P1A - Power and Energy Systems Modelling and Security

Future Grid Cluster Research-Industry Symposium

19 November 2015, The University of Sydney

Team: David Hill, Yan Xu, Gregor Verbič

PhD students: Hesam Marzhooghi, Mehdi Garmroodi, Ruidong Liu, Jaewoong Shim, Shariq Riaz, Ahmad Ahmadyar

Presented by

Dr Gregor Verbič

Centre for Future Energy Networks

THE UNIVERSITY OF SYDNEY

Outline

- Review
- Stability questions
- Research methodology
- Recent results
- Future research

P1 – Power and Energy Systems Modelling and Security

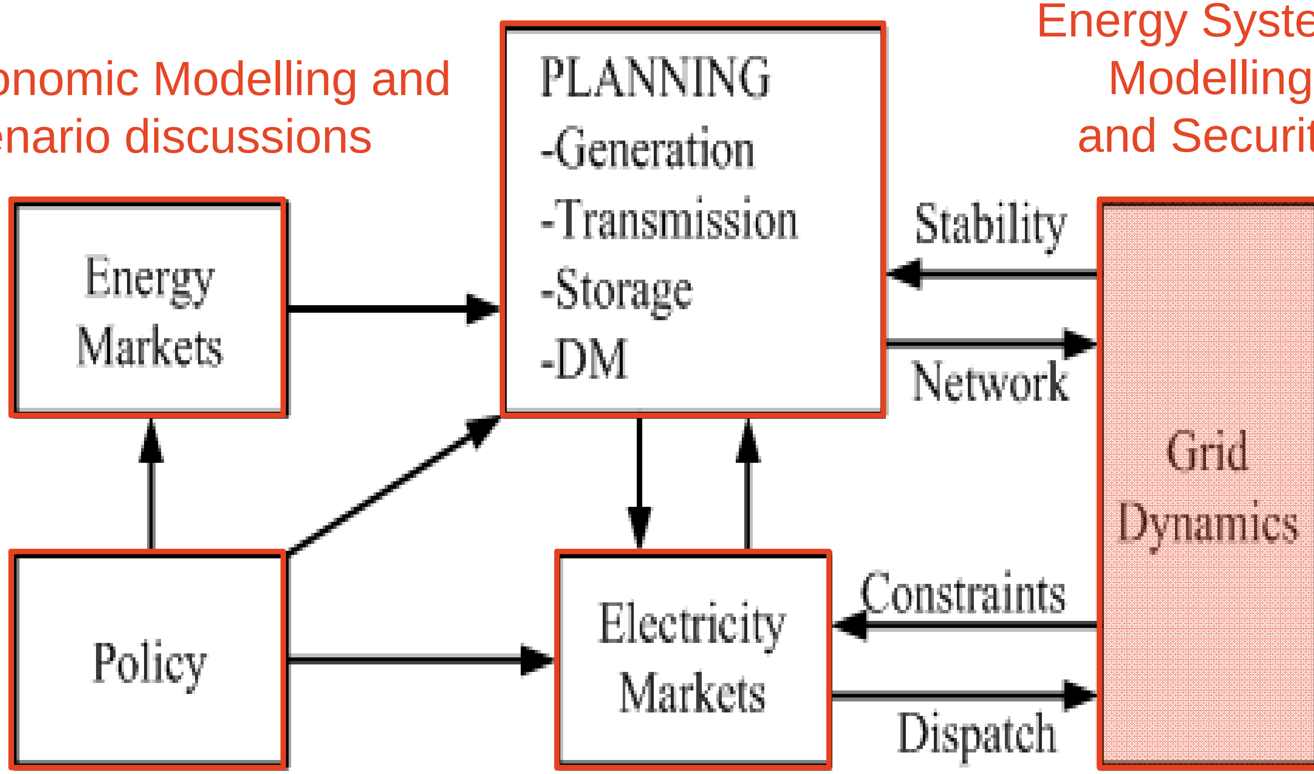
- To provide a modelling framework for the future Australian electricity grid out to 2050.
- To analyse beyond energy balancing to include grid power flows, stability implications, security and resilience to changing technologies.
- Diverse scenarios for levels and placement of renewable generation, different transmission topologies, differing load management and storage technologies will be considered.
- Balancing power, stability and vulnerability to collapse. Impacts of technology and policy change will also be assessed.

Relation to other projects

P2: Grid Planning and Co-optimization

P1: Power and Energy Systems Modelling and Security

P3: Economic Modelling and Scenario discussions

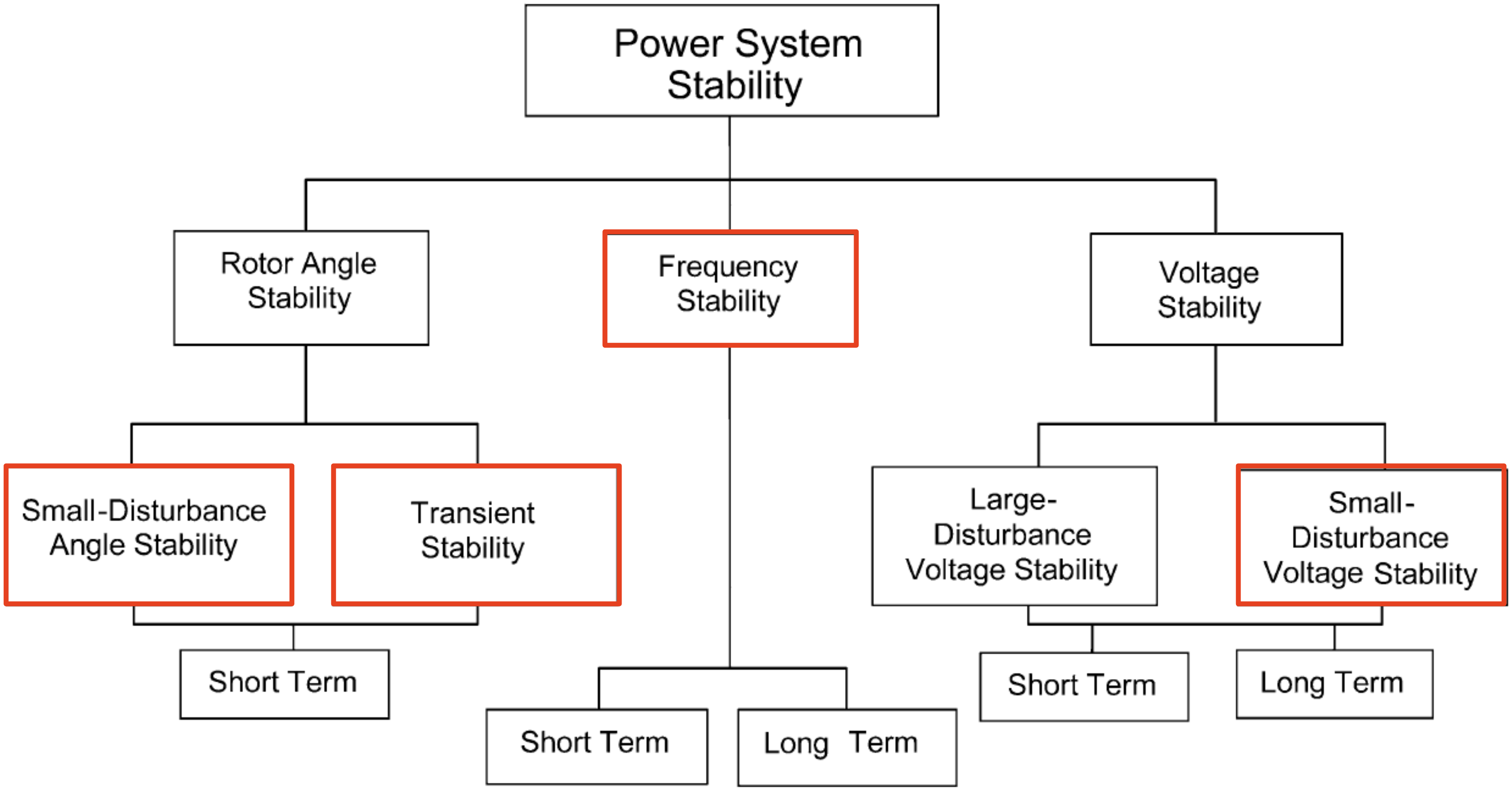


P4: Policy Analysis and Development discussions

Research plan – questions

- Accurate versus fast models for power flow and stability analysis of power system with RE, DR and storage
- How should aggregated load be represented in stability studies including DR and storage influences?
- What is the effect of various type, size and placement of RE and storage on power system performance and stability?
- How the electricity market with RE dispatch will affect power system performance and stability?
- How to find points of vulnerability directly rather than scan massive numbers of scenarios?
- Where are the tipping points of renewable penetration for being unable to use conventional controls (fault currents, voltage and frequency control from large generators) to stabilise the system?
- What levels of storage and demand response are needed for a given high level of renewable penetration?

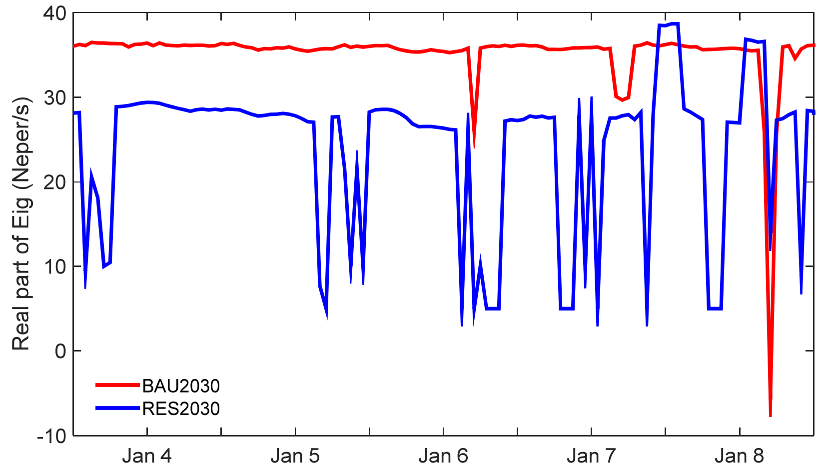
Stability questions

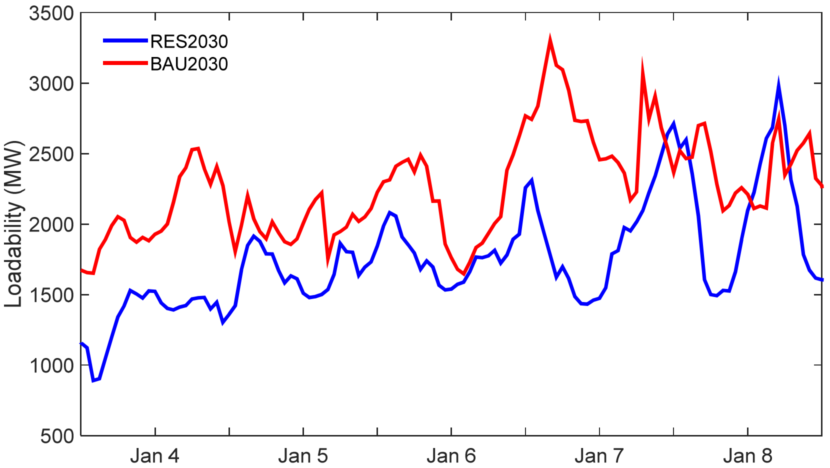


Kundur, P.; Paserba, J.; Ajjarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Hatziargyriou, N.; Hill, D.; Stankovic, A.; Taylor, C.; Van Cutsem, T.; Vittal, V., "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," in *Power Systems, IEEE Transactions on* , vol.19, no.3, pp.1387-1401, Aug. 2004.

Voltage stability

- Load flow calculated for every hour in a year
- Critical contingency screening
- Static voltage stability assessment based on modal analysis of load-flow Jacobian to identify weak points in the network
- Result: min $\lambda(J)$ and voltage stability margin (loadability)



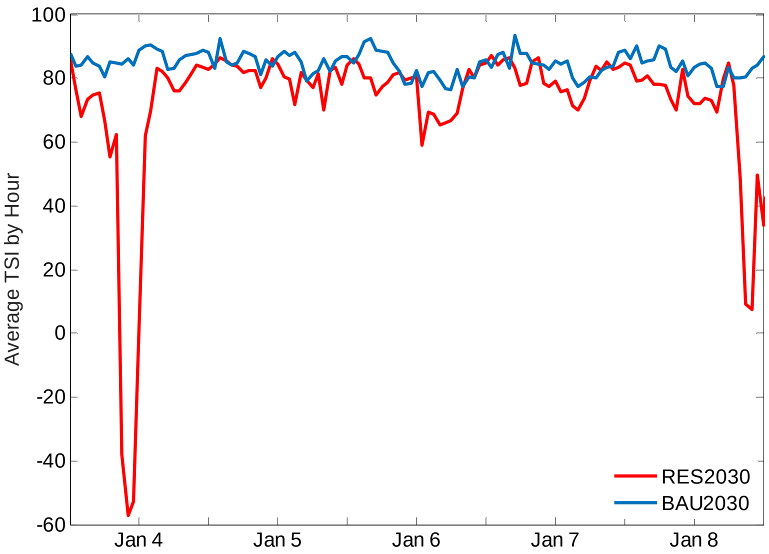


Transient stability

- For each bus in the system, a three-phase short-circuit (5 cycles without element tripping) is used to calculate the Transient Stability Index (TSI) using Extended Equal Area method (EEAC)
- Average TSIs used for stability assessment

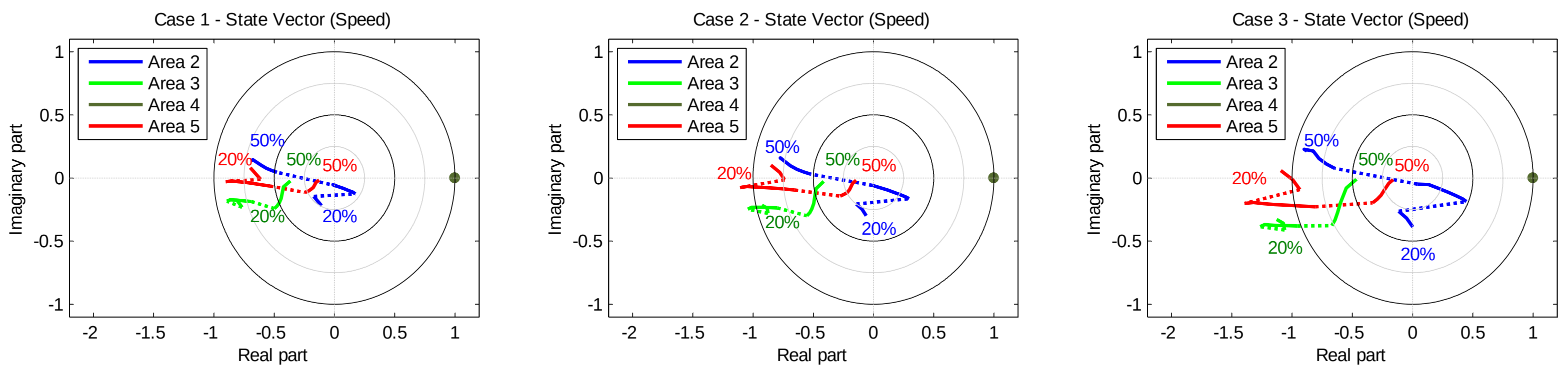
$$TSI(c) = \frac{1}{8760}\sum_{i=1}^{8760} TSI_i^c \qquad TSI(i) = \frac{1}{59}\sum_{c=1}^{59} TSI_i^c$$

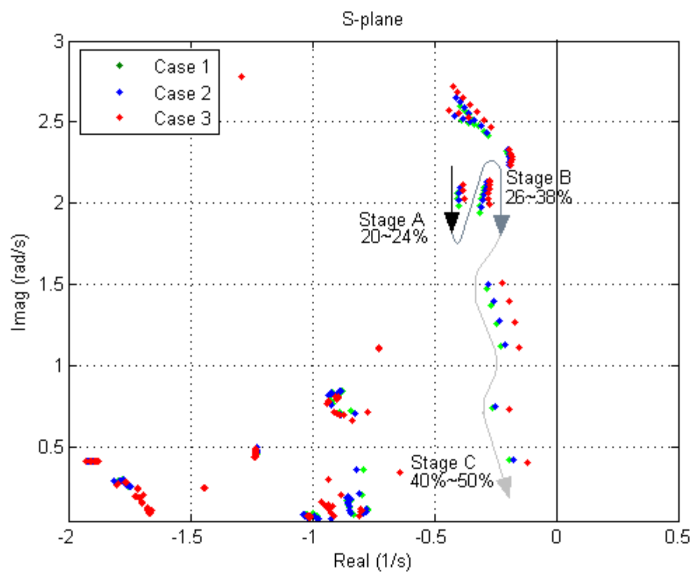
Fault bus location	Yearly average TSI
401	9.5
405	36.1
403	46.6
301	46.7
410	48.5
303	50.9
404	53.7
409	59.8
402	63.8
313	65.7



Small-signal stability

– Eigen-analysis of the dynamic Jacobian to calculate frequency and damping of critical oscillation modes

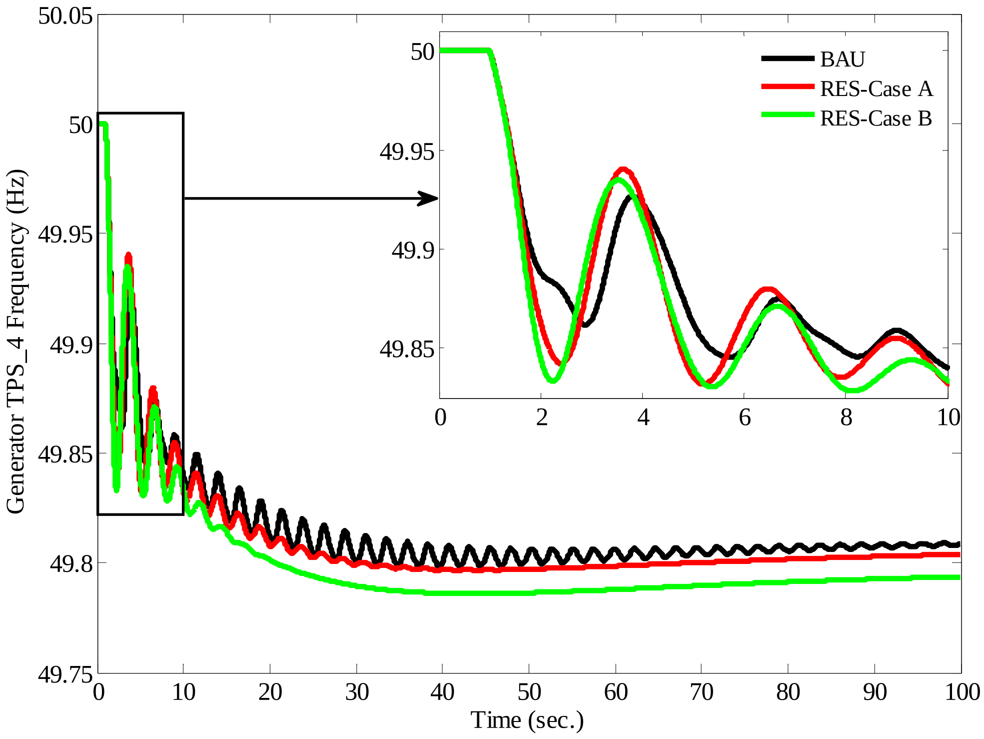




J. W. Shim, G. Verbic, K. Hur, and D. J. Hill, “Impact of Large Scale Penetration of Concentrated Solar Thermal Power on Oscillatory Stability of the Australian Future Grid,” in 5th Solar Integration Workshop, 2014.

Frequency stability

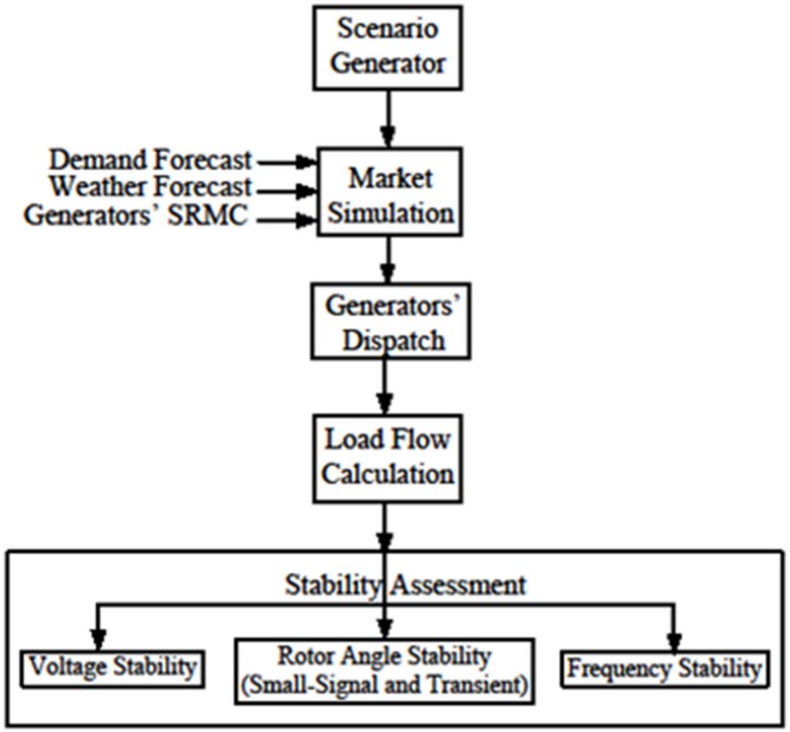
– Calculate rate-of-change-of-frequency and frequency nadir for critical contingencies using time-domain simulations



Marzooghi, H.; Hill, D.J.; Verbic, G., "Performance and stability assessment of future grid scenarios for the Australian NEM," in *Power Engineering Conference (AUPEC), 2014 Australasian Universities* , vol., no., pp.1-6, Sept. 28 2014-Oct. 1 2014.

Research methodology

- Market model based on a unit commitment problem with DC power flow constraints (no particular market structure assumed)
- Load flow calculation using hourly dispatch levels on
- Dynamic analysis using time-domain simulations and modal analysis of the dynamic system Jacobian
- Stability scanning techniques fast simulation, direct methods (e.g. EEAC for angle stability), fault ranking, search methods
- Stability sensitivity analysis

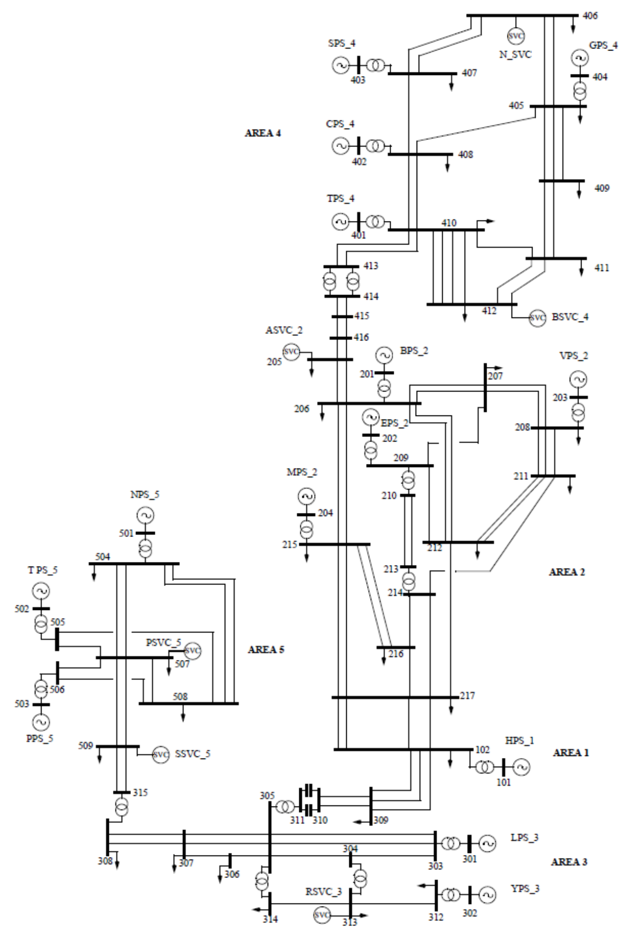


Software

– Off-the-shelf solver (CPLEX) to solve the custom built market model based on a unit commitment problem (Plexos used initially)
– MATPOWER – repeated (time series) load flow (faster), initial condition for stability
– DSA Tools – scanning for voltage stability (VSAT/PV, QV curves, eigenanalysis, simulation) and transient stability (TSAT/EEAC), fault ranking
– DigSILENT PowerFactory – scanning small-disturbance stability (need access to dynamic Jacobian)

Test System

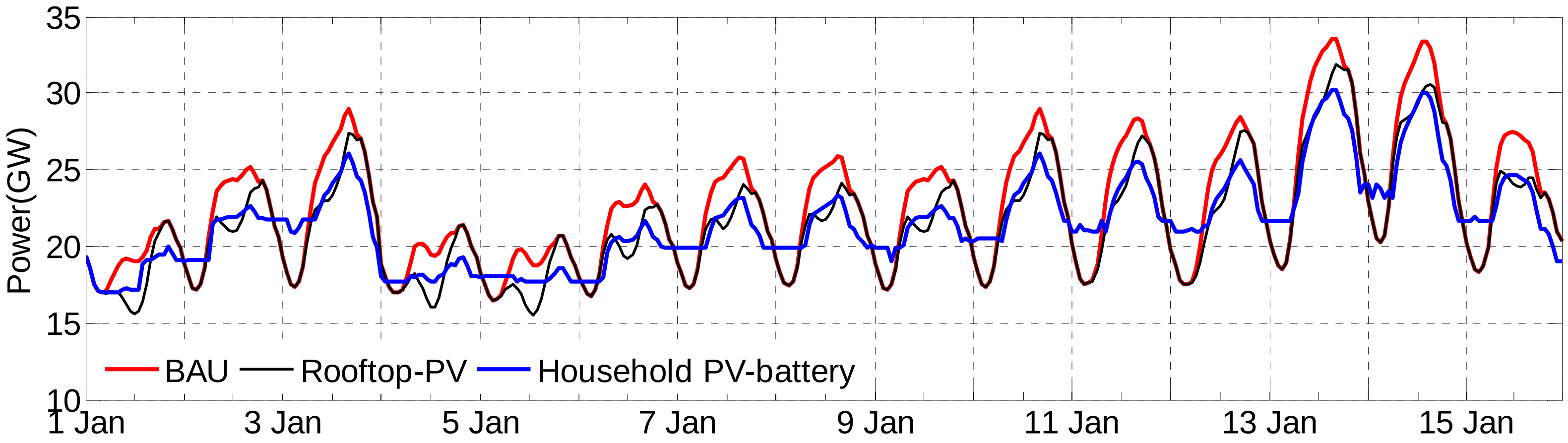
- A simplified 14-generator, 59-bus model of the NEM, initially developed for small-signal stability analysis
- Conventional generation replaced with RES (wind, CSP, PV)
- NTNDP data for solar, wind and demand traces
- Demand response model incorporated in the unit commitment model



Gibbard, M. and Vowles, D., “Simplified 14-generator model of the SE Australian power system,” Tech. Rep., 2010.

Aggregated demand response model

- The model assumes a significant uptake of residential PV-battery systems in the future
- The users are assumed to maximise self-consumption (low FiTs coupled with high electricity prices)
- Bi-level optimisation used to capture the independent objectives of the aggregator and the end-users



Riaz, Shariq; Chapman, Archie C.; Verbic, Gregor, "Comparing utility and residential battery storage for increasing flexibility of power systems," in *Power Engineering Conference (AUPEC), 2015 Australasian Universities* , vol., no., pp.1-6, 27-30 Sept. 2015.

Simulation scenarios – sensitivity analysis

- RES penetration (inspired by CSIRO FG Forum, AEMO 100% Study, The Zero Carbon Australia Project)
  - medium / high
- Demand response
  - no / low / medium / high
- Transmission
  - HVDC / AC
- Inertia
  - synchronous / inverter-based

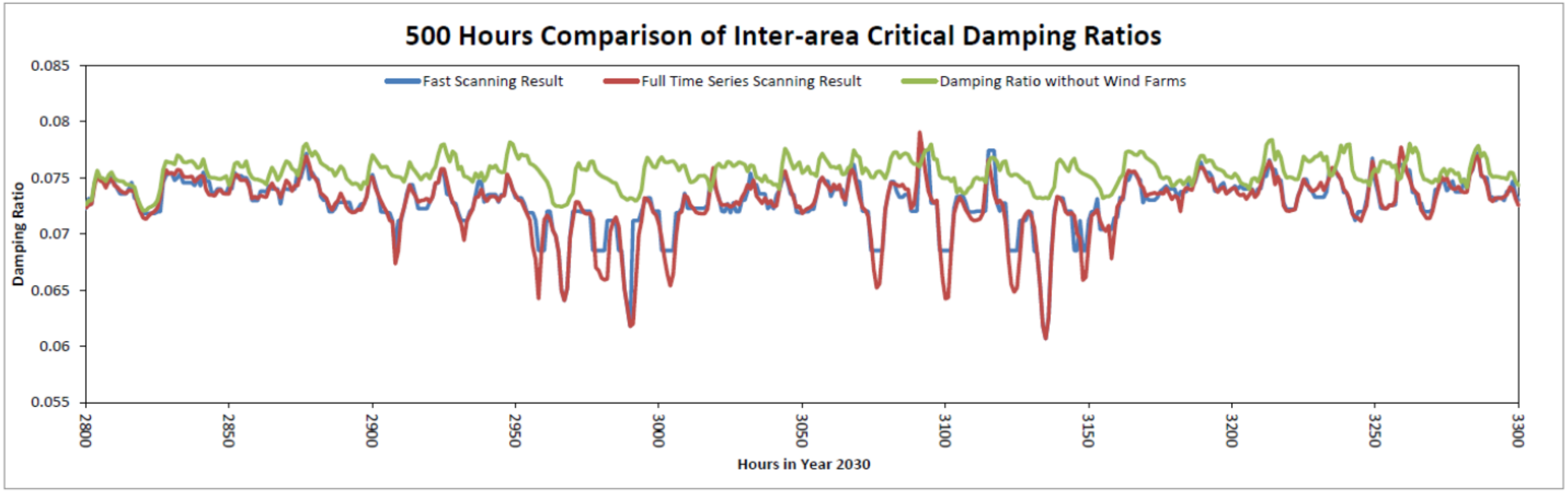
Year	No	Scenario Code	Scenario Description
2030	1	M2030-1-N	Medium RES- Augmentation for the NEM-No DR
	2	M2030-1-L	Medium RES- Augmentation for the NEM-Low DR
	3	M2030-1-M	Medium RES- Augmentation for the NEM-Medium DR
	4	M2030-2-H	Medium RES- Augmentation for the NEM-High DR
	5	H2030-1-N	High RES- Augmentation for the NEM-No DR
	6	H2030-1-L	High RES- Augmentation for the NEM-Low DR
	7	H2030-1-M	High RES- Augmentation for the NEM-Medium DR
	8	H2030-2-H	High RES- Augmentation for the NEM-High DR
2050	9	M2050-1-N	Medium RES- Augmentation for the NEM-No DR
	10	M2050-1-L	Medium RES- Augmentation for the NEM-Low DR
	11	M2050-1-M	Medium RES- Augmentation for the NEM-Medium DR
	12	M2050-2-H	Medium RES- Augmentation for the NEM-High DR
	13	H2050-1-N	High RES- Augmentation for the NEM-No DR
	14	H2050-1-L	High RES- Augmentation for the NEM-Low DR
	15	H2050-1-M	High RES- Augmentation for the NEM-Medium DR
	16	H2050-2-H	High RES- Augmentation for the NEM-High DR

Computation

- 8760 hours in a year
- 14 generators, 28 loads, 59 buses, 90 lines (no gas network yet)
- 18 parallel load/generation changes (voltage stability sensitivities)
- Calculations (HPC):
  - PF 8760 (10-15 mins)
  - TS 8760x 59 = 500,000 3-phase faults (3-4 days)
  - SSD 8760 (4-5 hours)
  - VS 8760x212x18 = 33.43 Million checks (N-1 for all sensitivities and equipment; 7-9 full days)
- In full system, will have many times more intervals, equipment, faults etc.
- Clearly, need ways to reduce computation

Fast scanning and clustering (future work)

- Idea: partition data into a certain number of clusters to avoid analysing the whole data set
- Self-adaptive bilevel K-means used for clustering
- Preliminary results: instead of 8760 simulation runs, only 607 simulations are needed to recreate of the critical inter-area damping



Simulation scenarios

1. BAU2030 (no RES except for existing hydro)

Technology	Energy (TWh)	Energy share
Black coal	114.4	52.40%
Brown coal	62.8	28.75%
GT	32.1	14.68%
Hydro	9.1	4.17%
Total	**218.4**	

2. RES2030 (~30% RES penetration)

Technology	Energy (TWh)	Energy share
Black coal	72.1	33.01%
Brown coal	34.3	15.68%
GT	37.1	16.97%
Hydro	9.1	4.17%
Wind	60.3	27.63%
PV	3.4	1.57%
CST	2.1	0.97%
Total	**218.4**	

3. 100% renewable scenario RES2040

Recent results – 2040 high-RES scenario

– Based on the UNSW study that considers the optimal mix of generating technologies for a100% RES in the NEM
– Generation mix optimised for 2010 demand

Technology	Capacity (GW)	Capacity share	Annual energy (TWh)	Annual energy share
PV	3.9	4.6%	10.6	5.2%
Wind	52.8	62.6%	147.9	72.4%
CST	2.8	3.3%	9.4	4.6%
Hydro	3.6	4. 3%	18.2	8.9%
GT	21.2	25.2%	18.2	8.9%
Total	**84.3**	**100%**	**204.3**	**100%**

Jenny Riesz, Ben Elliston, "Research Priorities for Renewable Technologies – Quantifying the importance of various renewable technologies for low cost renewable electricity systems", working paper.

Network augmentation

- Augment the network just enough to ensure the unbalancing hours are reduced to close to zero (ramping constraints binding in a small number of scenarios)
- Aim
  - Keep voltage angles differences below 30°
  - Keep line flows within thermal limits
- Increase in the transmission line capacities (w.r.t. 2010):
  - 4x on interstate lines
  - 4-6x in QLD zones NQ-CQ-SEQ (60% increase in peak load and 45% increase in demand energy, plus WFs in NQ and SEQ)
  - 3x in VIC zones MEL and LV (WFs in LV and weak connection between LV and MEL)
  - 2x in SA required (power transfer between SA and VIC)

2040 100% RES scenario

Copper plate

Technology	Capacity (GW)	Capacity share	Annual energy (TWh)	Annual energy share
PV	4.32	4.6%	11.74	5.2%
Wind	58.49	62.6%	163.84	72.4%
CST	3.10	3.3%	10.41	4.6%
Hydro	3.99	4.3%	20.16	8.9%
GT	23.49	25.2%	20.16	8.9%
Total	**93.39**	**100%**	**226.32**	**100%**

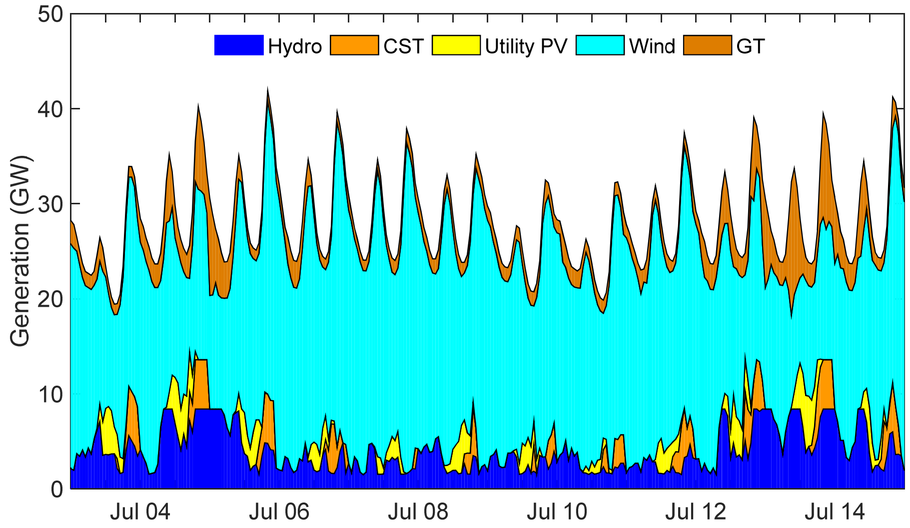
With transmission network

Technology	Capacity (GW)	Capacity share	Annual energy (TWh)	Annual energy share
PV	9.16	6.3%	11.23	5.0%
Wind	97.10	66.9%	154.94	69.1%
CST	5.20	3.6%	10.24	4.6%
Hydro	8.50	5.9%	20.78	9.3%
GT	25.08	17.3%	26.95	12.0%
Total	**145.04**	**100%**	**224.15**	**100%**

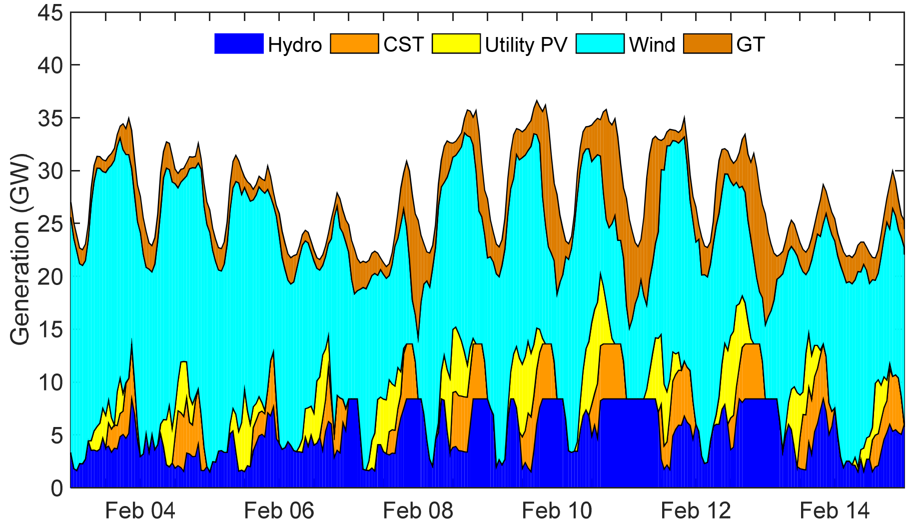
Unserved hours: 72 (0.82%), Unserved energy: 2.18TWh (0.97%)

Balancing results (conventional load model)

Winter



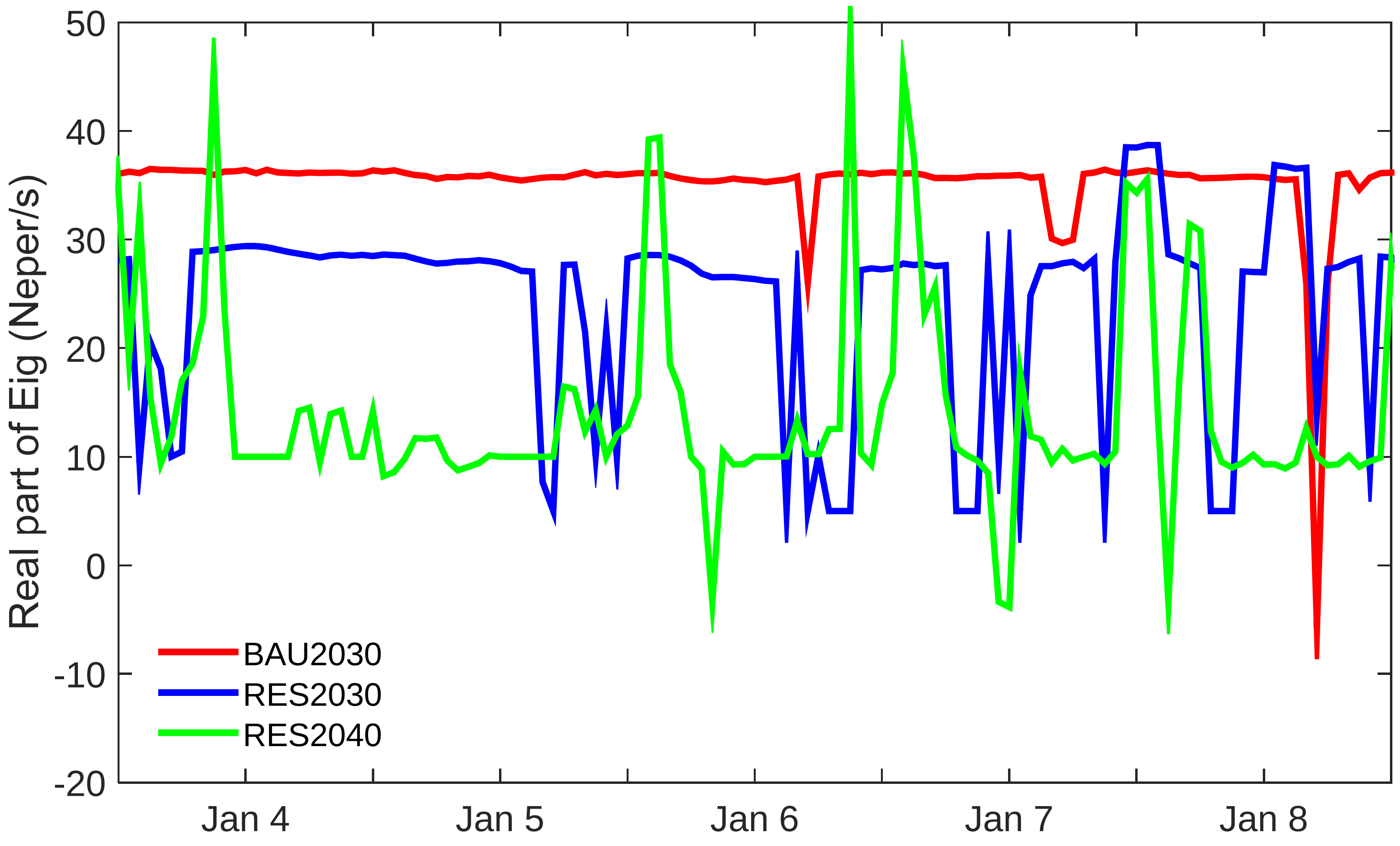
Summer



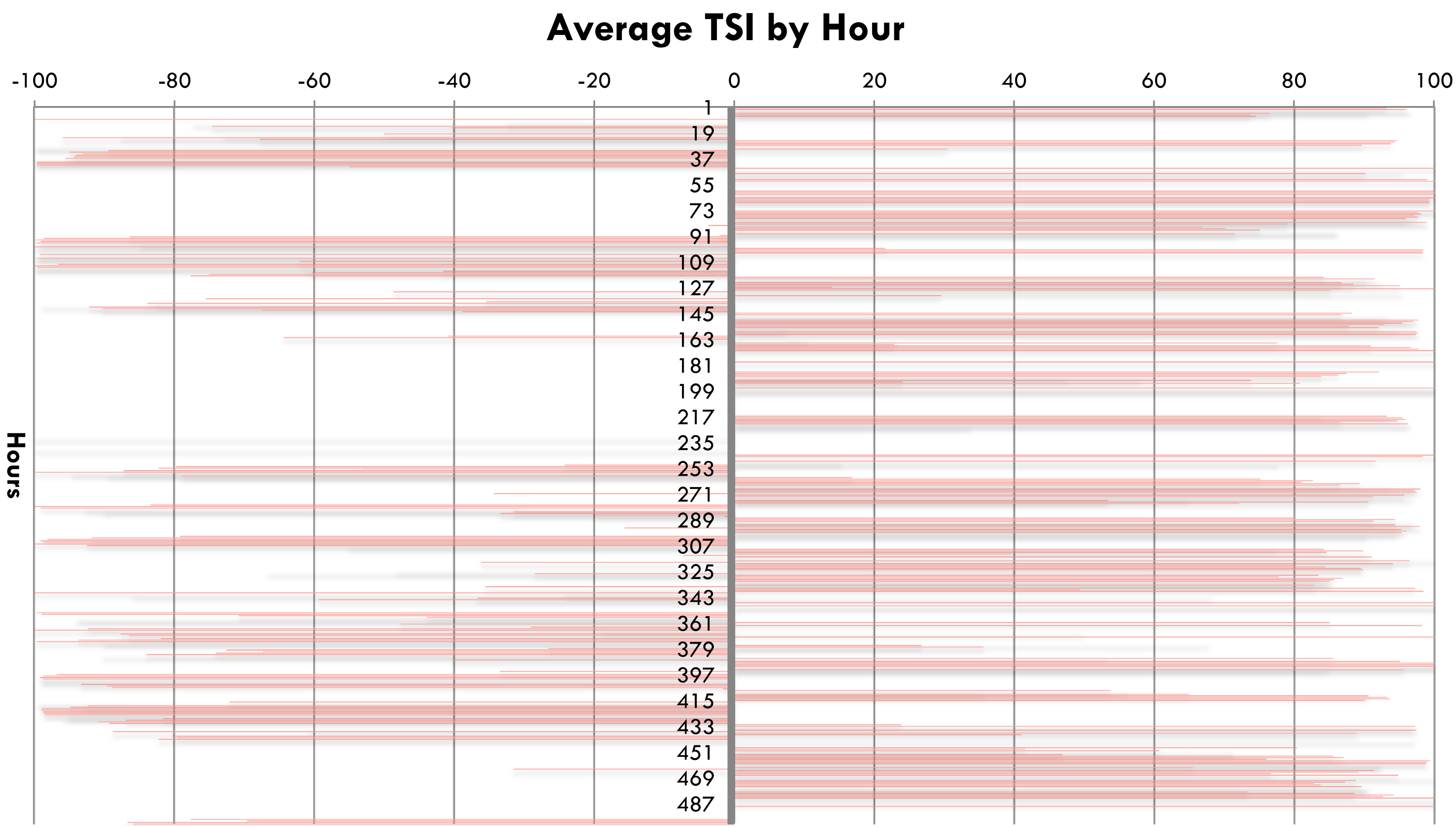
Voltage stability (loadability)

Voltage stability Scenario #	Generation Increase	Load Increase	Criticality ranking	Top 2 contingencies
1	All	All	2	1-Interstate NSW-QLD 2-Line410-413
2	All	Critical Loads (207-211-212-216-217-306-313-405-412-507-508)	5	1-Interstate NSW-QLD 2A-Line-410-412 2B-Line-407-408 2C-Line-312-313 2D-Line-507-508 (2A to 2D are the second top here)
4	Areas 1 and 2	Area 3	1	1-Interstate line NSW-VIC 2- Line-312-313
11	Area 5	Area 3	3	1-Line-505-507 2-Line-506-507
15	Area 3	Area 5	4	1- Interstate line limits

Voltage stability (minimal eigenvalue)



Transient stability



Future research (associated work)

1. Advanced indexes, ranking
   - Vulnerable points (weak grids?)
   - Stability margins
   - Stability scanning –AI search approaches, sampling, e.g. Taguchi's method
   - How to reduce computation – learning, identify most vulnerable areas
2. More automation in integrated computation tools

Publications

1. Garmroodi, M.; Hill, D.J.; Verbic, G.; Ma, J., "Impact of Tie-Line Power on Inter-Area Modes With Increased Penetration of Wind Power," in Power Systems, IEEE Transactions on , vol.PP, no.99, pp.1-9.
2. Garmroodi, M.; Hill, D.J.; Jin Ma; Verbic, G., "Impact of increased penetration of wind power on damping of low frequency oscillations in different network topologies," in PowerTech, 2015 IEEE Eindhoven , vol., no., pp.1-5, June 29 2015-July 2 2015
3. Marzooghi, H.; Verbic, G.; Hill, D.J., "Aggregated effect of demand response on performance of future grid scenarios," in PowerTech, 2015 IEEE Eindhoven , vol., no., pp.1-6, June 29 2015-July 2 2015.
4. Riaz, Shariq; Chapman, Archie C.; Verbic, Gregor, "Comparing utility and residential battery storage for increasing flexibility of power systems," in Power Engineering Conference (AUPEC), 2015 Australasian Universities , vol., no., pp.1-6, 27-30 Sept. 2015.
5. J.W.Shim, G.Verbic, K.Hur and D.J.Hill, "Impact of large scale penetration of concentrated solar thermal power on oscillatory stability of the Australian Future Grid," Proc 4th Solar Integration Workshop, Berlin, Germany November 2014.
6. J.W.Shim, G.Verbic, K.Hur and D.J.Hill, "Impact analysis of variable generation on small signal stability,"Proc Australasian Universities Power Engineering Conference (AUPEC 2014), Curtin University, Perth, Australia, 28 September – 1 October 2014.
7. H.Marzooghi, D.J.Hill and G.Verbic, "Performance and stability assessment of Future grid scenarios for the Australian NEM,"Proc Australasian Universities Power Engineering Conference (AUPEC 2014), Curtin University, Perth, Australia, 28 September – 1 October 2014.
8. M.Garmroodi, D.J.Hill, J.Ma and G.Verbic, "Impact of wind generation variability on small signal stability of power systems,"Proc Australasian Universities Power Engineering Conference (AUPEC 2014), Curtin University, Perth, Australia, 28 September – 1 October 2014.
9. H.Marzooghi, D.J.Hill and G.Verbic, "Aggregated demand modeling including distributed generation, storage and demand response," submitted to IET Generation, Transmission and Distribution.
10. H.Marzooghi, G.Verbic and D.J.Hill, "Aggregated demand response modelling for future grid scenarios," submitted to Journal Sustainable Energy, Grids and Networks (SEGAN).
11. H.Marzooghi, Y.Xu, D.J.Hill and G.Verbic, "Scenario, sensitivity and contingency based stability analysis of the Australian future grid," in preparation for IEEE Trans Power Systems.

Questions?

Gregor Verbič | Senior Lecturer
Centre for Future Energy Networks
School of Electrical & Information Engineering
Faculty of Engineering & IT

THE UNIVERSITY OF SYDNEY
Room 307, Electrical Engineering Building, J03
The University of Sydney | NSW | 2006
T +61 2 9351 8136 | **F** +61 2 9351 3847
E gregor.verbic@sydney.edu.au
W http://sydney.edu.au/engineering/electrical