High Renewable Energy Penetration and Power System Security: New Challenges and Opportunities

Michael Negnevitsky

ENERGY 2019
June 2 - 6, 2019
Athens, Greece

UTAS

Centre for Renewable Energy and Power Systems
UNIVERSITY OF TASMANIA

Prof Michael Negnevitsky

Chair in Power Engineering and
Computational Intelligence
Director of the Centre for Renewable
Energy and Power Systems
School of Engineering
University of Tasmania
Private Bag 65 Hobart
Tasmania, 7001 Australia

Contents

- Concept of power system security.
- Operating reserves.
- Inertial and primary frequency response.
- Impact of renewable energy generation.
- King Island isolated power system.
- Risk-based security assessment.
- Conclusions.

Introduction

- The word “security” in the context of a power system implies its security against a complete collapse, or a blackout. Secure operation involves practices aimed to keep the system operating normally when contingencies occur.
- An increasing penetration of intermittent renewable energy generation introduces additional uncertainties in power systems.

Power system security (cont.)

- Power systems are designed and operated to withstand contingencies selected on the basis of their probabilities.
- In practice, these contingencies are usually defined as the loss of any single major component in a power system.
- We cannot stop contingencies from happening, and we cannot predict when they will occur. But we can model potential contingencies and analyse their consequences.

Power system security (cont.)

- Because the specific times of failures are unpredictable, the system is operated at all times in such a way that it will not be left in a dangerous condition when any ***credible*** contingency occurs.
- Credible contingencies are most probable contingencies. For example, we know from experience that the probability of failure of a single component of the system is much higher than simultaneous failures of multiple components.

Power system security (cont.)

- We must plan and operate power systems so that even the worst credible contingency will not result in an unacceptable performance of the system.
- We must also ensure that after the first credible contingency occurs, the system operator will be able to adjust the system and prepare it for the next credible contingency.

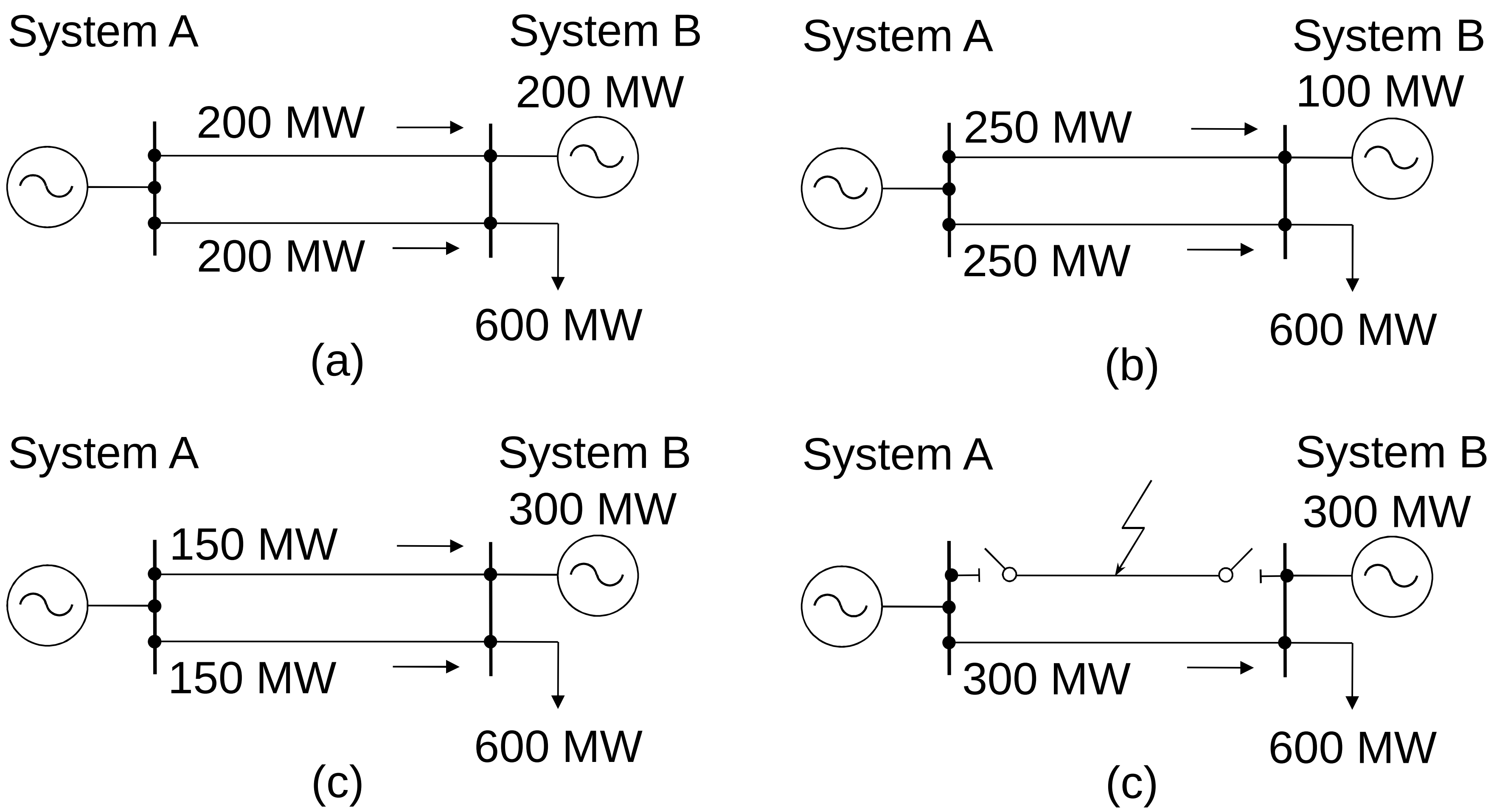
Operating reserves

- To ensure the required level of security, a power system must have sufficient reserves.
- These reserves are needed to balance short-term variations in supply and demand, mitigate the effects of load forecasting errors, handle peak demand, and manage fluctuations in renewable energy generation.
- But most of all, reserves are needed to withstand contingencies.

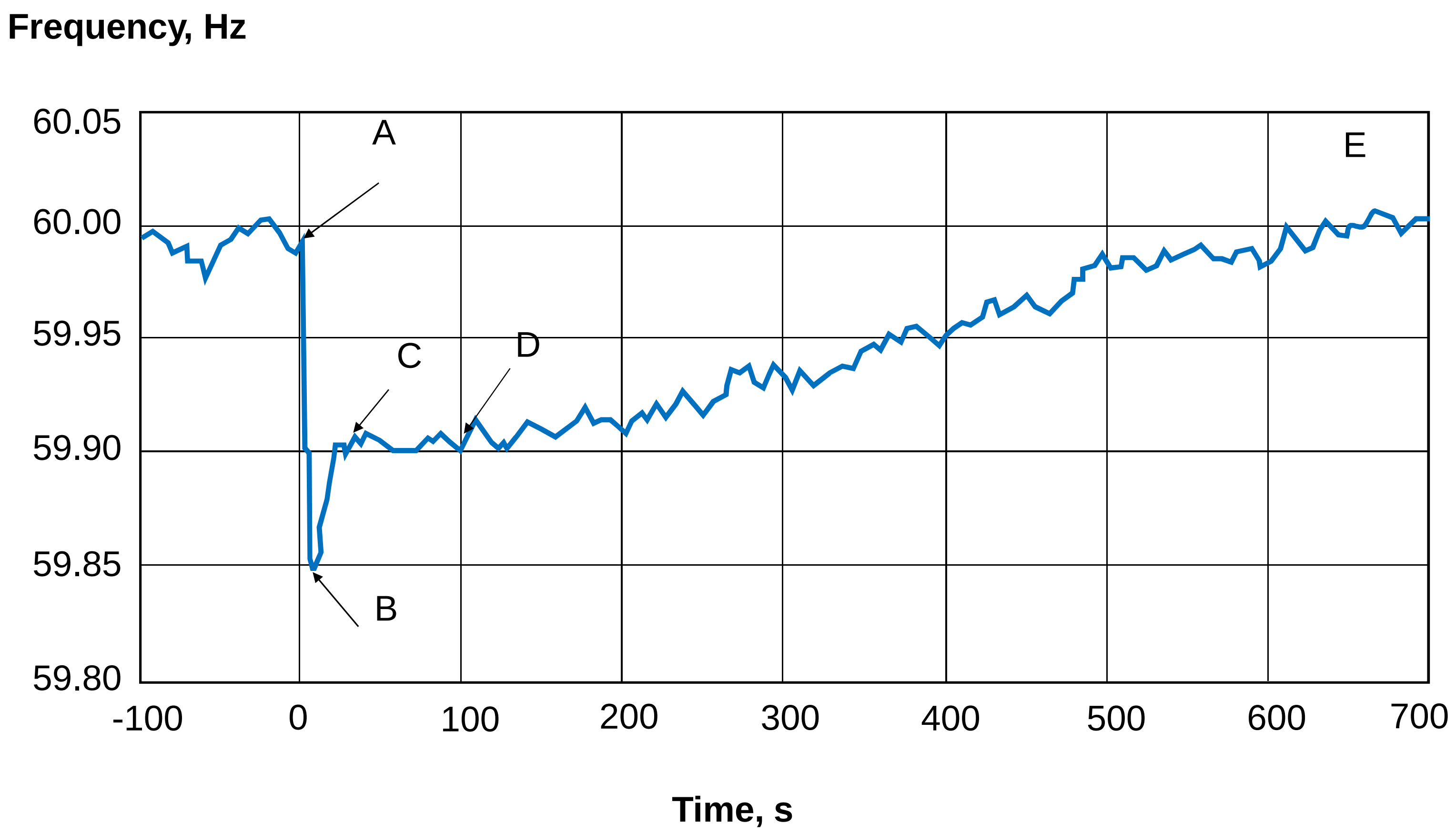
Operating reserves (cont.)

- Power system equipment is subject to random failures, and thus additional generation capacity is needed so that it can be called upon when a large generator or a heavily loaded transmission line is suddenly taken out of service. This additional capacity is referred to as *operating reserve*.

Contingency analysis for System B



Contingency event and a typical system response



Inertial response

- At the very instant of the generation loss, synchronous generators that are still connected to the grid release kinetic energy stored in their rotating masses (turbines, shafts and rotors), and thereby slow down the frequency decline.
- This type of response is called ***inertial* response**. Large fast rotating generators have larger inertial response than smaller or slowly rotating machines. The system inertia, or the cumulative inertial response of all rotating machines, determines the initial slope of the frequency decline.

Primary frequency response

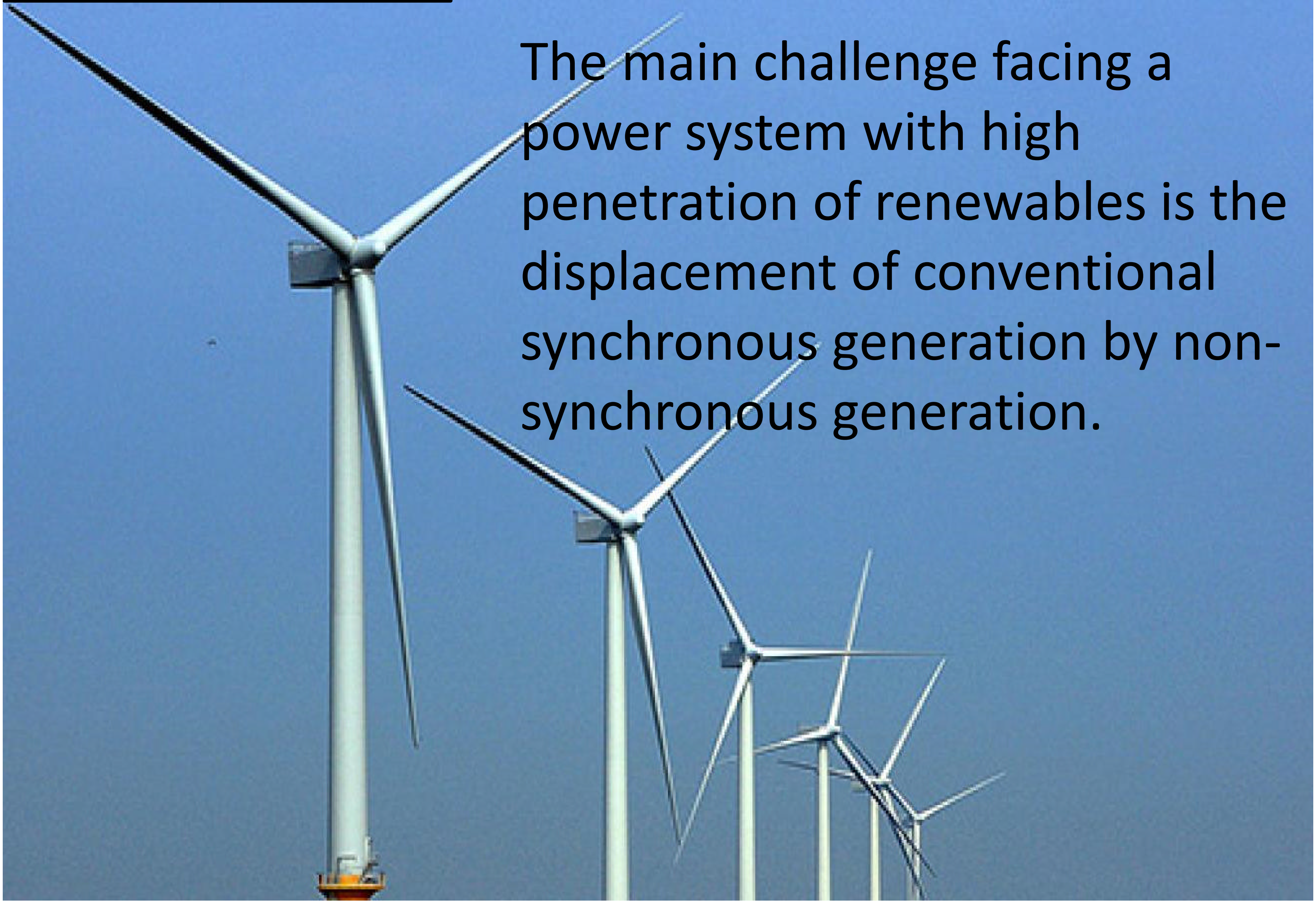
- Following a disturbance, turbine governors detect the frequency decrease and additional power is provided to balance the load. This type of response is called ***primary frequency* response**. It is used to restore power balance, and thus stabilise the frequency. The primary frequency response is usually delivered within 30 s.
- Maintaining sufficient reserves of active power is necessary for preventing under-frequency load shedding and frequency collapse, but it does not guarantee voltage stability.

Impact of Renewable Energy Generation

- An increasing penetration of intermittent renewable energy generation introduces additional uncertainties in power systems.
- However, the impact of variable generation on the system security is often exaggerated. For example, in the Ireland and Northern Ireland power system, the system stability degrades only when non-synchronous variable generation exceeds 50% of demand.
- No significant mitigation measures are required until the wind and solar penetration reaches 20%.

Impact of Renewable Energy Generation (cont.)

- Wind speed variations within the range of 15-25 m/s do not cause any changes in power generation because in this range, wind turbines operate at full output.
- On the other hand, wind variations within the range of 4-15 m/s can result in a substantial change of the turbine output. This problem can usually be mitigated by geographical dispersion of wind farms.
- For example, in Germany, a single wind farm can frequently exhibit hour-to-hour power swings of up to 60% of the installed capacity while aggregated power swings of wind farms over entire Germany do not exceed 20%.



The main challenge facing a power system with high penetration of renewables is the displacement of conventional synchronous generation by non-synchronous generation.

Impact of Renewable Energy Generation (cont.)

- Kinetic energy stored in the rotating masses of synchronous generators provides the system rotational inertia.
- Wind power generators are decoupled from the grid by electronic converters – they do not provide inertia to the system. This reduces the total system inertia.
- The system becomes more vulnerable to contingencies – even contingencies that previously were considered “safe” can now lead to frequency violations and the system’s instability.

Kinetic energy and inertia

Relationship between the stored kinetic energy and inertia:

$$E = \frac{1}{2} J \omega^2$$

where *E* is the kinetic energy stored in the rotating masses, [MW·s]; *J* is the moment of inertia around the axis of rotation, [kg·m^2]; and *ω* is the angular velocity of the rotor [rad/s].

Kinetic energy and inertia

Based on the amount of energy stored in the rotating mass, we can determine how long the generator can supply its rated power solely from the stored kinetic energy:

$$H = \frac{E_0}{S} = \frac{J\omega_0^2}{2S}$$

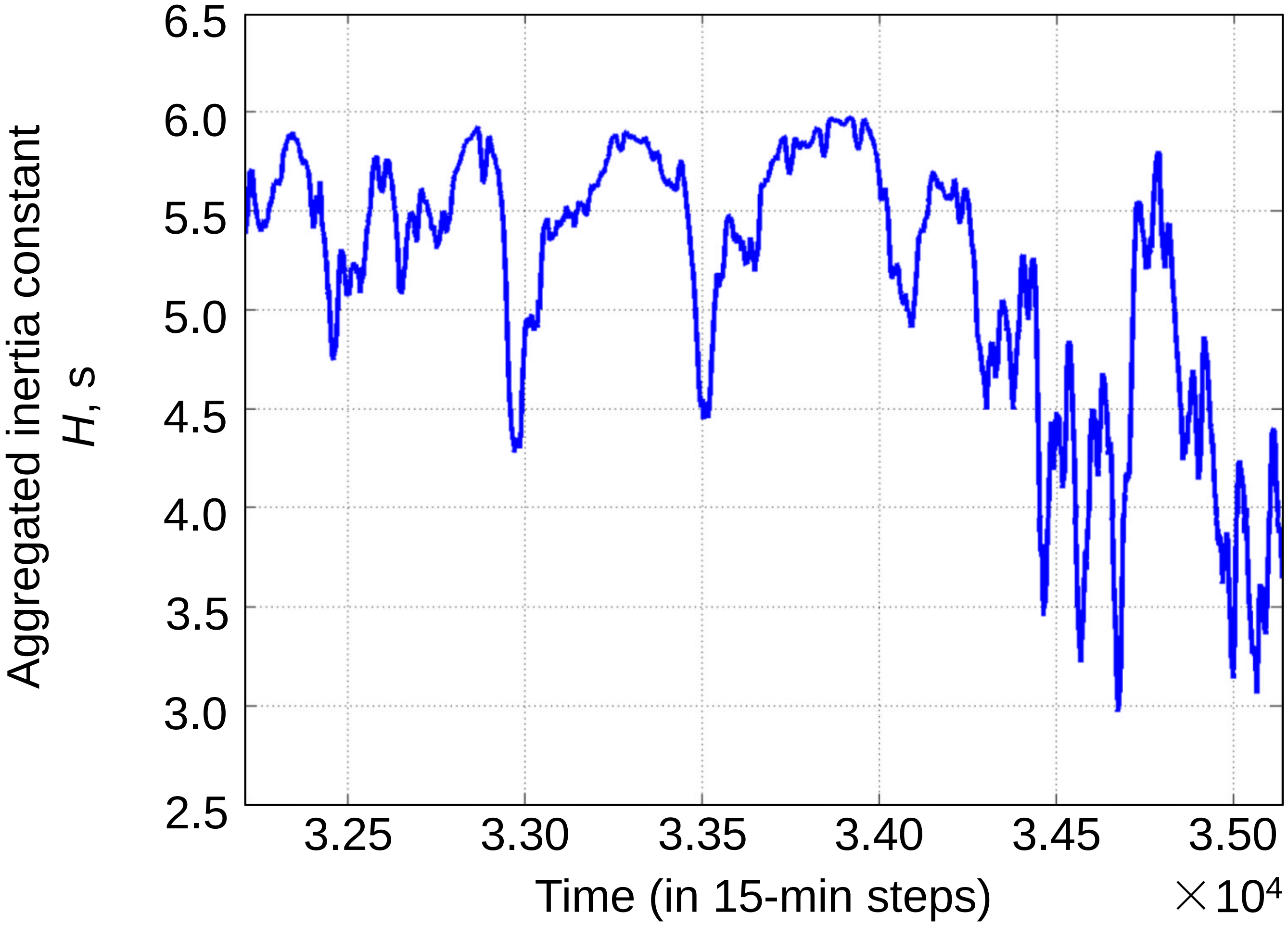
where H is the inertia constant, [MW·s/MVA]; E_0 the kinetic energy measured at the rated angular velocity of the rotor ω_0, [MW·s]; and S is the rated apparent power of the generator, [MVA].

Inertia constant

- The inertia constant is expressed in seconds. It indicates the duration that the generator can supply its rated power to the system using only its kinetic energy.
- For example, the inertia constant of 6 s means that the generator can supply its rated power to the system for 6 s using only energy stored in its rotating masses.

Inertia constant for conventional machines

Machine type	Inertia constant, MW·s per MVA
Thermal	
3600 r/min (2-pole)	2.5 – 6.0
1800 r/min (4 pole)	4.0 – 10.0
Hydraulic	2.0 – 4.0



Aggregated rotational inertia in the German power system (December 2012). Conventional generators provide inertia of 6 s and wind and PV generators do not contribute any inertia.

Case study

- Six 200 MVA and ten 100 MVA synchronous generators are supplying a total load of 2000 MW. The inertia constant of each 200 MVA unit is 5.0 s on the 200 MVA base, and the inertia constant of each 100 MVA unit is 4.0 s.
- Determine the frequency deviation following a sudden loss of one of the 200 MVA units.
- Examine the frequency dynamics of the system when five 100 MVA synchronous generators are displaced by non-synchronous renewable generation.

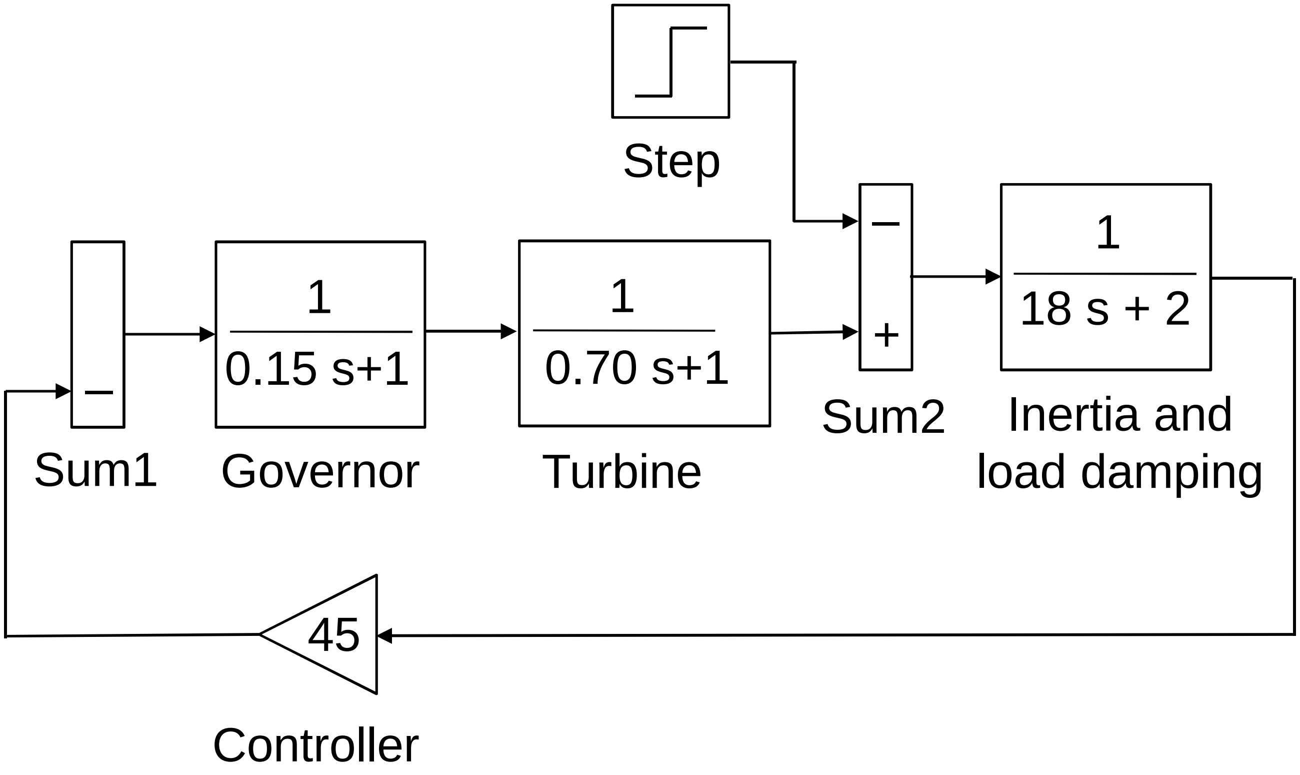
The total system inertia constant following the contingency:

$$H = \frac{5000 + 4000}{1000} = 9\ s$$

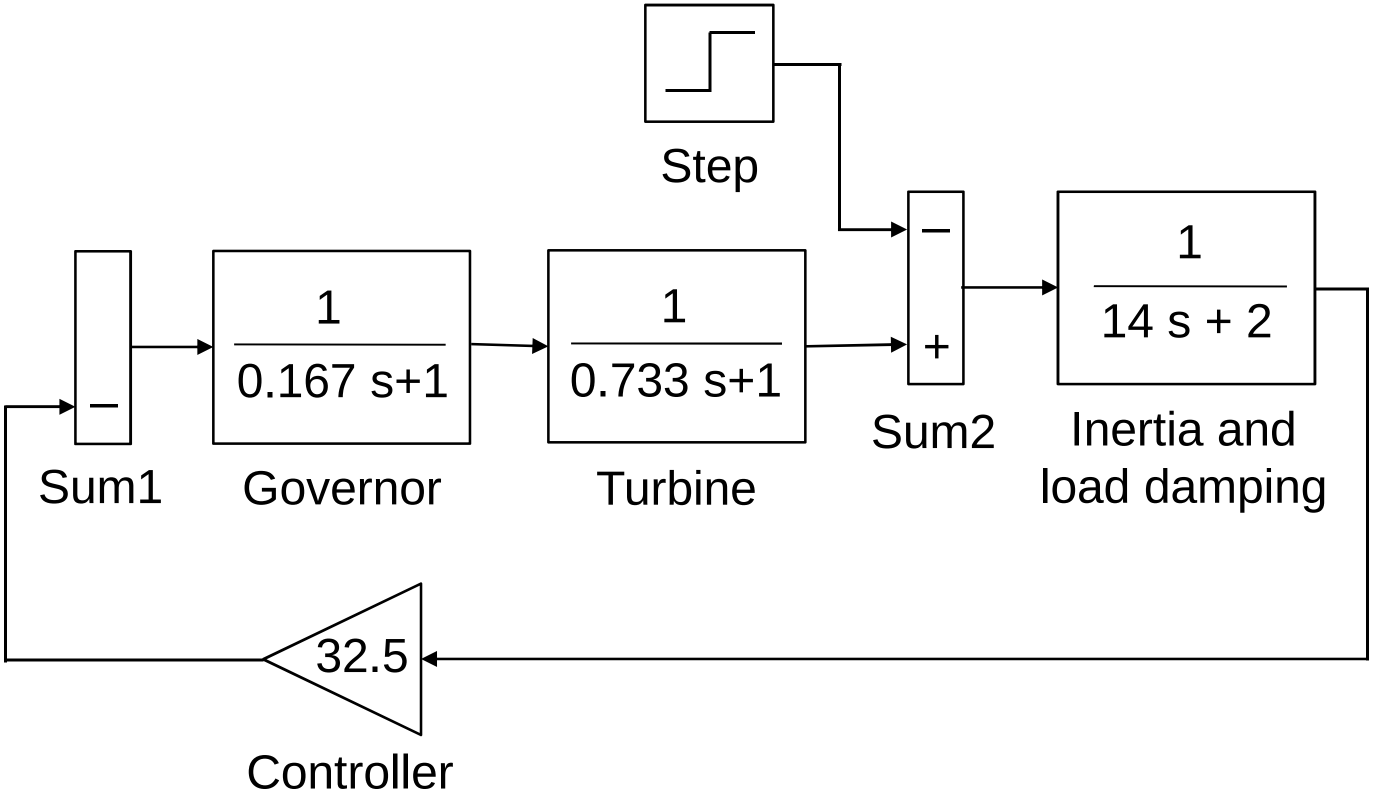
The system frequency dynamics when five 100 MVA synchronous generators are displaced by non-synchronous power generators:

$$H = \frac{5000 + 2000}{1000} = 7\ s$$

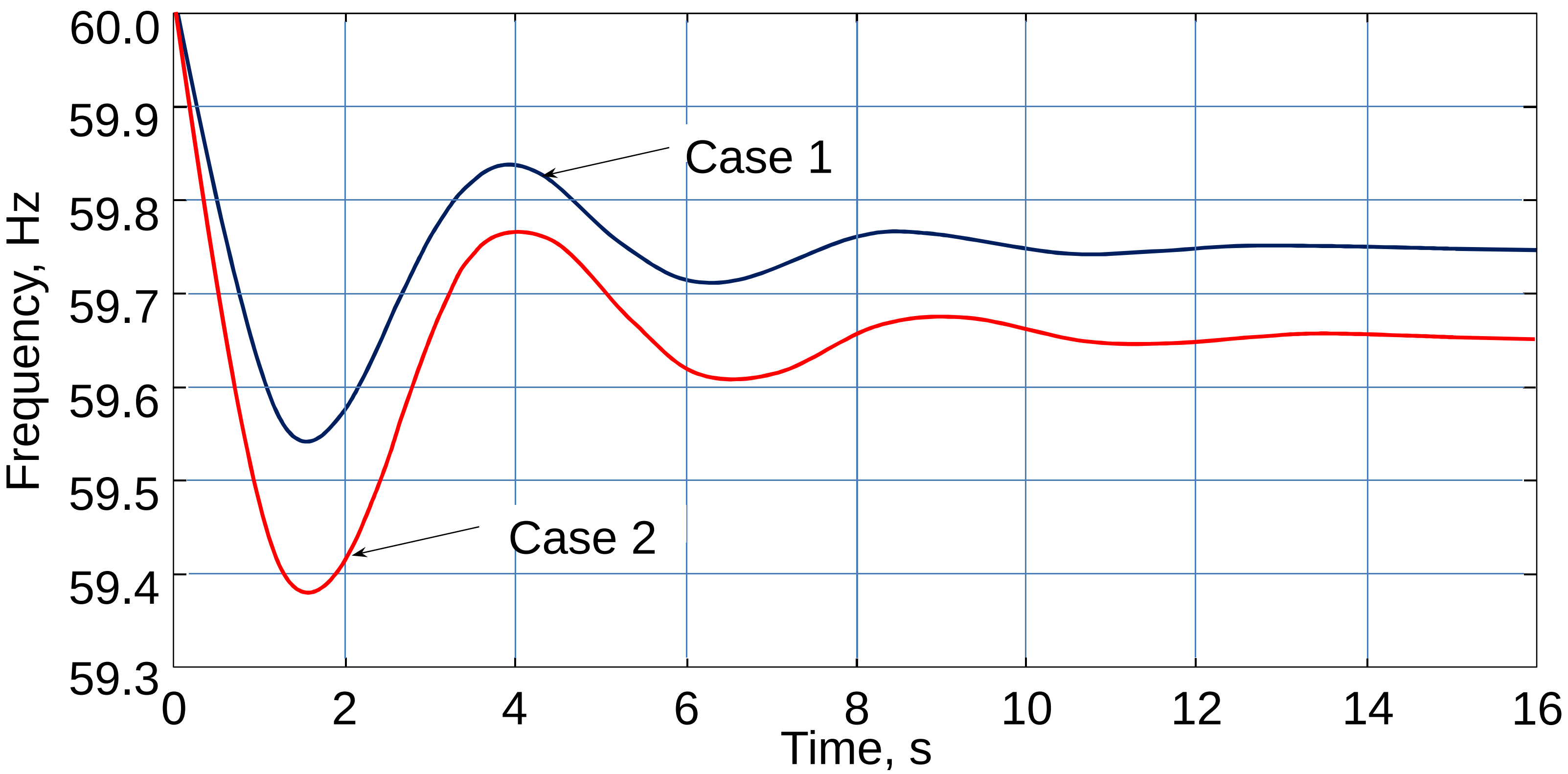
The MATLAB Simulink model of the system frequency dynamics



The MATLAB Simulink model for Example 9.3 when five 100 MVA synchronous generators are displaced by wind and solar PV generation



Frequency response of the power system



Frequency in the “lighter” case declines much faster, although in both cases, the system has sufficient rotating reserves to cover for the loss of the largest generator.

Frequency response of wind turbines

- The frequency response of wind turbines is dependent on active controls. These controls are designed to provide a response, which is *functionally* similar to the frequency response of synchronous machines.
- Modern wind turbines are also capable of providing “governor” frequency response. This is accomplished through blade pitch control. In order to provide “governor” response to low frequency events, wind turbines must operate below the level of maximum power output possible for a given wind condition.

Battery energy storage systems?

- As penetrations of renewable energy increase within a system, conventional approaches may become unable to manage system security.
- Battery energy storage is a common solution. But it is an emerging technology and currently expensive.
- Australian experience advocates approaches able to reduce both the system cost and complexity.

King Island isolated power system

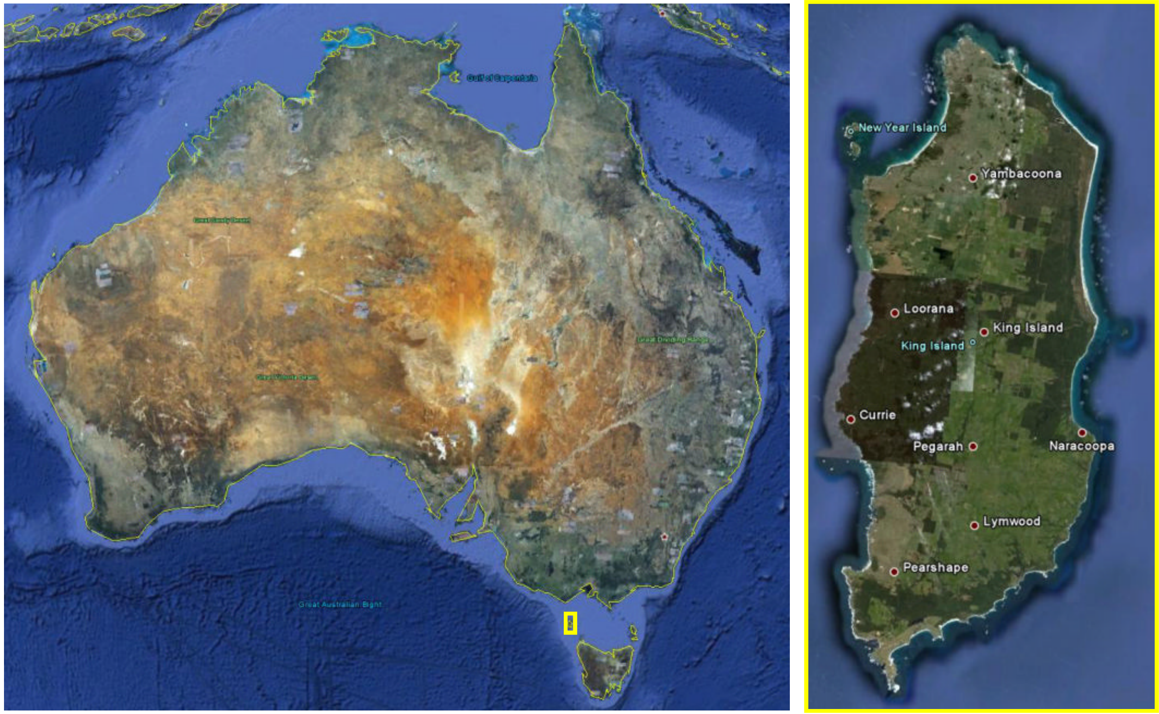
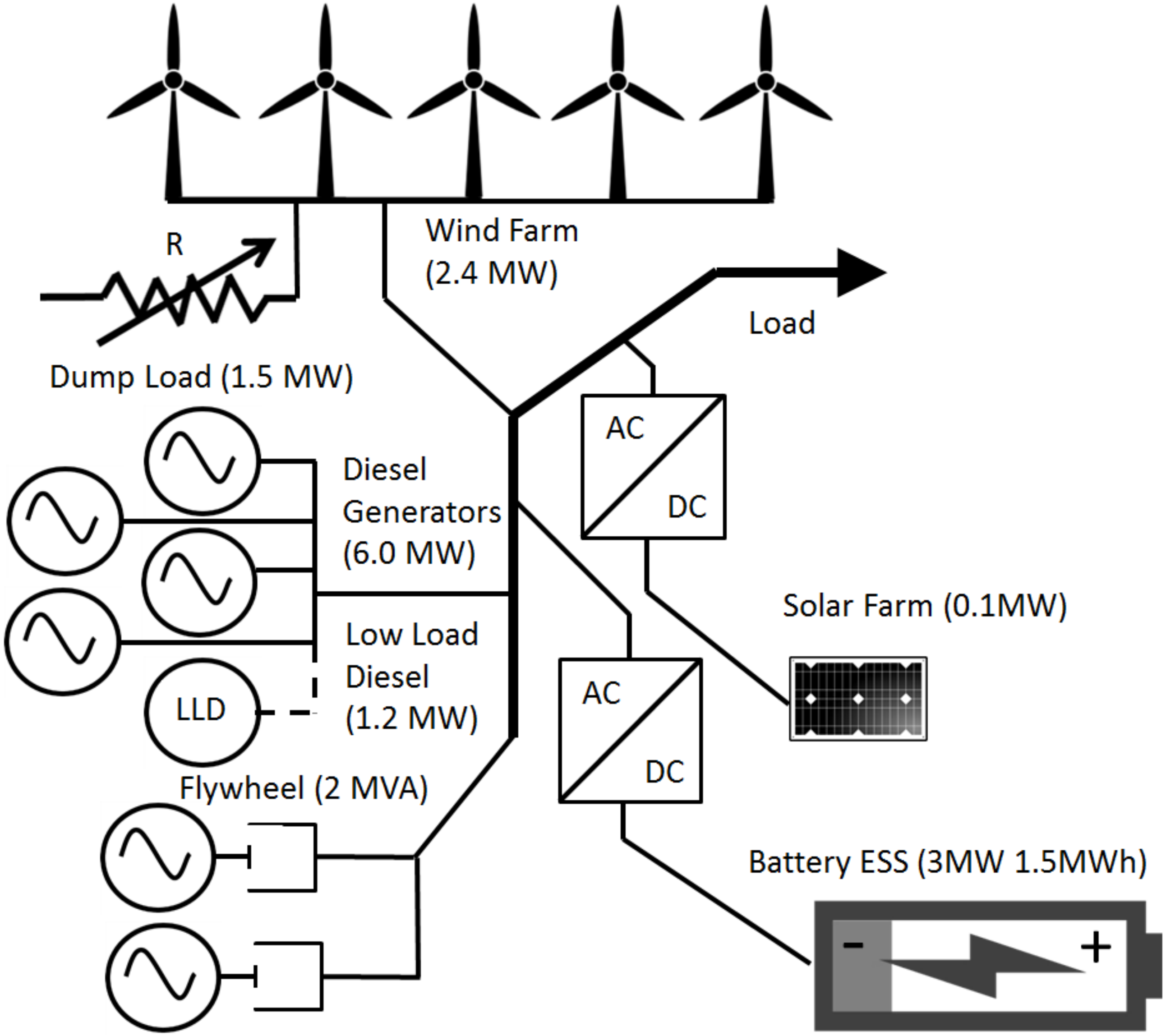


Image source: Google Earth

- Small, mostly agricultural island between Tasmania and mainland Australia, ideally placed for wind generation.
- Electricity network owned and operated by Hydro Tasmania – opportunity to implement whole system changes.
- Wind energy currently covers 65% of energy needed by the system.
- Instantaneous renewable energy penetration is very high (85% peak) but remains limited due to the intermittent nature of wind.

King Island power system



King Island power system

- The King Island load varies between 1 MW and 3 MW, with an average of around 1.5 MW.
- The wind resource on King Island supplies approximately 65% of the island's power supply (2.4 MW wind farm).
- The target of this system is to use all the available solar and wind power to reduce diesel usage.
- The station has been designed to run unattended. The system has evolved progressively over a period of 20 years, with system performance from 1998 to 2012.

King Island power system

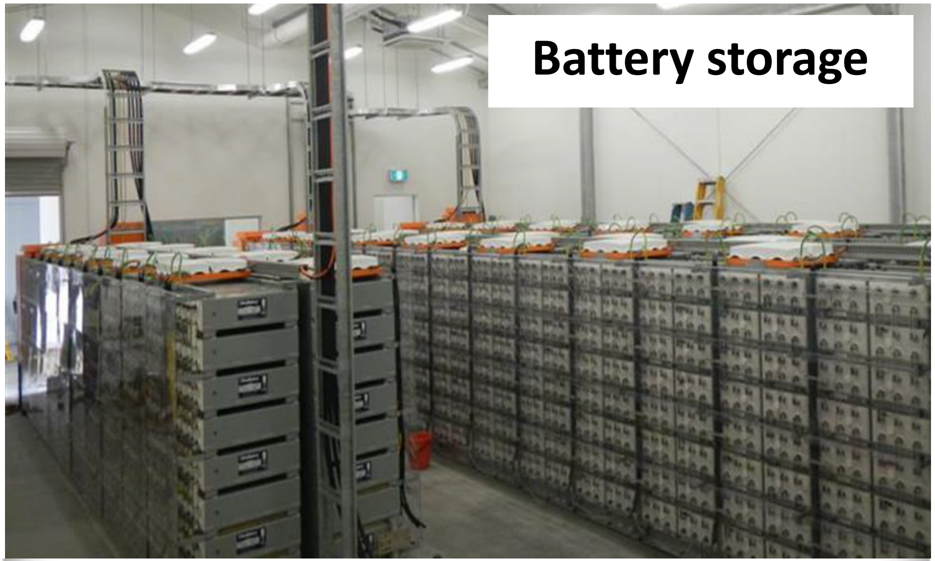
- The step change observed in 2004 involves the commissioning of the two Vestas V52 wind turbines (850kW each).
- In addition King Island was also the first MW scale system to achieve renewable penetrations above 50%. This milestone was achieved via a range of emerging technologies, installed from 2008 to 2014.
- Annual renewable energy penetrations has exceeded 65%. The system is also able to operate for with no diesel generation, achieving diesel off operation for up to 20% of the year.

King Island: technology portfolio

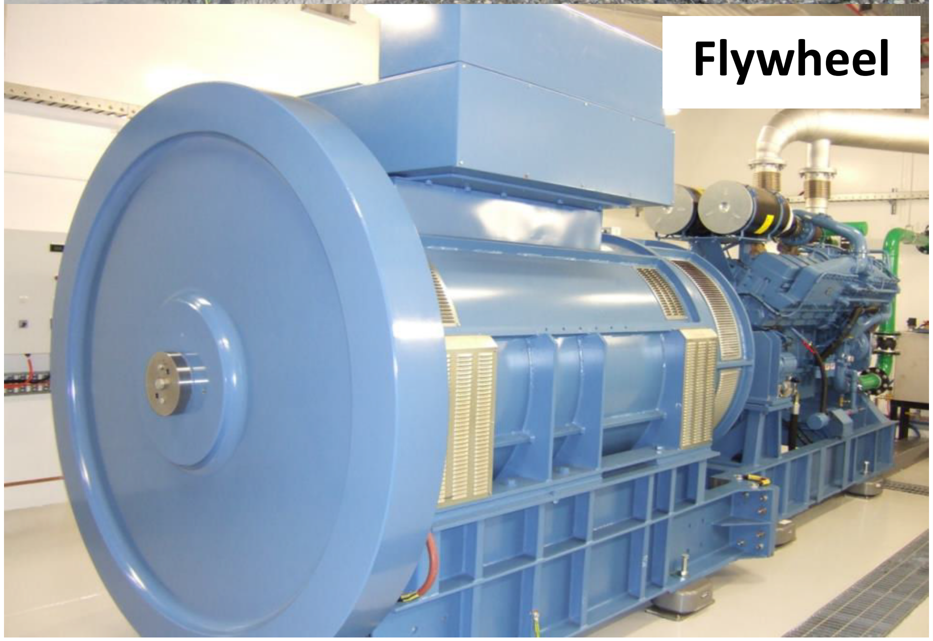
Technologies integrated:

- Dual axis solar PV tracking system (2008)
- Dynamic resistive frequency control (2008)
- Flywheel diesel uninterrupted power supply (2011)
- Biodiesel blending (2012)
- Demand side management (2012-2013)
- Battery energy storage system (BESS) integration (2014).

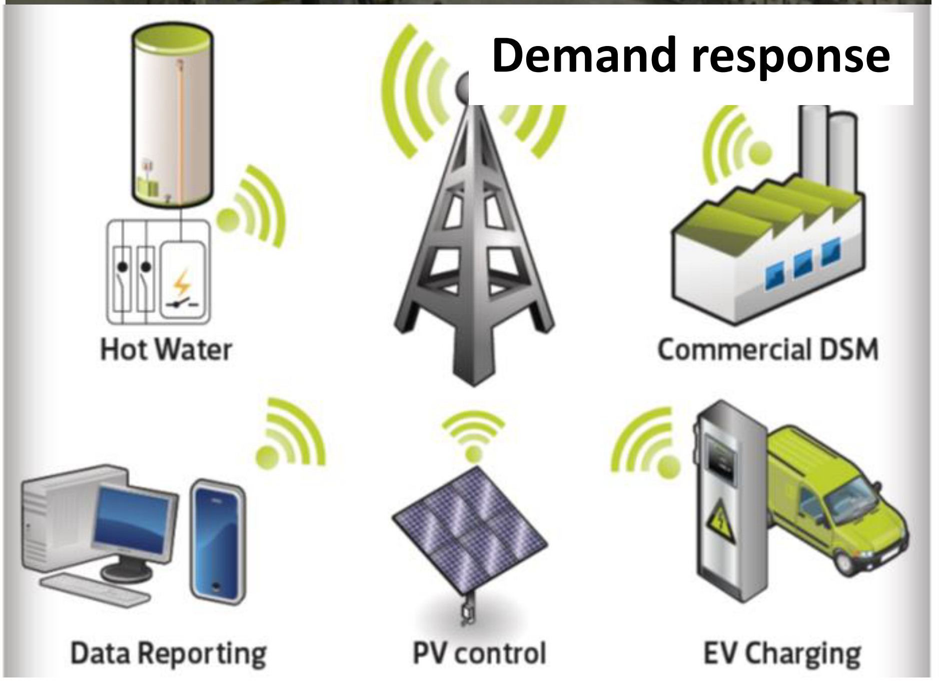
Dynamic resistor



Battery storage



Flywheel



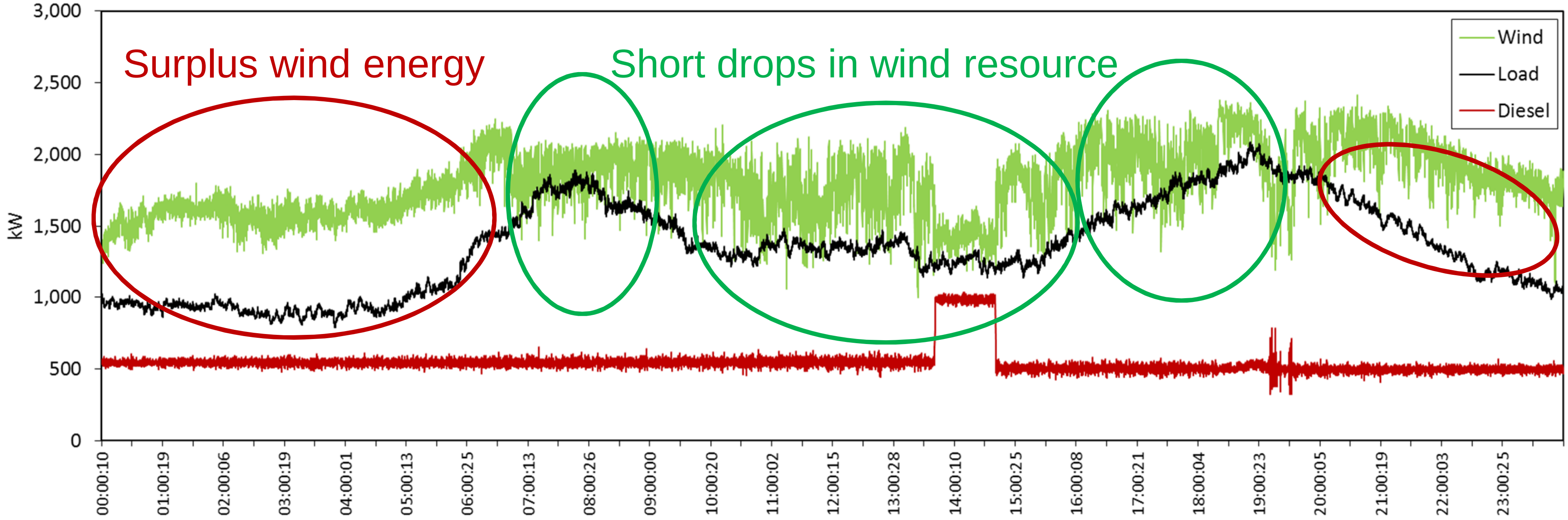
Demand response

King Island: flywheel diesel technology

- The flywheel diesel technology consists of a large flywheel generator, coupled to a diesel engine.
- The mechanical coupling allows for the generator to acts as a synchronous condenser, providing spinning reserve to the power system under high renewable penetrations.
- In the event that system frequency drops below acceptable limits the clutch engages to fast start the diesel engine.
- The technology provides the King Island power system approximately 30 s of inertia.

King Island: Fast Demand Response

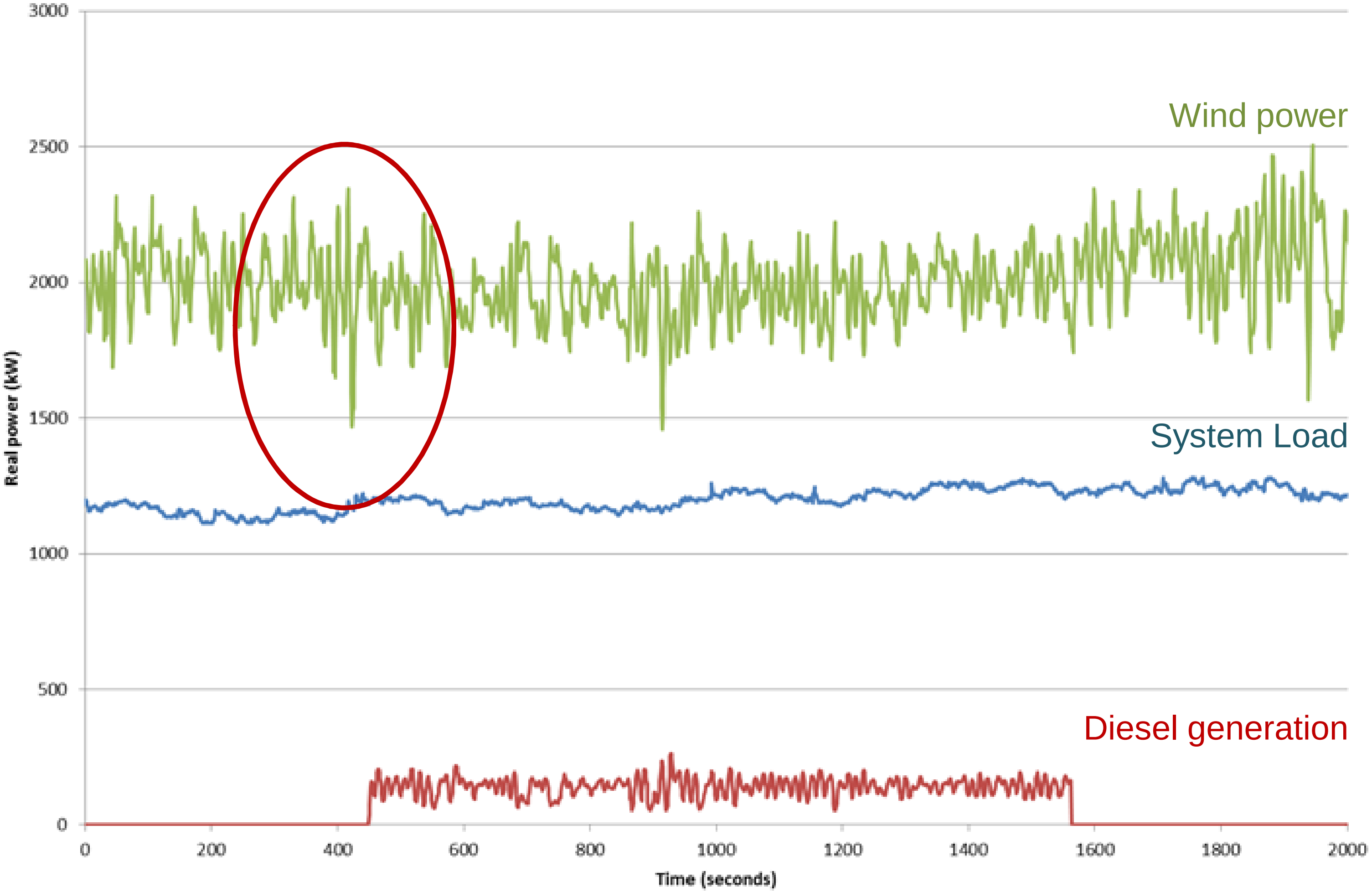
Example day on King Island



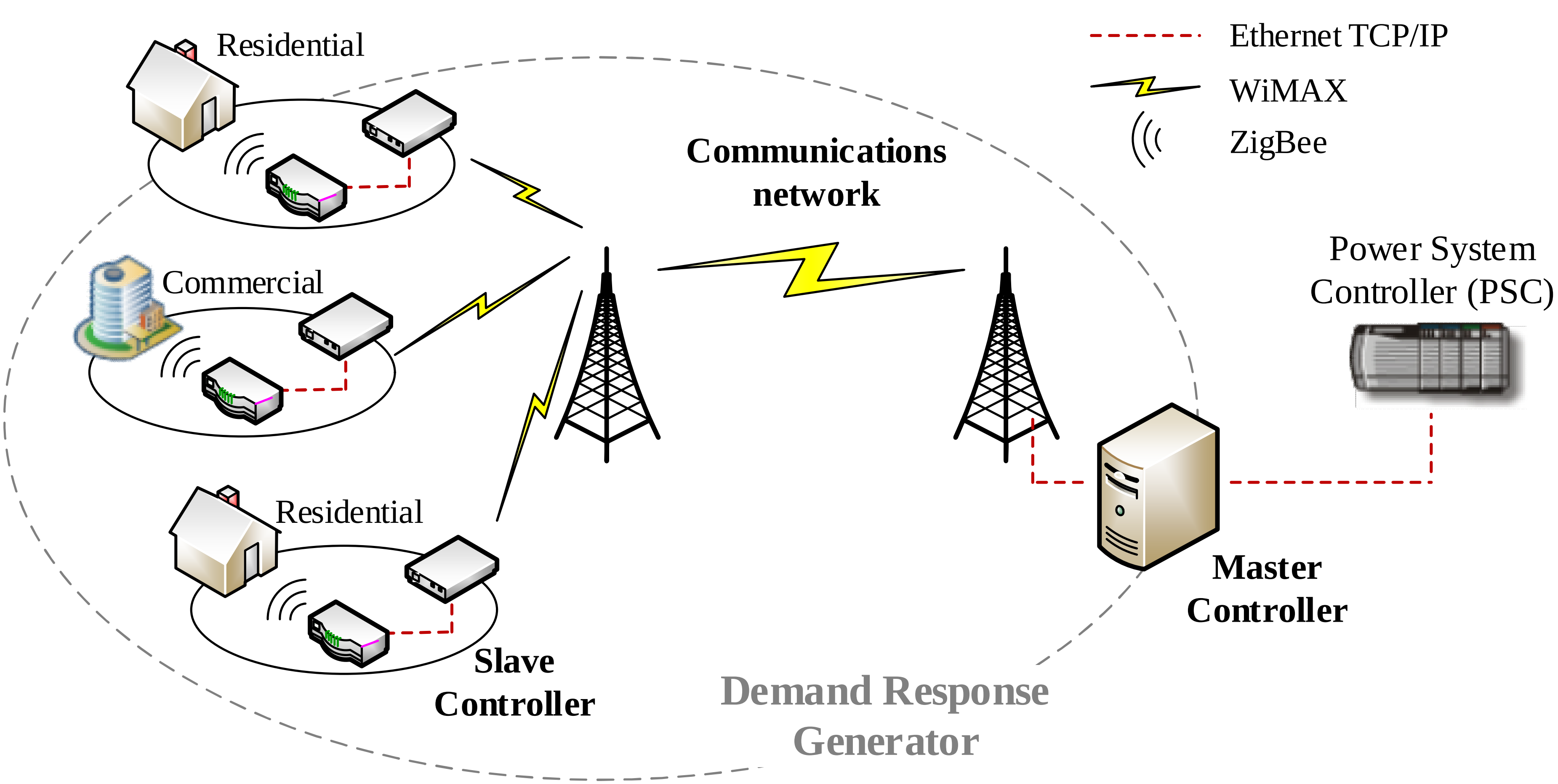
Surplus wind energy

Short drops in wind resource

Case for short-term power system support



Demand Response Generator



Ethernet TCP/IP

WiMAX

ZigBee

Residential

Commercial

Residential

Communications network

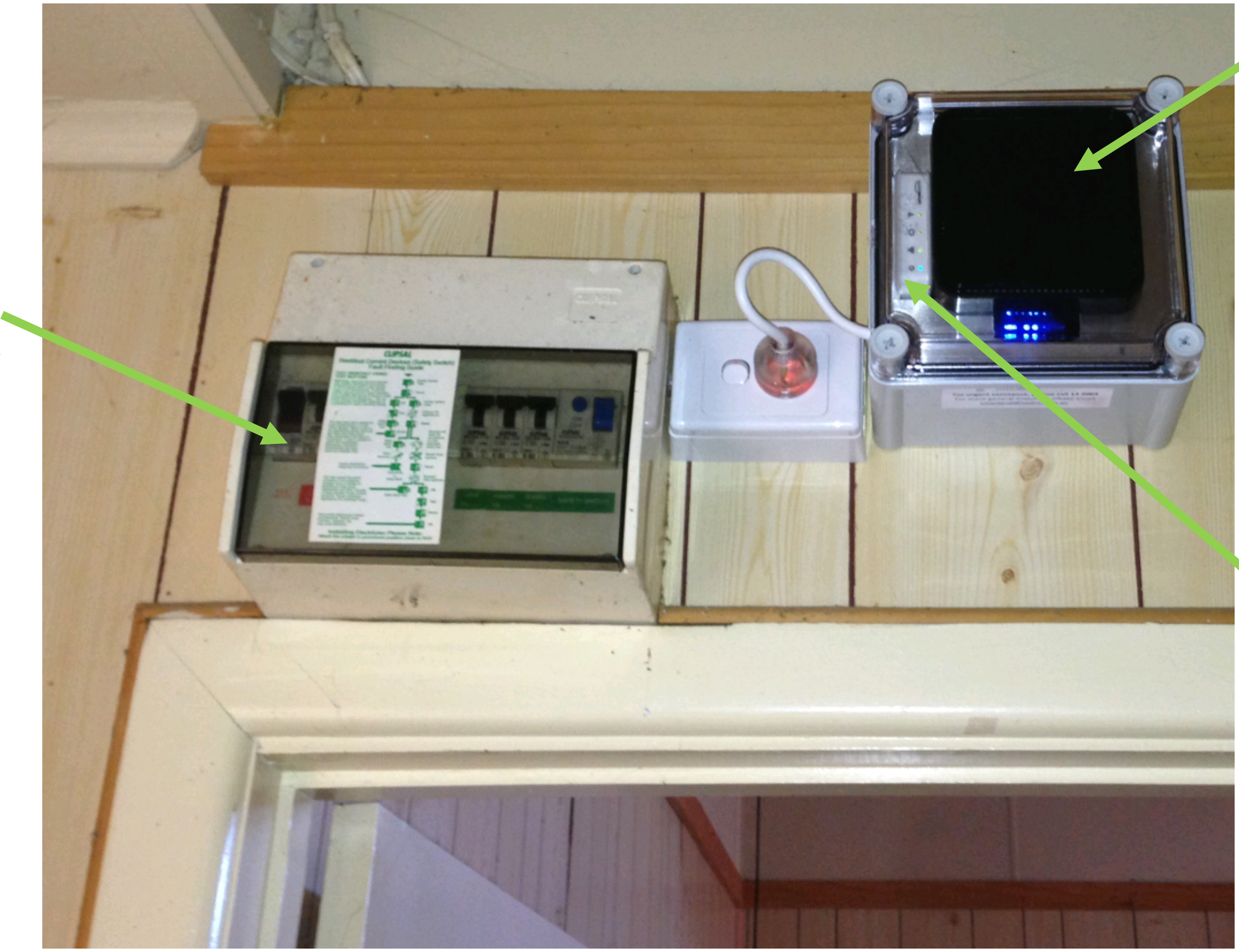
Power System Controller (PSC)

Master Controller

Slave Controller

Demand Response Generator

Installation example: Residential

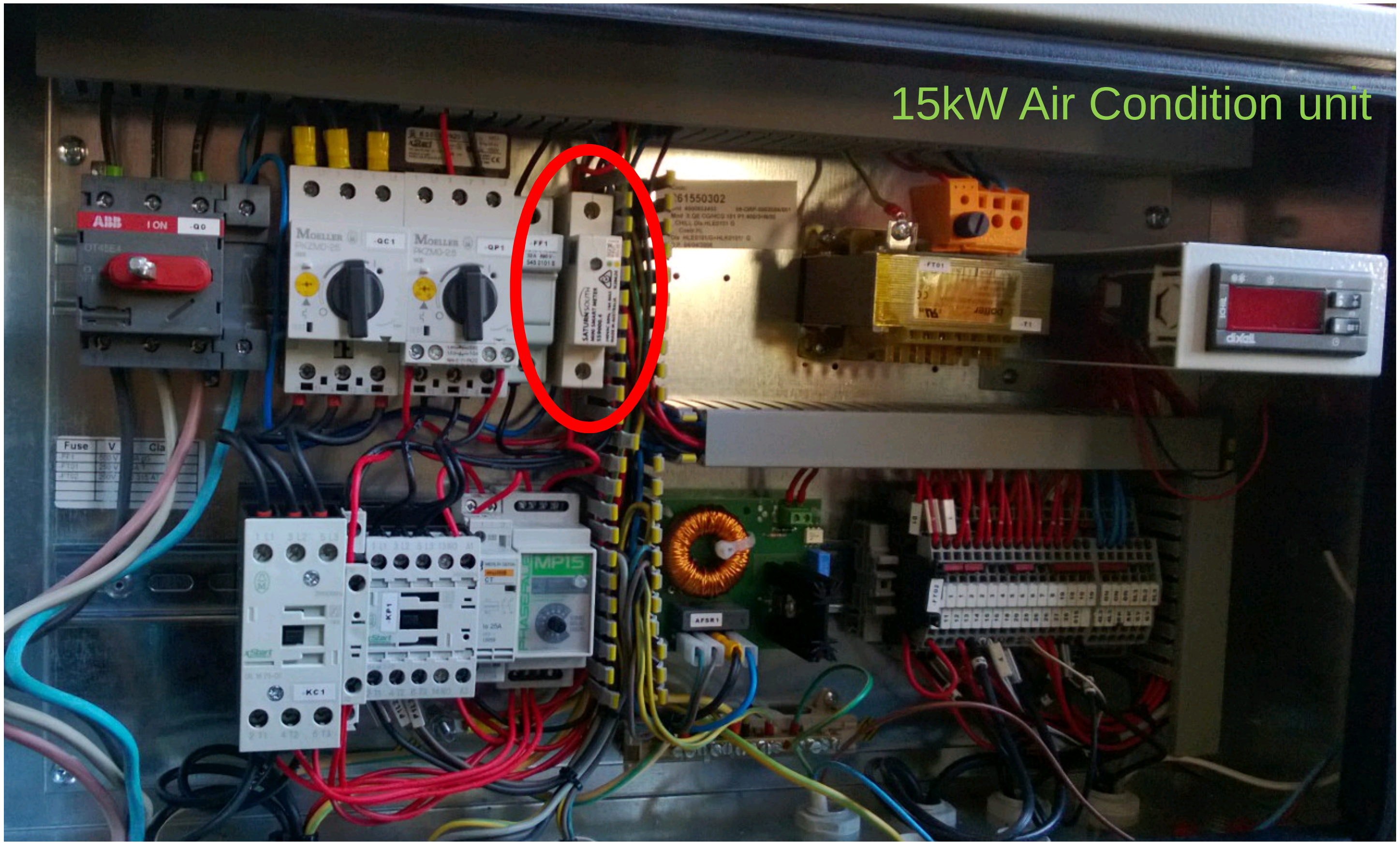


WiMax modem

Smart Switches

Gateway

Installation example: Commercial

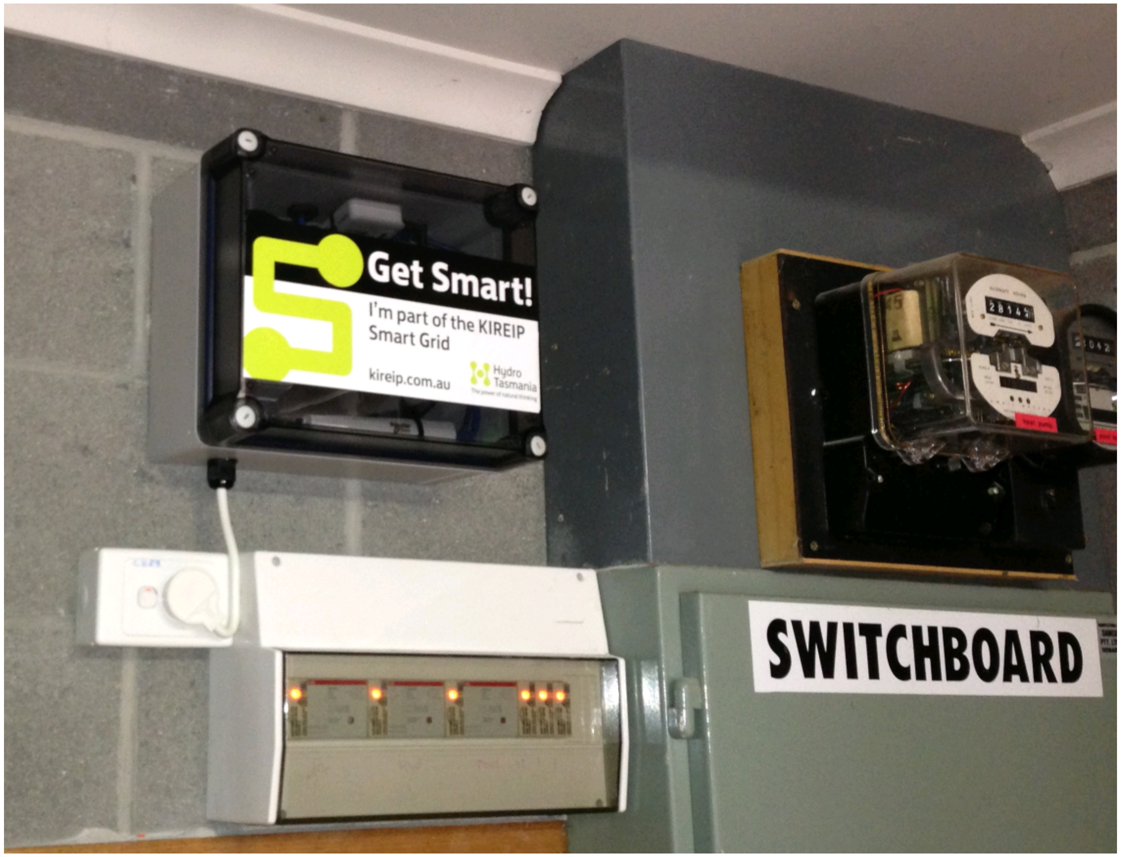


15kW Air Condition unit

Installation example: Local School

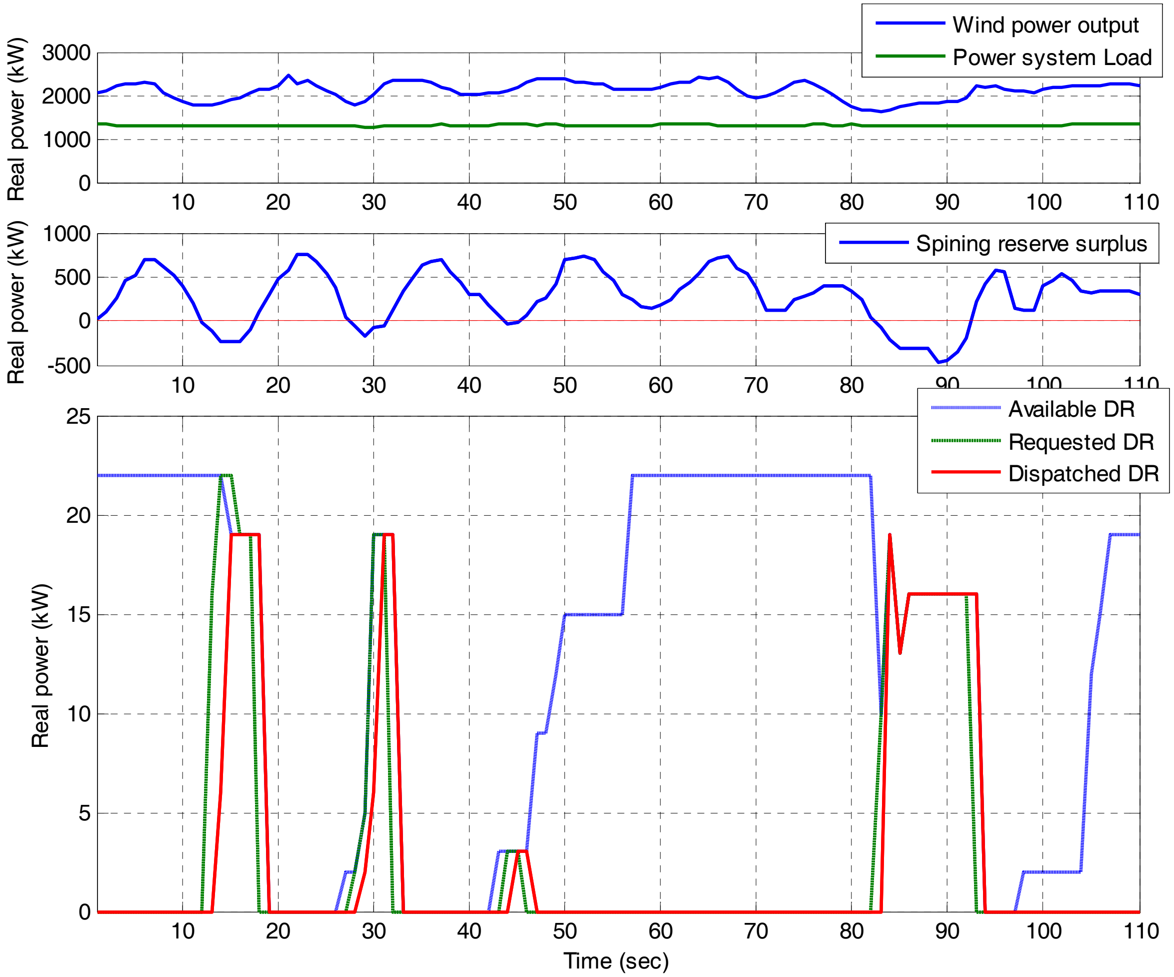
School controllable loads:

- **3-Phase hot water**
- **3-Phase Pool heaters**
- **3-Phase Heaters**
- **1-Phase Heaters**



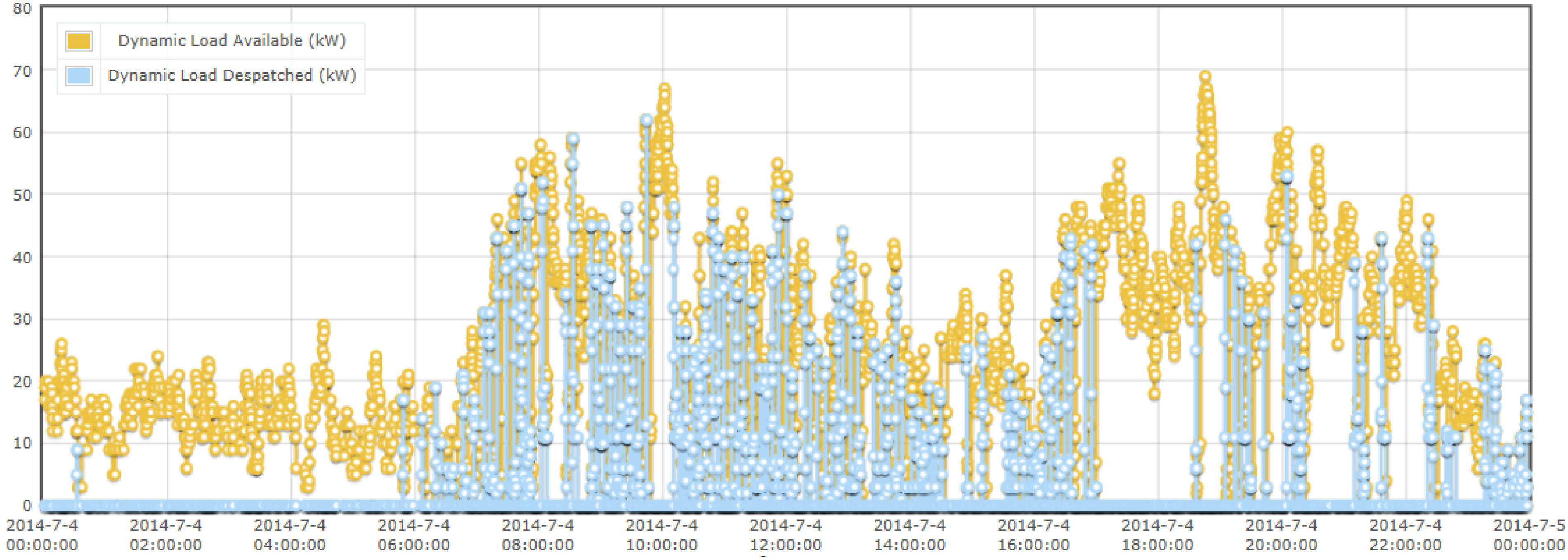
Demand response operation

- Demand response automatically initiated during times of low spinning reserve.
- Demand response recorded in within **1 second** from the moment of receiving a command.



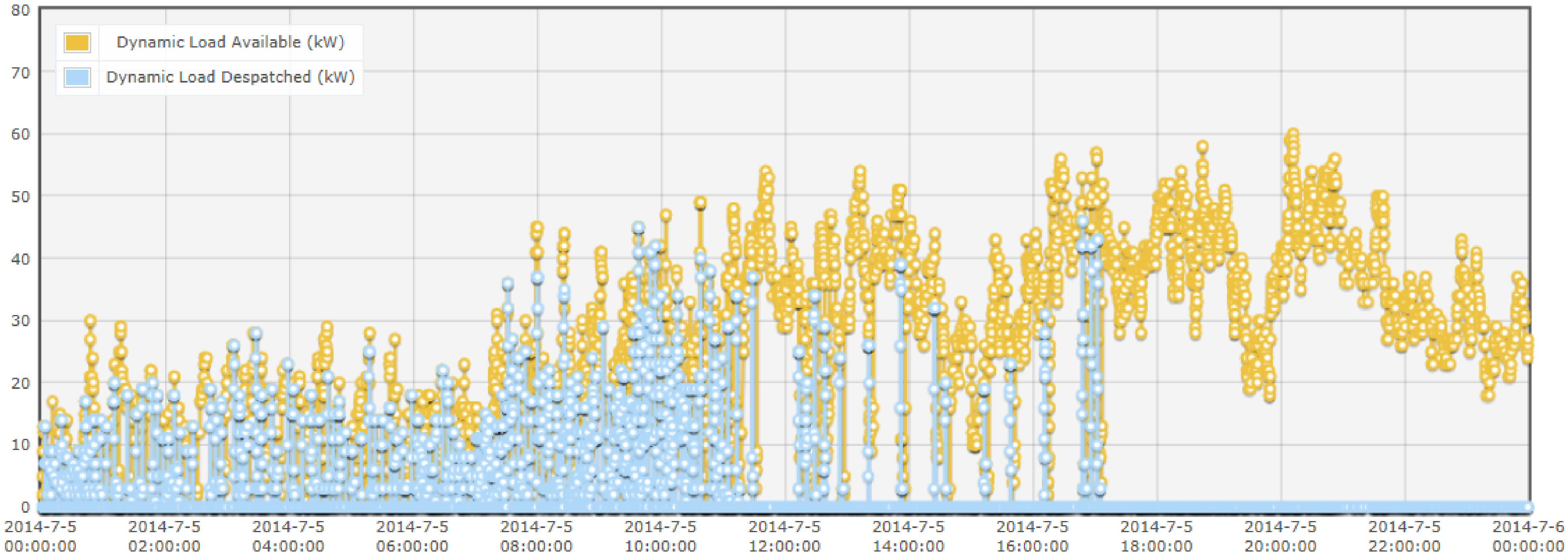
Demand response automated operation (I)

July 04th 2018



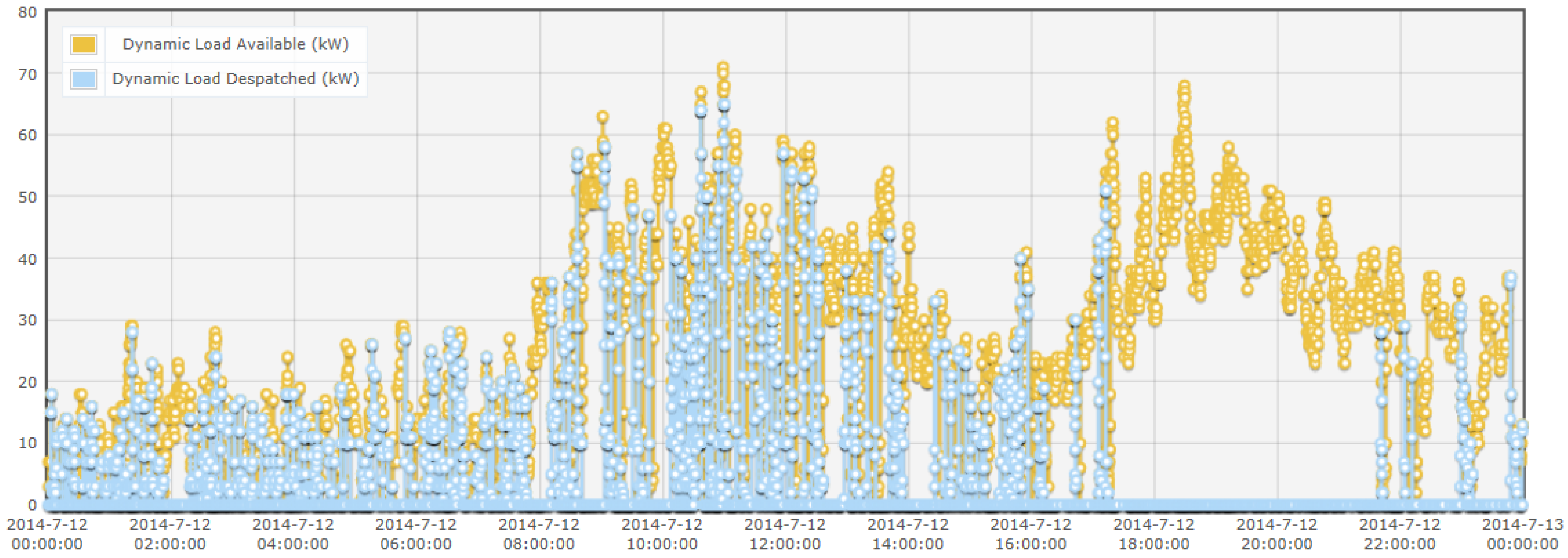
Demand response automated operation (II)

July 05th 2018



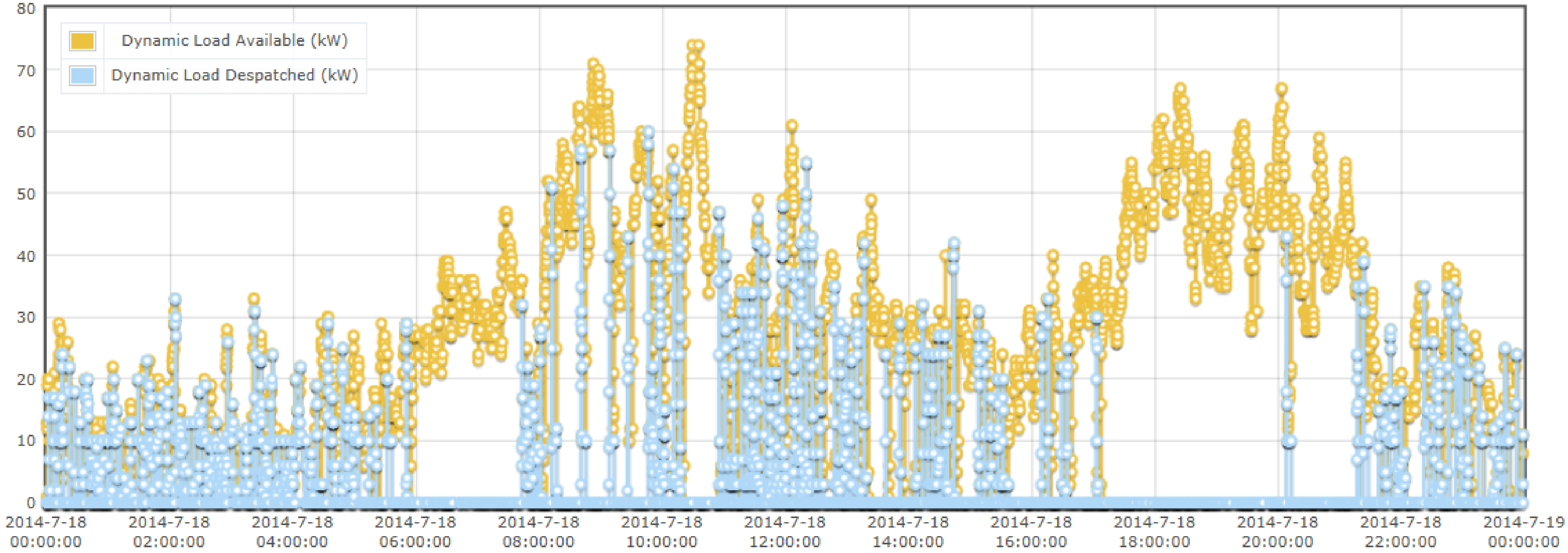
Demand response automated operation (III)

July 12th 2018



Demand response automated operation (IV)

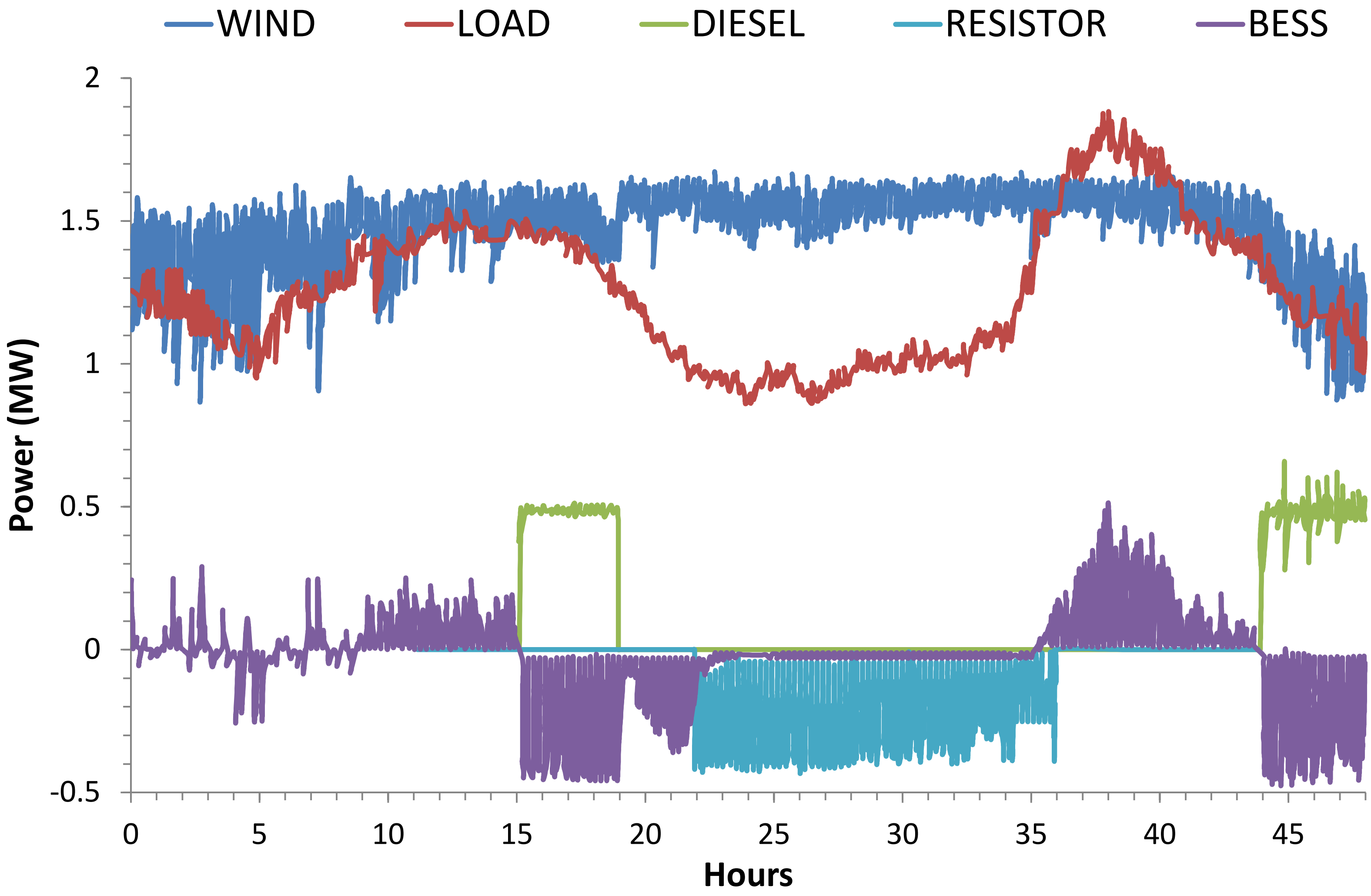
July 18th 2018



King Island: battery energy storage system (BESS)

- BESS integration was commissioned in 2013. At that time the BESS represented the largest in Australia – 3 MW / 1.6 MVh.
- The role of the battery is to extend the time for which the island can run diesel off, and to capture some of the spilt renewable generation otherwise sent to the resistive load.

King Island generation showing wind generation, island load, diesel generation, resistor load and battery load



Risk-based Security Assessment

- Traditionally security assessment is performed based on deterministic criteria. The *N*-1 security criterion requires a power system to withstand an outage of any single system component without violating any system operating limits.
- It has satisfied the needs of the power industry for decades. However, the deterministic approach to security may not be adequate in modern power systems with market driven dispatch and high penetration of renewable energy and distributed generation.

Risk-based Security Assessment

- Traditionally security assessment is performed based on deterministic criteria. The *N*-1 security criterion requires a power system to withstand an outage of any single system component without violating any system operating limits.
- It has satisfied the needs of the power industry for decades. However, the deterministic approach to security may not be adequate in modern power systems with market driven dispatch and high penetration of renewable energy and distributed generation .

Risk-based Security Assessment (cont.)

- Deterministic security criteria define a set of "credible" contingencies that the system should be able to withstand.
- However, that the deterministic contingency analysis does take the probabilities of contingencies into account – the selection of "credible" contingencies implicitly implies that these contingencies are more likely to occur in reality.

Risk-based security definition

- Security can be defined as the risk in the system’s ability to withstand random contingencies without interruption to customer service. The higher the risk the lower the security.
- Although risk cannot be eliminated fully due to unexpected faults and probabilistic behaviour of a power system, it can be assessed and managed within an acceptable level in power system planning, design and operation.

Risk-based security definition

- Risk-based security analysis is concerned with voltage violations, overloads and frequency response adequacy.
- Frequency response adequacy is defined as the capability of frequency response resources to prevent frequency from dropping below a certain limit.
- We need to assess the primary frequency response because of the risk of under-frequency load shedding, particularly in systems with low inertia.

Risk-based security assessment

- In risk-based security assessment, we do not use a predefined list of contingencies, but generate contingencies at random based on their probabilities.
- Then, we assess the consequences of these contingencies to determine whether loads are disconnected following voltage violations, overloads and significant imbalance between load and generation. This allows us to measure the impact of random contingencies in terms of loads not served.

Risk-based security assessment

- Using a model of the restoration process, we obtain the time needed to restore power, and thus, estimate the cost of the generated contingency.
- Finally, we repeat generating contingencies over and over, each time using a different set of random values. This process is called Monte Carlo simulation – a problem solving technique used to calculate the probability of certain outcomes by running multiple trials, called simulations, using random variables.

The value of risk

$$Risk = \sum_{n=1}^{N} \sum_{m=1}^{M} p(S_n) \cdot p(C_{nm}) \cdot Sev(C_{nm})$$

where *Risk* is the risk index,

$p(S_n)$ is the probability of the pre-contingency operating state S_n,

$p(C_{nm})$ is the probability of contingency C_m occurring in the state S_n,

$Sev(C_{nm})$ is the severity of the contingency C_m in the state S_n,

N is the total number of pre-contingency operation states, and *M* is the total number of contingencies considered in each state.

Conclusions

- The main challenge facing a power system with high penetration of renewables is the displacement of conventional synchronous generation by non-synchronous generation.
- Recent developments in wind turbine and battery storage technologies offer a hybrid solution for mitigating the effect of faster frequency dynamics in power systems with high penetration of renewable energy.

Conclusions (cont.)

- The deterministic approach to security may not be adequate in modern power systems with market driven dispatch and high penetration of renewable energy and distributed generation.
- In risk-based security assessment, we generate contingencies at random, based on their probabilities.