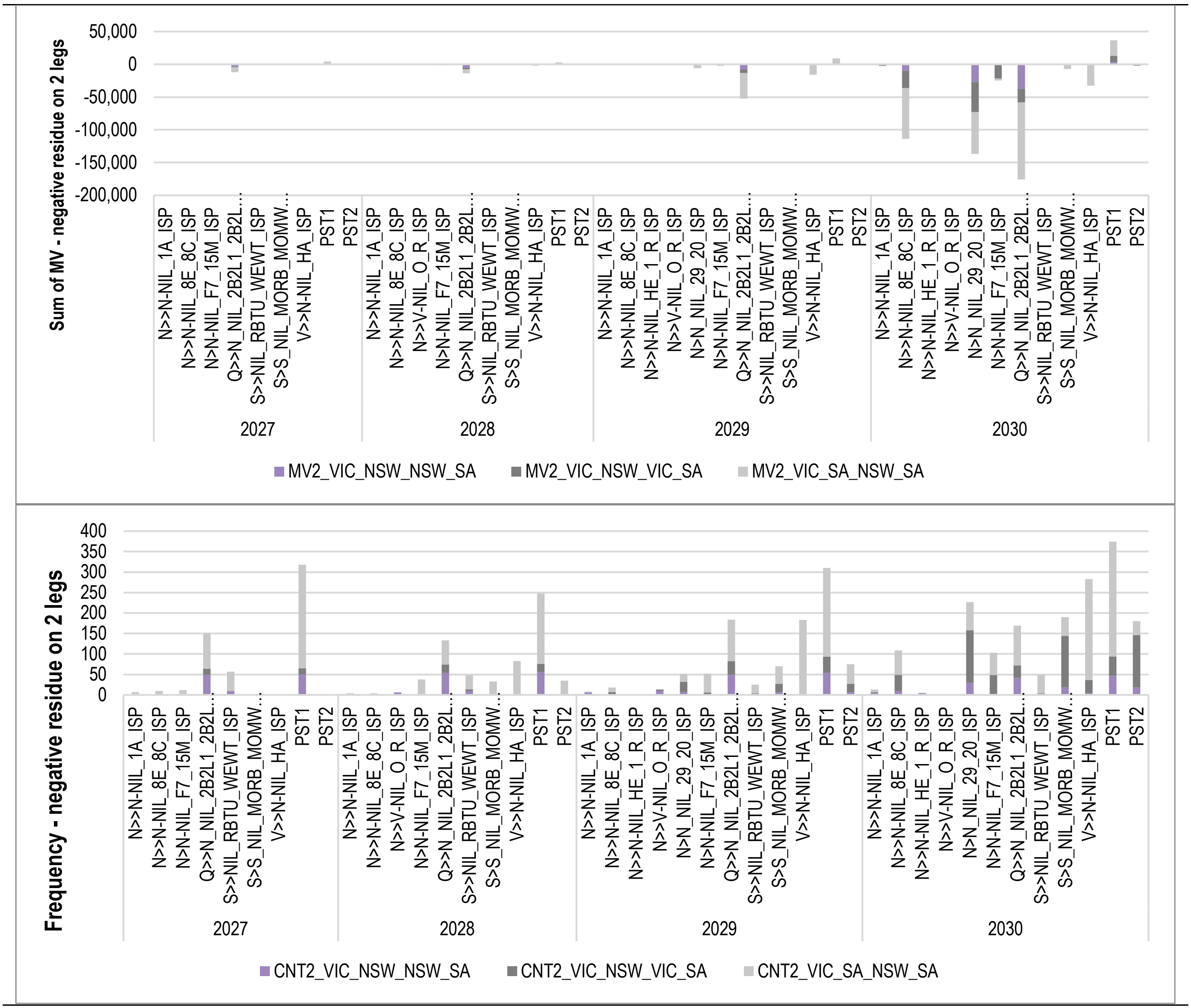


Figure 3.8 shows that when the loop constraint is included there is a material increase in the frequency and marginal values of binding constraints. Negative residues appear on the VIC-SA and NSW-SA legs as shown by the additional light grey and purple bars.

Figure 3.8 Frequency and sum of marginal values of binding constraints when there is negative residue on two legs – loop constraint and intra-regional constraints



Net negative residue

Figure 3.9 shows the sum of the marginal values of binding constraints when there is net negative IRSR on the loop and no loop constraint was included in the model. Around one per cent of periods in a year have net negative IRSR. This increases to around two per cent when the loop constraint is included (and the PST is operated optimally).

Figure 3.9 Frequency and sum of marginal values of binding constraints when there is net negative residue – no loop constraint, only intra-regional constraints included in model

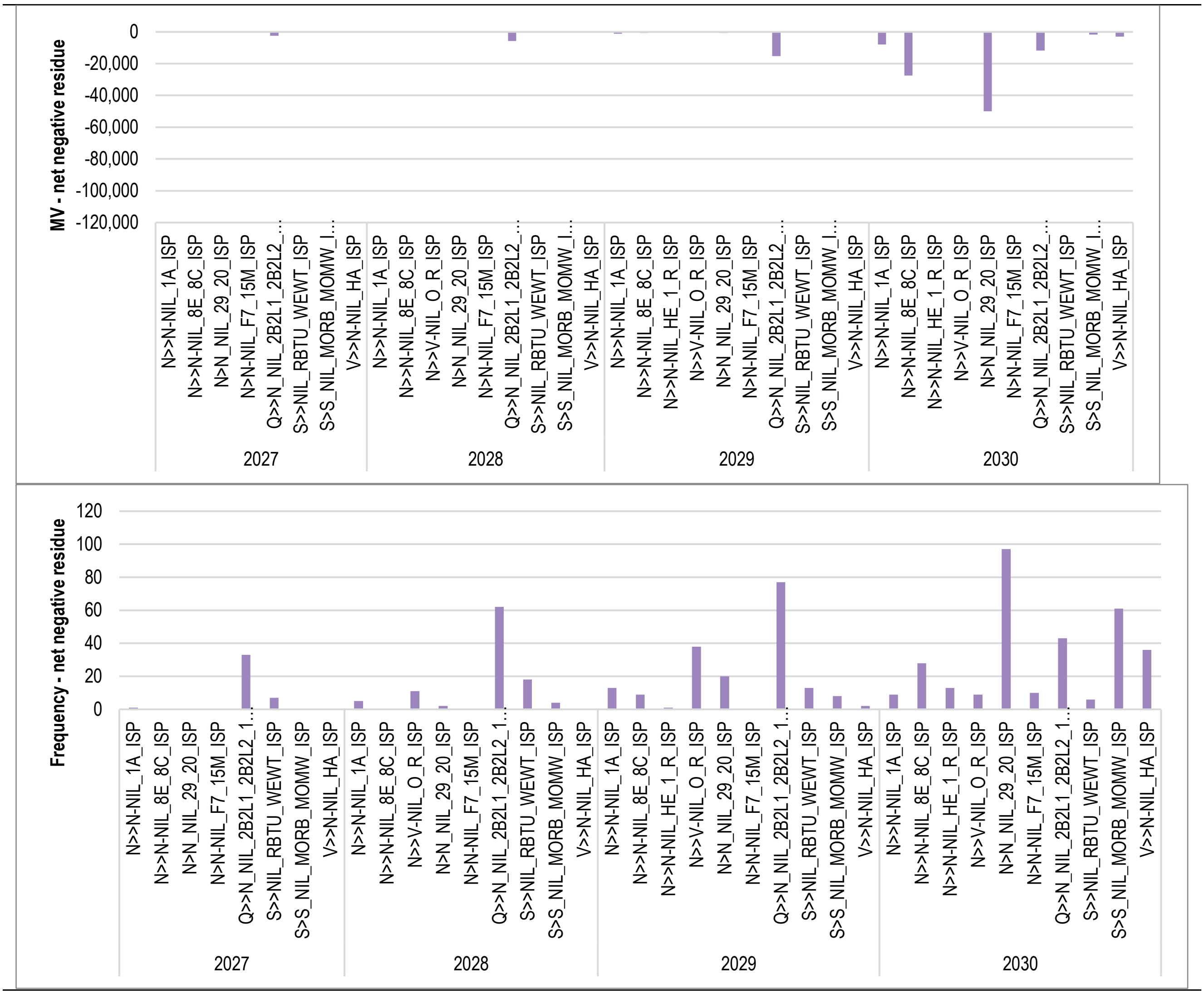
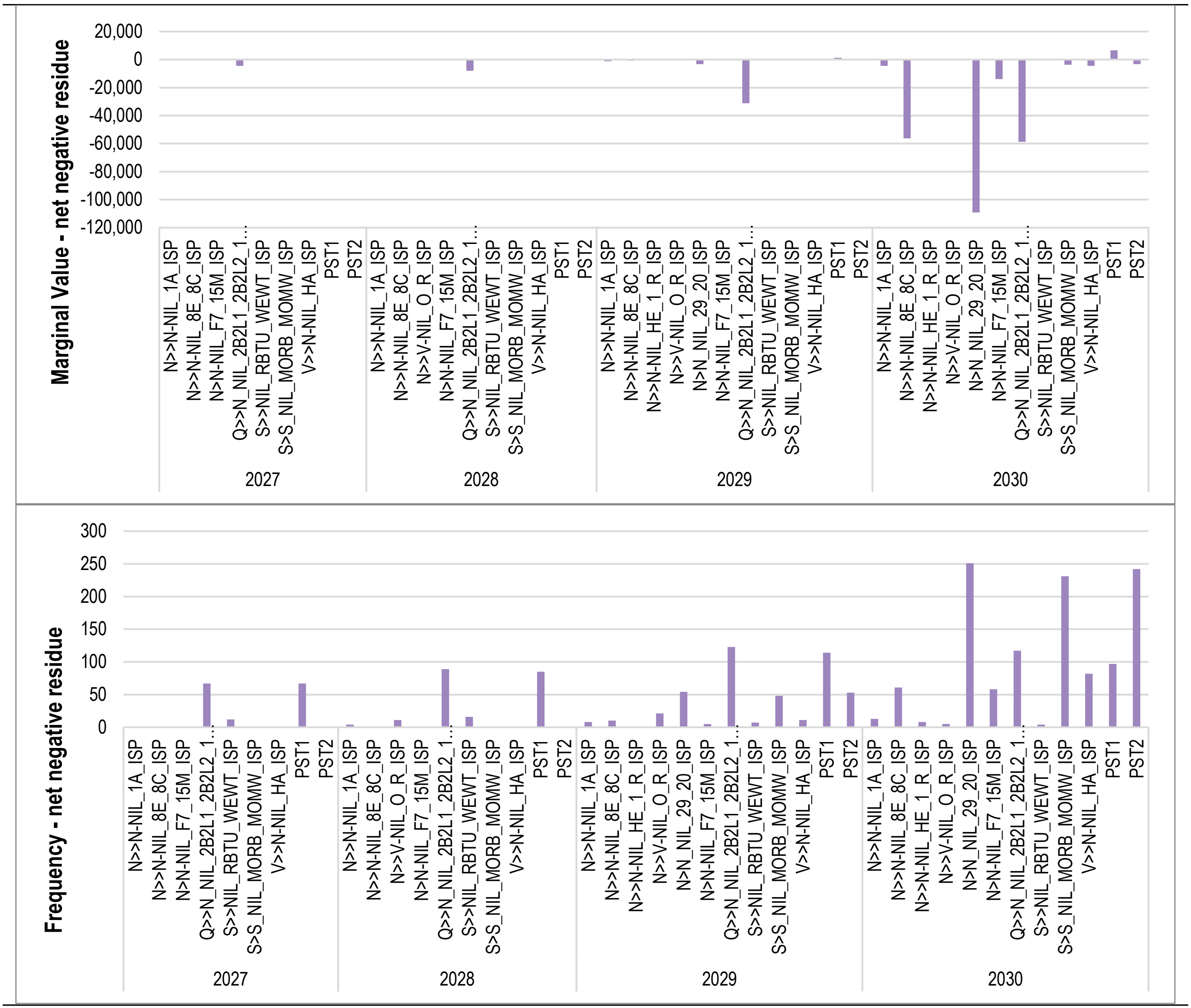


Figure 3.10 shows that when the loop constraint is included some of the marginal values double in value and the frequency of some binding constraints more than doubles.

Figure 3.10 Frequency and sum of marginal values of binding constraints when there is net negative residue – model includes loop constraint and intra-regional constraints



3.4 Impact of tap setting on net negative residue on the loop

Figure 3.11 and Figure 3.12 show that the loop constraint increases the frequency and magnitude of net negative residue. It also shows an increase in the value over time. In the future, a significant difference in net negative residue is expected to occur between tap setting 1, 2 and 3 in 2030. This means inefficient tap setting control could cause less optimal settlement. For example, because NSW-VIC has a low coefficient of 0.14 in the loop constraint, every 1MW change of NSW-SA could potentially force NSW-VIC flows to increase by around 7MW, worsening counter-price flows between VIC and NSW in some scenarios. The main result is that an optimal PST setting can improve settlement outcomes but cannot prevent net negative IRSR from happening.

Figure 3.11 Frequency of net negative residue under each scenario

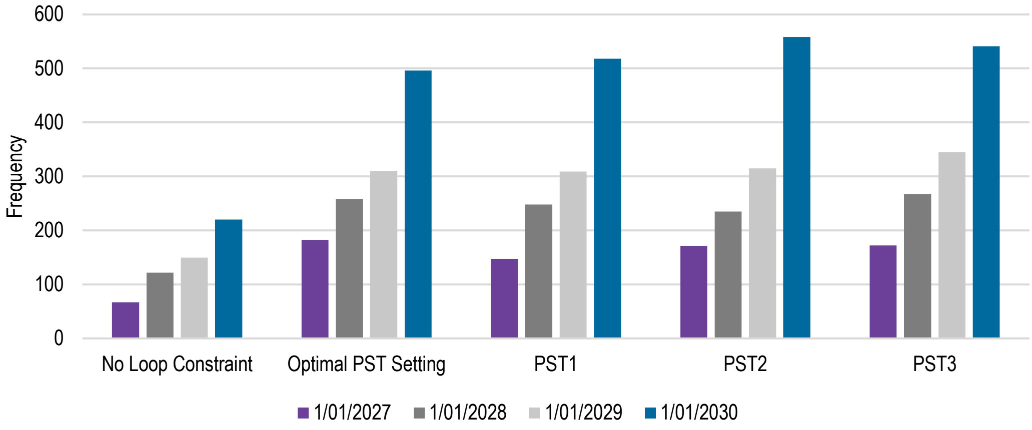
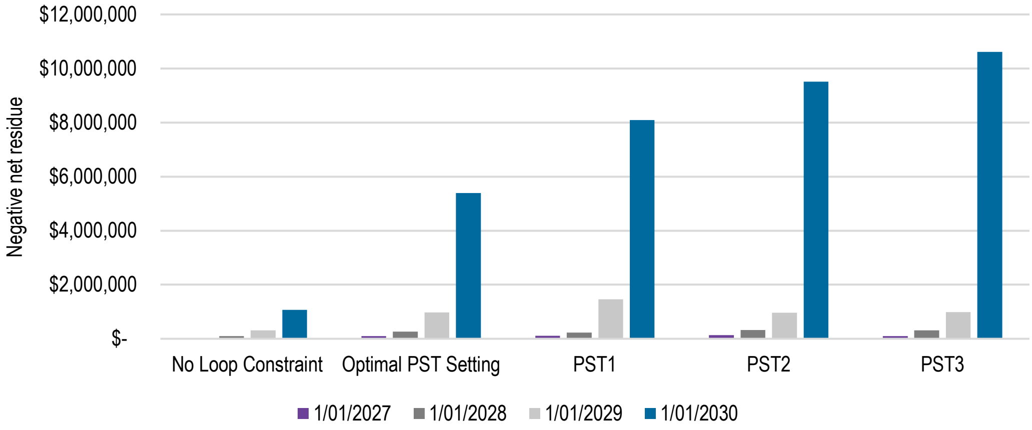


Figure 3.12 Magnitude of net negative residue under each scenario

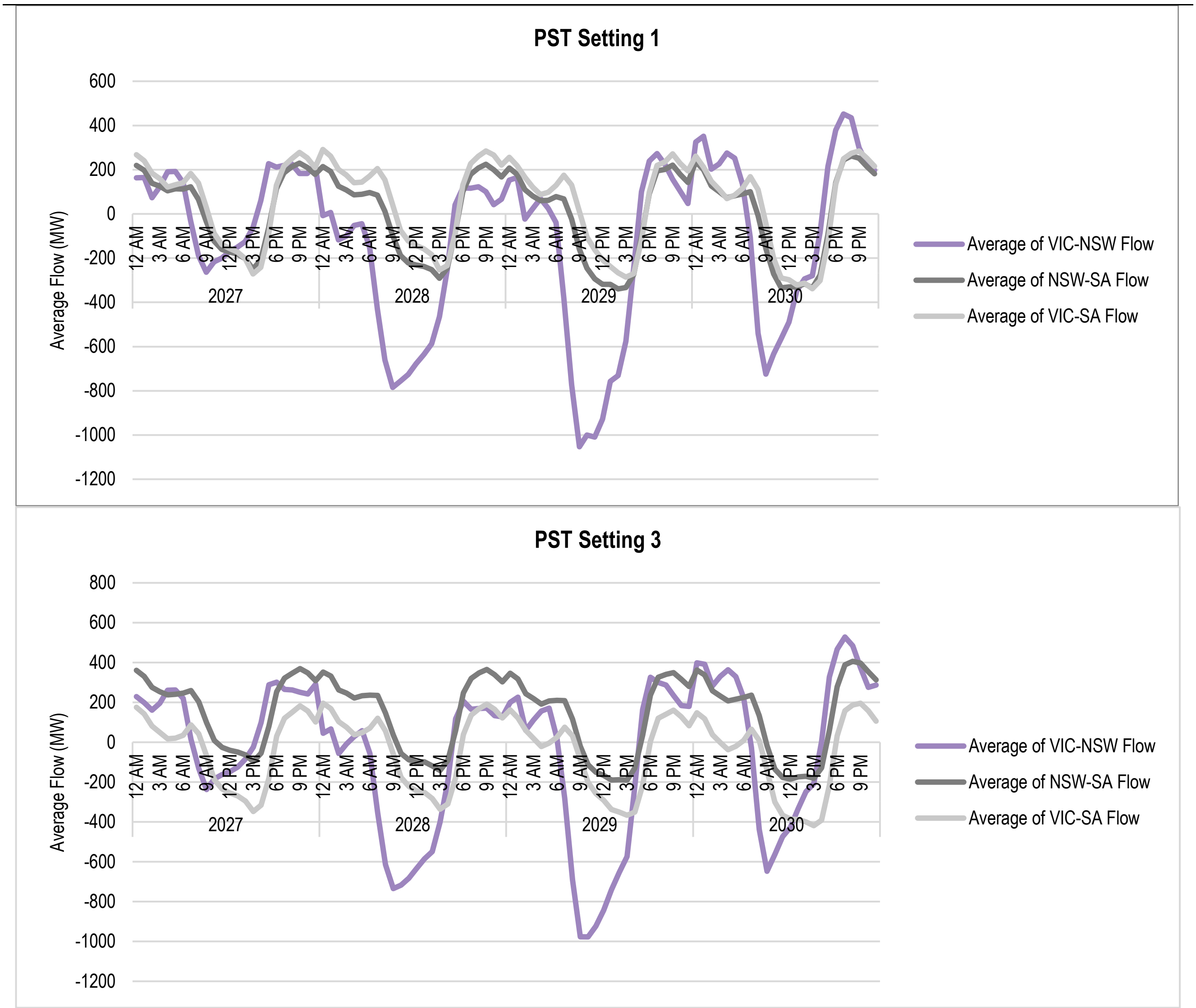


3.5 Impact of PST Setting on loop flows

Figure 3.13 compares the average annual loop flows by time of day in PST setting 1 and 3 to show the difference. Unsurprisingly, the highest impact of changing the PST setting is on NSW-SA flows with a loop flow coefficient of 1. Setting 3 results in an average increase of around 150MW which is close to the change in the right hand side of the loop flow constraint. The second highest impact is on VIC-SA flow with a relatively high coefficient of -0.81. Setting 3 results in an average decrease of around 100MW from setting 1.

The impact of the PST is also shown in Figure 3.12 by comparing the difference between NSW-SA Flow and VIC-SA flow under the two settings. In setting 1, where the PST(ϕ) is – 21 MW, NSW-SA typically has flows less than VIC-SA. In contrast, setting 3 has a PST(ϕ) of 186 and NSW-SA has a step up in flows compared to and above VIC-SA. This reflects the changing direction of the PST setting and the coefficient applied in the loop flow constraint, spreading flow around the loop.

Figure 3.13 Comparison of time of day loop flows between PST setting 1 and PST setting 3



3.6 Impact of PST on maximum interconnector utilisation

The tables below show the instances where each interconnector reaches its limit, for comparison under the Optimal PST and no loop constraint scenario. This shows that without the loop constraint, the VIC-SA and NSW-SA interconnectors on the loop reach their limits much more frequently. The VIC-NSW interconnector is less impacted as it has a lower coefficient. The loop flow constraint will impact the distribution of IRSR around the loop.

Table 3.3 Count of periods where interconnector reaches limit in forward direction

Year	VIC-NSW Flow - Optimal PST	VIC-NSW Flow - no loop constraint	NSW-SA Flow - Optimal PST	NSW-SA Flow - no loop constraint	VIC-SA Flow - Optimal PST	VIC-SA Flow - no loop constraint
2027	1870	1710	0	2657	1095	2213
2028	642	590	11	2733	1187	2138
2029	0	0	35	2101	1067	2494
2030	0	0	57	2045	1084	2700

Table 3.4 Count of periods where interconnector reaches limit in reverse direction

Year	VIC-NSW Flow - Optimal PST	VIC-NSW Flow - no loop constraint	NSW-SA Flow - Optimal PST	NSW-SA Flow - no loop constraint	VIC-SA Flow - Optimal PST	VIC-SA Flow - no loop constraint
2027	3565	3565	0	1606	850	1864
2028	2265	2207	0	1508	809	2111
2029	0	0	1	2011	955	1992
2030	0	0	0	2161	1241	1898

Reallocation of negative settlement residues

4

This chapter explores different ways to reallocate settlement residues on the loop when there is negative IRSR on one or two legs and the net IRSR is positive. In these examples, the reallocation approach was applied per period (hourly), with the annual totals shown below.

4.1 Reallocation using absolute MW flows

Figure 4.1 compares the default IRSR calculation (without reallocation) with a relatively blunt method where the IRSR is reallocated per period in proportion to the absolute flow on each interconnector. While this eliminates negative residues, it can cause IRSRs to deviate significantly from the default calculation. The formula to calculate the IRSR for each interconnector and period, is:

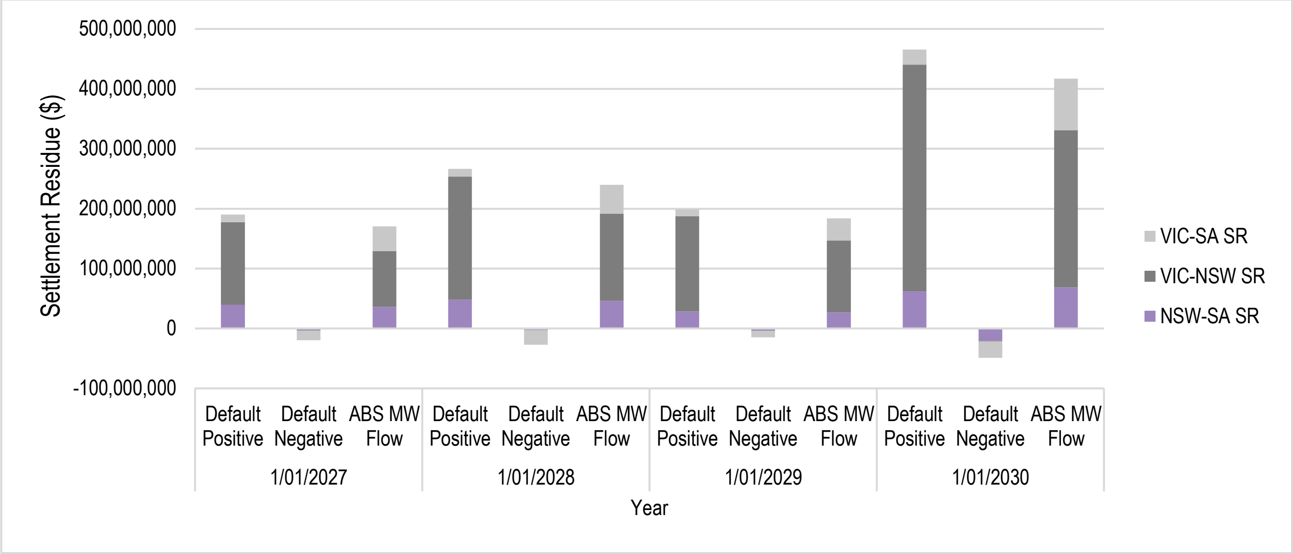
Box 4.1 Example formula using absolute MW flows

IRSR(VIC-NSW) in period t = $\frac{|Flow_{vic-nsw}(t)|}{|Flow_{nsw-sa}(t)|+|Flow_{vic-nsw}(t)|+|Flow_{vic-sa}(t)|} \times Net\ IRSR\ on\ loop\ (t)$

IRSR(VIC-SA) in period t = $\frac{|Flow_{vic-sa}|(t)}{|Flow_{nsw-sa}(t)|+|Flow_{vic-nsw}(t)|+|Flow_{vic-sa}(t)|} \times Net\ IRSR\ on\ loop\ (t)$

IRSR(NSW-SA) in period t = $\frac{|Flow_{nsw-sa}(t)|}{|Flow_{nsw-sa}(t)|+|Flow_{vic-nsw}(t)|+|Flow_{vic-sa}(t)|} \times Net\ IRSR\ on\ loop\ (t)$

Figure 4.1 Reallocation using "Absolute MW Flow" method (Optimal PST scenario)



4.2 Reallocation by scaling down positive residues

The SRA mechanism allows market participants to hedge against inter-regional price differences. Negative IRSR on a leg, means that the price is higher in the exporting region which benefits the participant so there is no need to hedge and we can zero out the IRSR in this period. In this instance, a participant may have sold a contract in the importing region but may be generating in the higher priced exporting region. As the SRA unit pays the difference between importing and exporting region price, the participant is already receiving the higher price in the exporting region.

After we zero out the negative IRSR, to ensure the net IRSR remains unchanged we need scale down the positive IRSR around the loop. For example, the formula where the NSW-SA leg is negative and the VIC-NSW and VIC-SA legs are positive is:

Box 4.2 Example formula to scale down positive residues

Scaler = $1 - \frac{|IRSR_{nsw-sa}(t)|}{IRSR_{vic-nsw}(t)+IRSR_{vic-sa}(t)}$

IRSR(VIC-NSW) for period t = $Scaler \times IRSR_{vic-nsw}(t)$

IRSR(VIC-SA) for period t = $Scaler \times IRSR_{vic-sa}(t)$

Zero out the negative leg: IRSR(NSW-SA) = 0

If there are two negative legs, for example on NSW-SA and VIC-NSW, the formula becomes:

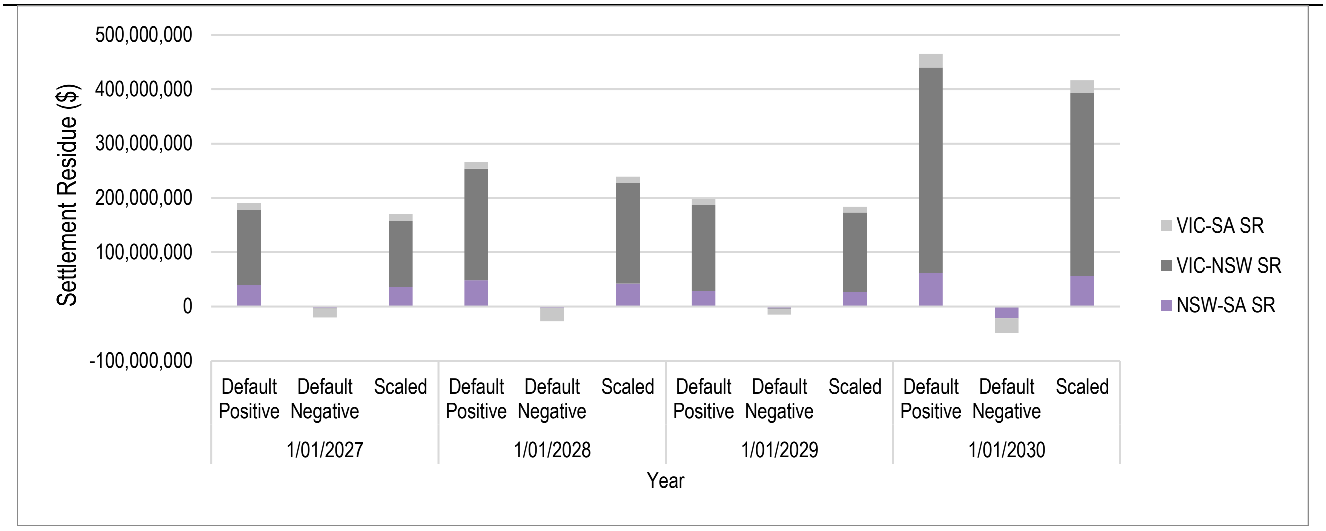
IRSR(VIC-SA) for period t = $IRSR_{vic-sa}(t) + IRSR_{nsw-sa}(t) + IRSR_{vic-nsw}(t)$

Zero out the negative legs: IRSR(NSW-SA) = 0, IRSR(NSW-VIC) = 0

Note that this method and the previous method only work when the net IRSR is positive. When negative, AEMO will need to manage this by disconnecting a leg of the loop or clamping as discussed in section 2.1.

Figure 4.2 shows that the changes between the default and scaling methods are relatively small, which suggests this method is reasonable. The IRSRs are scaled down by $10m to $40m. The highest difference is in 2030 where the VIC-NSW IRSR decreases by around $40m.

Figure 4.2 Reallocation by scaling down positive residues (Optimal PST scenario)



4.3 Reallocation using the loop flow constraint costs

This method was similar to the previous method because when there is negative IRSR on the loop, some constraint costs will be negative and others positive. We would then need to redistribute the numbers by scaling back the negative costs by the positive costs to equal the total loop constraint cost which is negative. This would produce the same result as in the previous method.

Appendices

Background: Inter-regional loop flow constraint

A

A.1 Introduction

The general principles of how AEMO proposes to model the inter-regional loop are based on a DC power flow (linear) approximation of the power system but generalised to interconnectors which are not simple physical power lines but notional power lines transferring power from one region to another. The model AEMO proposes to use is of the form:

PEC + c(1) x VNI + c(2) Heywood = PST(ϕ)   where:

c(i)   is a constant

PST(ϕ) is a MW offset based on the PST's tap change voltage phase shift of ϕ

A.2 Loop flow constraints

A loop flow constraint can be determined for a physical loop using a DC power flow approximation.

Active power flows along a branch from bus j to bus k are approximately

$F_{(j,k)} \approx -\mathrm{b}_{(j,k)}\ (\theta_j - \theta_k)$ where

$\mathrm{b}_{(j,k)}$ is the branch susceptance and

b = $\frac{-x}{\mathrm{r}^2+\mathrm{x}^2}$ where r is the resistance and x is the reactance

θ_j is the voltage angle or phase angle (radians) at bus j

If there is a loop then the sum of the phase angle differences around the loop will sum to zero which gives the following equation

$$\sum\nolimits_{(j,k)\ in\ loop} (\theta_j - \theta_k) = 0$$

Now if we divide the $F_{(j,k)}$ by $\mathrm{b}_{(j,k)}$ we will get

$$\sum \frac{F_{(j,k)}}{\mathrm{b}_{(j,k)}} = -\sum\nolimits_{(j,k)\ in\ loop} (\theta_j - \theta_k) = 0$$

Thus, the loop flow equality constraint equation is

$$\sum \frac{1}{\mathrm{b}_{(j,k)}} F_{(j,k)} = 0 = \sum c(j,k) F_{(j,k)}$$

If there is a phase shifting transformer on a branch then the power flow is

$F_{(j,k)} \approx -\mathrm{b}_{(j,k)}(\theta_j - \theta_k - \phi)$ where

ϕ is transformer tap angle (voltage phase shift)

If there is a loop with a phase shifting transformer in the loop then the sum of the phase angles around the loop will add to ϕ

$$\sum \frac{F_{(\mathrm{j,k})}}{\mathrm{b}_{(\mathrm{j,k})}} = \phi = \sum c(j,k) F_{(\mathrm{j,k})}$$

This constraint can be slightly rearranged so that one of the flow terms, say $F_{(1,\mathrm{g})}$ has a coefficient of 1.

$$\sum \frac{\mathrm{b}_{(1,\mathrm{g})} F_{(\mathrm{j,k})}}{\mathrm{b}_{(\mathrm{j,k})}} = \mathrm{b}_{(1,\mathrm{g})} \phi$$

A.3 Loop flow constraint using shift factors

An alternative version of the DC power flow equations uses power injection shift factors (PISF) or just shift factors. Shift factors (SF) are the power transfer distribution factors (PTDFs) when one of the buses is always a reference or swing bus. A shift factor is the sensitivity of the line flows to a change in an injection at a bus assuming that the reference bus balances the injection.

A shift factor shows how the flow in a branch will change if the injection at a bus changes by 1 MW. The shift factor at the reference bus always equals zero.

The change in flow of line m, ΔF_{m}, for changes in bus power injections ΔP_{n} (generation – load) is

$$\Delta F_{\mathrm{m}} = \sum S(m,n)\, \Delta P_{\mathrm{n}}$$

Where $S(m,n)$ is the change in flow on line m for a 1 MW increase in power injection at bus (node) n.

This linear approximation can be written in matrix form as

$$F = S\ P$$

For a physical loop we can find coefficients $c(m)$ such that

$$c'F = c'S\ P = 0 \qquad \text{for all P.}$$

The c' are such that c(j,k) = $\mathrm{scaler} \times \frac{1}{\mathrm{b}_{(\mathrm{j,k})}}$

A.4 Proposed NEM inter-regional loop flow constraints

Unlike the simple loop flow situation outlined earlier the NEM's interregional loop is not composed of single lines that physically connect a regional reference node to another regional reference node. Some lines connect buses in two regions but most lines in the inter-regional loop are intra-regional lines. Furthermore, in the case of VNI, it consists of four branches, including Redcliffe to Buronga, Lower Tumut to Murray, Upper Tumut to Murray and Jindera to Wodonga. The VNI flow in the NEMDE formulation is the summation of branch flows of all the VNI interconnecting branches.

AEMO's current proposal is to use a constraint composed of interconnector flow terms and an offset and not include any intra-regional network flow terms. This constraint was derived from AC power flow studies and then regressing the PEC flows on the other interconnector flows to estimate the flow coefficients and an offset.

PEC + c(1) x VNI + c(2) Heywood = PST(ϕ) where:

c(i) is a constant (constraint coefficient)

PST(ϕ) is a MW offset based on the PST's tap change voltage phase shift of ϕ

Suppose we consider this constraint in terms of a full loop flow constraint. In that case, it is clear that it is missing the intra-regional network flows or equivalently the power injections and shift factors for the intra-regional transmission lines. If this constraint is used it probably won't always produce an optimal dispatch and the correct LMPs. This could be rectified by introducing generator terms into this constraint to reflect their impact on intra-regional power flows for a full loop flow constraint.

A.5 Modelling of losses

The discussions above concerning modelling the inter-regional loop flow have not addressed the impact of losses. In its simplest form the phase angles around a loop will still add to zero but the flows on each line will have losses so the previous equations will not be strictly correct but may be adequate approximations.

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