THE UNIVERSITY OF QUEENSLAND
AUSTRALIA
CREATE CHANGE

Chapter 1: Basic Concepts, Classification and Definitions

by

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ELEC7310: Electricity Market Operations and Security

Introduction

- Power Systems
- Reliability, Security and Adequacy
- Power System Security
- Power System Stability
- Classification and Definition
- Major Incidents




Power Systems

- The first complete power system was built in 1882 by Thomas Edison in New York city USA.
- Since then, the power system has been evolving towards more reliable and recently more economically efficient complex system i.e. the electricity market in many countries.
- Although economic incentives are the main driving forces in modern power system development under a market environment, however, power system security or stability is still the very essential key factor of the over all system.
- Without stability a power system may experience various problems, including system wide blackout, or regional brown out or lost of supply at distribution levels.

Power Systems

- Before one can do stability analysis, it is again essential to have the Fundamentals knowledge of power system analysis.

- A power system is a network of conductors and devices which allows electrical energy to be transferred from the generating power stations to load centers through transmission network.

- It is composed of generation, transmission and distribution systems

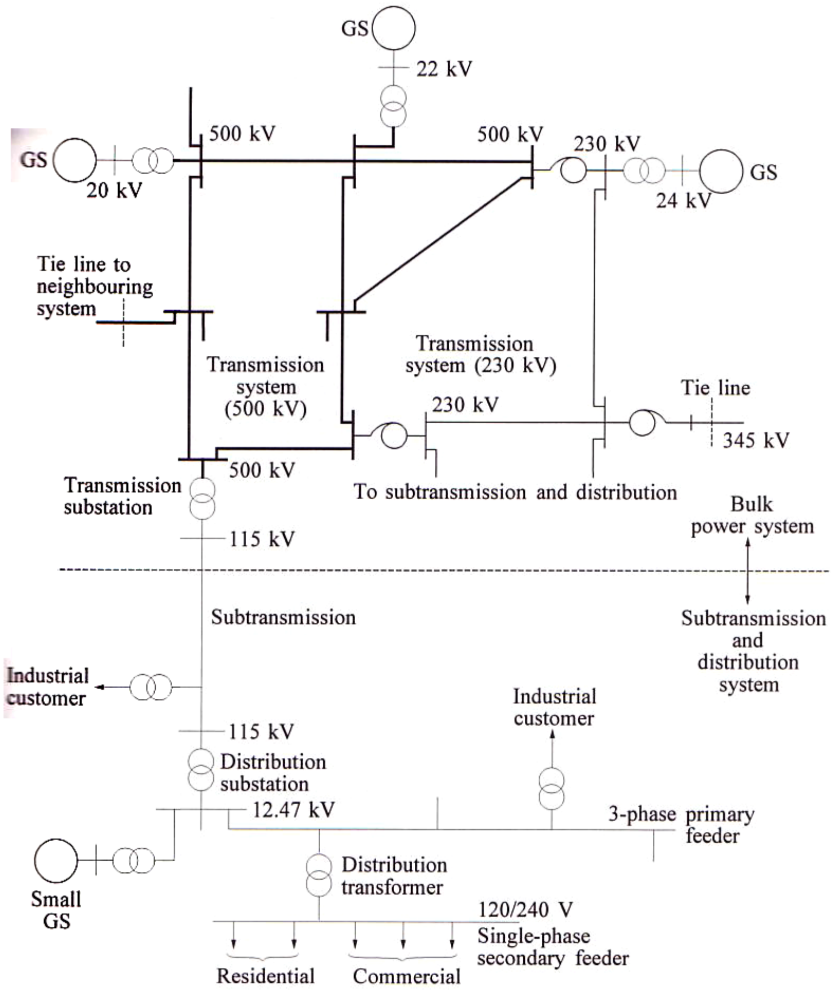


Power Systems

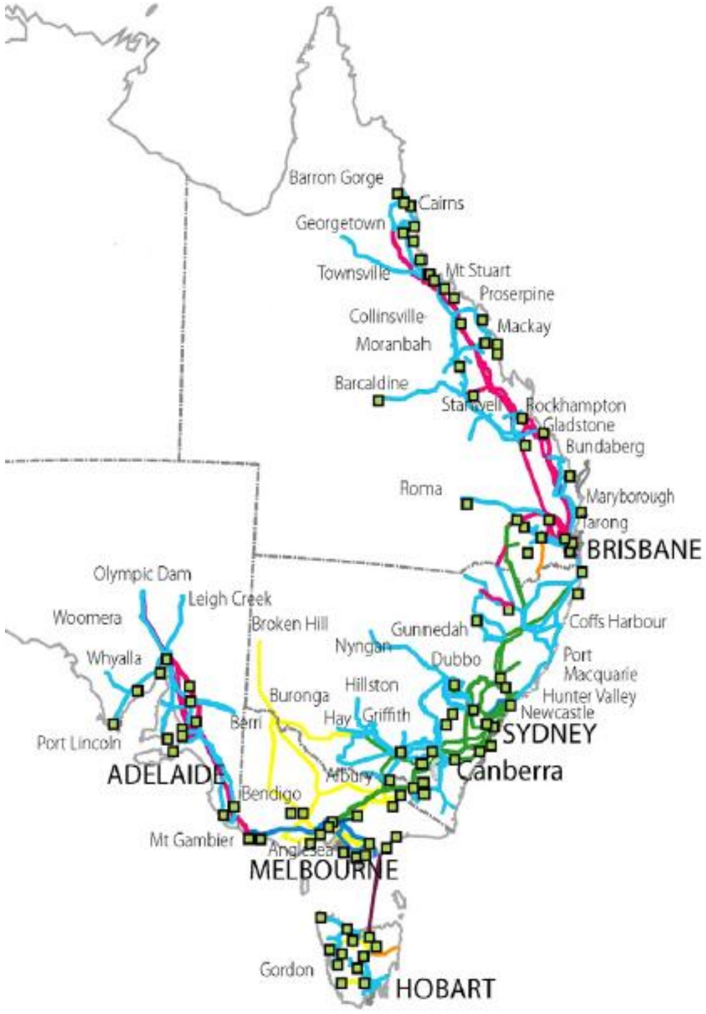
The transmission network can be further classified into,

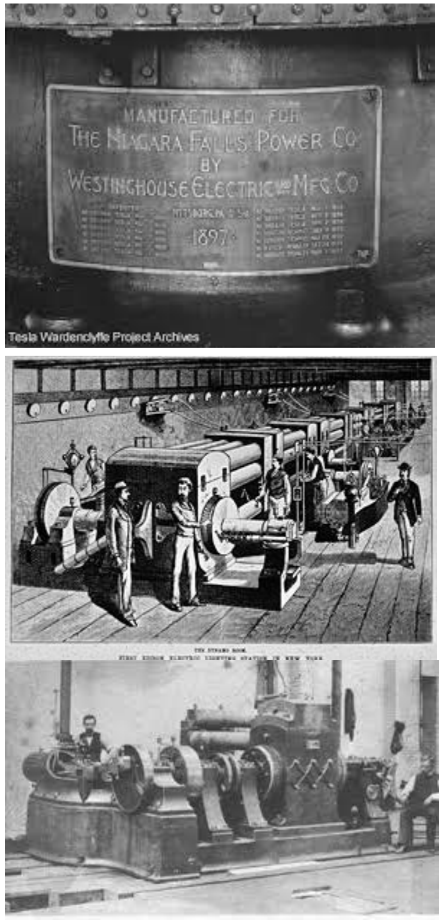
- **Transmission system**, which connects all major generators and main load centers in the system; it is the backbone of the overall power system with 230kV or above voltage level;
- **Sub-transmission system**, which transmits power from transmission substations to the distribution substations. Large customers are often connected at the sub transmission level. The voltage level is normally between 69kV – 138kV.
- **Distribution system**, which transfers power to individual customers. The primary distribution voltage level is normally 4.0kV – 34.5kV. Residential and commercial loads are connected at the secondary distribution feeders at 120/240V voltage levels.
- The standard transmission and distribution voltages are 750, 400, 275, 132, 66, 33, 11, 6.6 and 3.3kV.

Power Systems



Eastern Australian Power Grid





Power Systems

- Given the function of convert energy from other forms into electricity, transfer to the consumers, a power system should meet the following basic conditions.

- It must meet the changing load demand instantaneously with all variations.

- Energy should be supplied with minimal cost (economical, ecological etc.)

- The quality of power supply must be maintained to meet certain standards w.r.t.
  - frequency, voltage and reliability

Reliability, Security and Adequacy

- **Reliability** is the ability of the power system to provide an adequate supply of electrical energy.
  - Reliability has a very wide range of meaning; it is the overall system ability to perform its function.
  - A subdivision of reliability includes security and adequacy.

- **Security** relates to the ability of the system to respond to disturbances in the system

- **Adequacy** relates to the existence of sufficient facilities in the system to satisfy the consumer load demand. It’s related to static conditions.
- Most probabilistic techniques for power system reliability evaluation are in adequacy assessment.

Power System Security

- Security of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruptions to customer services.

- It relates to robustness of power system to imminent disturbances, hence, depends on
  - System operating conditions
  - Probability of disturbance

Power System Security

- is a measure of the general health of the system, including its capability to withstand the disconnection of a major system element and remain within defined technical limits in areas such as voltage, frequency, current flow etc. [NEMMCO]

- Power system security is very much related to system stability and dynamics.


Power System Stability

- Stability is important for secure system operation. This is also proven by many system blackouts which had been identified as results of power system instability of different kinds, such as transient, steady state or voltage instability.

- Strict definition of stability of a dynamic system, such as power system, can be found in many math and control literatures, e.g., Lyapunov stability theory. Some power system stability definition provides physically motivated definition which conforms to precise mathematical definition.

- A power system is said to be stable if it has the property that it retains a state of equilibrium under normal operating conditions and regains an acceptable state of equilibrium after being subjected to a disturbance.

Power System Stability

- Over the past decades, the power system around the world has been experiencing many significant changes leading to greater interconnection and integration of renewable power generation.

- This is particularly true in countries undergoing deregulation leading to interconnected electricity markets.

- For example, there are more interconnections planned to link the eastern states of Australia into the NEM, with a DC link already in operative connecting TAS and VIC.

Power System Stability

Before the increasing interconnection, power systems have more often experiencing transient instability problems.

Nowadays, more system instabilities have attracting attentions from the industry, these include voltage stability, frequency stability and inter-area oscillations, especially following several system wide cascading failures leading to blackout.

IEEE identifies the needs for new system stability definition to account for such emerging trends of interconnection.

Accordingly, considering the <u>interconnection</u> trends of today’s power system, power system stability is defined as,

Power System Stability

“ Power system stability is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact”

Power System Stability

"It refers to both static and dynamic concepts, and the stability issue generally includes system, angle and voltage stability respectively.

The proposals on stability were made as follows:

- Steady state stability refers to stability of a power system in steady state, except for the influence of small disturbances which may be slow or random;

Power System Stability

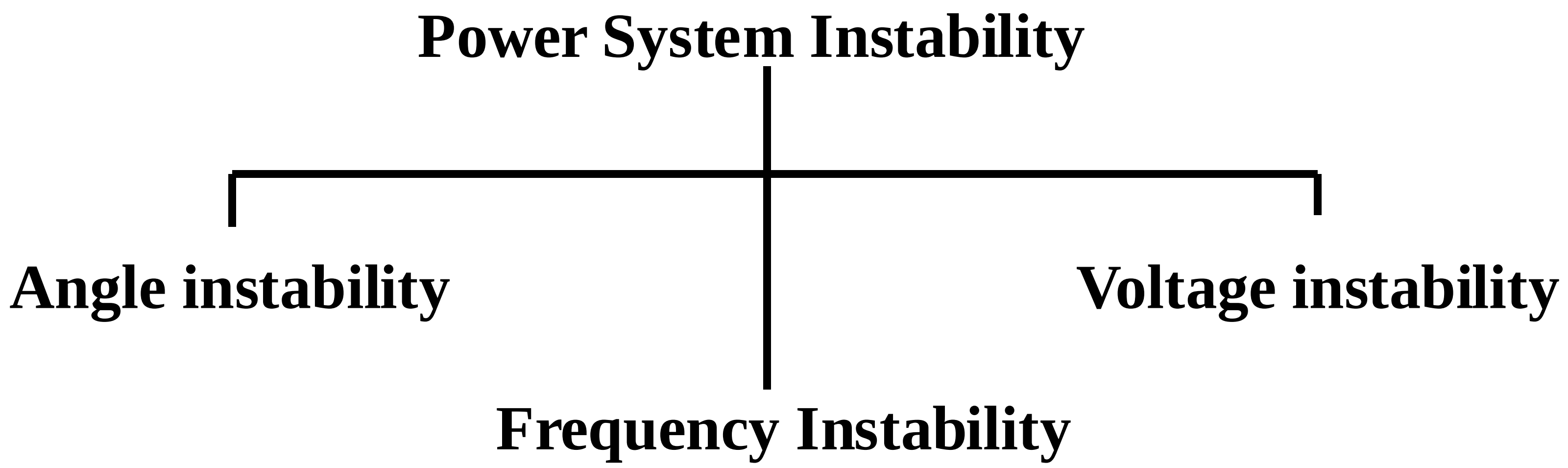
- More attention should be paid to broader concepts of system stability than specific definitions for angle and voltage stability.

- Also, in many respects, angle stability and voltage stability are used more as a time-scale decoupling than a variable decoupling.

- In situations where no obvious angle/voltage decoupling is involved, it would be more appropriate to talk of system stability in terms of short term or long-term behavior.

Classification and Definition

- A traditional classification



Classification and Definition

- Angle stability occurs due to torque imbalance of generators.

- There are two types torques considered in generators.
  - Synchronizing torque
  - Damping torque

- Angle stability can be classified into two:
  - Transient Stability
  - Small Signal Stability

Classification and Definition

- Small signal stability can be further classified into two:
  - Oscillatory instability
  - Non-oscillatory instability

Classification and Definition

- Voltage instability occurs due to reactive power imbalance
  - Due to small disturbance
  - Due to large disturbance

- The later voltage instability problem occurs due to large disturbance, switching events, dynamics of ULTC (under load tap changers) and coordination of protection and control.

- The former occurs mostly due to the steady-state P/Q –V relations and stability margins.

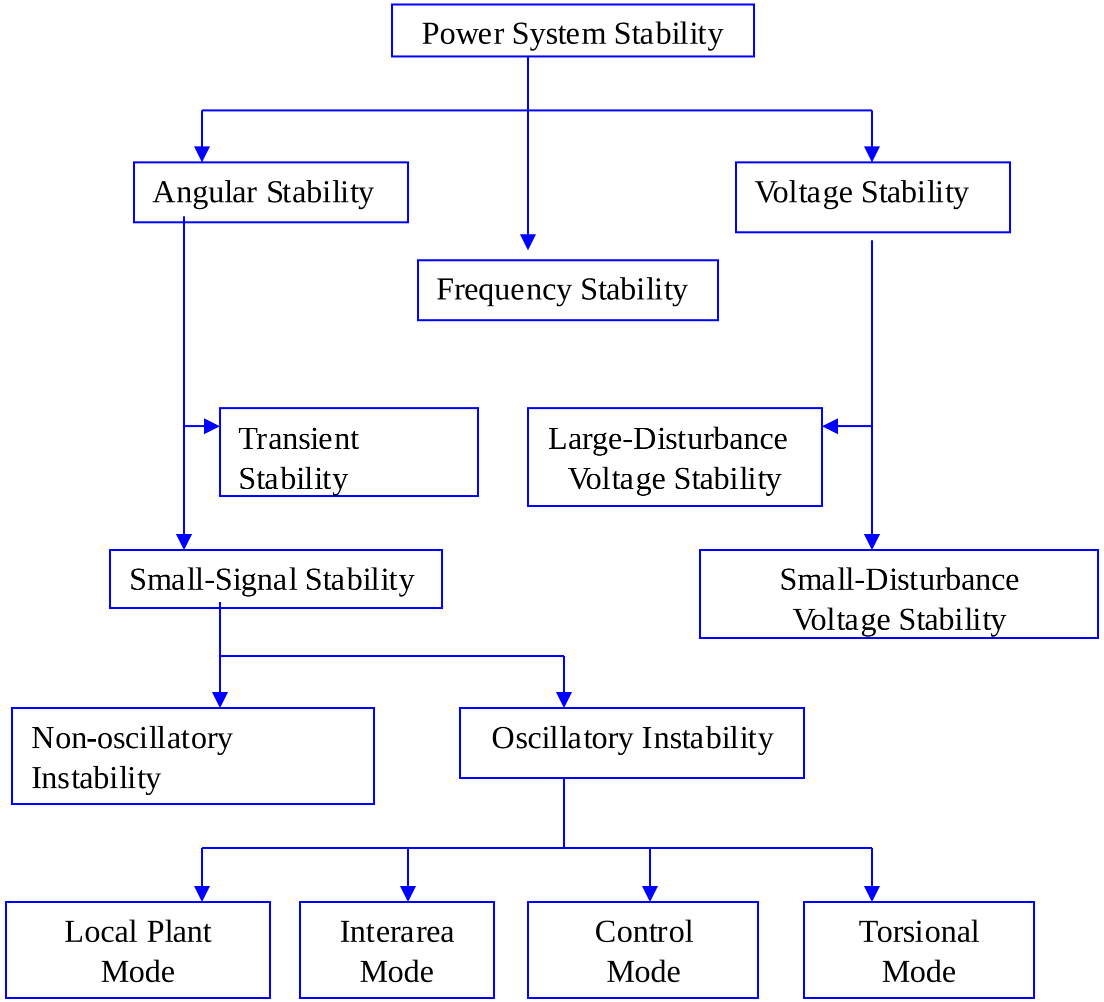
Classification and Definition

- The frequency instability problems are relatively new in the literature of power system stability due to grid integration of renewable energy generation.

- These problems are associated with the dynamic response of power systems to severe upsets or disturbances.

- The severe upsets result in large excursions of voltage, frequency, and power flows that thereby invoke the actions of slow processes, controls, and protections.

Classification



Angular Stability

- Angle stability is defined as the ability of the power system remain synchronism when subjected to a disturbance.
- It is mainly concerned with maintaining real power requirement in the system.
- The stability involves study of electromechanical oscillations inherent in power systems.

- Angle instability can be further divided into two

  - Transient stability (first swing stability)
  - Small signal stability

Transient Stability

- Transient stability refers to the large disturbances in the system.
- *can be defined as the ability of the system and its generating units to remain in synchronism following a large (severe) and sudden disturbance.*

- Examples of large disturbance

  - Faults in the transmission systems
  - Sudden change of bulk load
  - Loss of operating units,
  - Line switching

Transient Stability

- The post operating equilibrium point is different from the pre disturbance equilibrium point in case of such disturbances.

- Power transfer capabilities may be different
  - During the fault
  - After the fault compared to Before the fault

- Since the sever disturbances involve large deviation in rotor angles, non-linear dynamical model of the system is considered for the transient stability studies.

Small Signal Stability

- Small signal stability refers to ability of the system to maintain synchronism under small and sudden disturbances.

- Small disturbances occur continuously in the system due to small variation in loads and generations.

  - Oscillatory (due to insufficient damping torque)
  - Non-oscillatory (due to insufficient synchronous torque)

Small Signal Stability

- Small signal stability depends on several factors
  - Initial operating point
  - Generator excitation
  - Transmission system strength
  - Other controls in the system

- The oscillatory type of small signal instability can be further divided into:
  - Local modes
  - Inter-area modes
  - Control modes
  - Torsional modes

Voltage Stability

Voltage stability also called as “Loadability”

“Refers to the ability of the system to maintain load bus voltages within acceptable limit, following some disturbance or change in power demand”

IEEE definitions

VOLTAGE STABILITY

- *IS THE ABILITY OF A SYSTEM TO MAINTAIN VOLTAGE SO THAT WHEN LOAD ADMITTANCE WILL INCREASE BOTH VOLTAGE AND POWER ARE CONTROLLABLE*

Voltage Stability

VOLTAGE COLLAPSE

IS THE PROCESS IN WHICH INSTABILITY LEADS TO VERY LOW VOLTAGE PROFILE IN A SIGNIFICANT PART OF THE SYSTEM

VOLTAGE SECURITY

IS THE ABILITY OF A SYSTEM NOT ONLY TO OPERATE STABLY, BUT ALSO TO REMAIN STABLE (AS FAR AS THE MAINTENANCE OF SYSTEM VOLTAGE IS CONCERNED) FOLLOWING ANY REASONABLE CREDIBLE CONTINGENCY OR ADVERSE SYSTEM CHANGE

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Voltage Stability

CIGRE definitions

VOLTAGE STABILITY

A POWER SYSTEM, AT A GIVEN OPERATING STATE AND SUBJECT TO A GIVEN DISTURBANCE, IS VOLTAGE STABLE IF VOLTAGES NEAR LOADS APPROACH POST-DISTURBANCE EQUILIBRIUM VALUES. THE DISTURBED STATE IS WITHIN THE REGION OF ATTRACTION OF STABLE POST-DISTURBANCE EQUILIBRIUM

Voltage Stability

VOLTAGE INSTABILITY

VOLTAGE INSTABILITY IS THE ABSENCE OF VOLTAGE STABILITY, AND RESULTS IN PROGRESSIVE VOLTAGE DECREASE (OR INCREASE). DESTABILIZING CONTROLS REACHING LIMITS OR OTHER CONTROL ACTIONS (E.G. LOAD CONNECTION), HOWEVER, MAY ESTABLISH GLOBAL STABILITY.

Voltage Stability

Voltage instability has been observed in the stressed systems due to deficit of reactive power to support the voltages.

Factors affecting the voltage stability

- Reactive power transmission,
- Self recovering type of loads,
- Reverse action of transformer on load tap changer (OLTC),
- Certain controls, such as generator excitation control Reaching limit

Frequency Stability

- Ability to maintain a steady frequency within a nominal range, following a disturbance resulting in a significant imbalance between supply and demand

- In a small "island" system, frequency stability could be of concern for any disturbance causing a significant loss of demand or supply

- In a large interconnected system, frequency stability could be of concern only following a severe system upset resulting in the system splitting into one or more islands

- Depends on the ability to restore balance between supply and demand of island systems with minimum loss of demand and supply

Converter Stability

- CS could be broadly classified into fast and slow interactions:

- Cross coupling of converter interfaced generators (CIG) with electromechanical dynamics of rotating machines and the electromagnetic transients of the network, which may lead to unstable power system oscillations over a wide frequency range

- Fast Interactions: fast dynamics of the control of power electronic based systems with other fast dynamics of power systems and power electronic systems.

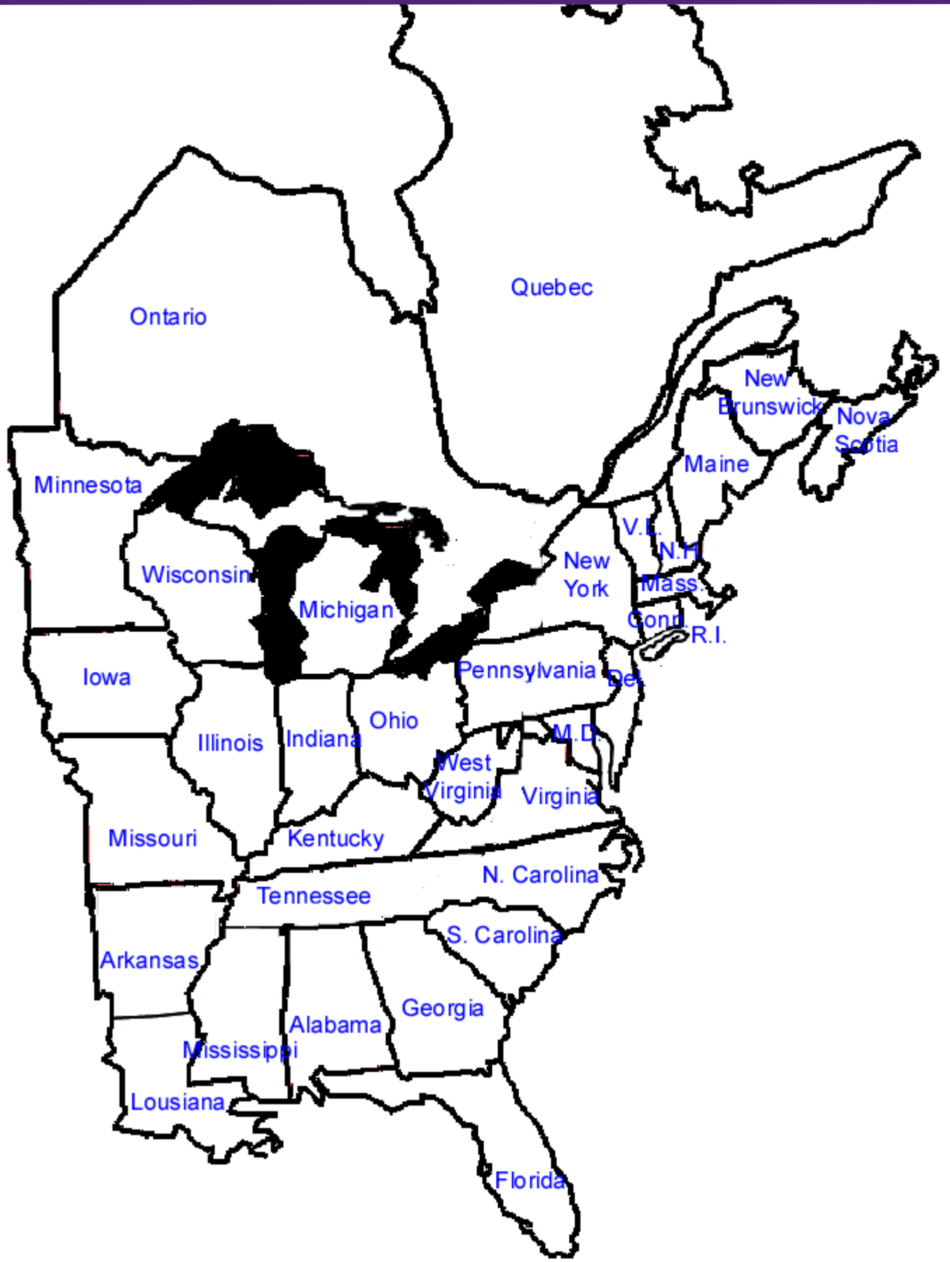
- Slow Interactions: slow dynamics of the control system of power electronic based devices with slow response elements of power systems.

List of Major Incidents-1

- **List of Major Incidents-1**

Northeast US and Canada on November 9, 1965

- Problem begun at 5:16 pm
- Normal load level in the region
- Within few minutes there was a complete shutdown
- Fully affected states: New York, Connecticut, Rhode Island, Massachusetts and Vermont were affected
- Partially affected states: New Hampshire, New Jersey and Pennsylvania and across the border most part of Ontario.



List of Major Incidents-1

- **List of Major Incidents-1**

Northeast US and Canada on November 9, 1965

- 30 million people were without light and power for over 13 hours
- President Johnson ordered to the chairman if Federal Power Commission to conduct an investigation.
- As one could imagine the blackout had a major impact on the industry.

List of Major Incidents-1

Events that caused the Northeast US and Canada on November 9, 1965 (from Praba Kundur)

The initial event was the operation of a backup relay (zone 3) at Beck GS in Ontario near Niagara Falls

- opened circuit Q29BD, one of five 230 kV circuits connecting Beck GS to load centers in Toronto and Hamilton

Prior to opening of Q29BD, the five circuits were carrying

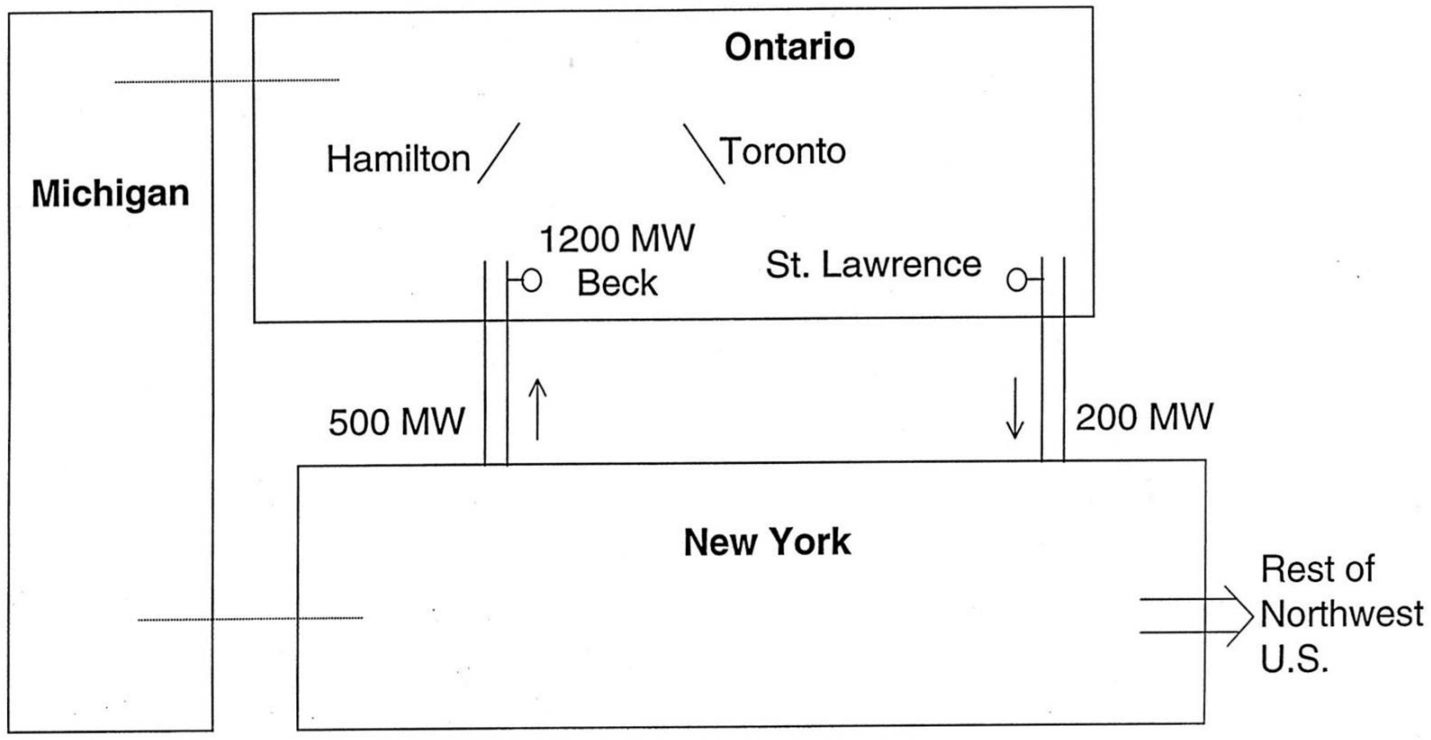
- 1200 MW of Beck generation, and
- 500 MW import from Western NY State on Niagara ties

Loading on Q29BD was 361 MW at 248 kV;

The relay setting corresponded to 375 MW

List of Major Incidents-1

Events that caused the Northeast US and Canada on November 9, 1965 (from Praba Kundur)



List of Major Incidents-1

Events that caused the Northeast US and Canada on November 9, 1965 (from Praba Kundur)

Opening of circuit Q29BD resulted in sequential tripping of the remaining four parallel circuits

Power flow reversed to New York: total change of 1700 MW

Generators in Western New York and Beck GS lost synchronism, followed by cascading outages:
Transient (Angle) Instability !

After about 7 seconds from the initial disturbance
system split into several separate islands

Eventually most generation and load lost due to the inability of islanded systems to stabilize:
Frequency Instability !

List of Incidents-2

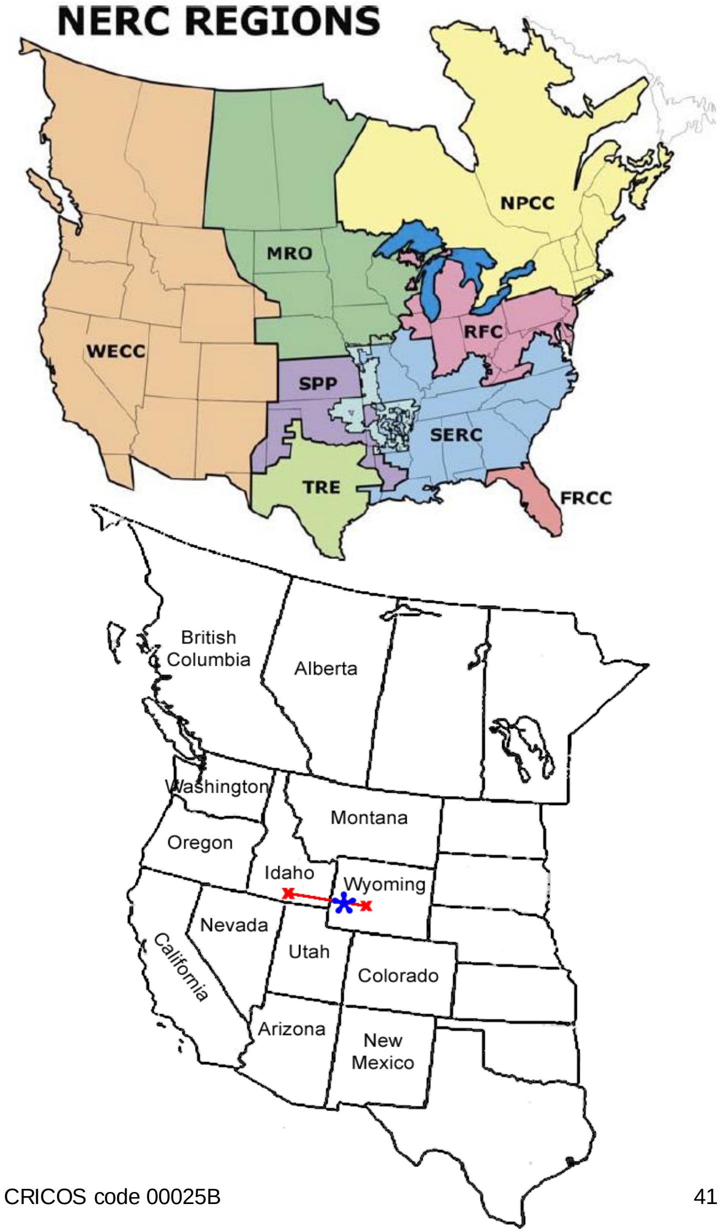
WSCC (WECC) Event on July 2, 1996 (from PK)

Started in Wyoming and Idaho area at 14:24:37

Loads were high in Southern Idaho and Utah;
High temperature around 38° C

Heavy power transfers from Pacific NW to California

- Pacific AC interties - 4300 MW (4800 rating)
- Pacific HVDC intertie - 2800 MW (3100 capacity)



List of Incidents-2

WSCC (WECC) Event on July 2, 1996 (from PK)

LG fault on 345 kV line from Jim Bridger 2000 MW plant in Wyoming to Idaho due to flashover to a tree

- tripping of parallel line due to relay mis-operation

Tripping of two (of four) Jim Bridger units as stability control; this should have stabilized the system

Faulty relay tripped 230 kV line in Eastern Oregon

<u>Voltage decay</u> in <u>southern Idaho</u> and slow decay in <u>central Oregon</u>

List of Incidents-2

WSCC (WECC) Event on July 2, 1996 (from PK)

About 24 seconds later, a long 230 kV line (Amps line) from western Montana to Southern Idaho tripped

- zone 3 relay operation
- parallel 161 kV line subsequently tripped

Rapid voltage decay in Idaho and Oregon

Three seconds later, four 230 kV lines from Hells Canyon to Boise tripped

Two seconds later, Pacific intertie lines separated

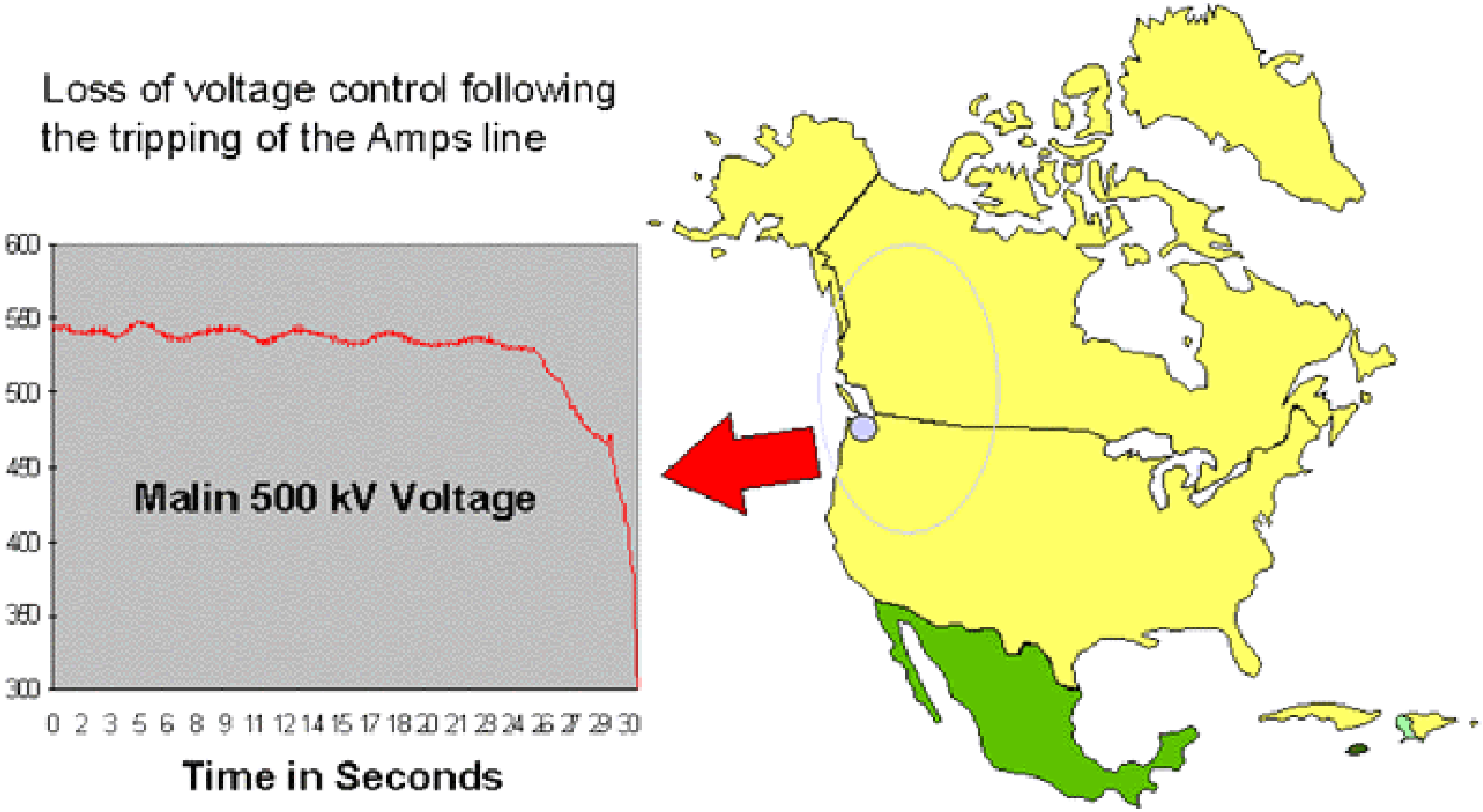
Cascading to five islands 35 seconds after initial fault

2.2 million customers experienced outages; **total load lost 11,900 MW**

It was a case of Voltage Instability

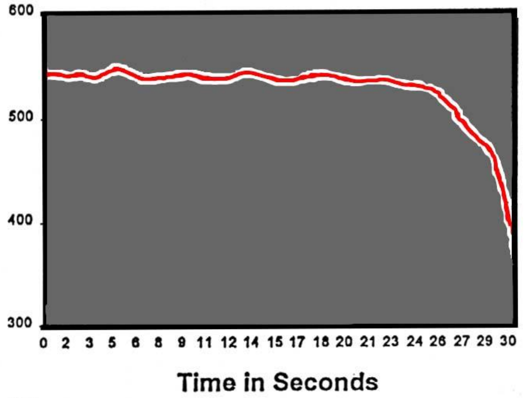
List of Incidents-2

WSCC (WECC) Event on July 2, 1996 (from PK)

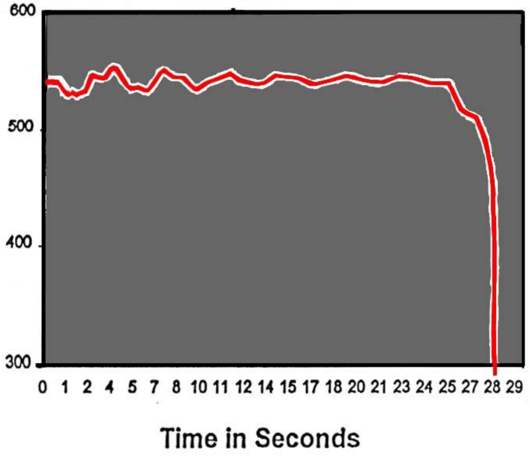


List of Incidents-2

WSCC (WECC) Event on July 2, 1996 (from PK)



Measured Voltage at 500 kV line



Simulated Voltage at 500 kV line

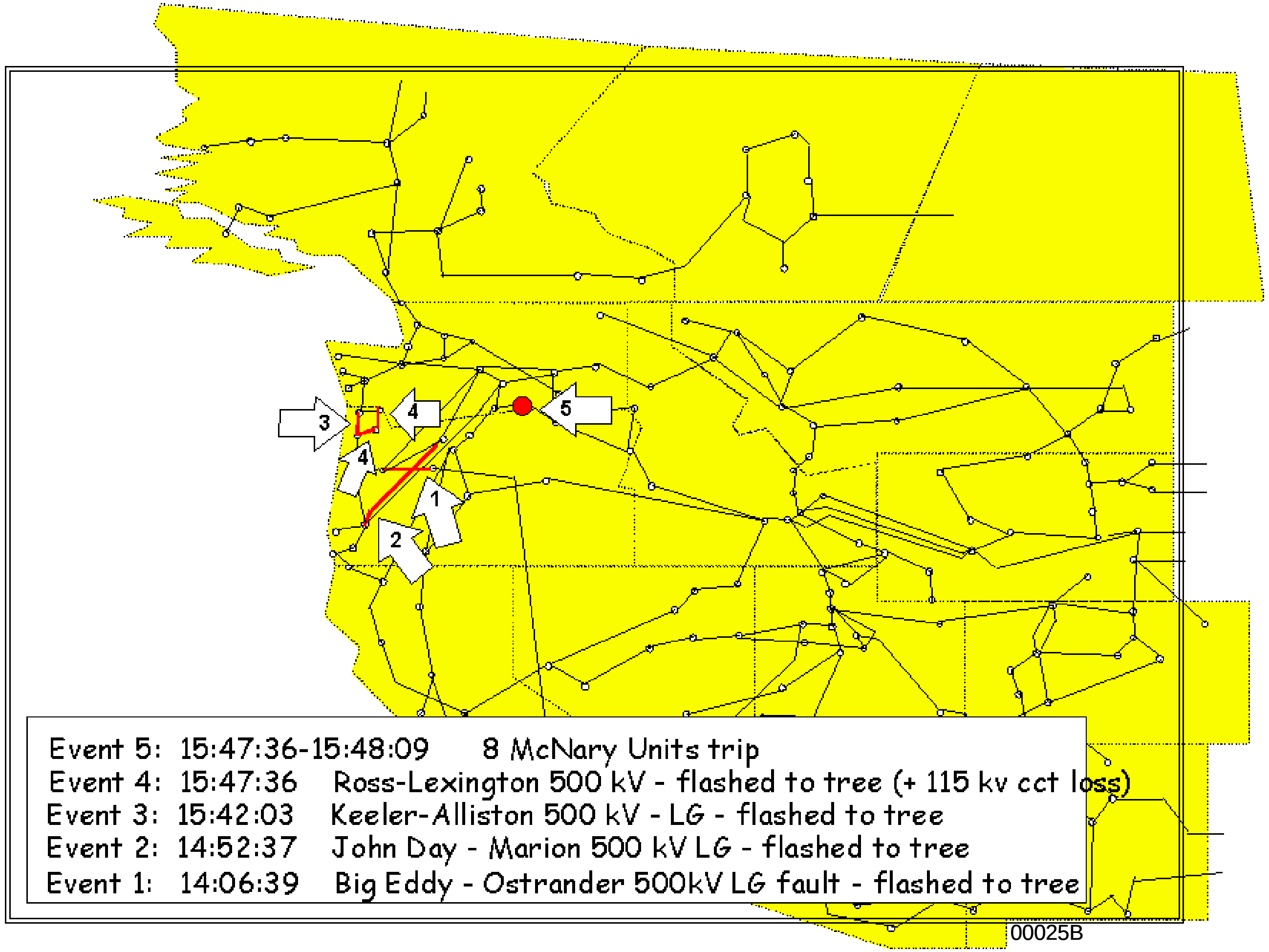
List of Incidents-3

WSCC (WECC) Event on August 10, 1996 (from PK)

- High ambient temperatures in Northwest;
  high power transfer from Canada to California
- Prior to main outage, three 500 kV line sections from lower Columbia River to load centres in Oregon were out of service due to tree faults
- California-Oregon Interties loaded to 4330 MW north to south
- Pacific DC Intertie loaded at 2680 MW north to south
- 2300 MW flow from British Columbia
- Growing 0.23 Hz oscillations caused tripping of lines resulting in formation of four islands
- loss of 30,500 MW load

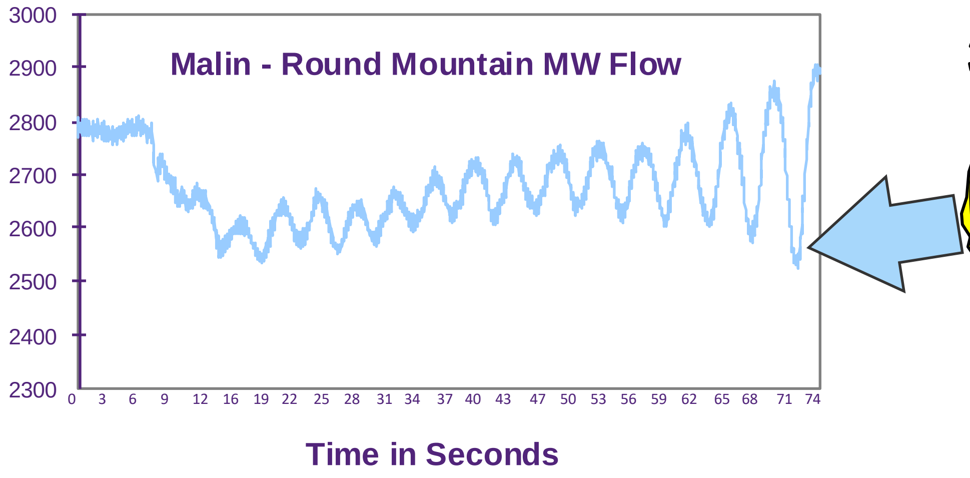
List of Incidents-3

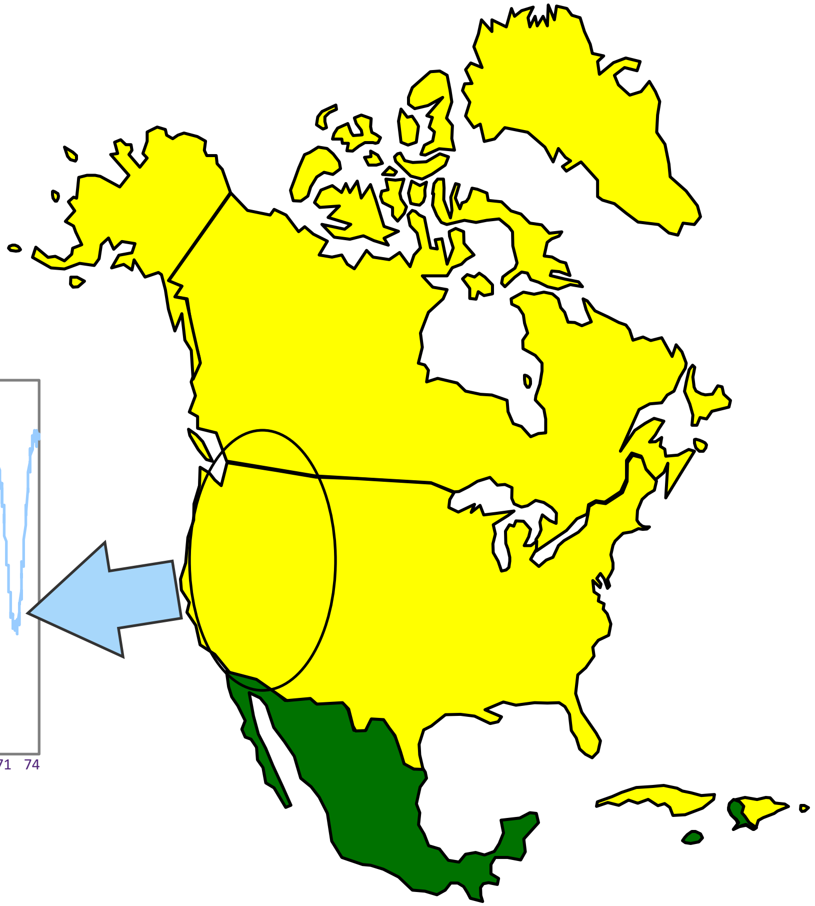
WSCC (WECC) Event on August 10, 1996 (from PK)



List of Incidents-3

WSCC (WECC) Event on August 10, 1996 (from PK)



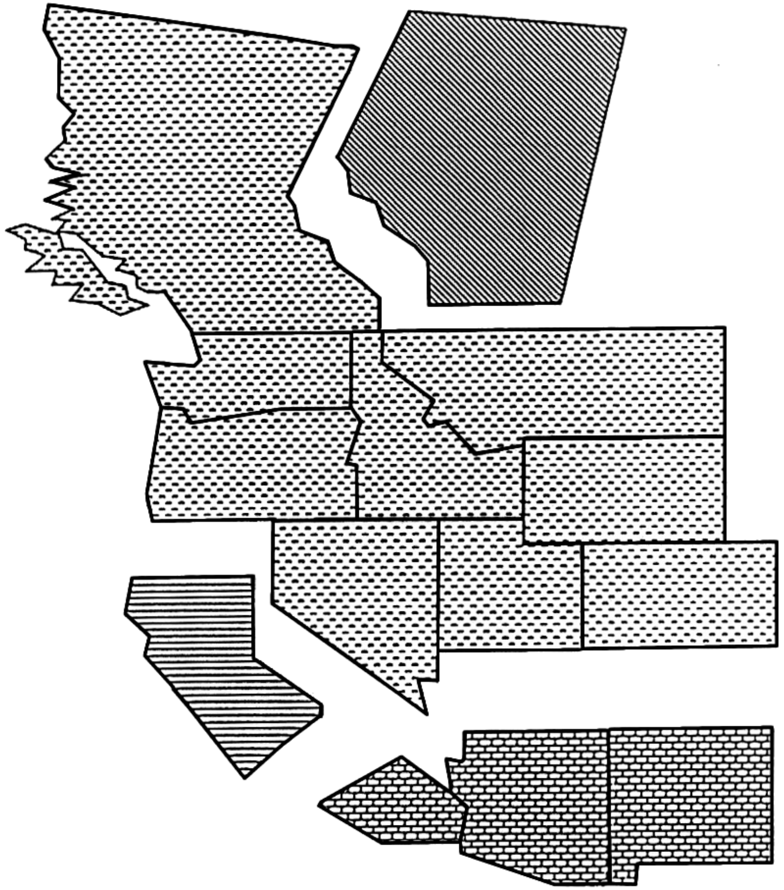


List of Incidents-3

WSCC (WECC) Event on August 10, 1996 (from PK)

As a result of the undamped oscillations, the system split into four large islands

Over 7.5 million customers experienced outages ranging from a few minutes to nine hours! Total load loss 30,500 MW



List of Incidents-3

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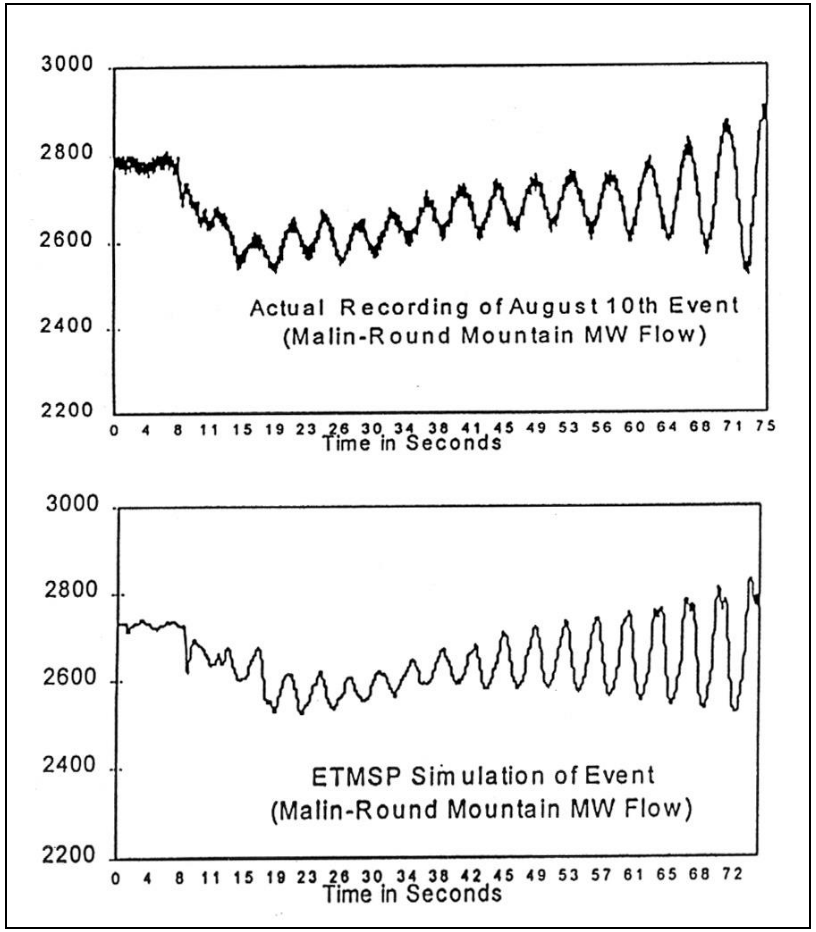
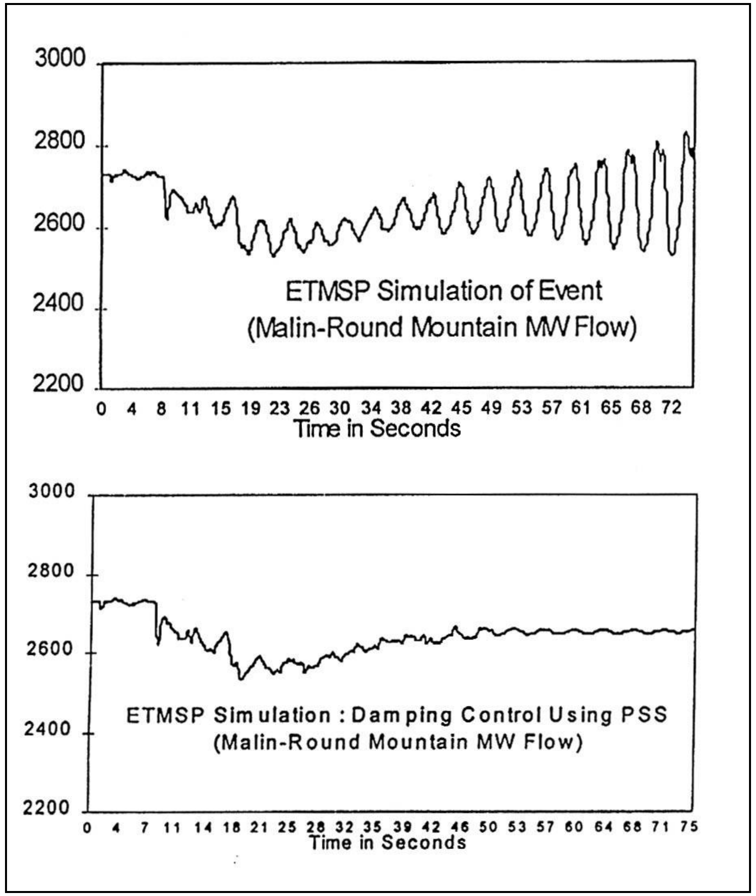


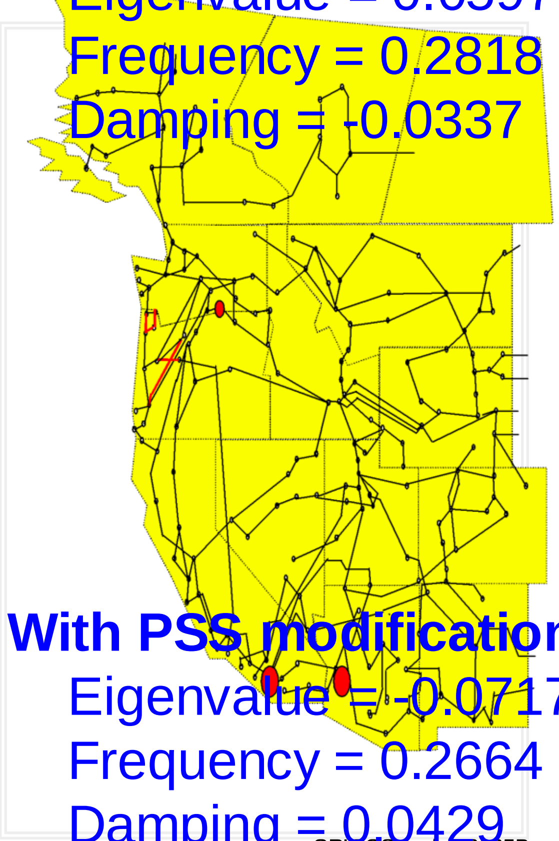
MEASURED RESPONSE

SIMULATED RESPONSE

List of Incidents-3

WSCC (WECC) Event on August 10, 1996 (from PK)





With existing controls

Eigenvalue = 0.0597 + j 1.771

Frequency = 0.2818 Hz

Damping = -0.0337

With PSS modifications

Eigenvalue = -0.0717 + j 1.673

Frequency = 0.2664

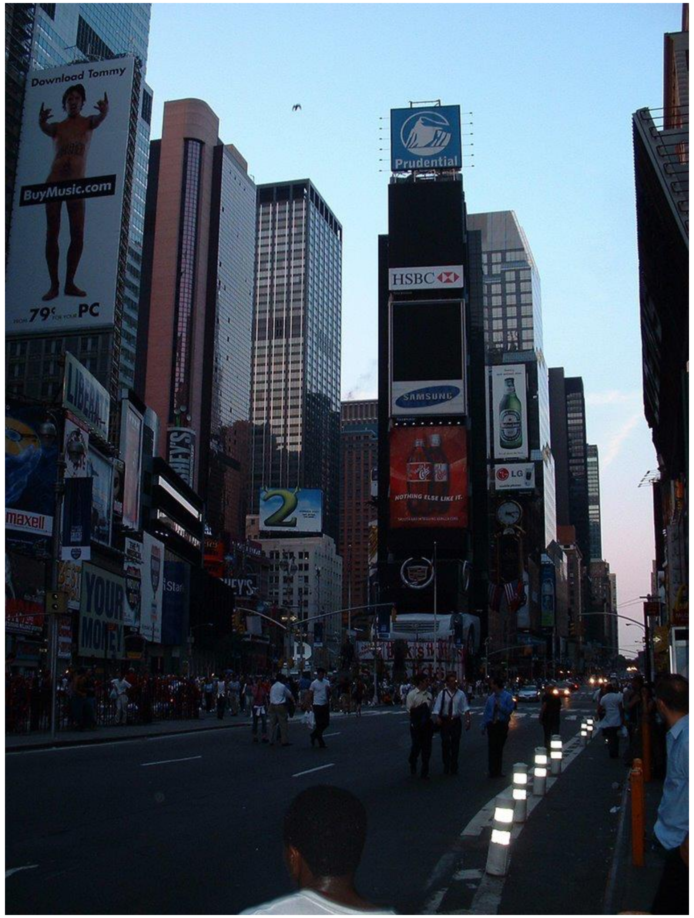
Damping = 0.0429

List of Incidents-4

August 14, 2003, US-Canadian Blackout

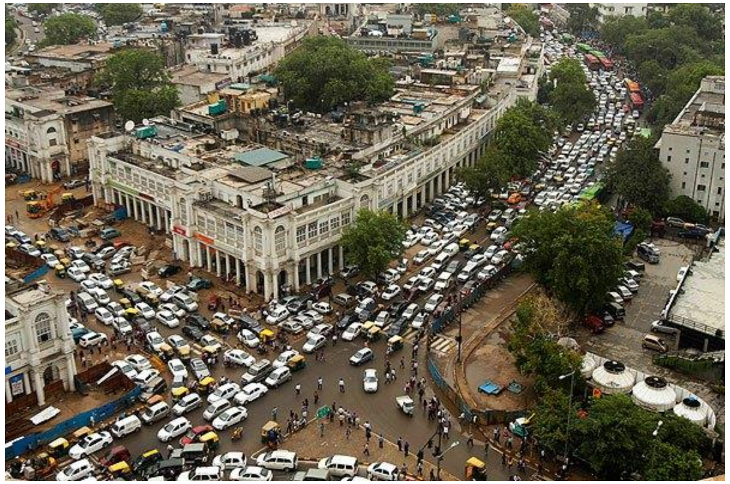
List of Incidents-4

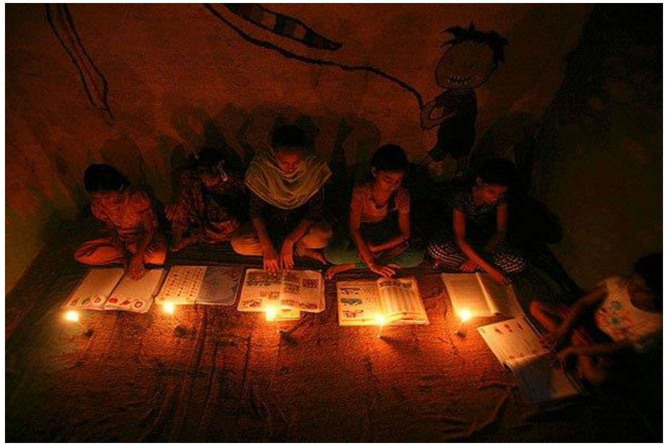
August 14, 2003, US-Canadian Blackout



List of Incidents-5

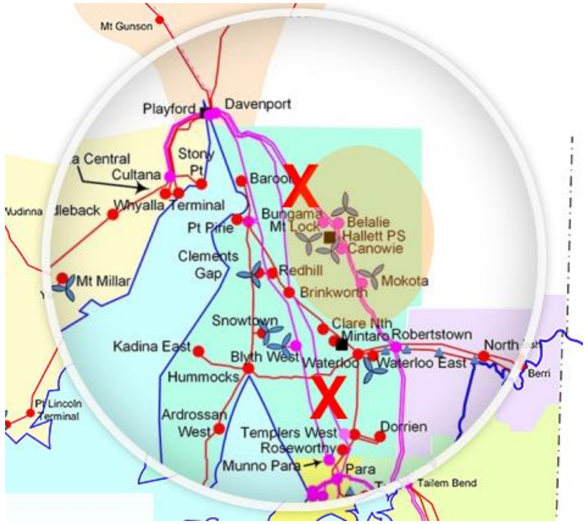
July 31, 2012, Indian Blackout





List of Incidents-6

Recent Frequency Instability Incidents



South Australian System Blackout, September 28, 2016

- Just prior to the incident, SCADA data showed that a total of 850,000 SA (South Australia) electricity customers were supplied with 1,826 MW of electricity demand:

- The demand was primarily served by the following generation and other small amount of generations

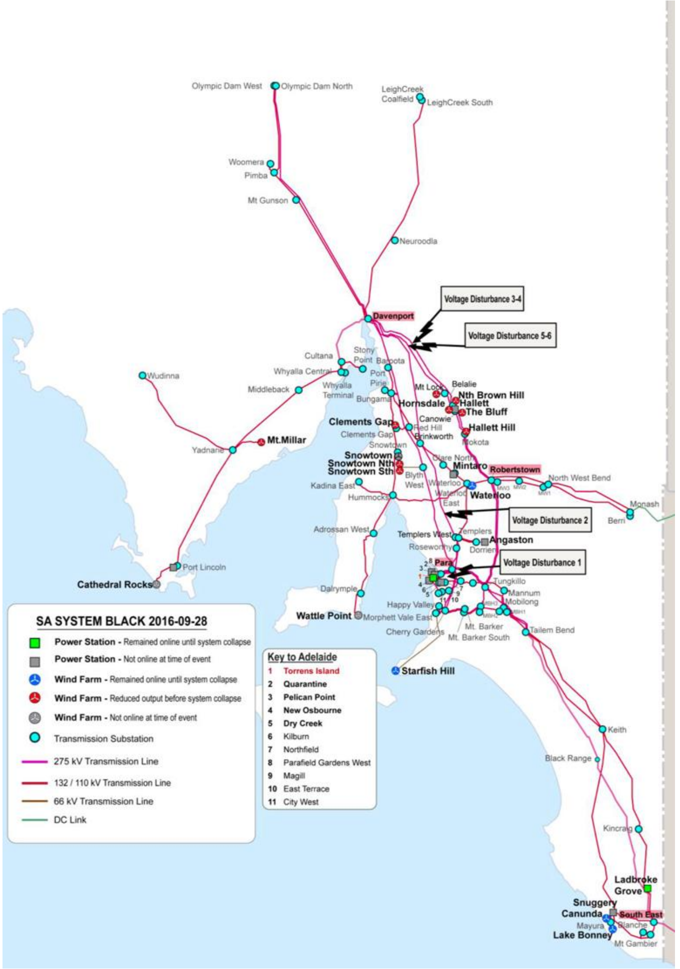
✓ 883 MW of wind generation within SA.

✓ 613 MW of imports via the two interconnections with Victoria (Heywood and Murraylink).

✓ 330 MW of gas generation within SA.

From AEMO Report

South Australian System Blackout, September 28, 2016



Sequence of events that let to system blackout

- On Wednesday 28 September 2016, tornadoes with wind speeds in the range of 190–260 km/h occurred in areas of South Australia.
- Two tornadoes almost simultaneously damaged a single circuit 275 kilovolt (kV) transmission line and a double circuit 275 kV transmission line, some 170 km apart.
- The damage to these three transmission lines caused them to trip.

From AEMO Report

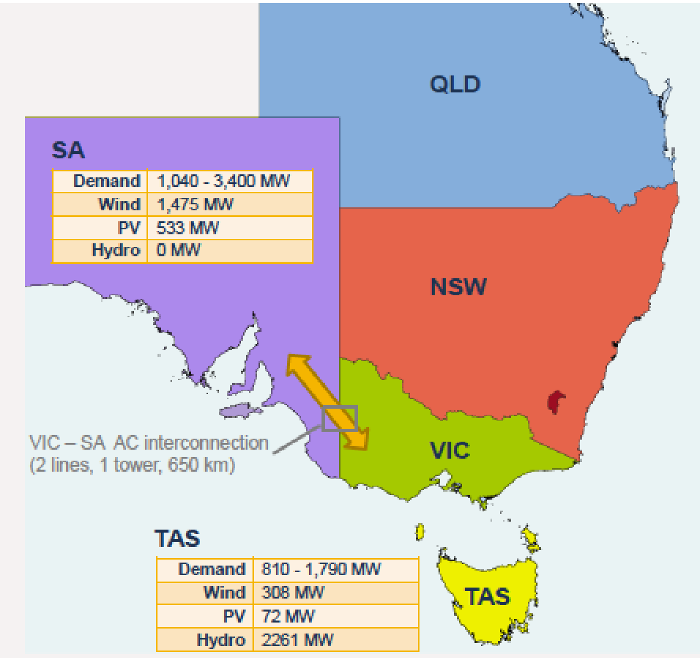
South Australian System Blackout, September 28, 2016

- A sequence of faults in quick succession resulted in six voltage dips on the SA grid over a two-minute period at around 4.16 pm.
- As the number of faults on the transmission network grew, nine wind farms in the mid-north of SA exhibited a sustained reduction in power as a protection feature activated.
- For eight of these wind farms, the protection settings allowed them to withstand a pre-set number of voltage dips within a two-minute period.



From AEMO Report

South Australian System Blackout, September 28, 2016



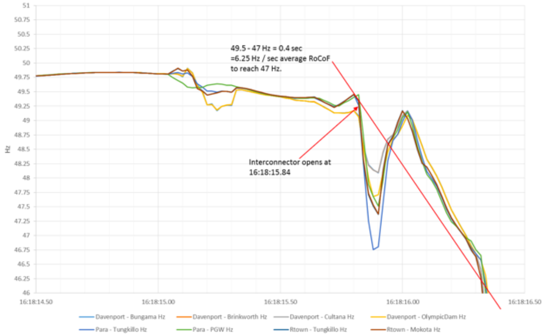
Heywood Interconnection:
275 kV double circuit with 650 MW

Murray Link: 220 MW HVDC

- Activation of this protection feature resulted in a significant sustained power reduction for these wind farms.
- A sustained power reduction of 456 megawatts (MW) occurred over a period of less than seven seconds.
- The reduction in wind farm output caused a significant increase in imported power flowing through the Heywood Interconnector.
- Approximately 700 ms after the reduction of output from the last of the wind farms, the flow on the Victoria–SA Heywood interconnector reached such a level that it activated a special protection scheme that tripped the interconnector offline.

From AEMO Report

South Australian System Blackout, September 28, 2016



- The SA power system then became separated (“islanded”) from the rest of the NEM.
- Without any substantial load shedding and due the “system separation,” the remaining generation was much less than the connected load and unable to maintain the islanded system frequency.
- As a result, all supply to the SA region was lost at 4.18 pm (Blackout occurred).
- AEMO’s analysis shows that following system separation, frequency collapse and the consequent blackout was inevitable.

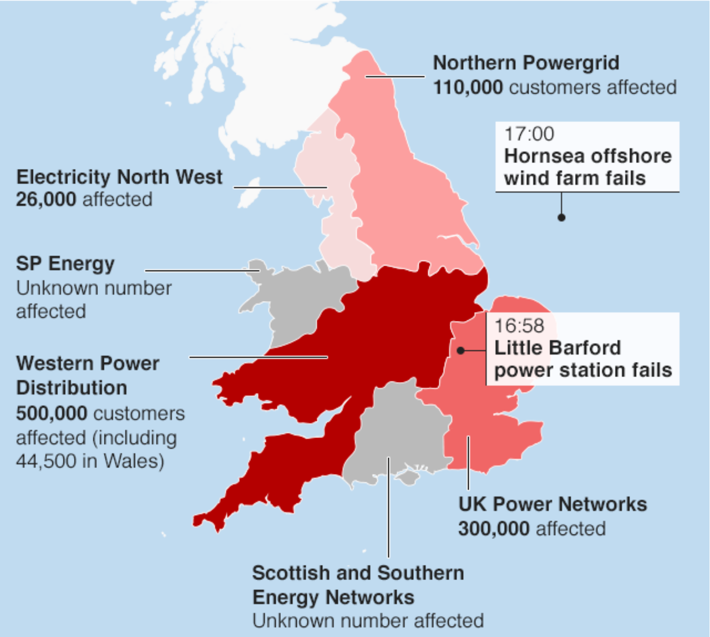
From AEMO Report

List of Incidents-7

East England Power Incident, August 9, 2019

England and Wales power cut

Customers affected in each electricity supply area

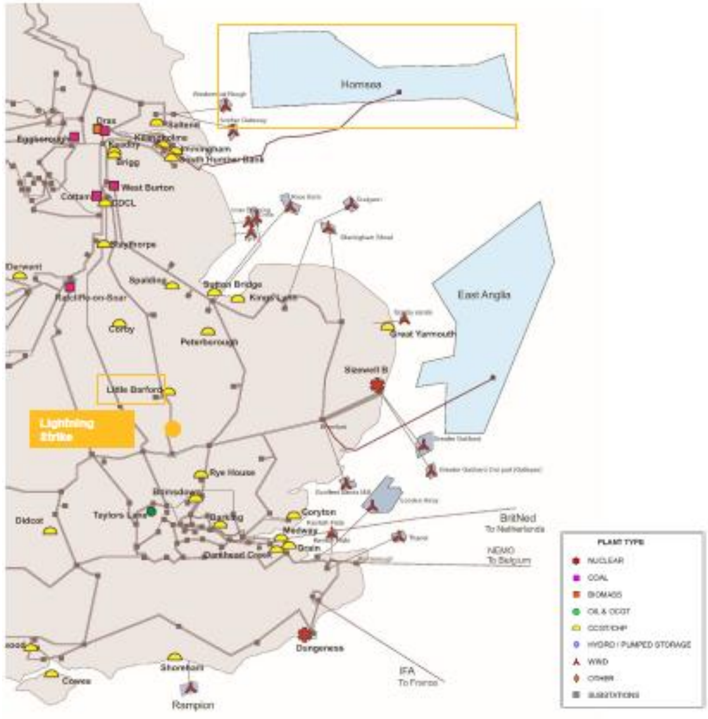


Source: Electricity supply companies / National Grid BBC

- Power system was running normal and no big changes in demand forecast but the weather conditions were anticipated – Wind and rain in most part of England and Wales.
- There were heavy rain and lightning activities in the Eastern area.
- The amount of electricity needed was forecasted to be something like previous Friday, i.e., August 2.
- Among different power plants in operation to feed the demand, around 30% from Wind, 30 % Gas-fired, 20% Nuclear, 10% from Distributed Generators (e.g., Water, pumped storage, coal and biomass) and 10% from Interconnectors.

 From nationalgridESO

East England Power Incident, August 9, 2019



At 16:52

- There was a lightning strike on a transmission circuit north of London - the Eaton Socon – Wymondley Main.
- The protection systems operated immediately, disconnecting and clearing the disturbance on the line in under 0.1 seconds.
- The line re-set itself and returned to normal within 20 seconds.
- System was very used to dealing with lightning strikes and handle over 1,000 a year with no loss of customer supplies.
- There was a small loss of embedded generation due to the lightning strike and this is normal and expected for a lightning strike on a transmission line.

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At 16:52

- However, immediately following the lightning strike, and within seconds of each other, two large generators reduced their energy supply to the grid:
  - Little Barford gas power station
  - Hornsea windfarm

- The total generation lost from the two generators was 1,378MW.

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- This unexpected loss of generation meant the frequency fell and went outside the normal range of 50.5Hz – 49.5Hz.
- The National Grid Electricity System Operator (ESO) balances supply and demand second by second to maintain the frequency of the system at 50Hz.
- In case of an event of large frequency change, the ESO keeps backup power, designed to cover the loss of the single biggest generator to the grid.
- At this time, the ESO was keeping 1,000MW of backup power.
- All the normal backup power and tools were used, this include 475MW of battery storage.

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Near simultaneous outages at two large power stations

Source: C4 News

- However, the scale of the generation loss was large that the frequency continued to fall - to 48.8Hz.
- At this point, the automatic secondary back up system (the Low Frequency Demand Disconnection scheme) kicks in.
- Customers are automatically disconnected to ensures the safety of the network in a controlled way and in line with parameters pre-set by the distribution network operators.
- In this point, 5% of Britain’s electricity supply (1 million customers) was turned off to protect the other 95%.
- This has not happened in over a decade and is an extremely rare event.

Stability Challenges in Modern Power Systems

- Modern power systems are dominated with Inverter Based Generator (IBG) compared to traditional power grids which are predominantly synchronous generators.
- Inverter/converter stability is one of the new challenges that modern power systems will face.
- As the penetration of renewable energy increasing, many of the synchronous machines are retiring, hence rotational inertia becoming a scare commodity.
- Intermittency is another unavoidable characteristic with renewable energy plants.
- Lack of inertia or no inertia and high intermittency could lead to more frequency and voltage instability problems.
- Having inverters/converters in large numbers in proximity could lead to oscillation and resonance.

Thank you

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Power System Time Scales