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Bode Lecture

Power System Dynamics and Control – *Structure, data and learning*

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Outline

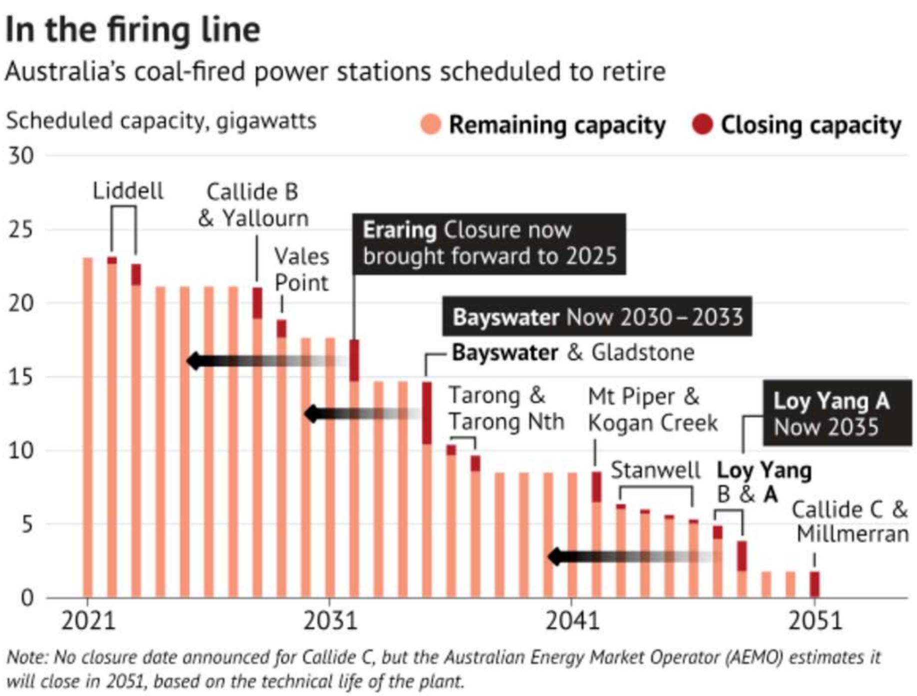
- Background
- Power and control
- Structure, data and learning
- Future grids
- Conclusions

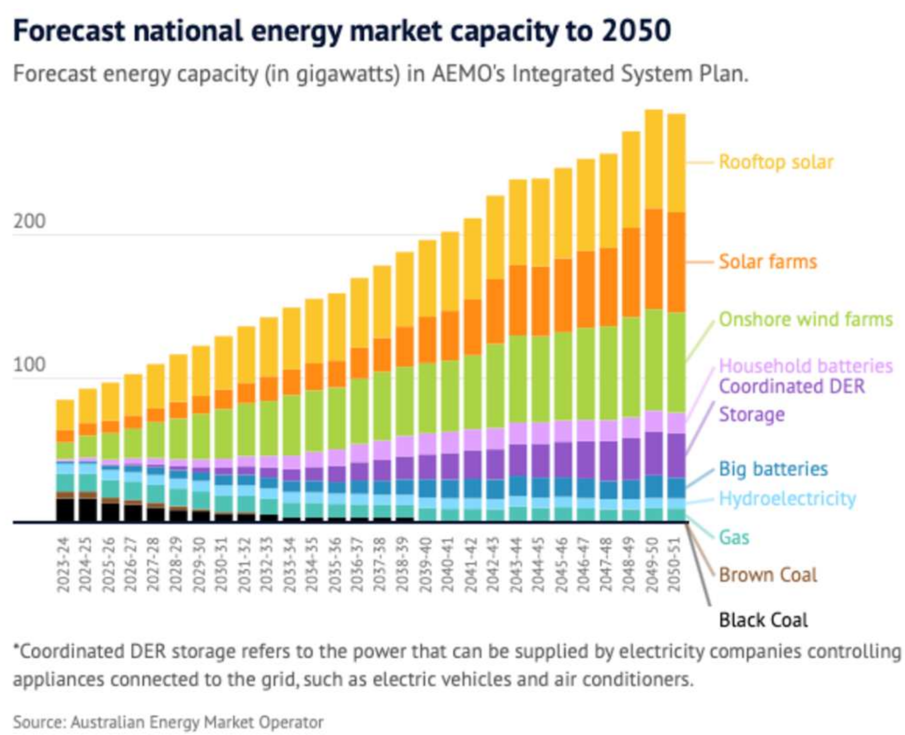
Power system transitions

1. AC vs DC ‘current wars’ – losses, safety etc
2. Transmission – analysis, transient stability [Gorev, Park]
3. Interconnected systems – oscillations, frequency control [Cohn 1950, Concordia]
3. Remote generation – voltage collapses, load dynamics, security control [Kundur]
4. Energy crises 1970’s – system efficiency [Systems Engineering for Power, Fink]
5. Electricity markets 1990’s – grid physics lost, planning issues [Major reforms]
6. ‘Smart grids’ 2010’s – distribution feedback [Research revival]

Towards 100% renewable power

- Connection to emissions targets and climate change [Bode lecture, P. Khargonekar 2021]
- Two transitions [Australian NEM]





Tipping point

- South Australia blackout, September 2016
- "Tesla's big battery started with an Elon Musk Twitter exchange...

Musk talks about Tesla's battery plan in July 2017."
(ABC News)

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Power systems and control

Power is nothing without control – Pirelli Tyres

- PLAN – network, operations
- BALANCE – energy, power, ramping
- STABILISE – limits, dynamics
- CONTROL – regulate, efficiency
- RECOVER – from emergencies

Mathematical complexity

- System stress gives more difficult dynamics (nonlinearity)
- More interconnection (large networks)
- Multi-level (granular)
- Less known/predictable (uncertainty)
- Mixed discrete and continuous actions (hybrid)

Power flow model

Rewrite the linear nodal circuit equations in terms of powers and voltages:

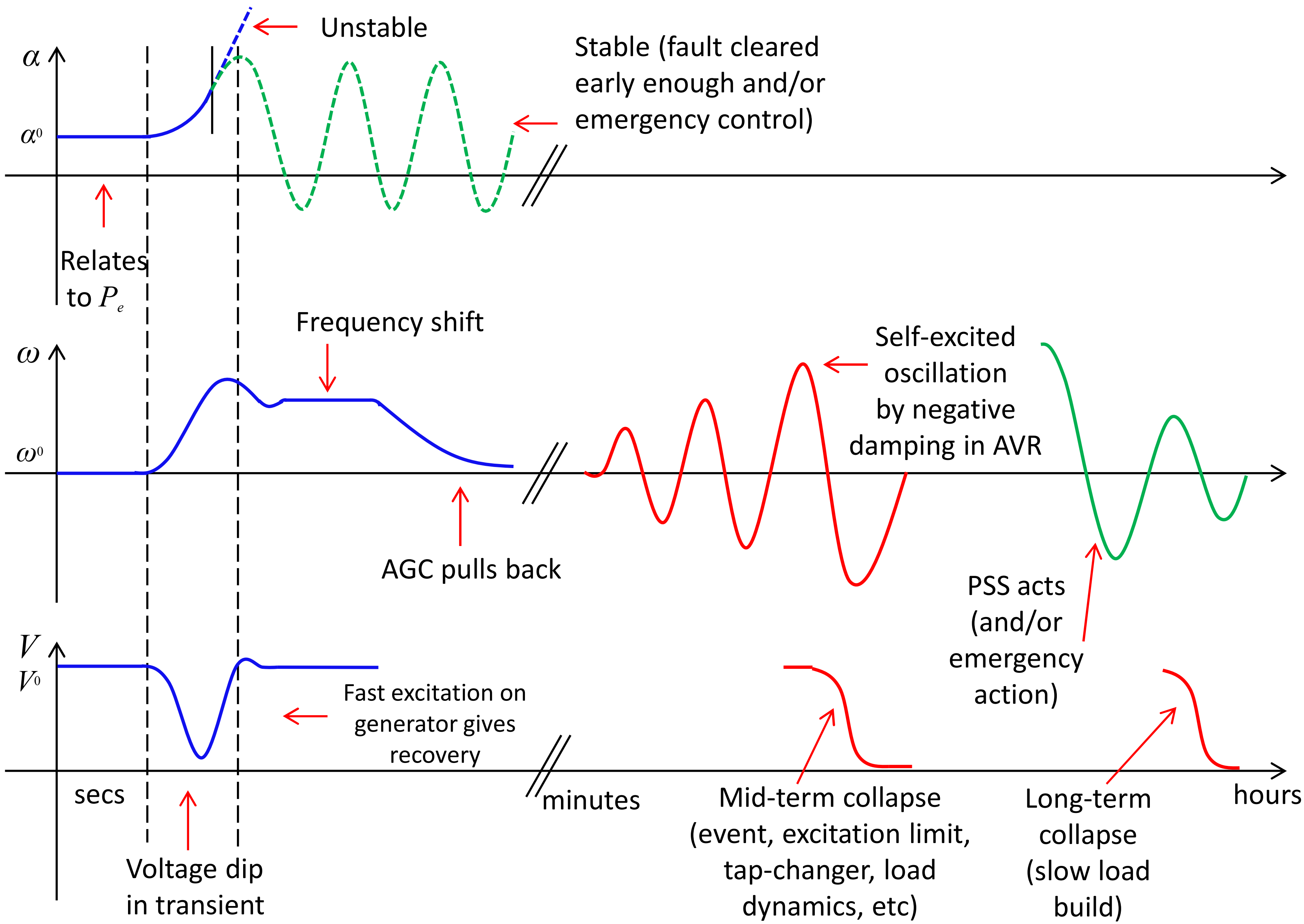
- Becomes highly nonlinear

$$P_K = V_K \sum_{n=1}^{N} V_n \left[G_{kn} \cos\left(\delta_k - \delta_n\right) + B_{kn} \sin\left(\delta_k - \delta_n\right)\right]$$

$$Q_K = V_K \sum_{n=1}^{N} V_n \left[G_{kn} \sin\left(\delta_k - \delta_n\right) - B_{kn} \cos\left(\delta_k - \delta_n\right)\right]$$

Ref: J.D. Glover, T.J. Overbye and M.S. Sarma, *Power System Analysis and Design*, 6th Ed., Cengage Learning, 2017.

What can happen after a fault?



Classical generator-based controls

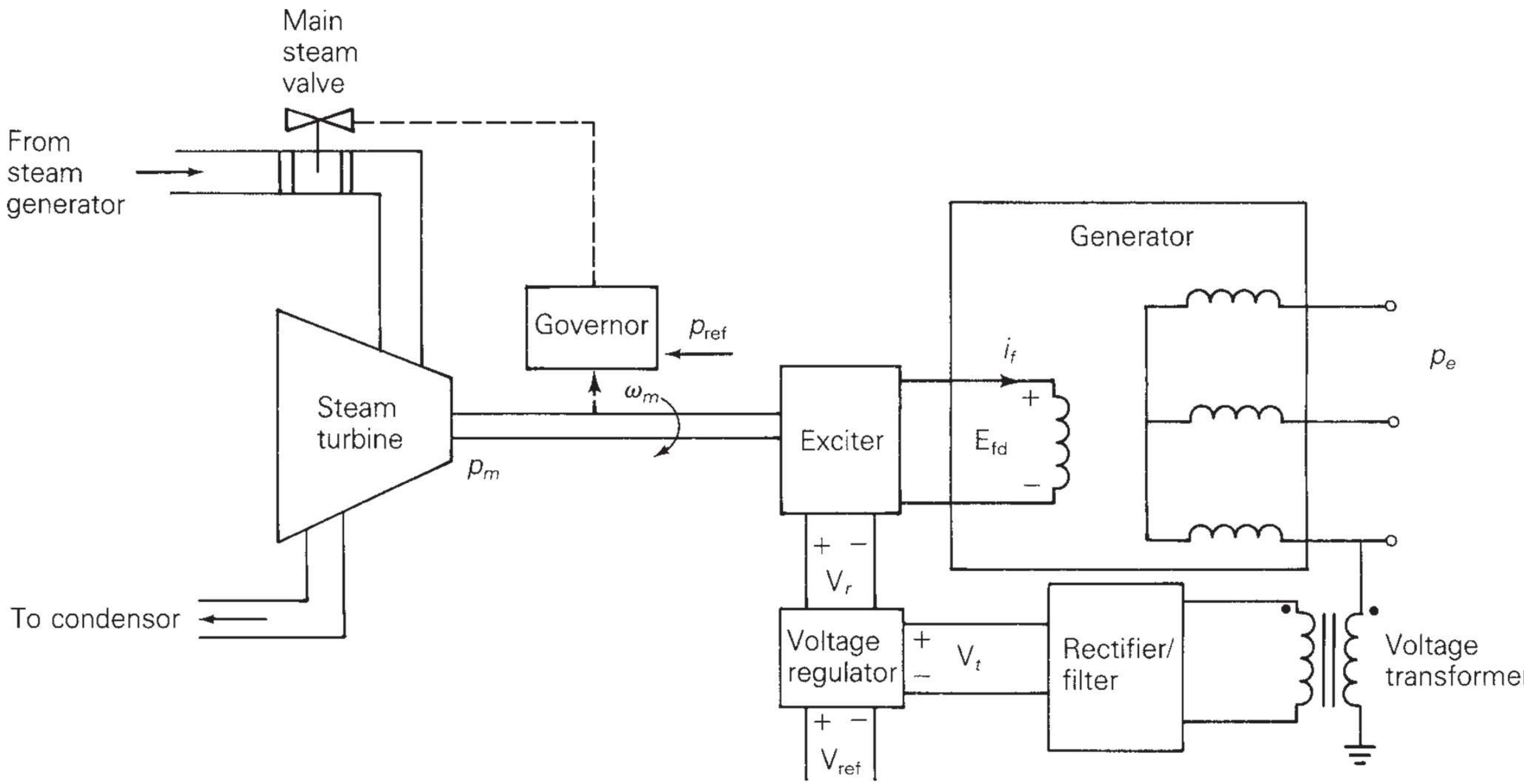


FIGURE 12.1 Voltage regulator and turbine-governor controls for a steam-turbine generator

Ref: J.D. Glover, T.J. Overbye and M.S. Sarma, *Power System Analysis and Design*, 6th Ed., Cengage Learning, 2017.

Two-area load frequency control

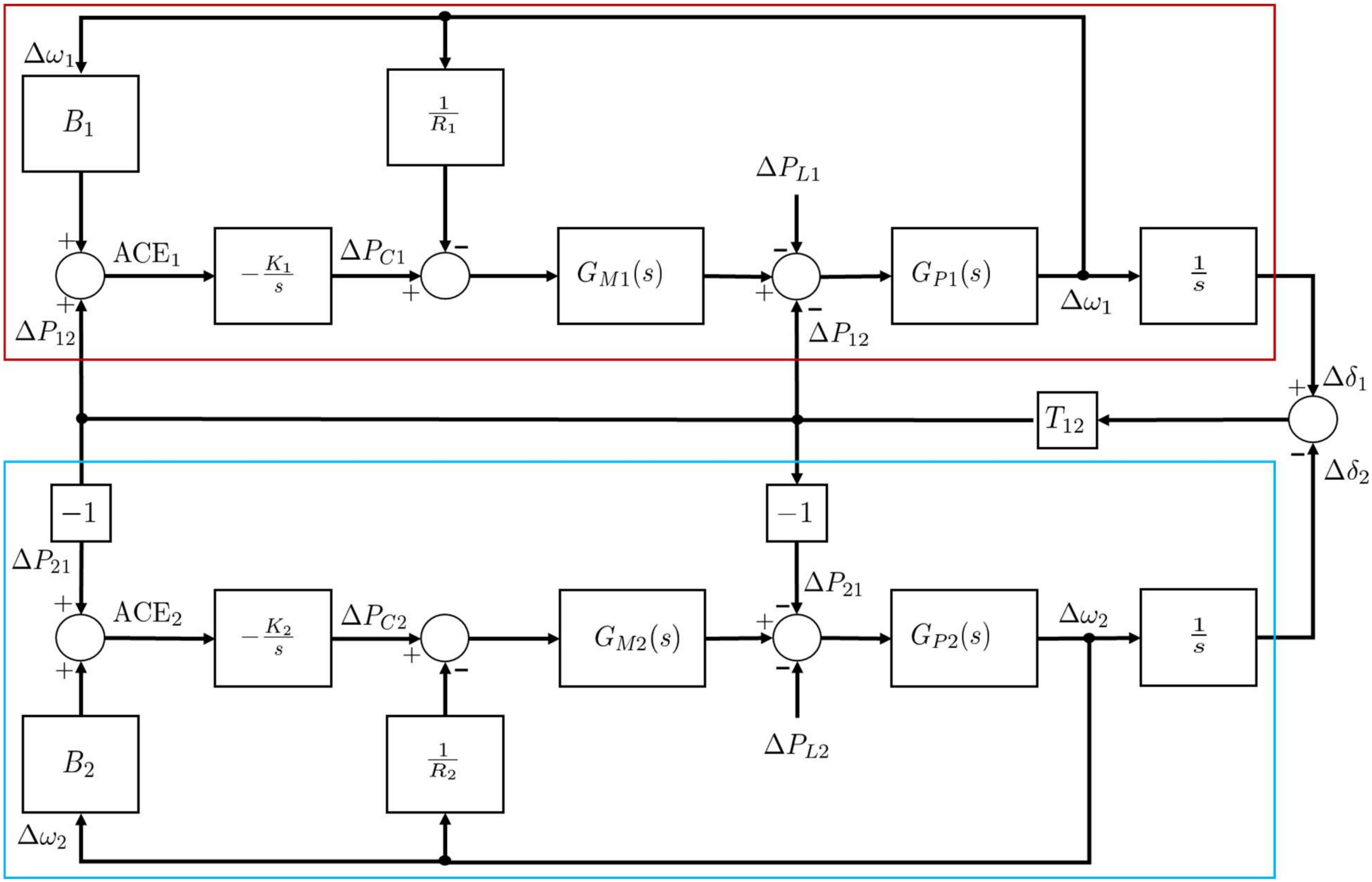
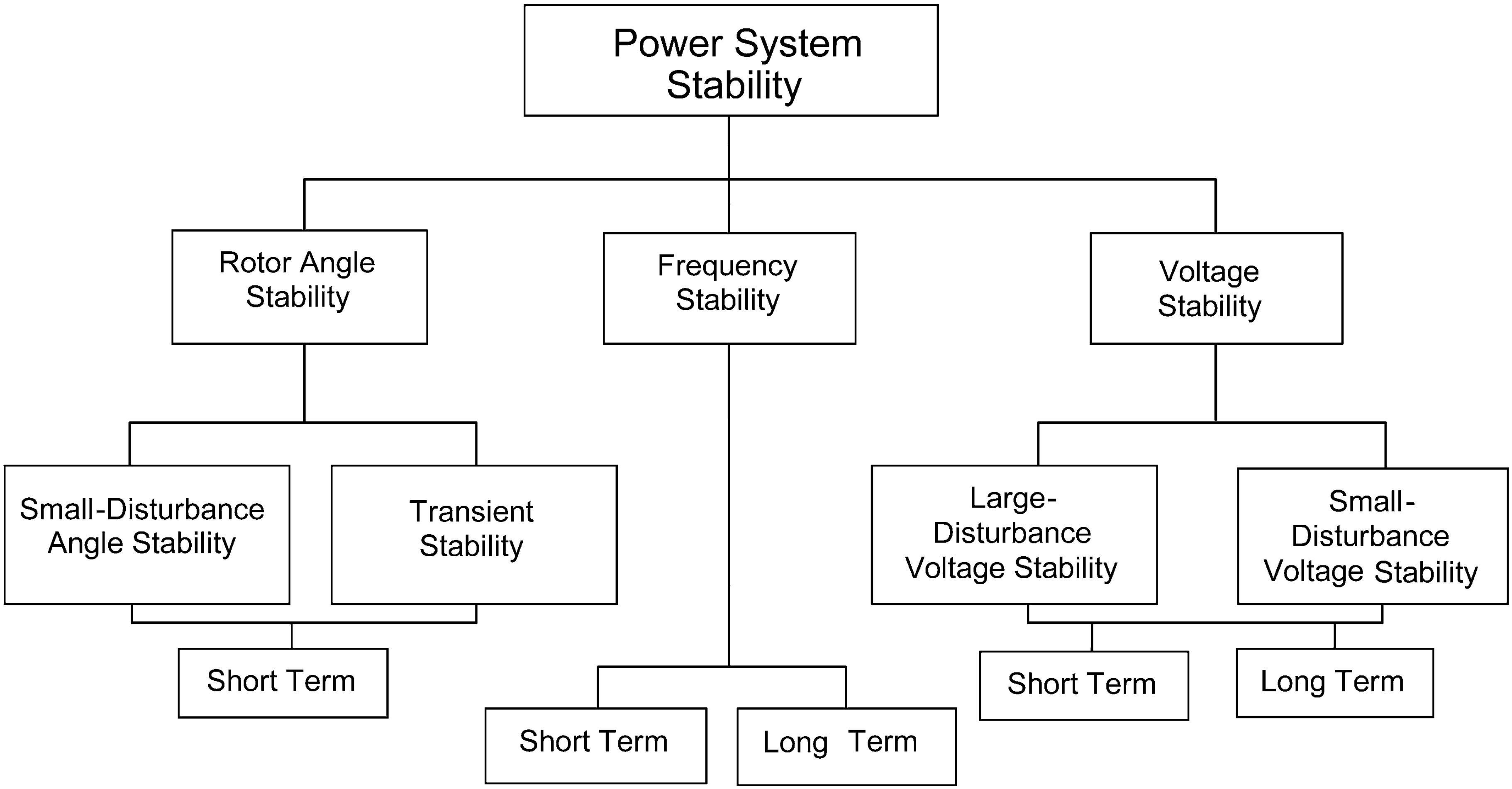


Figure 11.13 Tie-line bias control added.

Ref: A.R. Bergen and V. Vittal, *Power System Analysis*, 2nd Ed., Prentice Hall, 2000.

Classic stability issues



 Classification of power system stability.

Ref: P. Kundur,..., D.J. Hill,..., "Definition and classification of power system stability," *IEEE TPWRS*, vol. 19(2), pp. 1387-1401, 2004.

Advanced applications (selected)

- State estimation [Schweppe, MIT]
  - Hiskens, QEGB, Australia
  - Many others
- Linear state-space
  - Decentralised etc
- Nonlinear
  - Many Russian (VSC etc)
  - Ilic, NY ISO, feedback linearizing controller
  - Ilic, EdF, automatic voltage control
  - Chow, DYNRED, PowerTech, singular perturbation
- Lyapunov/TEF
  - Pavella, Elia Belgium
  - Chiang, TEPCO-BCU, Bigwood

Advanced applications (selected)

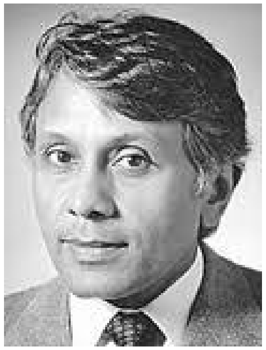
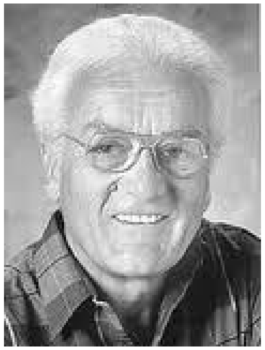
- MPC
  - Low, EV charging, PowerFlex
  - Maeght, RTE, France, zonal congestion management
- Adaptive
  - Older gain scheduling etc
  - Malik, Adaptive PSS, ABB
- Robust
  - Kundur, H_∞, PowerTech
- Intelligent
  - Many

Outline

- Background
- Power and control
- Structure, data and learning
  – a control theorist's journey in power systems
- Future grids
- Conclusions

Ref: T. Liu, Y. Song, L. Zhu and D.J. Hill, "Stability and control of power grids," invited paper, *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 5, pp. 689-716, 2022.

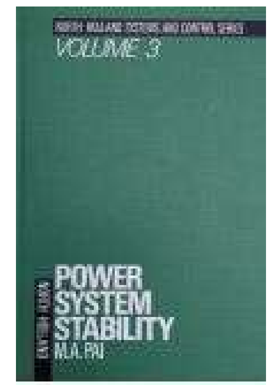
Systems engineering for power

- Berkeley project 1978-80
- Many universities (also MIT, Boston, Illinois, Washington,. . .)
- Many disciplines (systems, control, computing etc)
- Many future power systems professors
  H-D. Chiang, J. Chow, M. Ilic, C-C. Liu etc

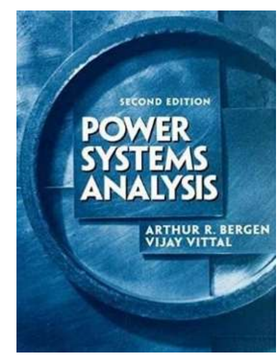
Transient stability and structure

- ‘Lyapunov’s last stand’
  - Theoretical basis ($n > 2$ failures for rigorous function)
  - Algorithm accuracy



- Pai’s book, Art Bergen’s new text draft

► A.R. Bergen and D.J. Hill, “A structure preserving model for power system analysis,” IEEE Trans Power Apparatus and Systems, 1981



Simple network-preserving model

Generators

$$\dot{\delta}_i = \omega_i$$

$$M_i \dot{\omega}_i = -D_i \omega_i + P_i^0 - \sum_{j \neq i} b_{ij} \sin\left(\delta_i - \delta_j\right)$$

Loads/VRE

$$D_i \dot{\delta}_i = P_i^0 - \sum_{j \neq i} b_{ij} \sin\left(\delta_i - \delta_j\right)$$

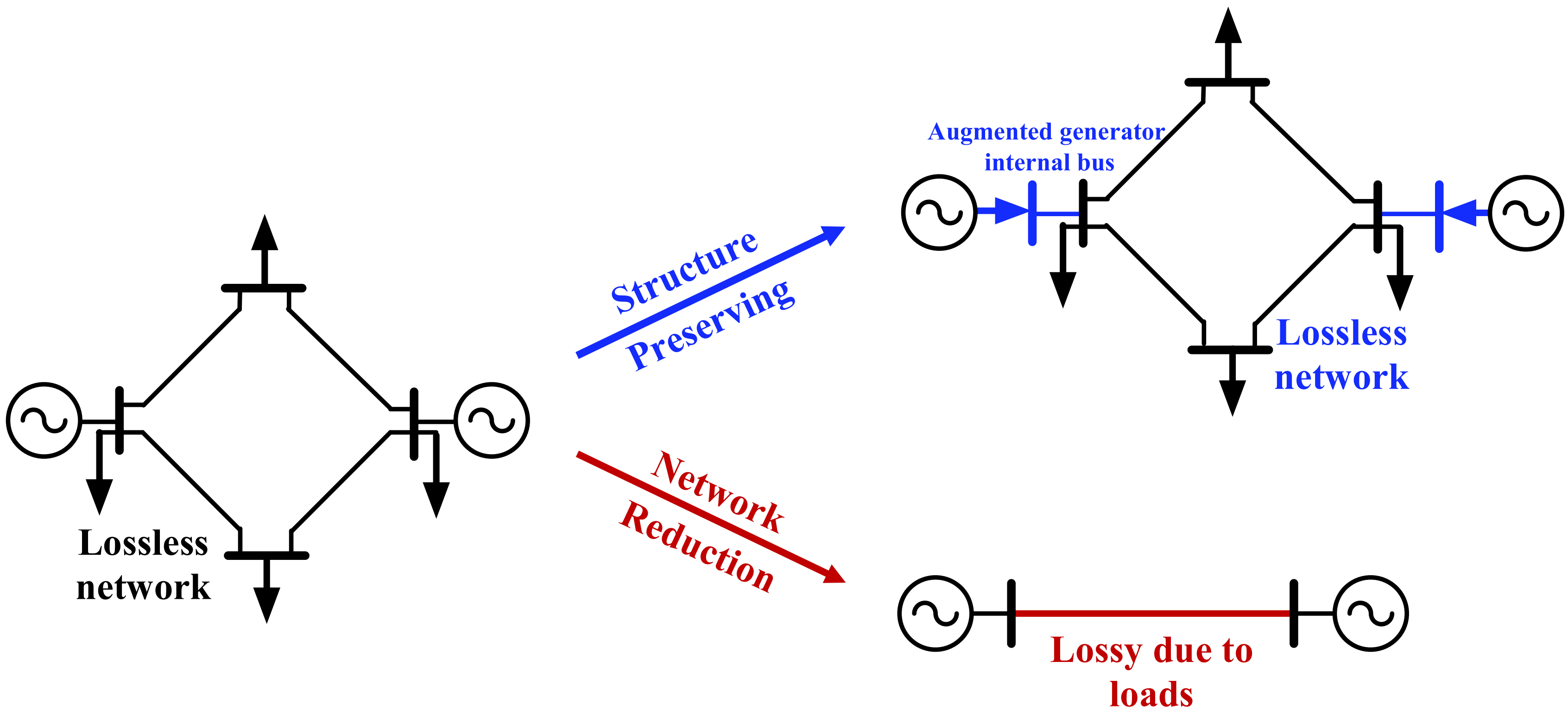
Power flow

- Angle stability: $\omega_i = \omega_j = \omega_s$ (synchronization)

  $$\delta_i - \delta_j = c_{ij}$$

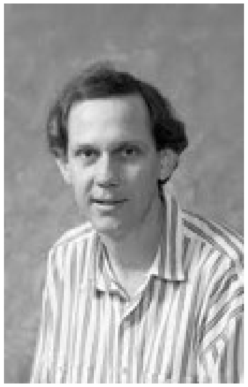
- First rigorous Lyapunov function – multimachine system, nontrivial loads
- Later shown includes inverter-based VRE [N. Ainsworth and S. Grijalva, IEEE Trans Power Systems, 2013]

Network-preserving vs classical models



- The artificial losses caused the theory problems (non-integrability)
- The reduced model completely kills the network structure, giving a fully connected reduced graph

DAE dynamic model



$$P_{di} = P_{di}\left(V_i\right)$$
$$Q_{di} = Q_{di}\left(V_i\right)$$

$$\dot{\alpha}_g = T_g \omega_g$$
$$\dot{\omega}_g = -M_g^{-1} D_g \omega_g - M_g^{-1} T_g^t \left(P_g(\alpha_g, \alpha_\ell, V) - \tilde{P}_M^0\right)$$

$$0 = P_\ell\left(\alpha_g, \alpha_\ell, V\right) + P_d(V) \quad := f_\ell\left(\alpha_g, \alpha_\ell, V\right)$$
$$0 = [V]^{-1}\left(Q_b(\alpha_g, \alpha_\ell, V) + Q_d(V)\right) \quad := g\left(\alpha_g, \alpha_\ell, V\right)$$

- Voltage dependence of loads added
- Lyapunov theory extended
- Multiple solutions on energy surfaces

Ref: I.A. Hiskens and D.J. Hill, "Energy functions, transient stability and voltage behaviour in power systems with nonlinear loads," *IEEE TPWRS*, vol. 4(4), pp. 1525-1533, 1989.

Extensions and unsolved

- More detailed models (generators, network controls) ['Berkeley school', Padiyar, others]

- Algorithms, applications [Chiang, Wiley 2013]

- Unsolved: rigorous Lyapunov functions for NPMs where the real-power loads have general dependence on voltages

$$P_{di} = P_{di}^{0} \leftarrow P_{di}(V_i)$$
$$Q_{di} = Q_{di}(V_i)$$

Challenge for network-preserving

- The Lyapunov (or energy) functions expressed in a Lure-Postnikov topological form, e.g.

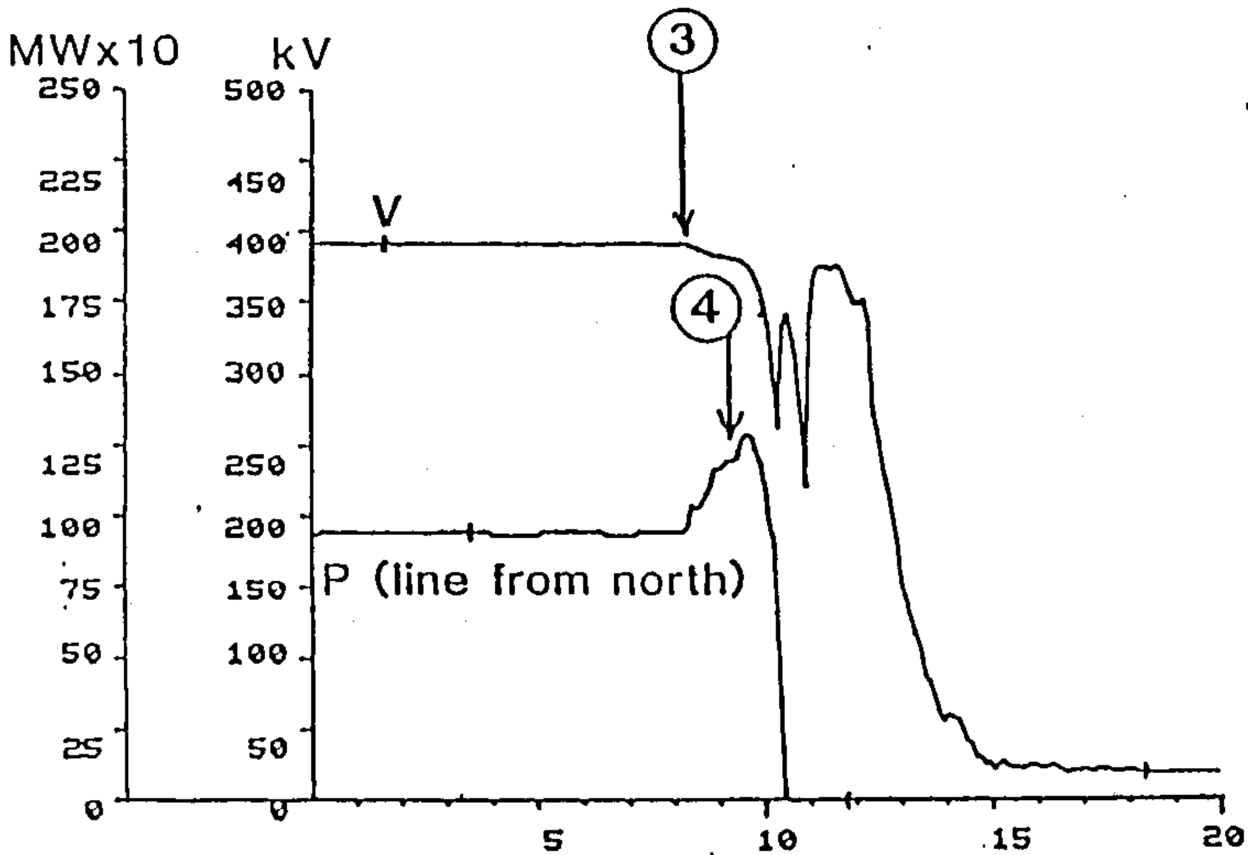
$$E(\omega, V) = \sum_G \tfrac{1}{2} M_i \omega_i^2 + \sum_L W_k\left(\sigma_k - \sigma_k^0\right)$$

line angle differences

- More general structure for voltage dependence

- For the classical model with transfer conductances
  - Cannot have this form [N. Narasimhamurthi, IEEE Trans Circuits and Systems, 1984]
  - Lyapunov function for transient stabilization [R. Ortega et al., IEEE TAC, 2005]

Voltage collapse



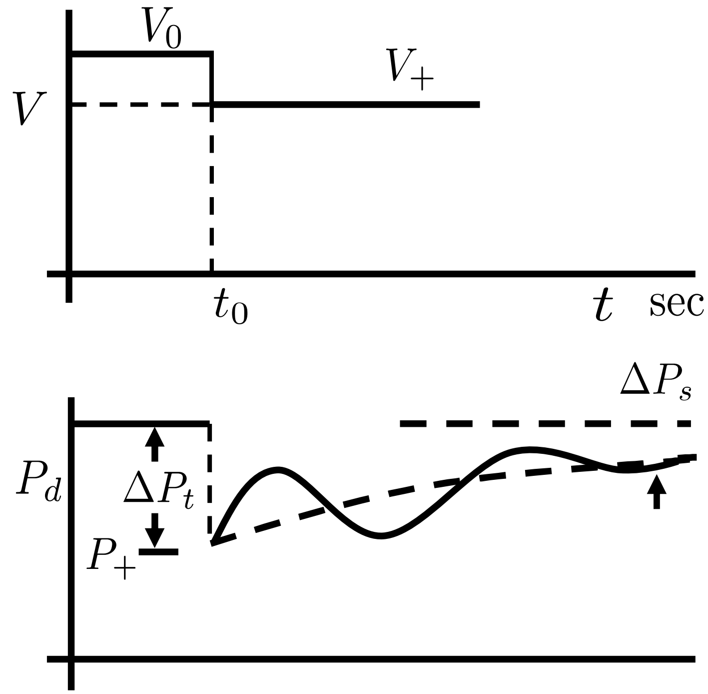
Sweden December 1983 Recording at a Western busbar

Frequency survived well beyond start of the *V* collapse.

Load dynamics and data

- Guest Professor in Institutionen för Reglerteknik, Lunds Universitet
- Stability and control issues for Sydkraft, Vattenfall
- Discussion with engineer Kenneth Walve led to dynamic recovery model
- Aggregate behaviour, nonlinear identification
- Data from PMUs, special experiments
- PhD students to industry built protection systems

Dynamic load recovery model



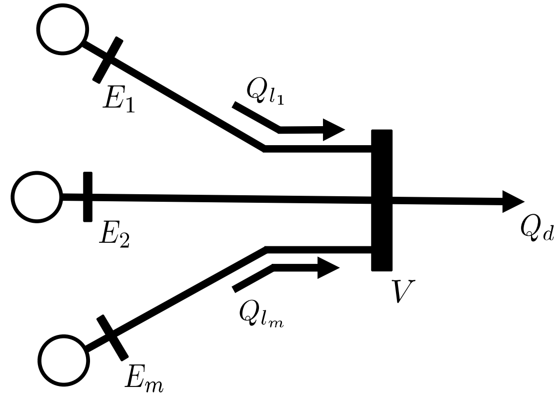
$$T_p \frac{dP_r}{dt} + P_r = P_s(V) - P_t(V) = P_0 \left(\frac{V}{V_0}\right)^{\alpha_s} - P_0 \left(\frac{V}{V_0}\right)^{\alpha_t}$$

$$P_d = P_r + P_0 \left(\frac{V}{V_0}\right)^{\alpha_t}$$

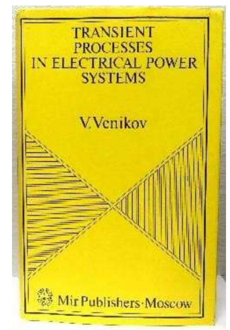
Ref: D.J. Hill, “Nonlinear dynamic load models with recovery for voltage stability studies,” *IEEE TPWRS*, vol. 8(1), pp. 166-176, 1993.

Basic stability result

– dynamic version of Venikov criterion



© 1993 IEEE Node in a Complex System



A general stability criterion is as follows.

Result Assume $E(V^*) > 0$ and $J_t(V^*) \neq 0$. The system at equilibrium point V^* is small-disturbance voltage stable iff $J_t(V^*)$ and $D(V^*)J_s(V^*)$ have the same sign.

Uses the steady-state J_s and transient Jacobians J_t derived from static and transient load characteristics

Ref: D.J. Hill, "Nonlinear dynamic load models with recovery for voltage stability studies," *IEEE TPWRS*, vol. 8(1), pp. 166-176, 1993.

Load-side DAE model

$$\dot{n} = T^{-1}\left(V^0 - V_r\right) \qquad := f_1\left(V_r\right)$$

Transformer tap dynamics

$$\dot{x}_p = a_p\left(x_p, V\right) \qquad := f_2\left(x_p, V\right)$$

$$\dot{x}_q = a_q\left(x_q, V\right) \qquad := f_3\left(x_q, V\right)$$

Load recovery dynamics

$$0 = g_1\left(V, x_p, P_d\right)$$

$$0 = -P_l(\delta, V, n) + P_d \qquad := g_2\left(\delta, V, n, P_d\right)$$

$$0 = g_3\left(V, x_q, Q_d\right)$$

$$0 = -Q_l(\delta, V, n) + Q_d \qquad := g_4\left(\delta, V, n, Q_d\right)$$

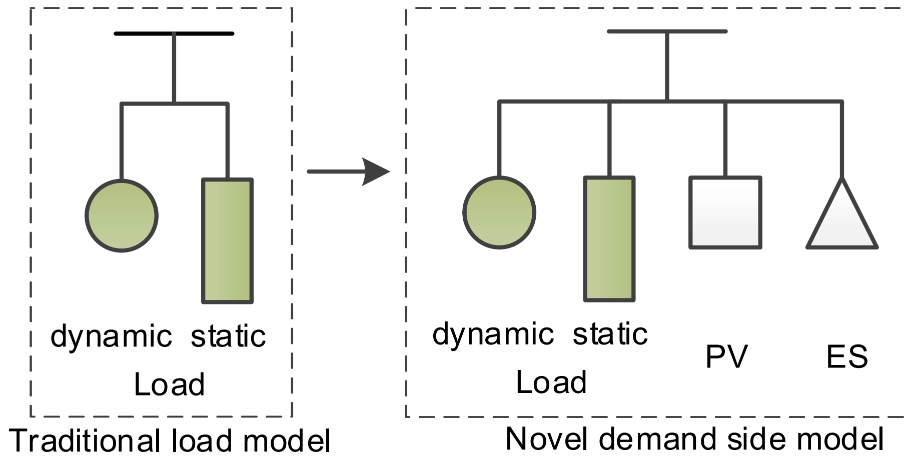
$$0 = P_g(\delta, V, n) - P_g^o \qquad := g_5(\delta, V, n)$$

Power flow equations

Ref: D.J. Hill and I.A. Hiskens, "Modeling, stability and control of voltage behavior in power supply systems," *SEPOPE*, 1994.

Load identification

- Nonlinear aggregate (generic) models
- Aggregate data based vs physically based model structures or hybrid
- Ambient vs event data
- Complexity increasing with DERs, local storage, demand-side management
- Non-intrusive Load Modelling (NILM) needed toward household level, privacy issues



© 2020 IEEE Structure of composite demand side model.

Ref: X. Zhang, D.J. Hill and C. Lu, “Identification of composite demand side model with distributed photovoltaic generation and energy storage," *IEEE Trans. Sustainable Energy*, vol.11(1), pp. 326-336, 2020.

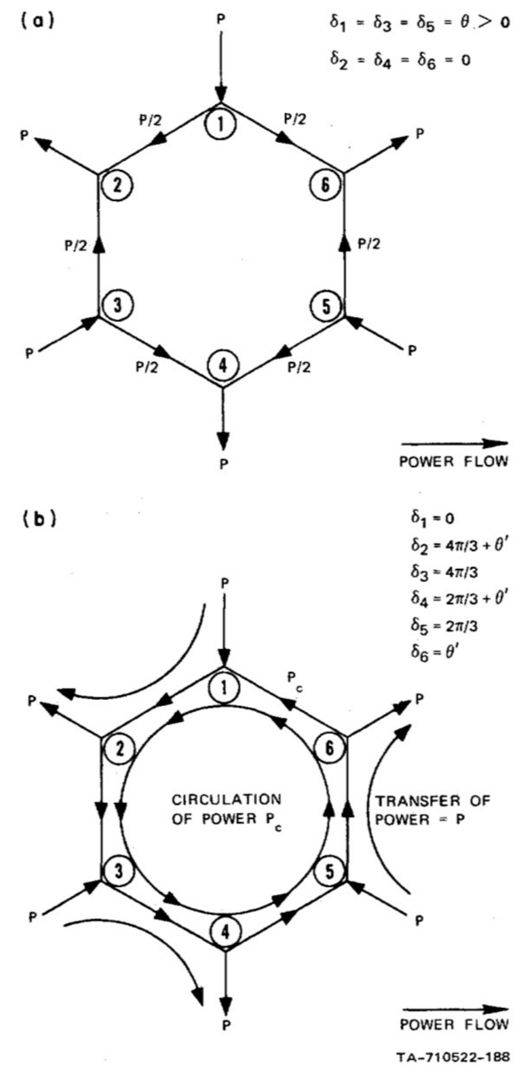
Network science ideas

- Behaviour determined by interaction of (graph) structure, coupling and node dynamics, e.g. $c \geq |d/\lambda_2|$ for identical node dynamics
- Concepts of fragility, robustness, vulnerable nodes etc
- Results allow for scale, e.g. scale-free relates to granularity
- Nature finds good motifs so networks can be robust to connection changes (work by Slotine at MIT, passivity results)

Ref: D.J. Hill and G. Chen, “Power systems as dynamic networks,” *ISCAS*, 2006.

Role of graph

- Nonlinearity gives multiple equilibria in angle and voltage
- Power networks have another possibility: multiple stable equilibria arising from the graph
- But not just a connectivity feature

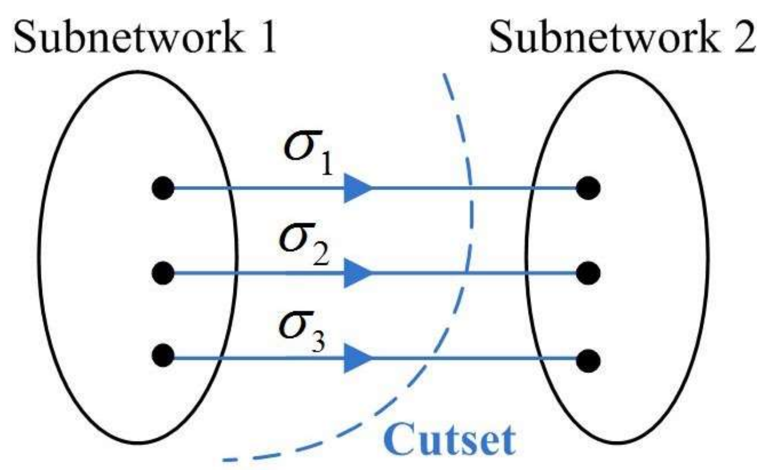


© 1972 IEEE Fig. 3. Example of two stable load-flow solutions

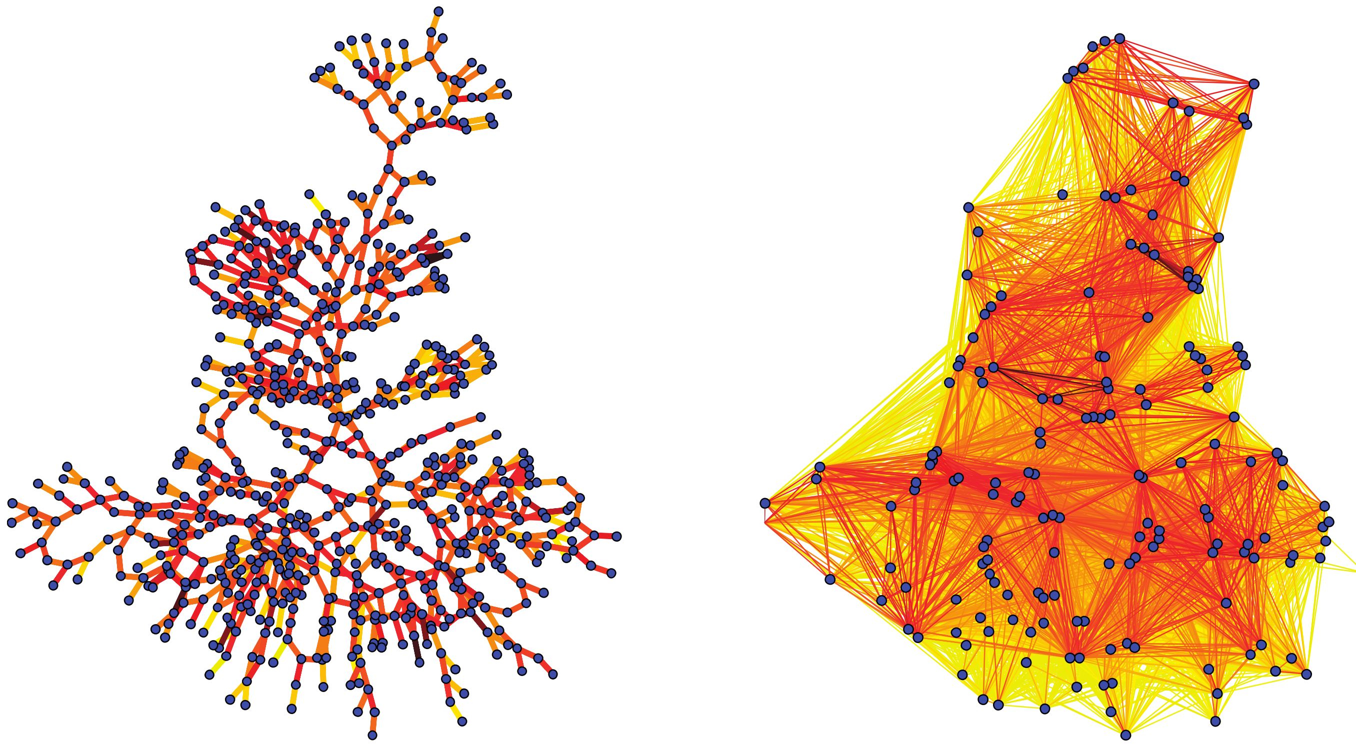
Ref: A.J. Korsak, "On the question of uniqueness of stable load-flow solutions," *IEEE TPAS*, vol. PAS-91(3), pp. 1093-1100, 1972.

New stability theory – networks and graphs

- Synchronization viewpoint
- Graph properties central
- Stability criteria in terms of Laplacians, graph (critical) cutsets and equivalent weights on better models
- Some results
  - Hill and Chen, ISCAS 2006
  - Dorfler and Bullo, SIAM 2012; PNAS 2013
  - Song, Hill and Liu, IEEE TCNS 2018
  - Song, Hill and Liu, FTEES 2020
  - Zhu and Hill, SIAM JCO 2018



Physical vs reduced network – by physicists



Physical versus effective network for the power grid of Northern Italy.

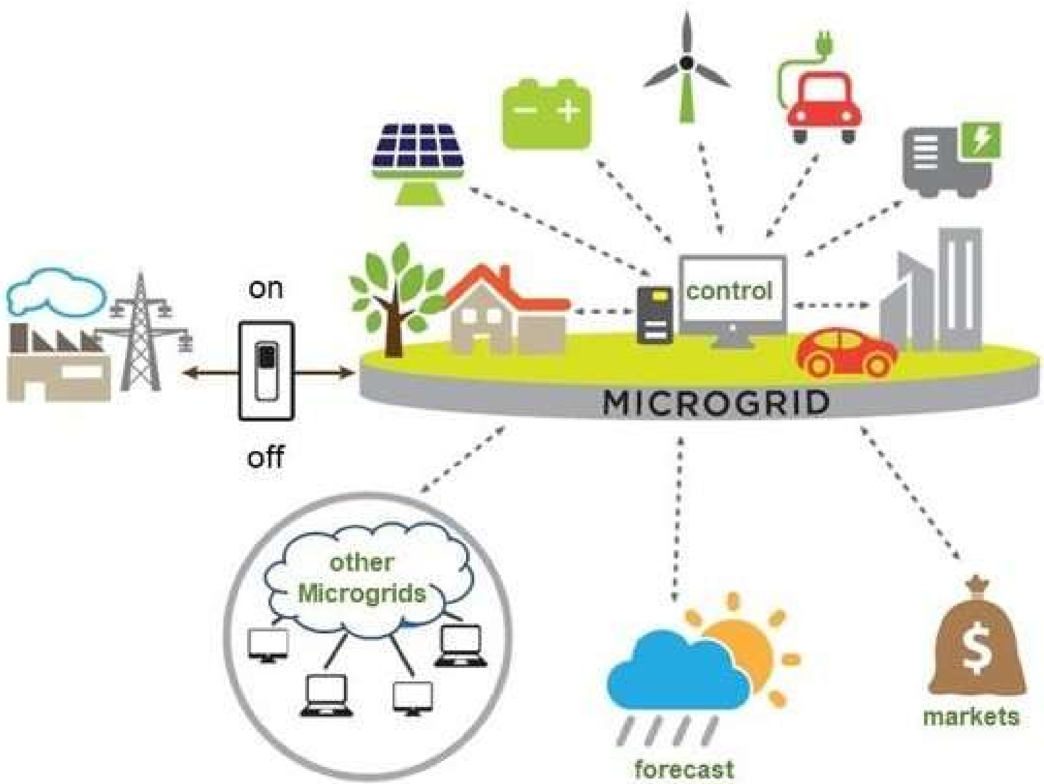
a, Representation of the physical network of transmission lines, which has 678 nodes and 822 links. **b**, Representation of the network of effective admittances, which is an all-to-all network with 170 nodes corresponding to the generators in the system (a subset of the nodes in **a**). The colour scale of the lines indicates the link weights, ranging from yellow to red to black (scaled differently for each panel), defined as the absolute value of the corresponding admittance. For clarity, in **b** we show only the top 50% highest-weight links.

Ref: A.E. Motter, S.A. Myers, M. Anghel and T. Nishikawa, "Spontaneous synchrony in power-grid networks," *Nature Physics*, vol. 9, pp. 191-197, 2013.

Impact of DG connection topology

- DG plug-and-play

  A large number of small-size DGs are to be connected to the microgrid (an expansion with increasing nodes and lines)



Ref: Microgrid Concept (LBNL, USDOE, 2019).

Impact of DG connection topology

- Theorems

1) Algebraic connectivity

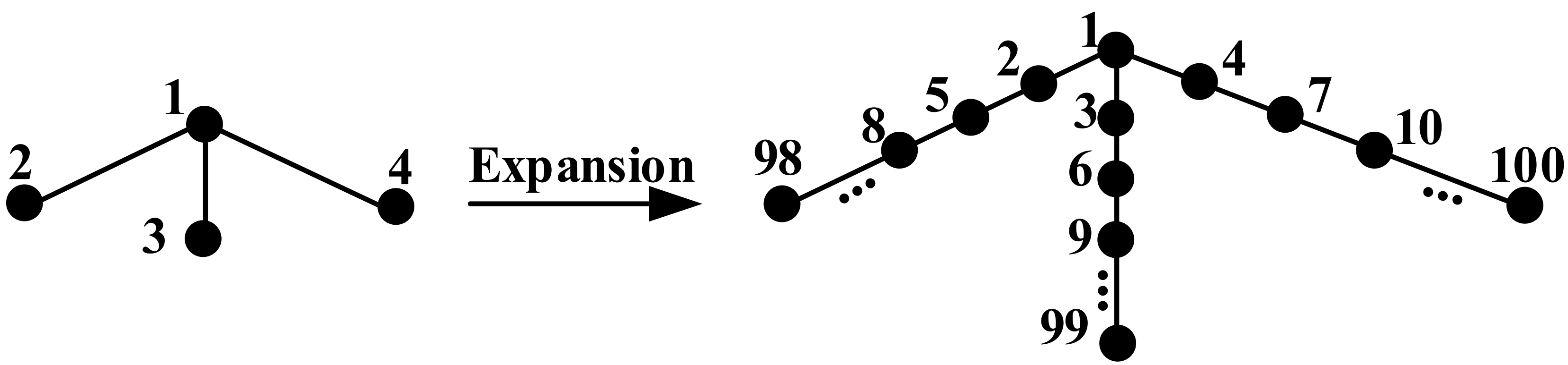
   Then $\lim_{n\to\infty} \lambda_2(L_{\mathcal{G}}) = 0$ if there exists a node i such that $\lim_{n\to\infty} \frac{d_i}{n} = 0$, where n is number nodes and d_i is degree of node i.

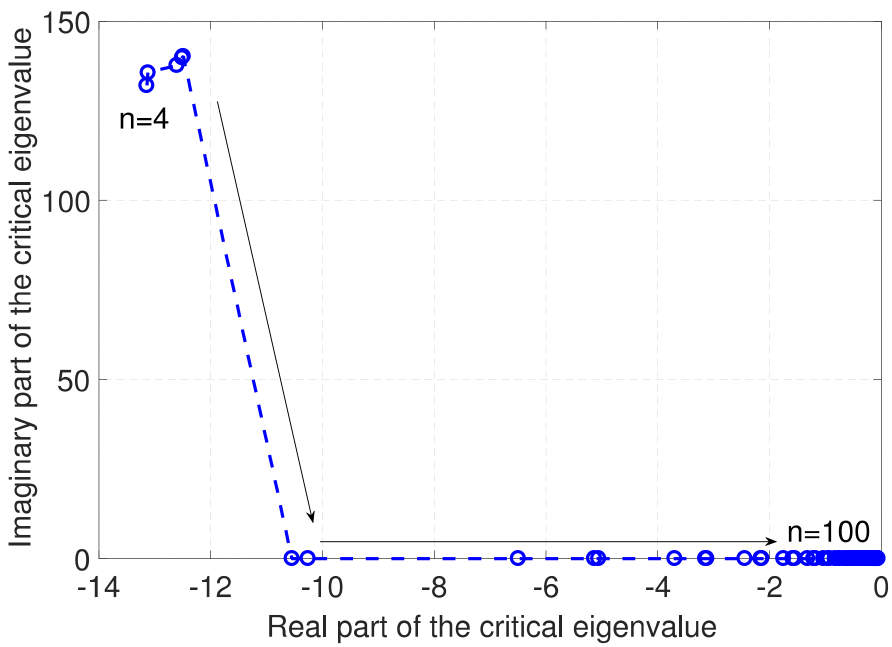
2) An eigenvalue of the system dynamic Jacobian approaches zero if the algebraic connectivity of the microgrid approaches zero.

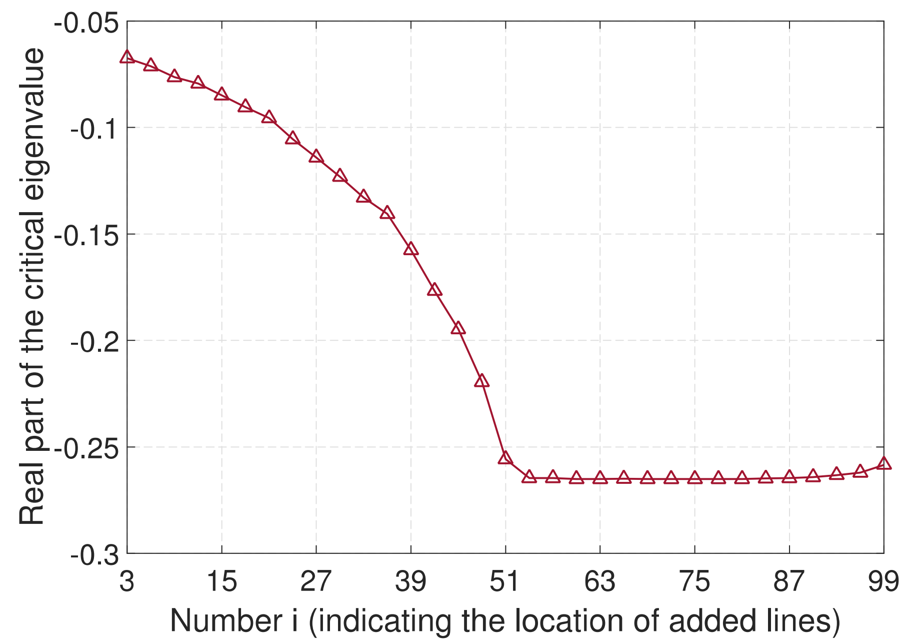
Note: the precondition $\lim_{n\to\infty} \frac{d_i}{n} = 0$ holds in the common tree-like connection where new DGs are connected to nearby nodes via single lines.

Ref: Y. Song, D.J. Hill and T. Liu. "Impact of DG connection topology on the stability of inverter-based microgrids," *IEEE TPWRS*, vol. 34(5), pp. 3970-3972, 2019.

Impact of DG connection topology

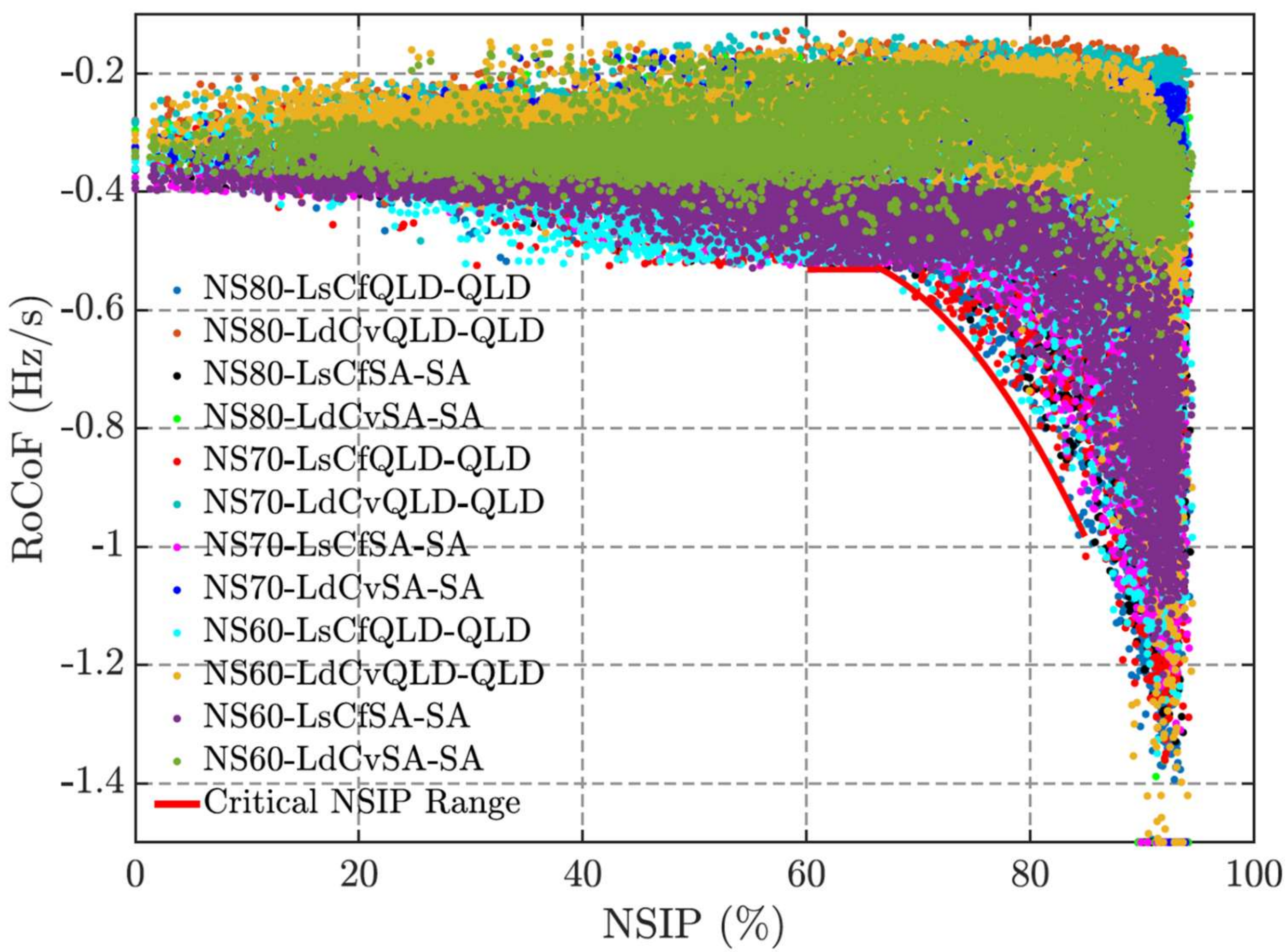






Ref: Y. Song, D.J. Hill and T. Liu. "Impact of DG connection topology on the stability of inverter-based microgrids," *IEEE TPWRS*, vol. 34(5), pp. 3970-3972, 2019.

Frequency scenarios – an Australian study



© 2018 IEEE Minimum RoCoF following a credible contingency based on NSIP.

Ref: A.S. Ahmadyar, S. Riaz, G. Verbič, A. Chapman and D.J. Hill, "A framework for assessing renewable integration limits with respect to frequency performance," *IEEE TPWRS*, vol. 33(4), pp. 4444-4453, 2018.

Deep learning for transient stability prediction

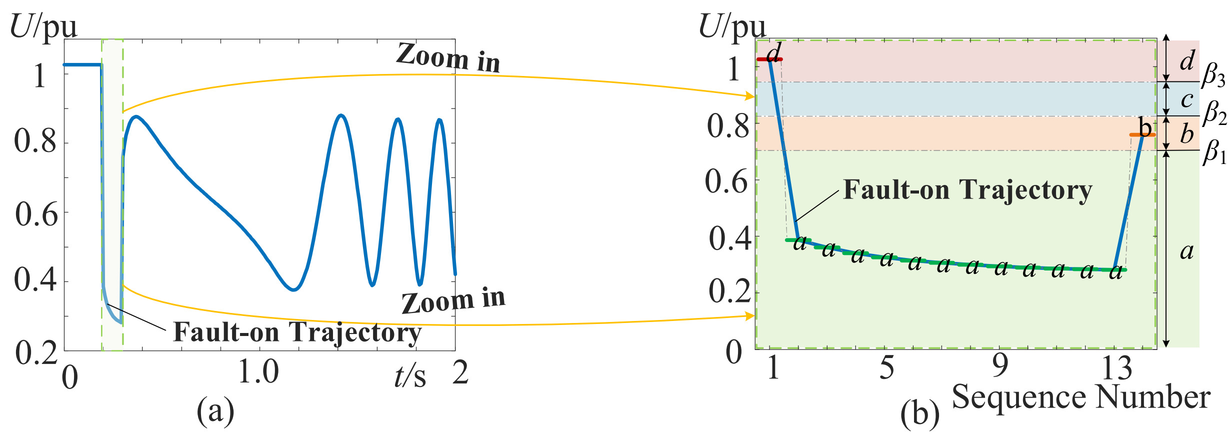


 Illustration of SAX based trajectory quantization

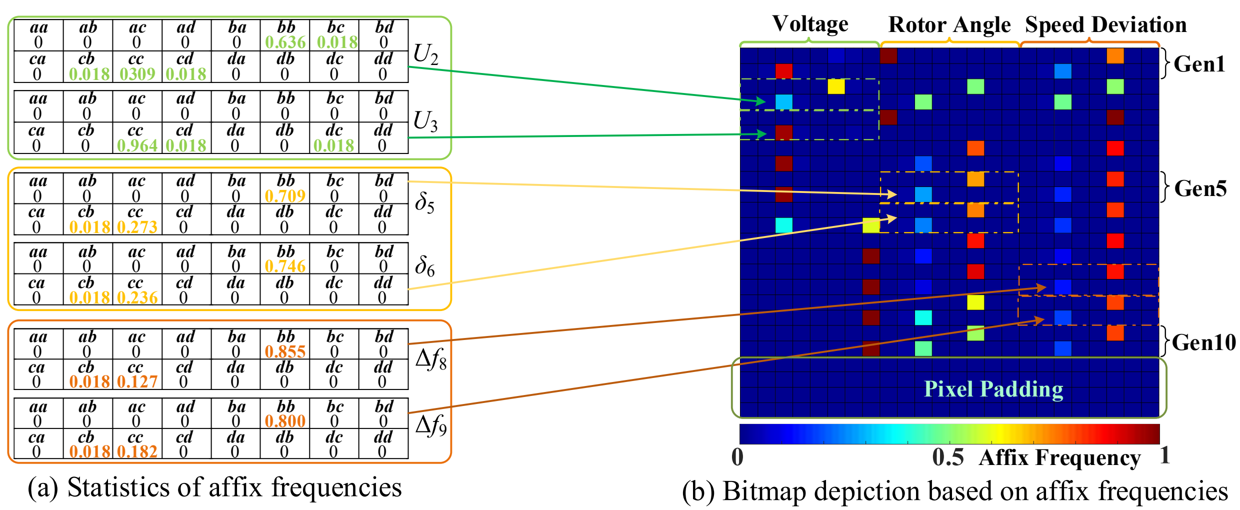
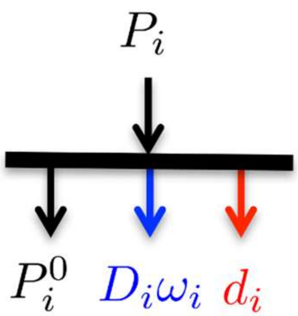


 Illustration of 2-D pictorial representation

Ref: L. Zhu, D.J. Hill and C. Lu, "Hierarchical deep learning machine for power system online transient stability prediction," *IEEE TPWRS*, vol. 35(3), pp. 2399-2411, 2020.

Structure in frequency control

Linearized structure-preserving model:



$$\dot{\delta}_i = \omega_i$$

$$M_i\dot{\omega}_i = -D_i\omega_i + P_{m_i} - \sum_{j\neq i}^{N} I_{ij}\left(\delta_i - \delta_j\right), \qquad i \in \mathcal{G}$$

$$0 = D_i\omega_i + d_i + \sum_{j\neq i}^{N} I_{ij}\left(\delta_i - \delta_j\right), \qquad i \in \mathcal{L}$$

- Generators-side control – AGC
- Load-side control – d_i
  - System-level control effect – FRM
  - Non-disruptive for end-user – LRM

$\Leftarrow$

- Consensus-based control
- Switching control

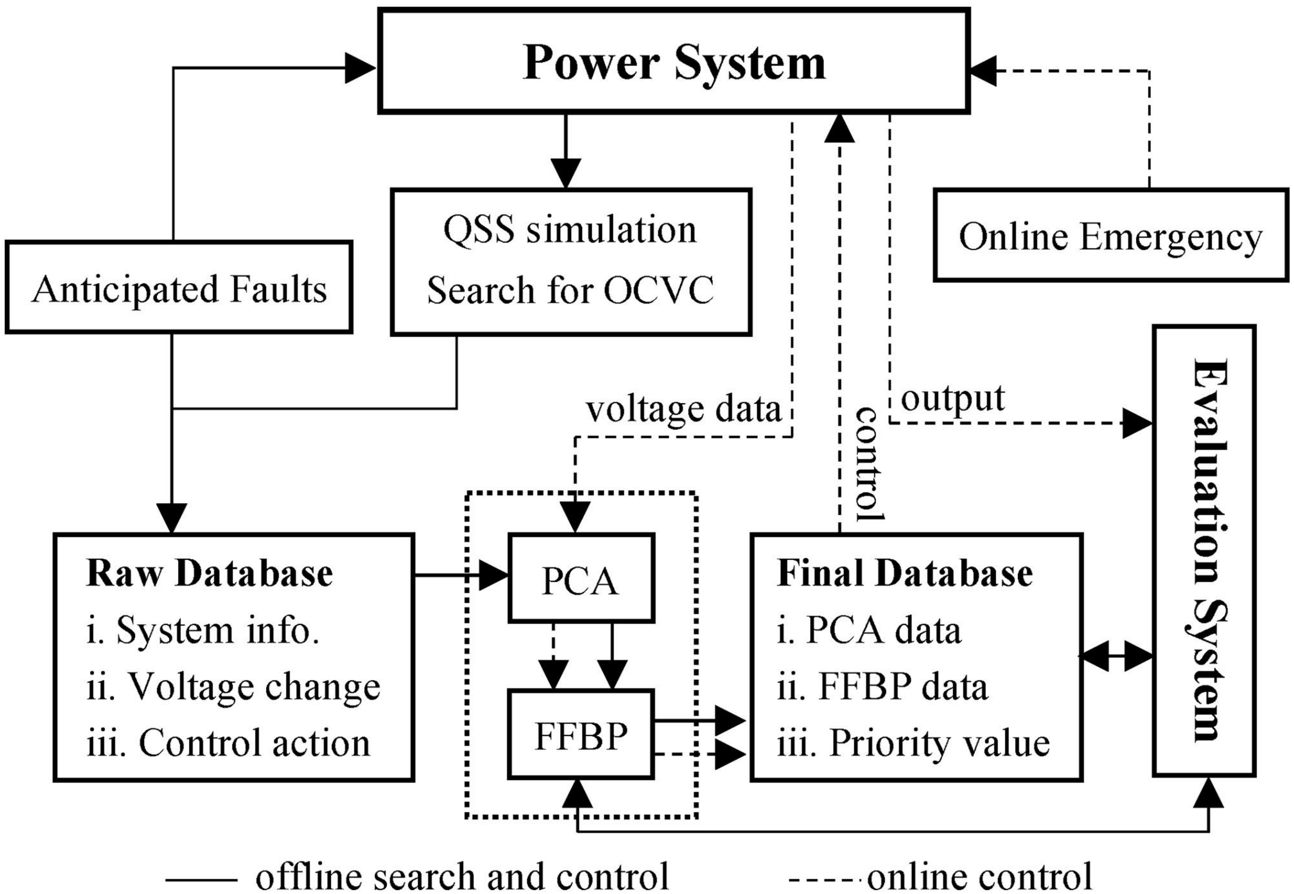
Theorem: The system settles down to the load restoration subsystem after switching a finite number of times, and the equilibrium point of the system is asymptotically stable.

Ref: T. Liu, D.J. Hill and C. Zhang, “Non-disruptive load-side control for frequency regulation in power systems,” *IEEE Trans. Smart Grid*, vol. 7(4), pp. 2142-2153, 216.

See also work by S.Low group, Caltech on distributed load control of frequency, e.g. IEEE TAC, 2014

Data-based voltage control

– learning for fast response



 Data-based Learning and Control System for LTVS.

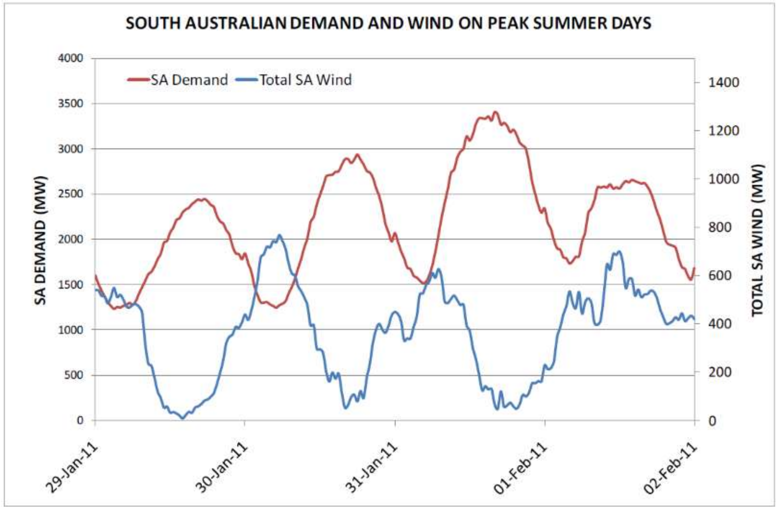
Ref: H. Cai, H. Ma and D.J. Hill, "A data-based learning and control method for long-term voltage stability," *IEEE TPWRS*, vol. 35(4), pp. 3203-3212, 2020.

Outline

- Background
- Power and control
- Structure, data and learning
- Future grids
  - Towards 100% IBR
- Conclusions

Towards 100%

- Two transitions
  - Decarbonisation
  - DERs (rooftop PV etc)



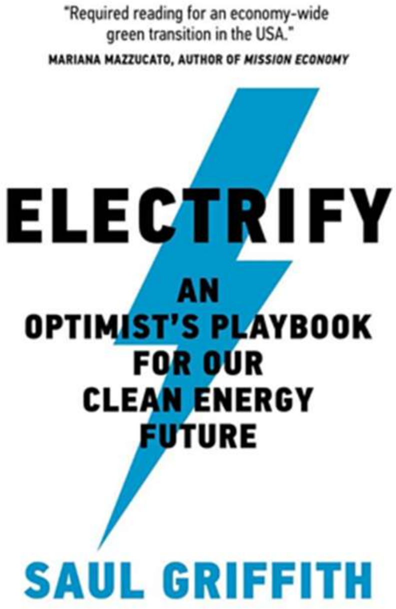
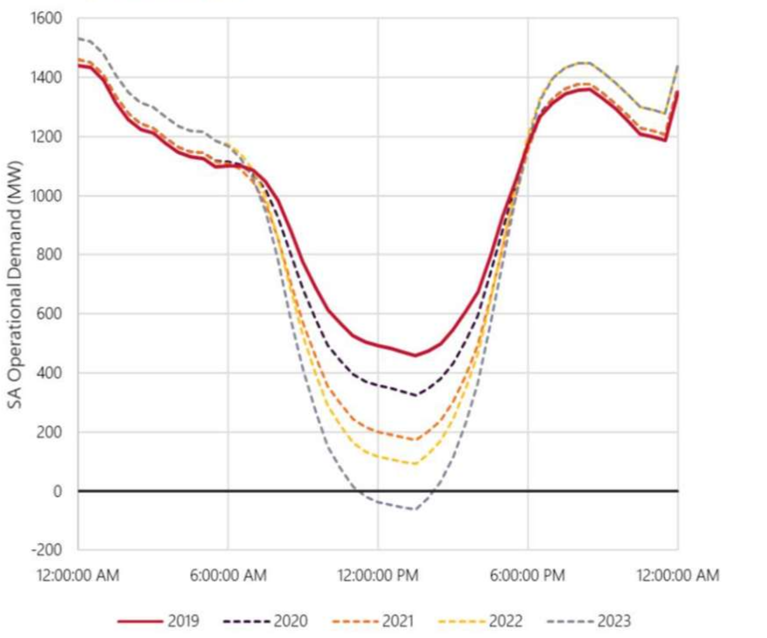
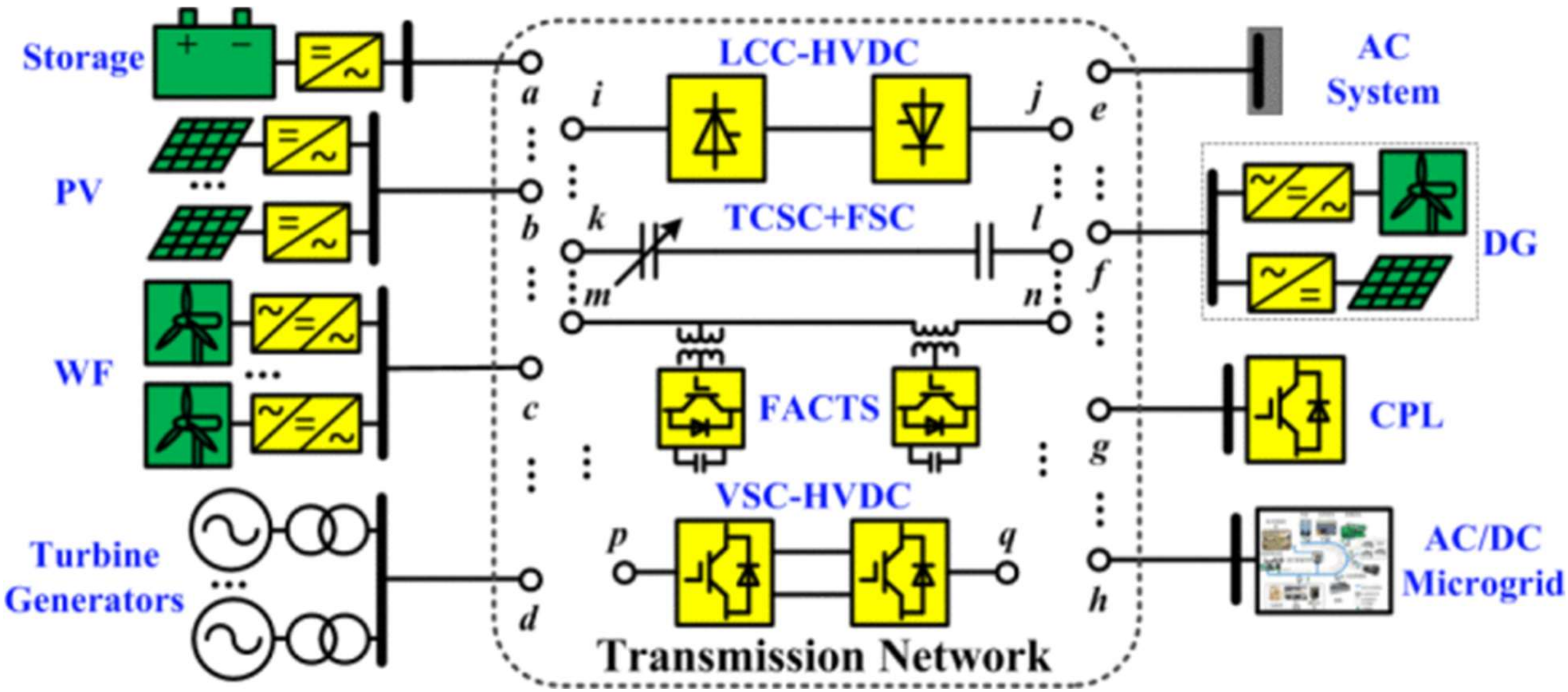


Figure 2 Effect on South Australian operational demand from increasing distributed PV generation (10 November 2019)



Future grid

- Inverters everywhere (IBRs)



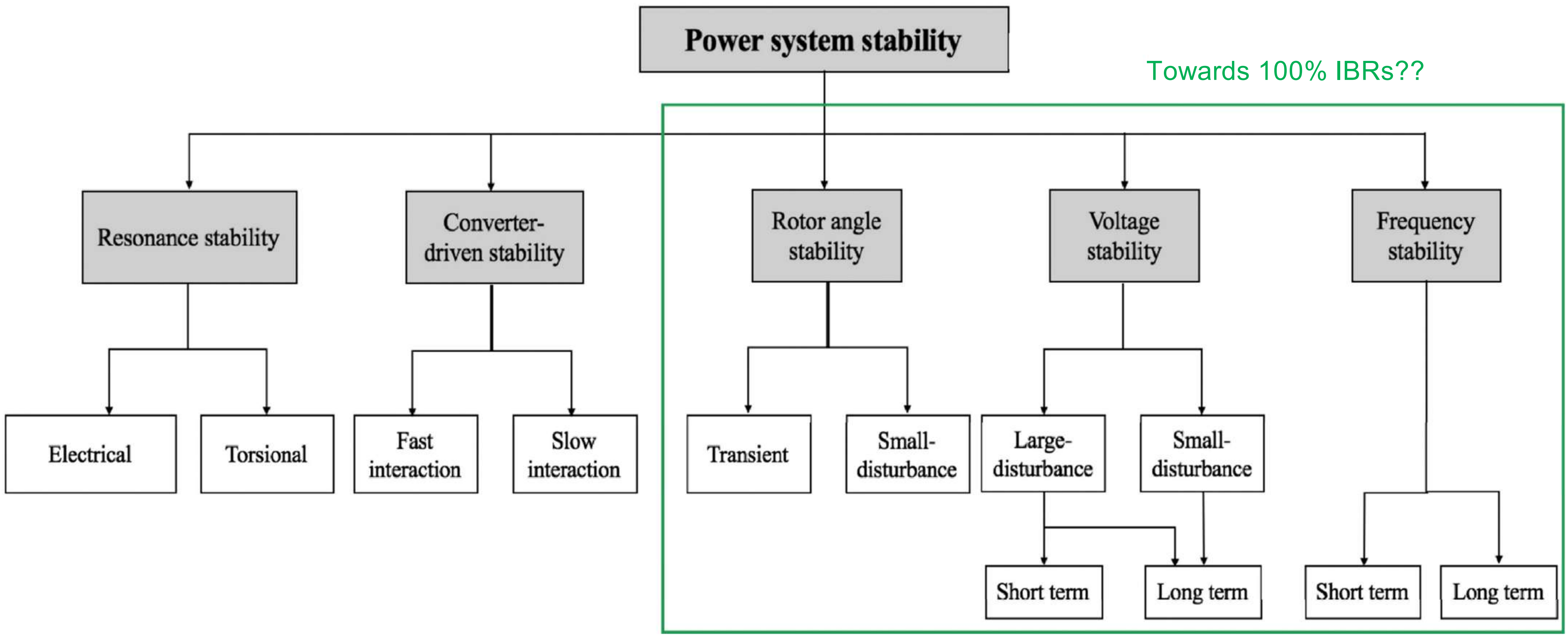
 Typical power system integrating high-penetration renewables

Ref: H. Liu, X, Xie and W. Liu, "An oscillatory stability criterion based on the unified *dq*-frame impedance network model for power systems with high-penetration renewables," *IEEE TPWRS*, vol. 33(3), pp. 3472-3485, 2018.

Eight big scientific questions for FGs – Hill, Plenary Session, PowerTech 2019, Milan, Italy

1. New (faster) stability of high converter systems
2. Granular/distributed everything: markets, control etc, i.e. DER, aggregator, DO, DSO, RTO, ISO
3. Computation scaling (more computer science)
4. Data-based (adaptive) control
5. Better structures
6. Grid flexibility
7. Trilemma (long-term management)
8. Resilience integrated systems

New stability

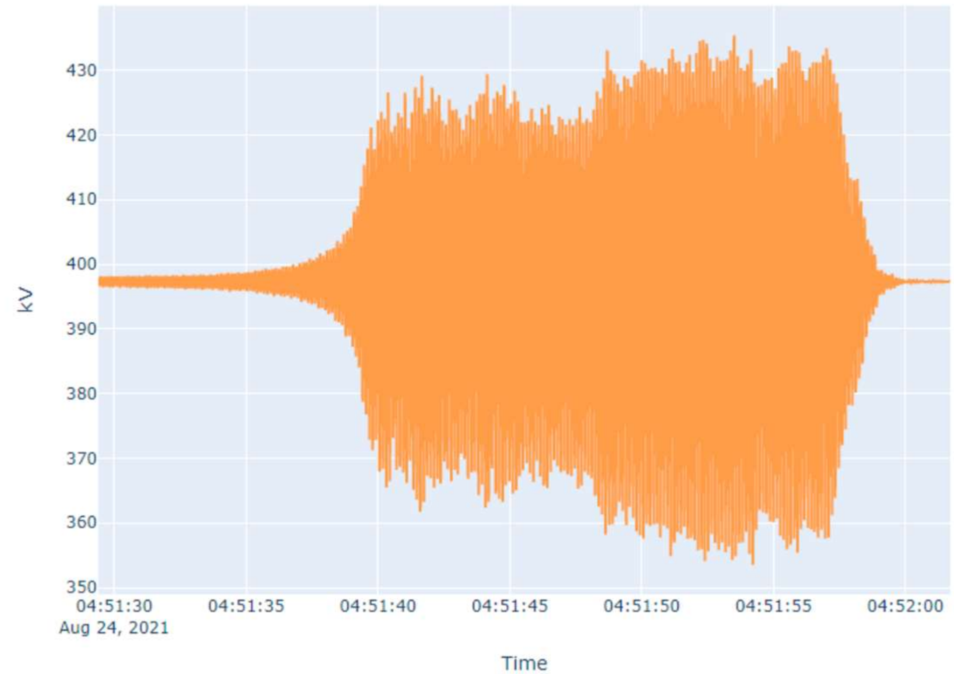


© 2021 IEEE Classification of power system stability

Ref: N. Hatziargyriou,..., D.J. Hill,..., "Definition and classification of power system stability – Revisited & extended," *IEEE TPWRS*, vol. 36(4), pp. 3271-3281, 2021.

New oscillations – windfarms

- On 24/08/2021 severe voltage disturbances in Scotland's SSEN-T and SPEN transmission systems
- Lasted 20-25 seconds, about 30 mins apart, users tripped off
- Similar situations in Australia, North China etc
- But system-wide versions not understood



Ref: J. Leslie and M. OMalley, G-PST Research Agenda for Transformed Power Systems, ESIG talk, 30 November 2021.

Theory only just beginning

Control replaced by markets

- Recall conventional control (1950-1990's) with AGC, stabilizers, emergency control designed using classical control and novel nonlinear control respectively
- Australian National Electricity Market has
  - ancillary services markets for frequency, no bias
  - investigating inertia, system strength markets
- Legacy system plus new system co-existing adds to confusion, e.g. inertia debate
- More complicated control problem vs new market opportunities?

Outline

- Background
- Power and control
- Structure, data and learning
- Future grids
- Conclusions

Conclusions

- Power Systems a complete subject, i.e., theory to practice, not just a place to apply tools
- First step to get ‘right model’, then adapt tools:
  - Lyapunov theory
  - System identification
  - Graph theory
  - .....
- Conventional models part data-based and physical structure-based
- Add learning for faster control

Future

- Two transitions: 1) decarbonisation of big grid; 2) distributed resources
- Greater spatio-temporal complexity, ‘unknown unknowns’
- The end-to-end power system is embedded in the weather system
- Need for new modelling, dynamics and distributed control – role of data-based?
- Larger energy community involved, i.e. scientists, economists, lawyers, but dynamics and control is no less important
- The need for a new era of fundamentals is here - Systems Engineering for Power 2.0?

Thankyou students and postdocs 1983- now