Modelling and Control of Stochastic Networks

The South Australian Electricity Grid

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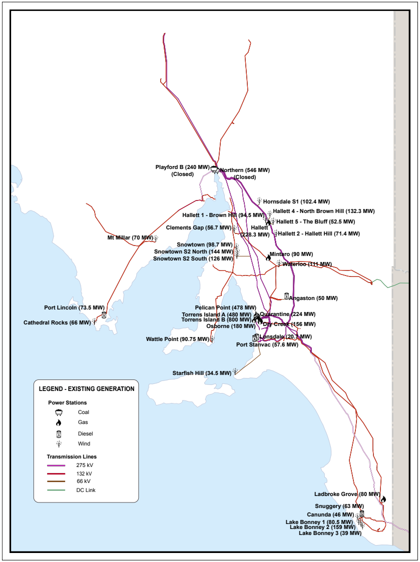
Registered capacity and electricity generated in SA (2015–16)

High penetration of intermittent renewable energy



Energy source	Registered capacity MW	Registered capacity % of total	Electricity generated GWh	Electricity generated % of total
Gas	2,668	44.6	4,538	36.4
Wind	1,576	26.3	4,322	34.7
Coal	770	12.9	2,601	20.9
Rooftop PV	679	11.4	938	7.5
Other	289	4.8	60	0.5
Total	5,982	100.0	12,459	100.0

Source: Australian Energy Market Operator

Following the closure of the last coal-fired power plant in SA, from 10 May 2016 to 31 July 2016, 51% of electricity generated in the state came from wind and rooftop PV

Market and security challenges faced by SA

- Dependable supply of scheduled power:
  - High penetration of intermittent renewable energy
  - Limited connectivity with other regions in the NEM
- High and volatile wholesale electricity prices:
  - Variability in wind and solar power generation
  - Difficulty in making wind and solar forecasts, especially about the future
  - Balance of electricity generation is gas-fired
- Secure operation of the power system:
  - Ancillary services (e.g., frequency control, voltage stability, RoCoF, inertia) historically provided by conventional synchronous generators
  - Inverter-connected renewable energy generation is displacing conventional synchronous generation as the state transitions to a low-carbon economy
  - Tight availability of locally provisioned ancillary services when islanded

State-space model predictive control (MPC)

Renewable energy processes

- State-space model represents a physical process by describing its outputs as a function of state variables which depend on control signals or increments
- For example, the process of power dispatched from a wind farm coupled with a utility-scale battery may be represented as:

$$\underbrace{\begin{bmatrix} e(t+1) \\ p_{b+}(t) \\ p_{b-}(t) \\ p_w(t) \end{bmatrix}}_{\boldsymbol{z}(t+1)} = \underbrace{\begin{bmatrix} 1 & \delta\eta & -\delta/\eta & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} e(t) \\ p_{b+}(t-1) \\ p_{b-}(t-1) \\ p_w(t-1) \end{bmatrix}}_{\boldsymbol{z}(t)} + \underbrace{\begin{bmatrix} \delta\eta & -\delta/\eta & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{B} \underbrace{\begin{bmatrix} \Delta p_{b+}(t) \\ \Delta p_{b-}(t) \\ \Delta p_w(t) \end{bmatrix}}_{\boldsymbol{\Delta u}(t)},$$

$$\underbrace{\begin{bmatrix} e(t+1) \\ p_d(t+1) \end{bmatrix}}_{\boldsymbol{y}(t+1)} = \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 1 \end{bmatrix}}_{C} \underbrace{\begin{bmatrix} e(t+1) \\ p_{b+}(t) \\ p_{b-}(t) \\ p_w(t) \end{bmatrix}}_{\boldsymbol{z}(t+1)}$$

Control law evaluation

Optimisation of predicted performance

MPC controller determines control signals, or increments, by optimising a performance index that penalises tracking error and control effort

- Let $\boldsymbol{r}(t) \in \mathbb{R}^m$ be a set-point vector, and define the quadratic cost function

$$f = \left\| \sqrt{\Omega}\, \left(\boldsymbol{r}(t{+}1) - \boldsymbol{y}(t{+}1)\right) \right\|_2^2 + \lambda \left\| \sqrt{\Psi}\, \boldsymbol{\Delta u}(t) \right\|_2^2,$$

  where $\lambda \geq 0$ is a scalar weighting coefficient, and $\Omega \in \mathbb{R}^{m\times m}$ and $\Psi \in \mathbb{R}^{q\times q}$ are positive semidefinite diagonal weighting matrices
- Process constraints take the form of bounds on observable and internal state variables, the latter expressed in terms of control increments
- Quadratic optimisation problem is written in standard form:

$$\begin{aligned}
\underset{\boldsymbol{\Delta u}(t)}{\text{argmin}} \quad & \frac{1}{2}\boldsymbol{\Delta u}(t)^T \left(B^T C^T \Omega C B + \lambda\Psi\right) \boldsymbol{\Delta u}(t) \\
& + \big(CA\boldsymbol{z}(t) - \boldsymbol{r}(t{+}1)\big)^T \Omega C B \boldsymbol{\Delta u}(t) \\
\text{subject to} \quad & \underline{\boldsymbol{x}} \preceq \boldsymbol{x}(t{+}1) \preceq \overline{\boldsymbol{x}}, \\
& \underline{\boldsymbol{\Delta u}} \preceq \boldsymbol{\Delta u}(t) \preceq \overline{\boldsymbol{\Delta u}}
\end{aligned}$$

Dependable supply of wind power with battery energy storage

- Soaring wholesale electricity prices in SA during July 2016:
  - During the month RRP averaged \$229/MWh, more than three times the average price of any other region in the NEM
  - On 13 July 2016 electricity traded at \$7,068 during the 06:30 trading interval
  - AER reported "[t]he major contributing factor to the high price was wind forecast error"
- Conjecture that if wind farms were to dependably supply power scheduled during pre-dispatch, then wholesale electricity prices would be less volatile and, on average, lower
- Empirically examine the dependability of supply of power dispatched by a wind farm coupled with a utility-scale battery to enable time shifting by:
  - Extending the incremental state-space model to a multi-period setting
  - Scheduling power dispatched by the wind farm during pre-dispatch — up to 40 hours ahead of dispatch
  - Minimising the tracking error of (predicted) power dispatched to the grid relative to scheduled power using pre-dispatch UIGF forecasts produced by AWEFS

Optimisation of distributed energy resources in a microgrid

- Suppose that:
  - Microgrid has a thin gateway connection to the main grid
  - Each household has rooftop solar panels and a residential battery
- State-space model represents power imported from/ exported to the main grid as a function of load, rooftop PV generation, and power charging/ discharged from the battery
- MPC controller minimises power imported from the grid, or cost of power imported from the grid
- Perform virtual trials and Monte Carlo simulations to examine:
  - Tariff structure that minimises power imported from the grid during peak times
  - Optimisation techniques (e.g., linear versus quadratic) and process constraints that reduce maximum demand
  - Savings achieved by optimising at the microgrid level rather than the individual household level
  - Rating/ capacity levels of distributed energy resources at which optimising at the microgrid level becomes moot

Theories and techniques

Mathematical, statistical and computational

Research program, *Modelling and Control of Stochastic Networks*, employs theories and techniques including:

- Control theory
- Optimisation
- Time series analysis
- Estimation of probability distributions of random variables
- Monte Carlo simulations and virtual trials
- Network analysis/ graph theory
- High performance computing and (big) data management