Black System

South Australia 28 September 2016 and resulting grid code modifications

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UVIG Nashville October 11, 2017

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17 October, 2017

CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered "non-GAAP financial measures" under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE's cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

Outline, and Disclaimer

Outline:

- Australian System: South Australia, the NEM, AEMO
- 28 September 2016 – Timeline of the System Black
- Aftermath and Grid Codes

Disclaimer:
Situation in Australia is sensitive. This presentation represents my distillation of the salient points and learnings. It is solely mine, and doesn't represent an official position of GE (or anyone else).
-Nick

Official Australian Energy Market Operator Postmortem

BLACK SYSTEM
SOUTH AUSTRALIA
28 SEPTEMBER 2016

AEMO
AUSTRALIAN ENERGY MARKET OPERATOR

Published: **March 2017**

http://www.aemo.com.au/-/media/Files/Electricity/NEM/Market_Notices_and_Events/Power_System_Incident_Reports/2017/Integrated-Final-Report-SA-Black-System-28-September-2016.pdf

Note: Figures with numbers are taken directly from the AEMO Report

Opening comments from the AEMO Report

Broad objectives: *(paraphrased by Nick. Document is 273 pages)*

1. Was the plant's performance in-line with AEMO's dynamic power-system models and the relevant performance & system standards?
2. Should there be changes to access standards?
3. Would the results be different if wind farm generation output had not been reduced by protection?
4. What would have happened if loss of multiple transmission lines was a 'credible contingency' on that day?
5. What should special protection schemes (SPS) do?
6. Did the SVCs work properly?
7. Deeper looks, including:
   ... more windfarm drops;
   ... from high or rapidly changing winds;
   ... of unnecessary impedance relay operations;
   ... of overvoltage due to load-shedding or islanding conditions
   ... of low system inertia after separation

The South Australian System

AEMO – Australian Electricity Market Operator
Runs the grid market for the NEM – National Electric Market.

- Represents most of the load and generation in Australia
- Geographically limited to the eastern population centers
- Grid is essentially linear with South Australia (SA) at the end of the line
- SA has lots of good wind & solar; Relatively expensive thermal

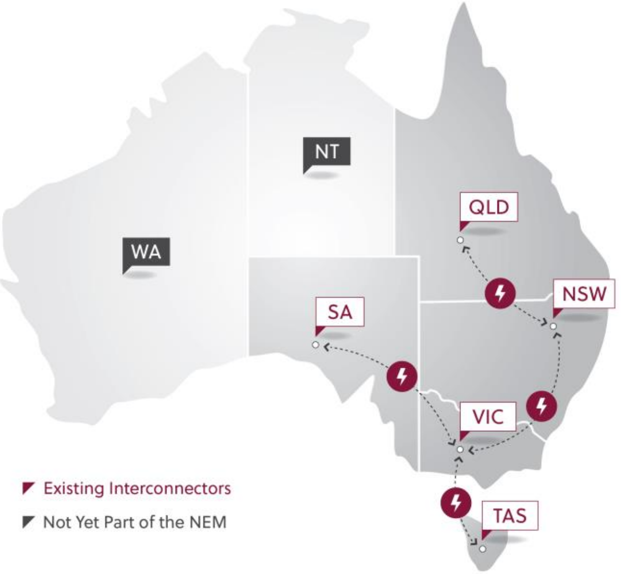


Figure 1. AEMO Report

Operation just before the Storm

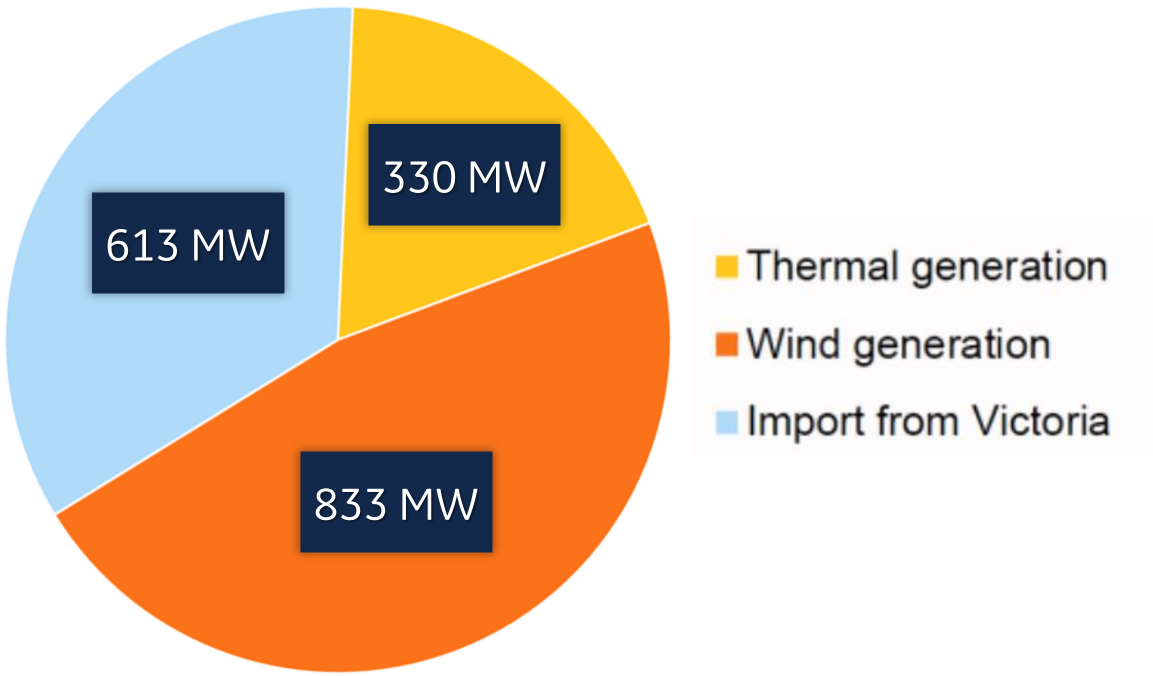
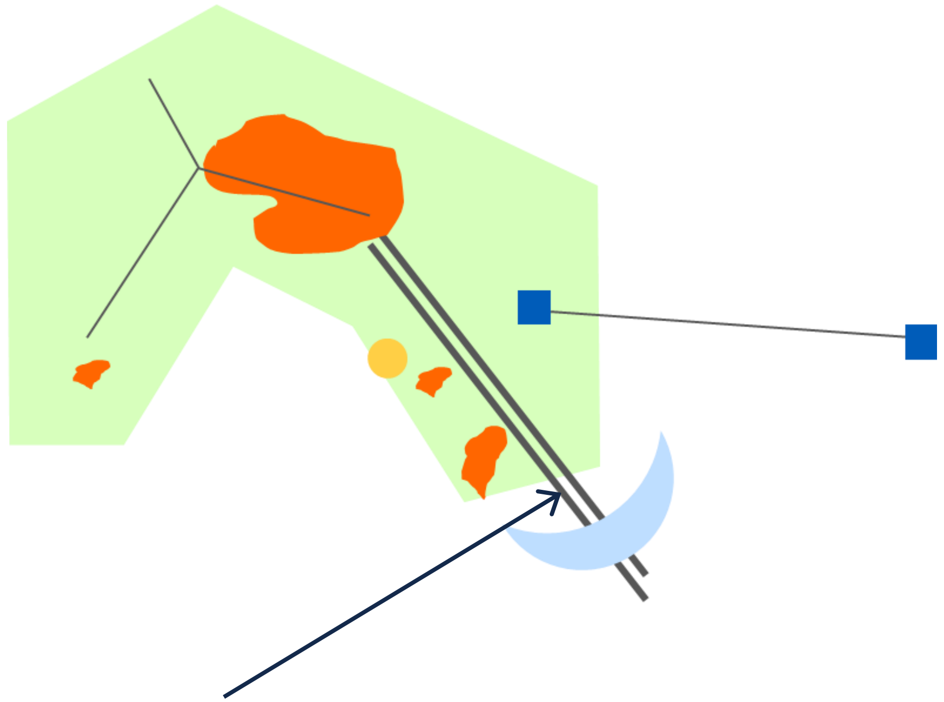


Figure 1. AEMO Report



- Double circuit, single tower 275kV transmission line.
- Simultaneous loss of both 275kV circuits is not considered a credible contingency…

No anticipated need for defensive operation posture

- Weather forecast: average wind speeds in 50-75km/hr, gusts 90-140km/hr.
- Looking back: “low pressure system…triggered especially severe thunderstorms (including tornados).” Tornados with wind speeds of 190-260 km/hr occured
- 263 lightning strokes in 5 minutes before event
- But mostly not “the type considered when analyzing the cause of electrical faults”

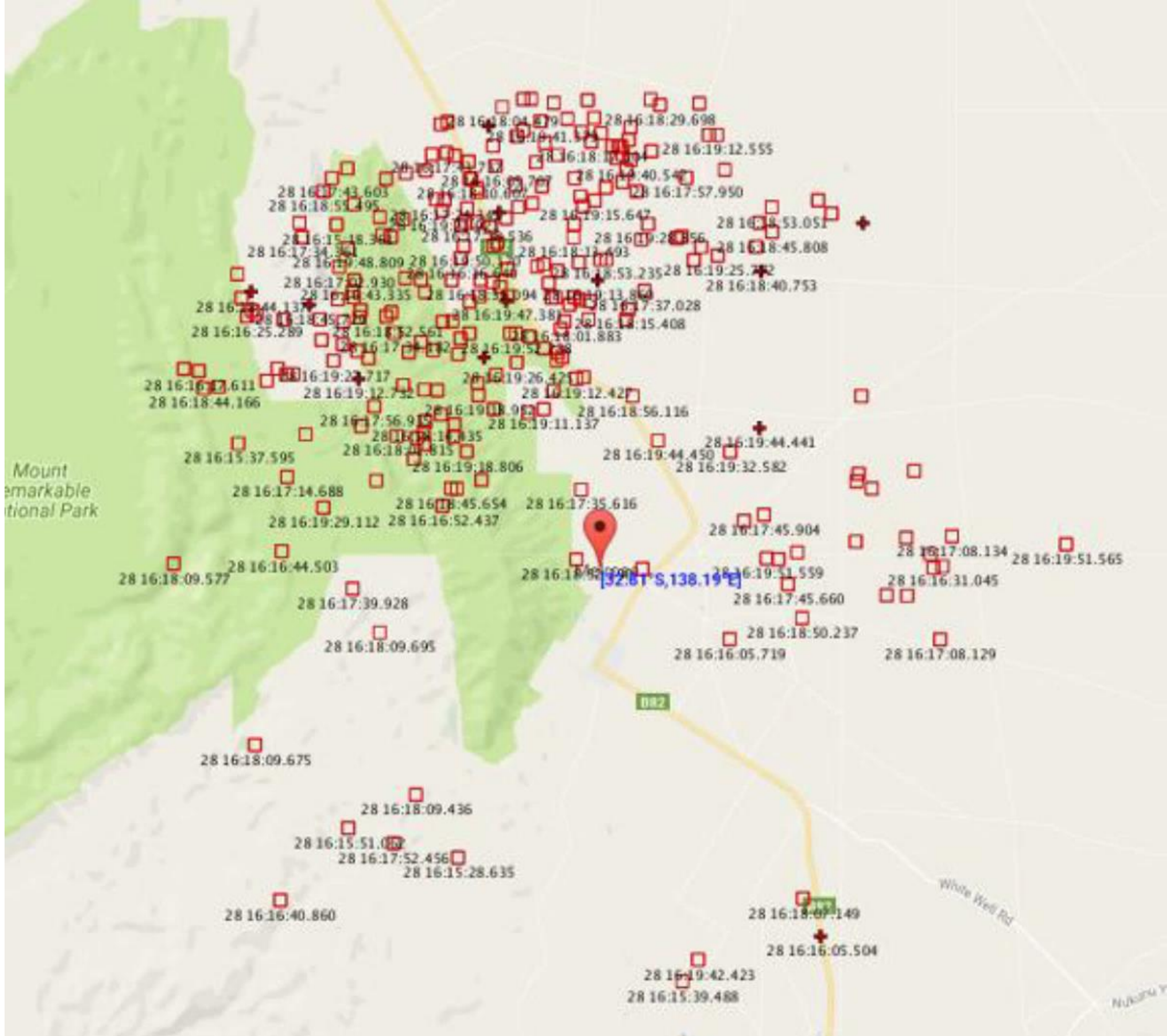
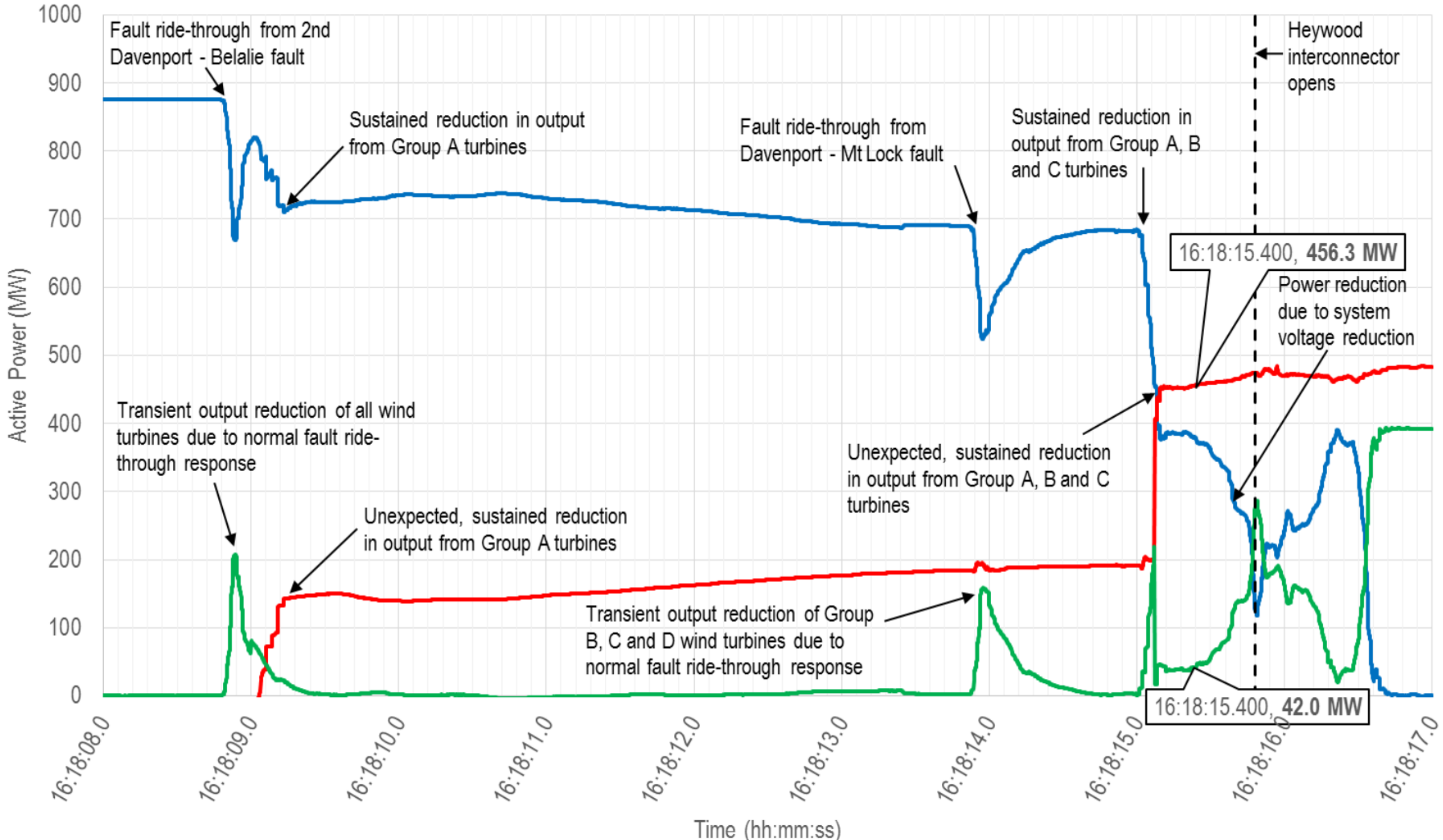


Figure 7. AEMO Report

5 Faults and a Failed Reclose in 87 seconds



Total wind farm output – Sustained vs transient power reduction, 28 September 2016

16:18:15:1

Fast reduction in power by Group B wind turbines due to the occurrence of 6 successive voltage disturbances within 2 minutes.

This resulted in activation of protection to stop the turbines.

At the same time, all on-line Group C wind turbines dropped their active power to zero due to zero power mode fault ride-through response

Line Loading on the AC Interconnector

Double AC 275kV Circuit on a Single Tower

- The line had been recently upgraded with series compensation, to raise the transfer limit to 650MW.
- There is no operational mechanism to *rapidly* deload the interconnector in the event of an acute imbalance/overload condition.
- 1^{st} line of protection of the South Australia system for this class of event is under-frequency load-shedding.

Let's look at some of the key system measurements as the system failed . . .

Classic Loss of Synchronism

Heywood Interconnector power flow and voltages across SA power system

Loss of 2nd block of wind turbines pushes system beyond its stability limit… imbalance is about 1000MW, never gets above 900MW… game is over right here.

AC Flow >700MW going into final stages of the event

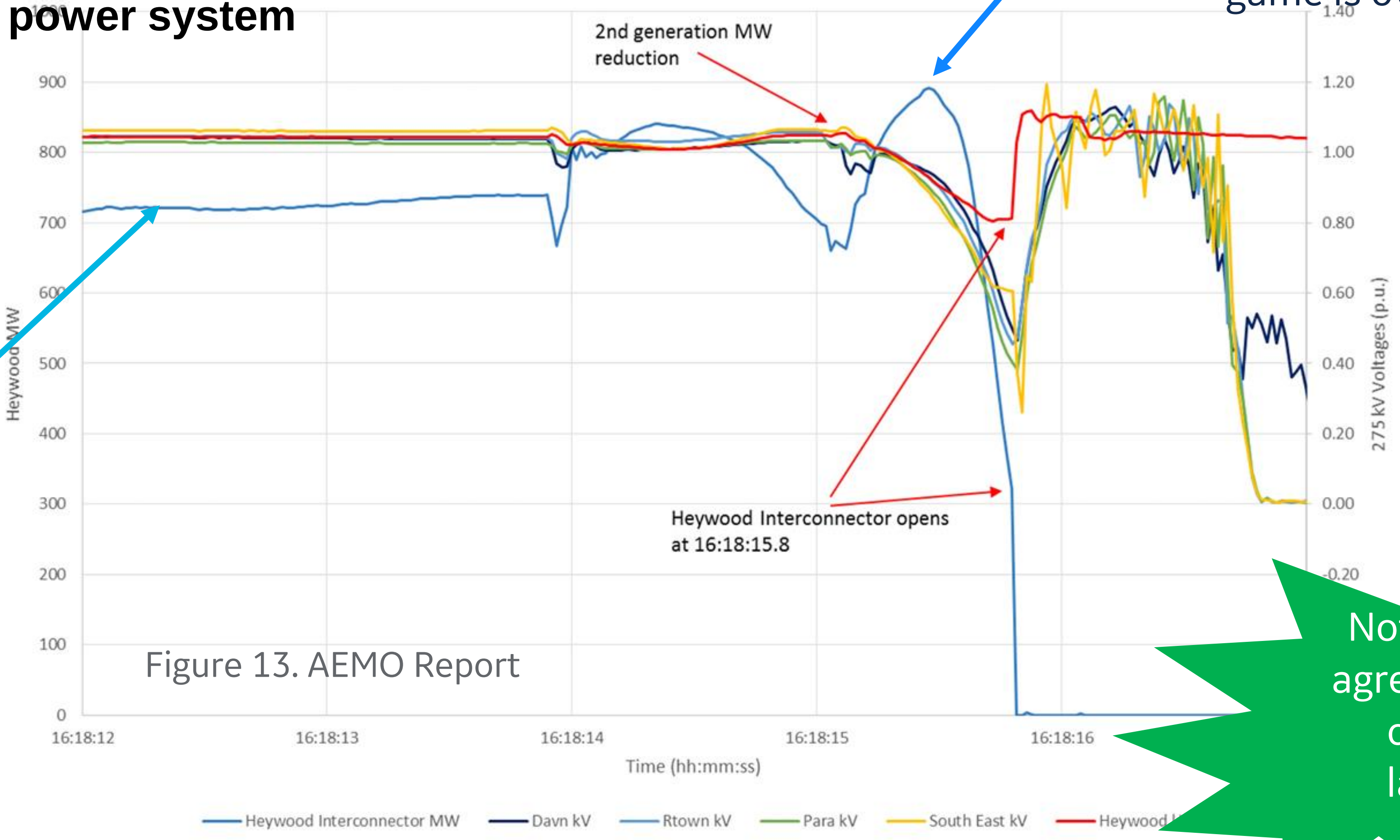


Figure 13. AEMO Report

Not everyone agrees with my choice of language

Classic Loss of Synchronism: Bus Angles Pull Apart

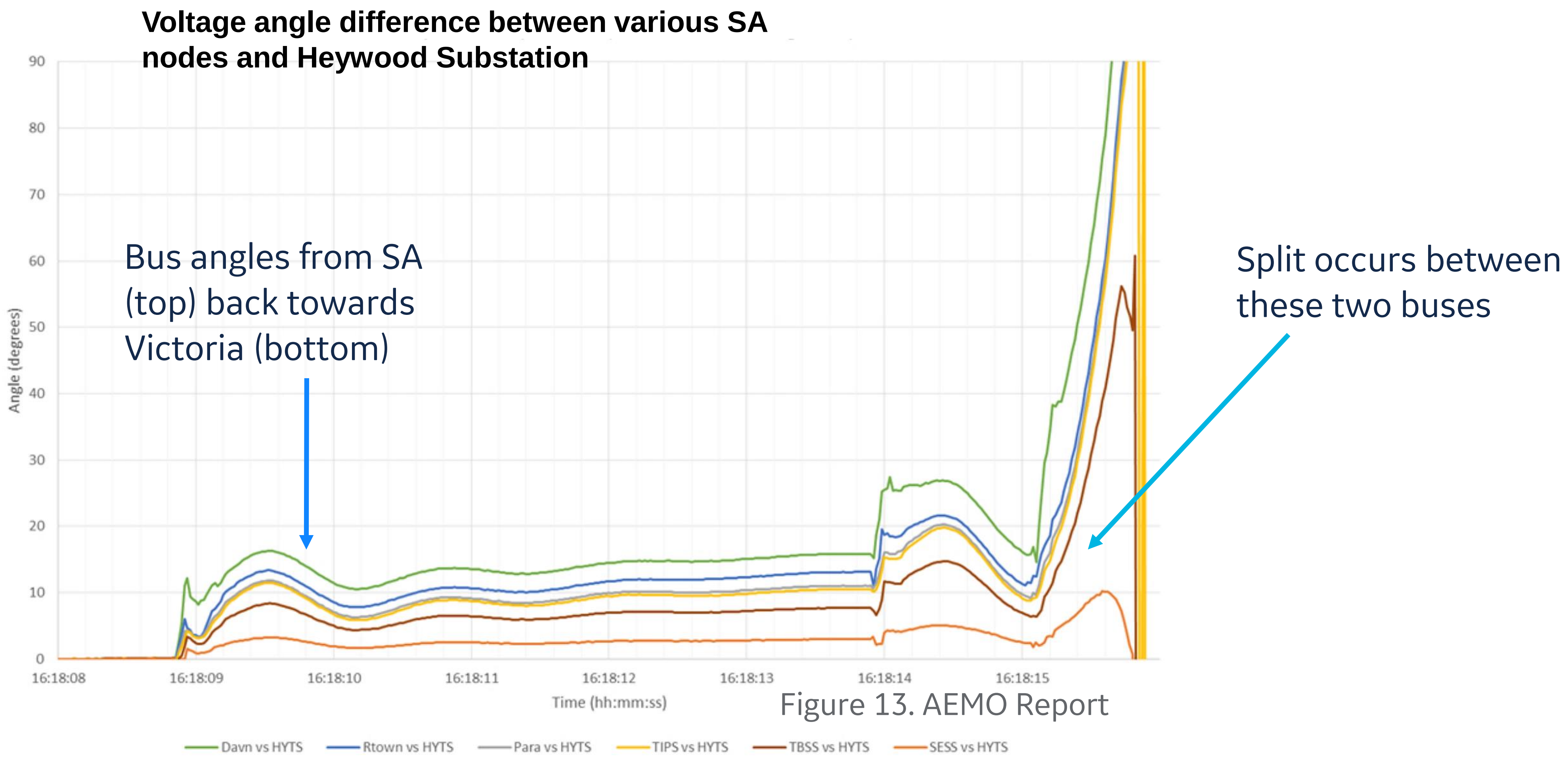


Figure 13. AEMO Report

This was not really a frequency event

Frequency and ROCOF in various SA nodes immediately before the system separation

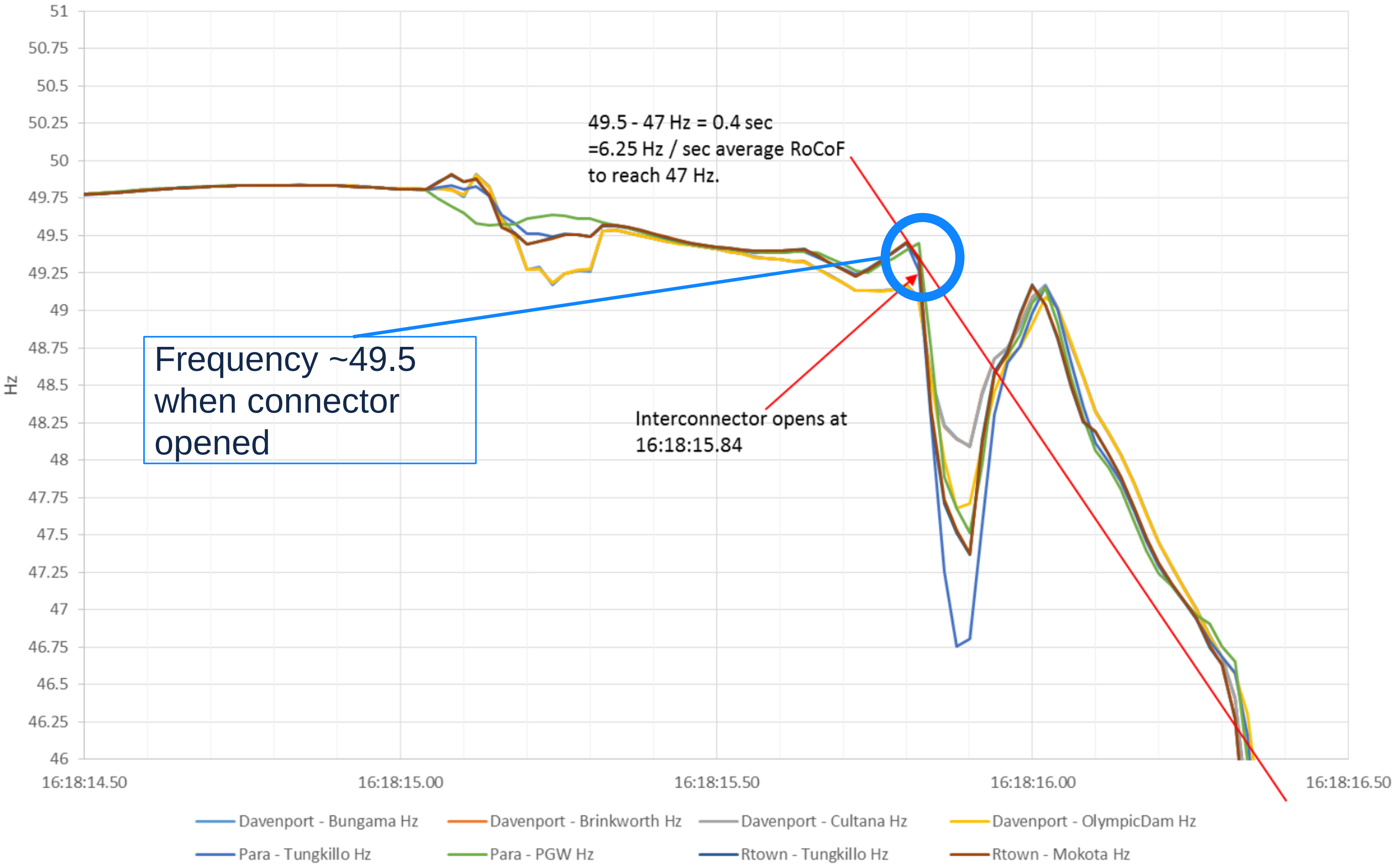


Figure 6. AEMO Report

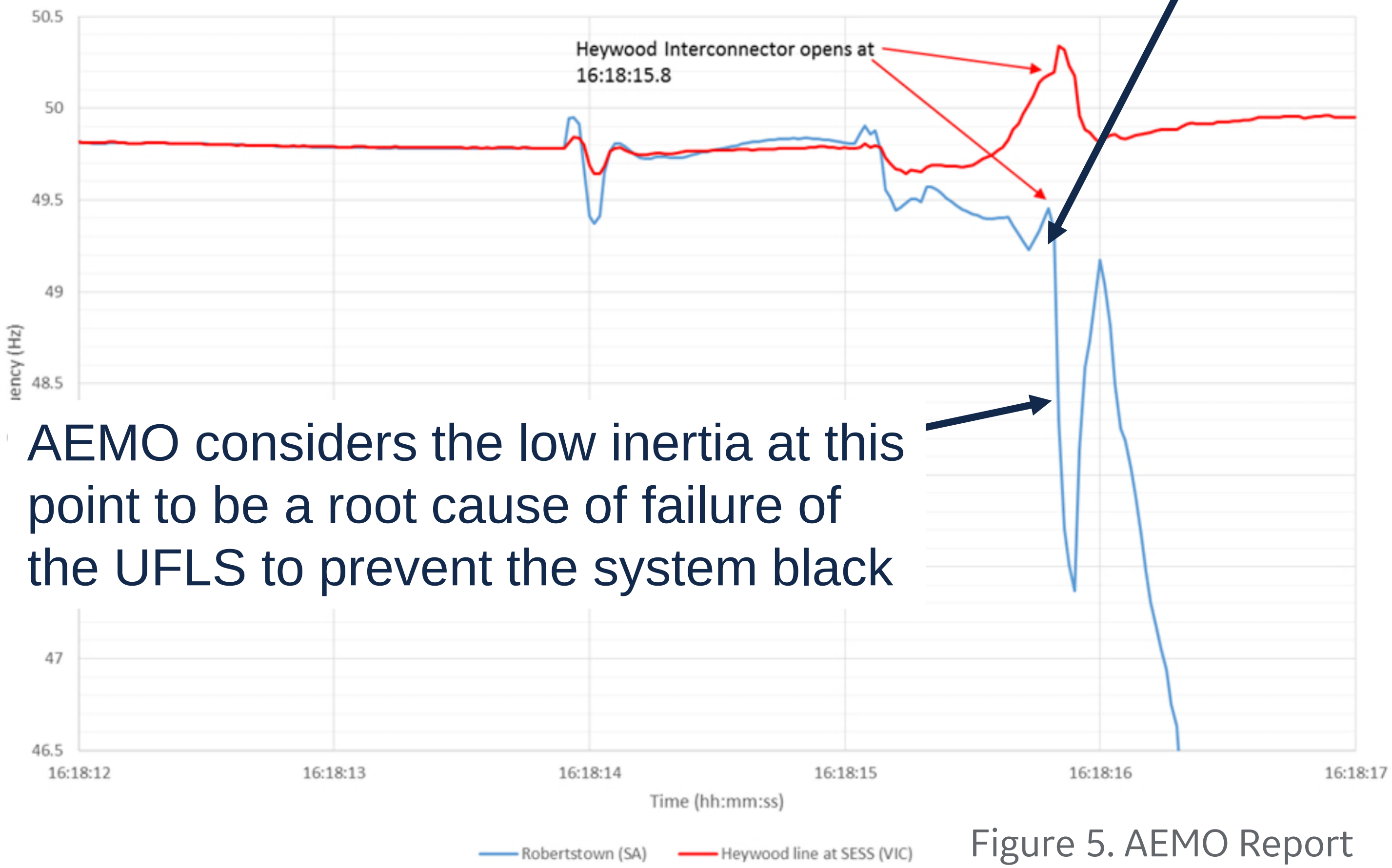
Frequency and Separation

The 1st line of defense was UFLS

- Nowhere NEAR fast enough to save the system

RoCoF after separation is astronomical: >6 Hz/sec

SA frequency compared to Victoria during event



AEMO considers the low inertia at this point to be a root cause of failure of the UFLS to prevent the system black

Figure 5. AEMO Report

Voltages during the System Separation

275 kV voltage decline across SA prior to separation

Nick's comment:

Could multiple large dynamic reactive devices have saved this system?

Maybe...

Dynamic overvoltages on separation are already scary; would have to be very careful to not create a new, more severe DOV risk.

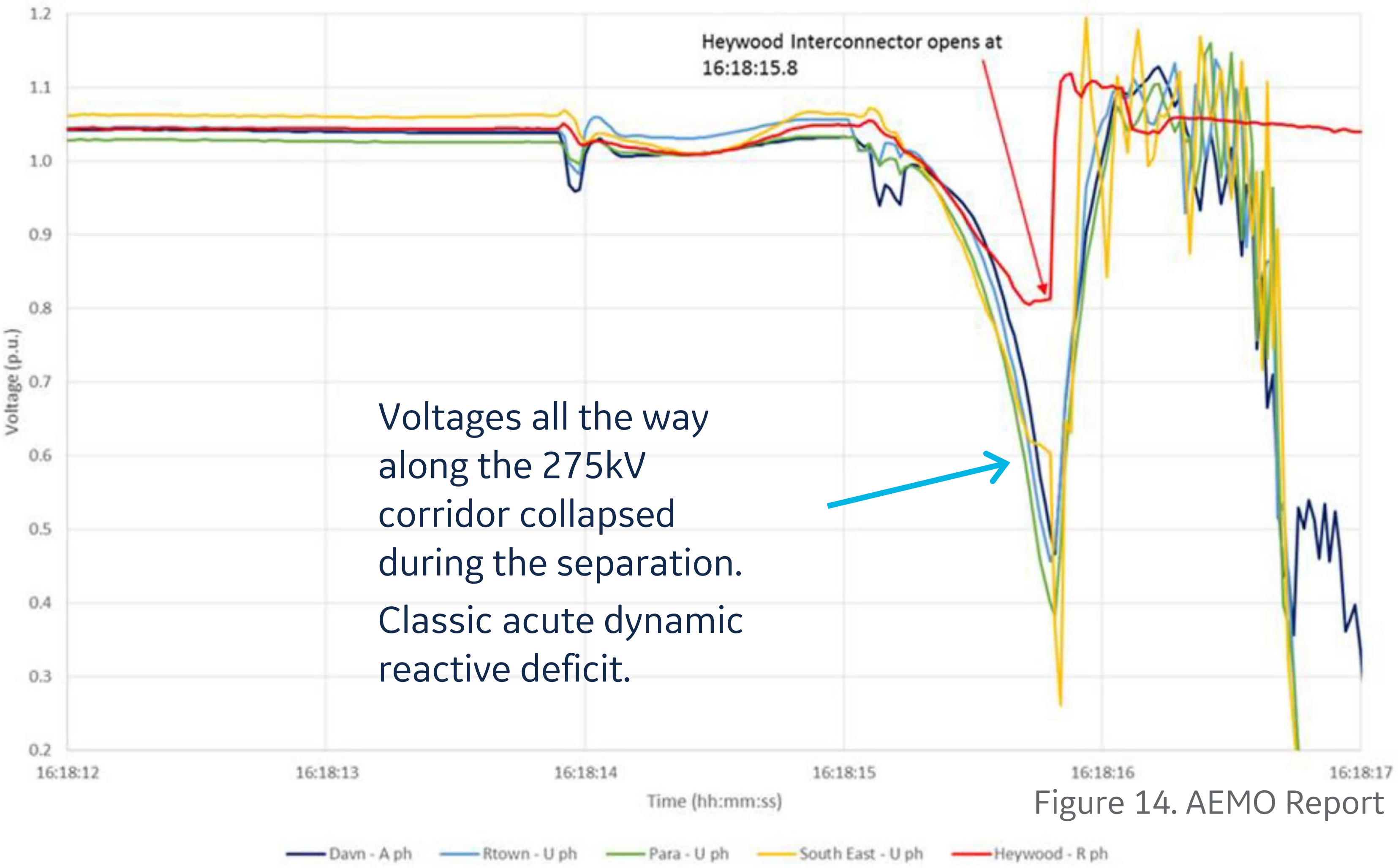


Figure 14. AEMO Report

Grid Code: AEMO sends a shot across the bow of the industry


RECOMMENDED TECHNICAL STANDARDS FOR GENERATOR LICENSING IN SOUTH AUSTRALIA

ADVICE TO ESCOSA

Published: **31 March 2017**

AEMO


ELECTRICITY RULE CHANGE PROPOSAL

GENERATOR TECHNICAL REQUIREMENTS

August 2017

AEMO

AUSTRALIAN ENERGY MARKET OPERATOR

https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Reports/AEMO-GTR-RCP-110817.pdf

AEMO has recommended that the grid code be amended to require fault ride-thru for multiple events, to be applied to all types of generation.

Some details (quotes):

- "Conditions should apply to all generation types, not just wind." page 3.
- "... a requirement for generating systems to remain in continuous operation for number of repeated faults..." page 7
- "... all types of generating systems need to be resilient to repetitive disturbances." Section 3.1 page 24.
- " ...prescribe performance of generating systems during contingency (faults) events, in the recovery period following clearance of faults, in the event of multiple contingency events occurring, for voltage disturbance (under and over voltage) events." Section 3.3.1 Page 27 ... leading up to:

Note: These are direct quotes from the AEMO March document. Final document is similiar

The pièce de résistance:

Multiple low-voltage disturbance ride-through

The generating system –including each of its generating units, dynamic reactive power support plant and battery storage units– must be capable of withstanding any combination of voltage disturbances resulting in the voltage at the respective LV terminals of the equipment to drop below 85% of the nominal for a total duration of 1,800 ms within a 5-minute interval, regardless of the disturbance type, duration and residual voltage at the generating unit's terminals.

Note that this requirement applies in addition to the S5.2.5.4 requirements with respect to long-duration, shallow-voltage disturbances.

Examples of conditions where successful fault ride-through response is required include:

- 15 faults, each cleared within 120 ms.
- 18 faults, each cleared within 100 ms
- 5 faults each cleared within 220 ms
- 7 faults, each cleared within 100 ms

What about Torsional Effects?

From AEMO:

"… real evidence exists where Adelaide metropolitan synchronous generators successfully rode through three severe faults each resulting in a voltage drop by more than 90% in a total period of less than 2 seconds."

From IEEE Guide for AC Generator Protection Std. C37.102-2006:

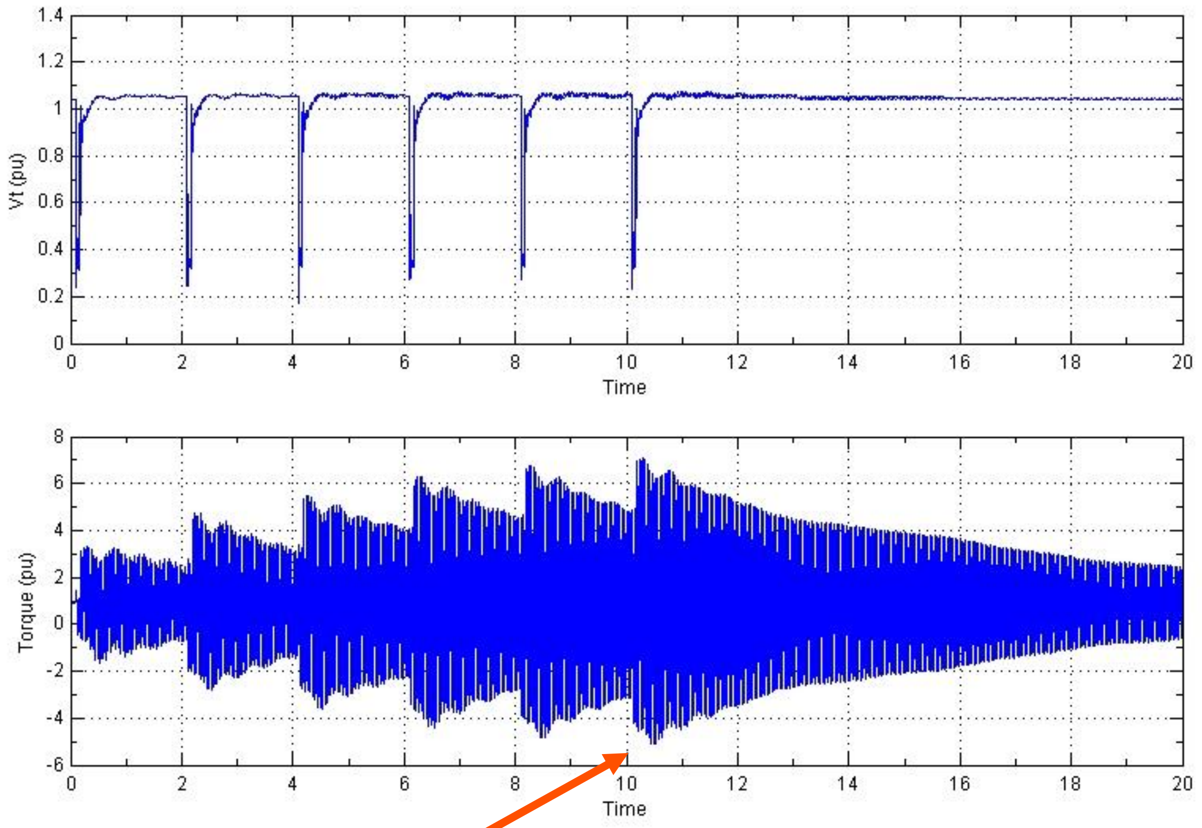
"..switching operations involving the opening or closing of circuit breakers at or near a generating station may produce transient power and current oscillations that may stress or damage turbine generators.."

Torsional thought exercise

What do many consecutive faults look like to a synchronous turbine-generator rotor?

Steam Turbine Subject to Six 4-cycle Faults (Simulation)

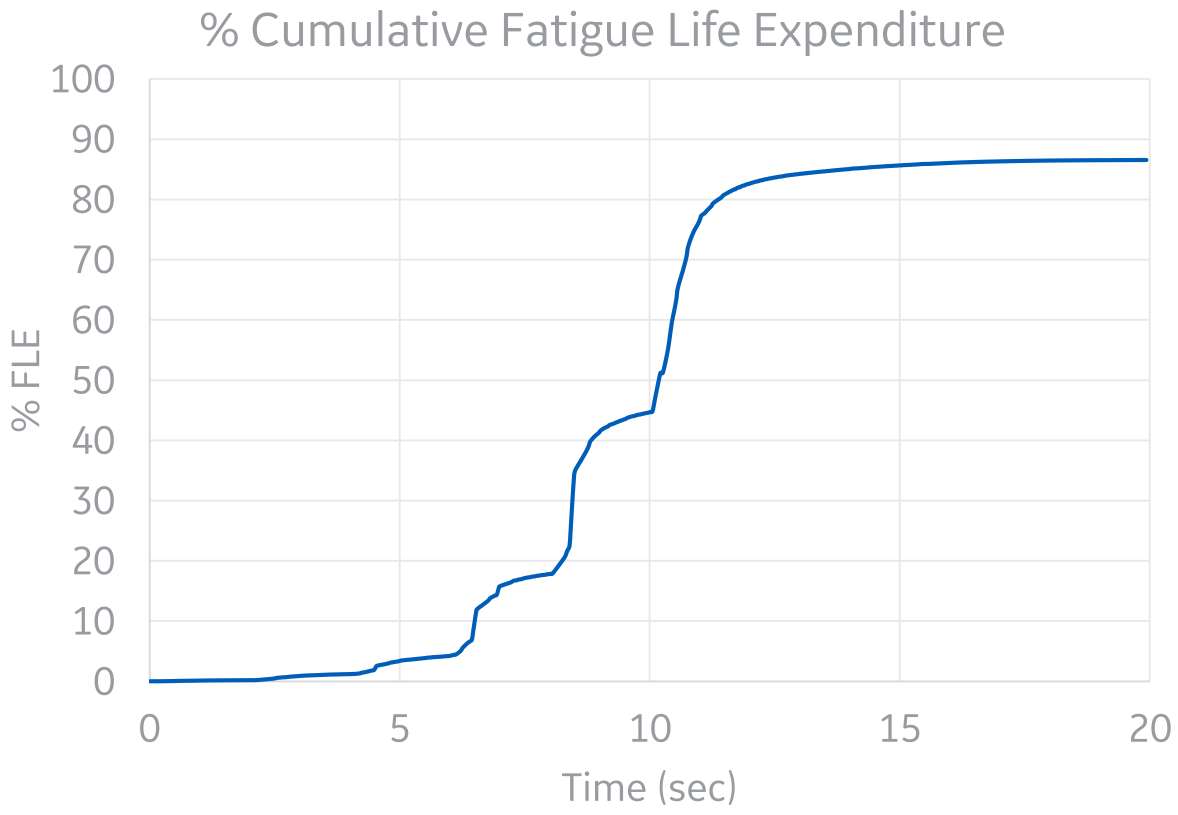
- Upper plot shows terminal voltage, lower plot shows shaft torque for one section of a large steam turbine generator
- 3-φ, 4-cycle fault near plant, applied every two seconds
- No stability or voltage recovery issues
- Each fault stimulates torsional oscillations and twisting on turbine-generator shaft
- Low damping, decay is over several seconds. At 2 seconds, very little decay
- Each successive fault causes higher shaft torque
- Fatigue Life Expediter (FLE) for a single 3- φ is <1%
- Cumulative FLE for this event is >30%.



Approaching failure (100% loss of life) for 6 events.
We *guess* 7 events would have failed the shaft.
New AEMO standard is for 15 events.

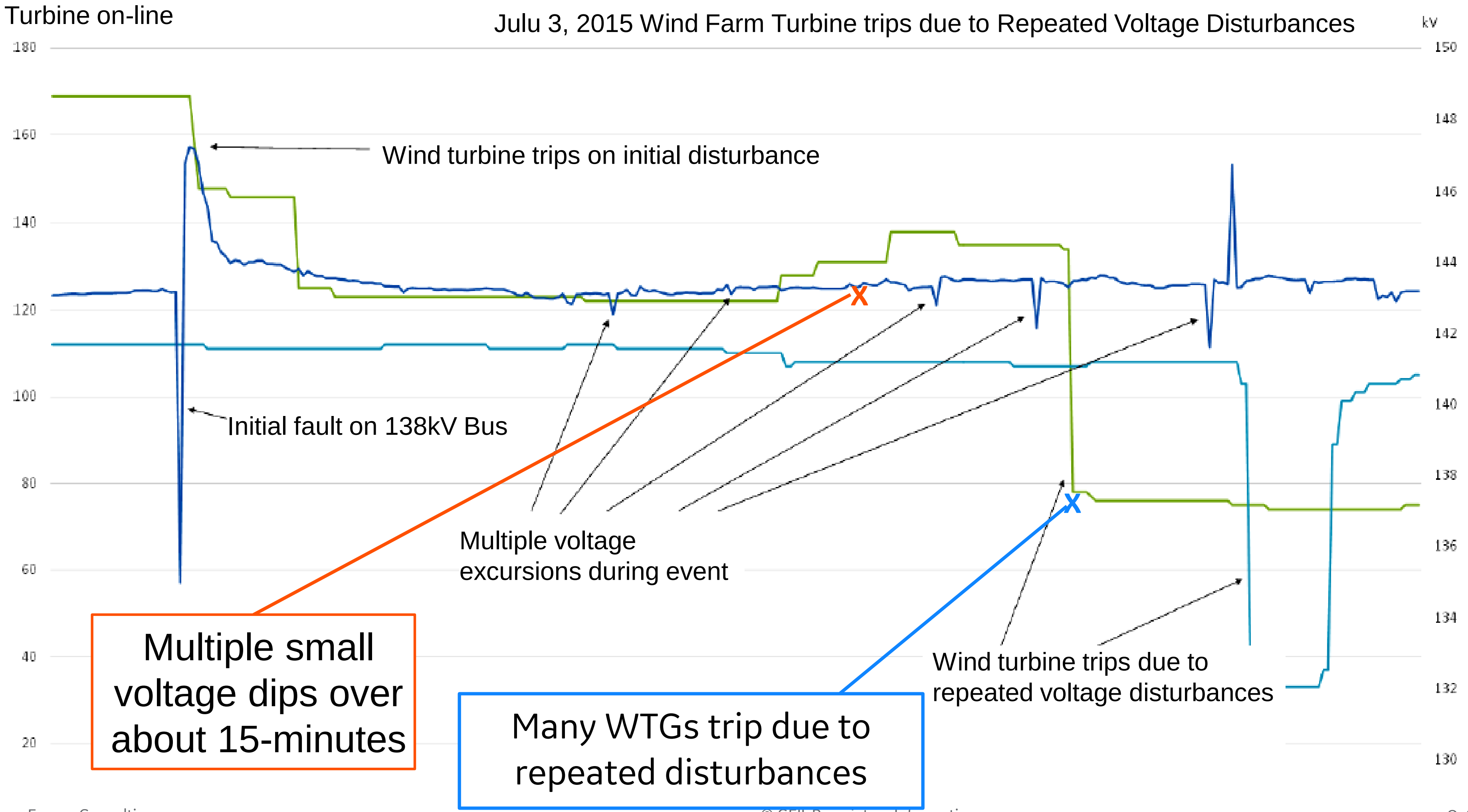
Steam Turbine loos-of-life after Six 4-cycle Faults (Simulation)

- Most grid equipment designed for2 close-in faults.
- E.g., series capacitor MOV protection handles 2 worst-case external faults.
- Here, the first 2 faults cause very little FLE.
- 3rd fault (at 4 seconds) results in about 5% FLE. high, but not catastrophic.
- Events 5 and 6 would require the unit to be taken out of service and inspected for shaft damage. Major outage, expensive, oos for extended period.
- If damage, forced outage will be many many months and many $MM.
- If a thermal units is forced to ride through 15 consecutive close-in faults, vendors will be forced to over-design shafts and existing units would have to be exempt .



Before you get too excited…

Here's an example (from the US, NOT Australia), taken from the new NERC Lessons Learned* document



*Lessons Learned: Loss of Wind Turbines due to Transient Voltage disturbances on the Bulk Power System". NERC 2017

What’s really going on here?

Purely editorial comments from Nick

1. The synchronous generation community has never protected against multiple, sequential, violent disturbances.
2. Practice and standards, (e.g., IEEE C37-102-2006), are designed to avoid actively *creating* them (by, for example, avoiding unsafe reclosing practice).
3. The risk of synchronous generators failing is (a) real, but (b) extremely remote.
4. Protection is possible, but very rarely applied and relatively expensive*
5. Philosophy is “ride through until you are so damaged that your equipment fails and trips”. Even if loss of life occurs, no one looks for it.

The power industry has averted its gaze from this remote risk for decades… apparently a perfectly reasonable strategy.

What's really going on here? – part II

Purely editorial comments from Nick

1. The wind (and solar) industry has kicked the hornets nest by including protection against multiple events.
2. They have exacerbated the problem by, in some cases, making the protection (a) *way too sensitive* and (b) *arbitrary*, rather than based on actual equipment risks.
3. The utility community has responded, in some cases, by creating new standards of disturbance tolerance that
   a) are arguably impossible to meet (as written) by synchronous generation, and
   b) radically alter the risk/responsibility equation for manufacturers and equipment owners.

Philosophial discussion points

- Is all planning criteria now changed from N-1 to N-∞ ?
- Do generator stator end-windings, arresters, transformers, bus bars, power plant auxiliaries, relays, line traps, series compensation MOVs … have to tolerate 15 consecutive, violent faults in rapid succession?
- What is the burden of proof? Of "compliance"?
- Has the risk just shifted from the grid to the OEMs?
- Will all power plants have to be tested?   (synchronous plants aren't even tested for single FRT capability…. Just wind and solar)
- Is maintaining synchronism required?

A path forward?

More opinions from Nick

- Grid operators have a legitimate concern regarding inverter-based generation (and other resources) disconnecting or misbehaving for multiple events.
- Presumably, the intent of the new standards is not to outlaw existing synchronous generation, or to add undue cost burden to a wide range of power equipment.
- A standard is needed that balances the two, requiring:
    - Equipment to stay operating for multiple "reasonable" disturbances, and
    - Allowing equipment risk-based protection for all generating resources.

There's still work to be done.

IEEE (new) 1547

P1547/D6.7.2, May 2017
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

The requirements for continued operation (Ride-Through), or Restore Output shall apply to multiple consecutive voltage disturbances within a Ride-Through Operating Region, for which the voltage range and corresponding cumulative durations are specified in Table 14 for Category I, Table 15 for Category II, and Table 16 for Category III. These requirements are subject to the following:

Exception: DER shall be allowed to trip if the timing of multiple consecutive voltage disturbances during a specific event stimulate electromechanical oscillations to the degree where DER synchronism is lost or potential damage to the DER is caused.

New 1547 provides some qualification, particularly w.r.t. torsional vibrations:
Is it enough?

Restoration & Blackstart

A separate, but important note

- System restoration of South Australia had a number of hiccups.
- Of particular note (and frustration to all involved):

  A number of power plants, who were paid for the ancillary service of providing blackstart support, failed to start.

  Not good.

- Security of starting, including for duel/multi-fuel thermal units has always been important, but is now more critical than ever.
- This will get closer scrutiny world-wide.

This is could get very interesting

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Thank You !

GE