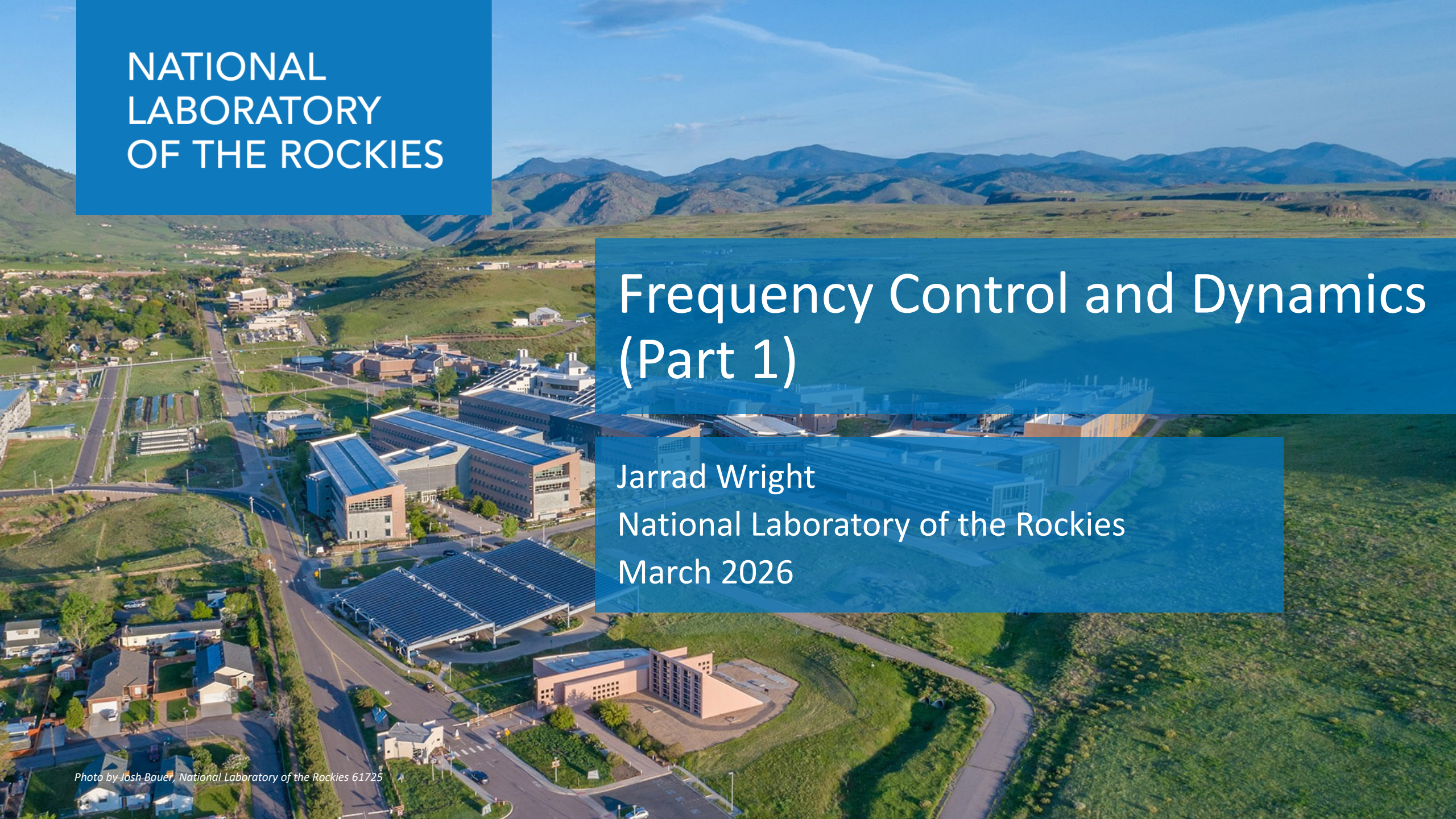


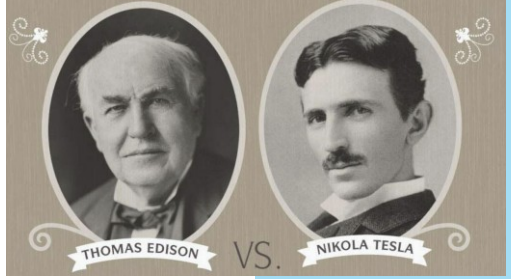

# Frequency Control and Dynamics (Part 1)

Jarrad Wright
National Laboratory of the Rockies
March 2026

*Photo by Josh Bauer, National Laboratory of the Rockies 61725*

# Frequency Principles

# Direct Current (DC)




# Alternating Current (AC)

- **Good:**
  - Converts AC to DC, transmits DC power over long distances, and inverts DC to AC
  - Controls power flow on DC line to a specific value (controllability)
  - Is economical for long distance transmission (overhead lines cheaper, lower losses)
  - Can operate close to thermal limits in almost all cases
  - Provides direct control between regional AC grids
  - Enables synchronous interconnection (60 Hz and 50 Hz AC systems can be interconnected)
  - Capable of emergency power/black start
  - Is short-circuit limited (controlled injection)
  - Capable of power oscillation damping
- **Bad:**
  - Uneconomical for short distance transmission (substations more expensive)
  - Intermediate substations require multi-terminal DC (not prevalent—complexity).

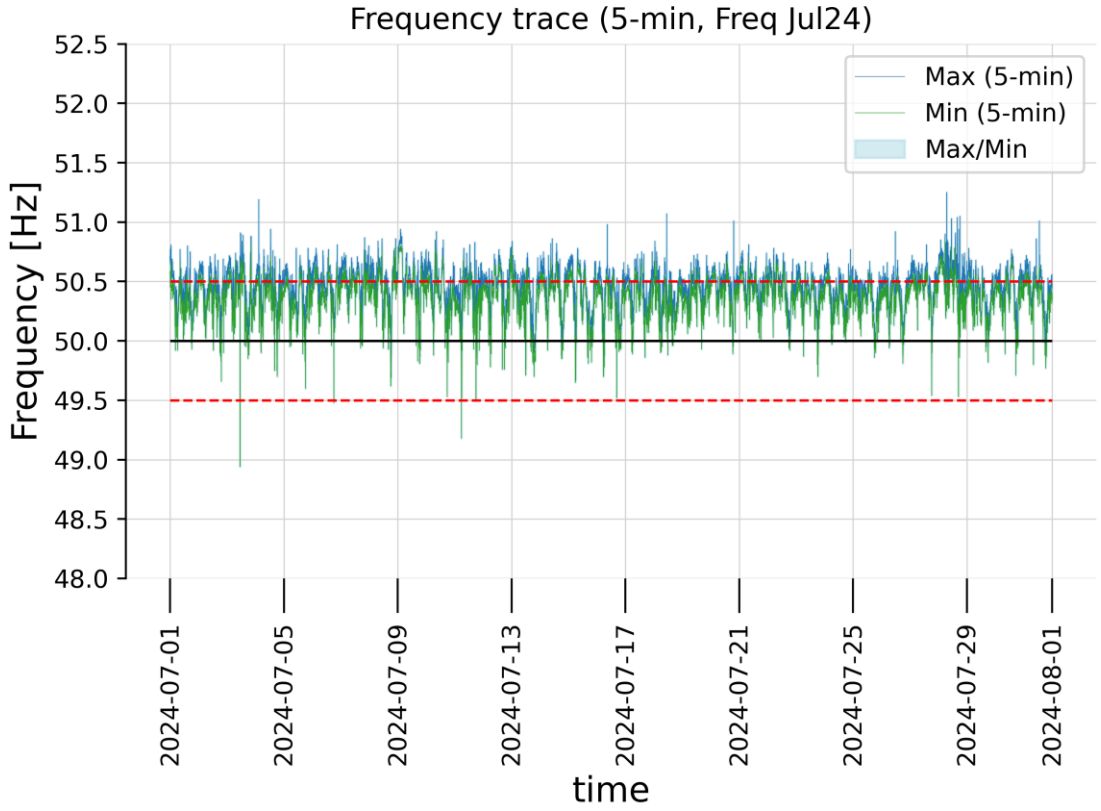
- **Good:**
  - Can easily step-up and step-down voltages (usability)
  - Serialization is easy (many substations radial/meshed can serve load)
  - Enables reduced current and losses at high voltages
  - Increased transfer capability with series compensation (reduce line reactance).
- **Bad:**
  - Limited maximum transfer megawatt (MW) capability across longer distances (voltage stability — surge impedance loading, transient stability limits)
  - Subsynchronous resonance concerns if lines are series compensated
  - Needs reactive power support for voltage regulation (shunt capacitors/reactors, SVCs, STATCOMs)

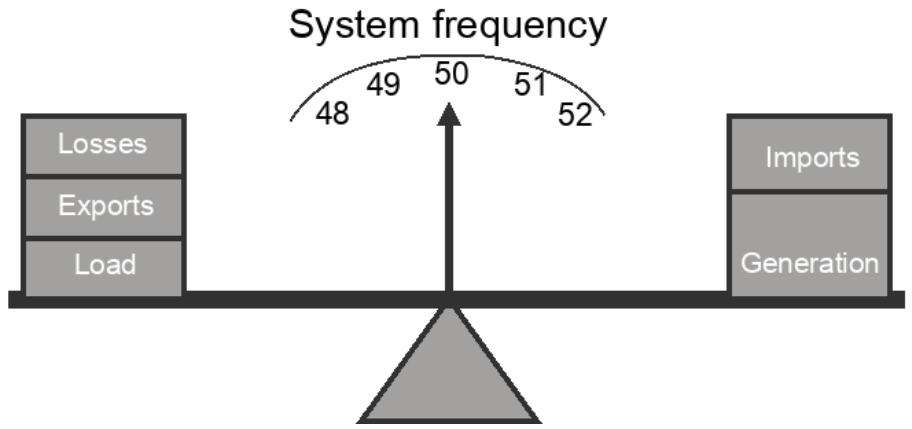
# What Is the System Frequency?

- Frequency is the rate at which AC systems oscillate (**50/60 Hz**).
- Frequency is one of the **two heartbeats** of a power system:
  - Frequency
  - Voltage.
- Frequency in an **interconnection is the same** (Southern African Power Pool, Eastern African Power Pool, etc.).
- An interconnection can contain a number of **control areas.**

# What is the System Frequency?

- Actual frequency is the balance between supply and demand.




Source: NLR analysis (based on ESCOM sourced data)

# Frequency Deviations

**Generator tolerances**

- Deviations cannot be too large (mechanical damage)
- Limits specified in grid codes:
  - Continuous operations range
  - Deadbands
  - High- and low-frequency cumulative performance requirements.
- On hydro units
  - Frequency insensitive due to low turbine speeds (larger tolerances to frequency deviations).

**End-use consumer tolerances**

- Computer equipment, 47–53 Hz
- Consumer electronics, ±5%
- Household appliances, ±1–2 Hz
- Motors, IEC 34001
- Variable speed drives, ±1–2 Hz
- Timing systems, ±0.5 Hz
- Metering devices, <0.25 Hz.

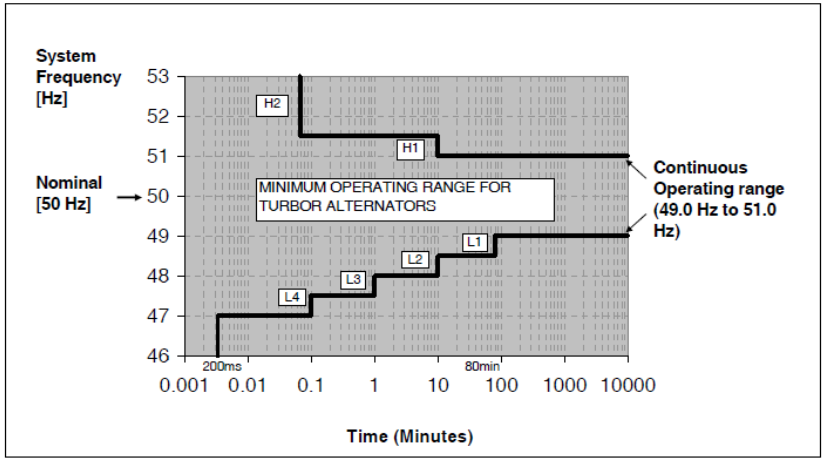
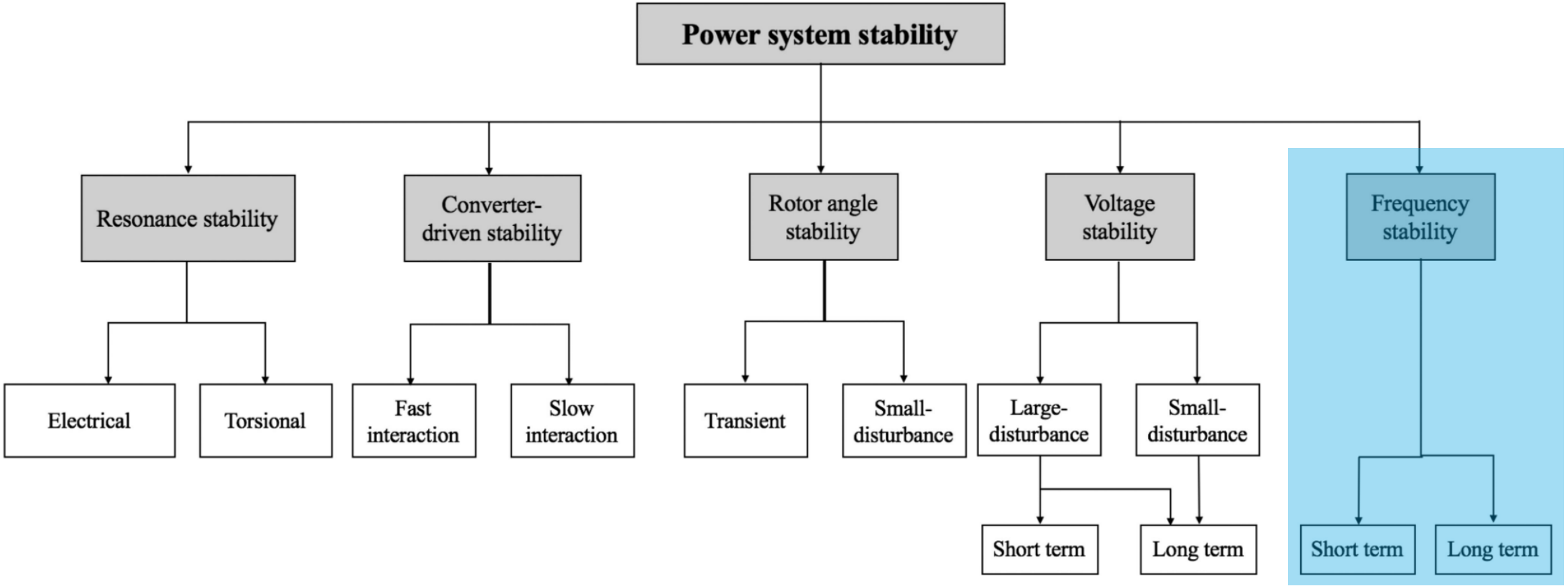



*Image from Transmission Grid Code (South Africa), 2022*, https://www.nersa.org.za/electricity/grid-code

# Frequency Stability

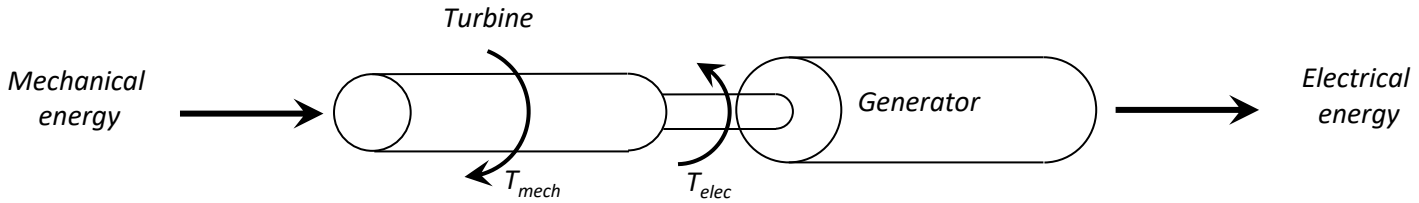
# Where Frequency Stability Fits In




Source: Hatziargyriou, N., et al. 2021. "Definition and Classification of Power System Stability – Revisited & Extended." *IEEE Transactions on Power Systems* 36 (4): 3271–3281, 2021. doi: 10.1109/TPWRS.2020.3041774.

# Frequency Stability

- Swing equation governs the balance of active power:




$$T_a = T_{mech} - T_{elec}$$

$$J\frac{d\omega_m}{dt} = T_a = T_{mech} - T_{elec}$$

$$2H\frac{d\omega_r}{dt} = T_{mech} - T_{elec}$$

$$H = J\frac{1}{2}\frac{J\omega_{0m}^2}{VA_{base}}$$

$J$ : Combined moment of inertia of turbine + generator
$\omega_m$ : Angular velocity of the rotor
$H$ : Inertia constant

| Type of generating unit | $H$ |
|---|---|
| Thermal unit<br>(a) 3600 r/min (2-pole)<br>(b) 1800 r/min (4-pole) | <br>2.5 to 6.0<br>4.0 to 10.0 |
| Hydraulic unit | 2.0 to 4.0 |

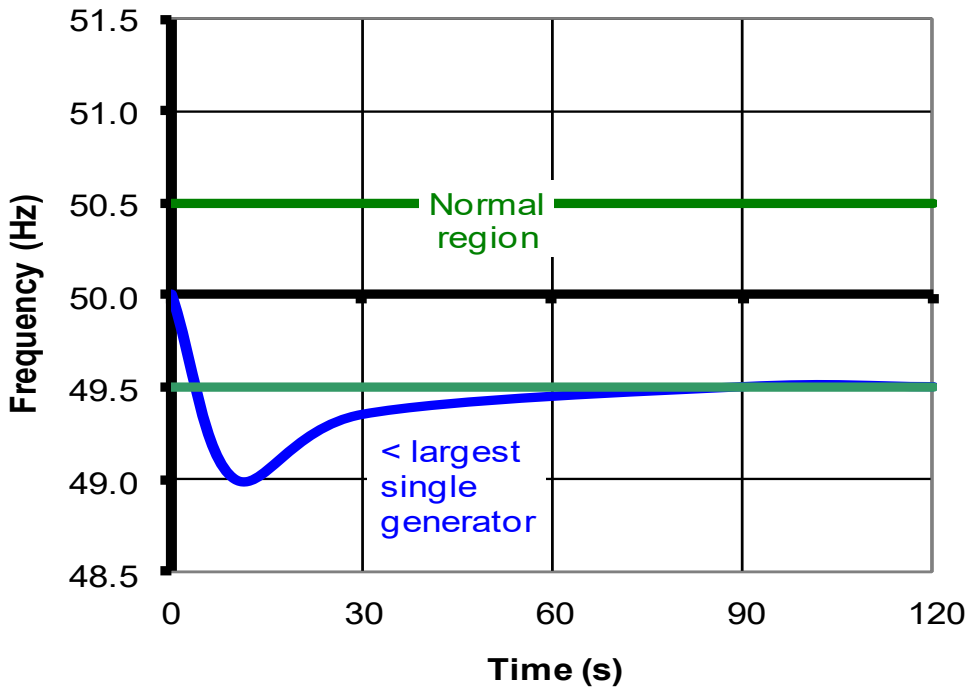
Source: Adapted from Kundur, P. 1994. *Power System Stability and Control*. McGraw-Hill.

# Frequency Stability

- The larger the interconnection, the easier it is to control frequency.
  - For expected deviations in the balance between generators/loads/interconnectors and large disturbances, frequency deviations resulting from power system imbalances should not be too large.
  - Disturbance sizes, deviations, and limits are defined in Grid Codes.

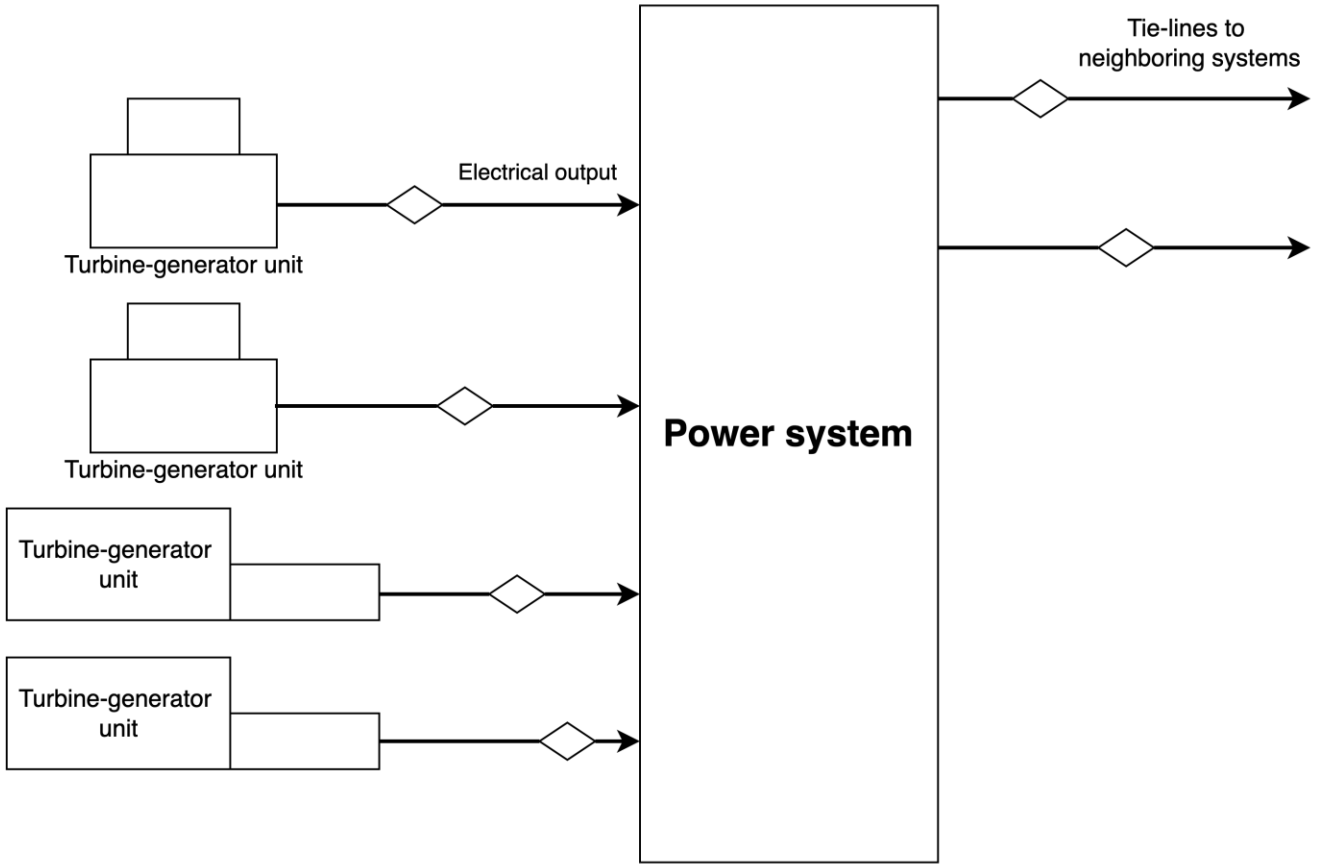
**NOTE:** ESCOM operates the Malawi system as its own interconnect (for now).

Demonstration of example normal operating operating range (green) and frequency deviation following largest single contingency



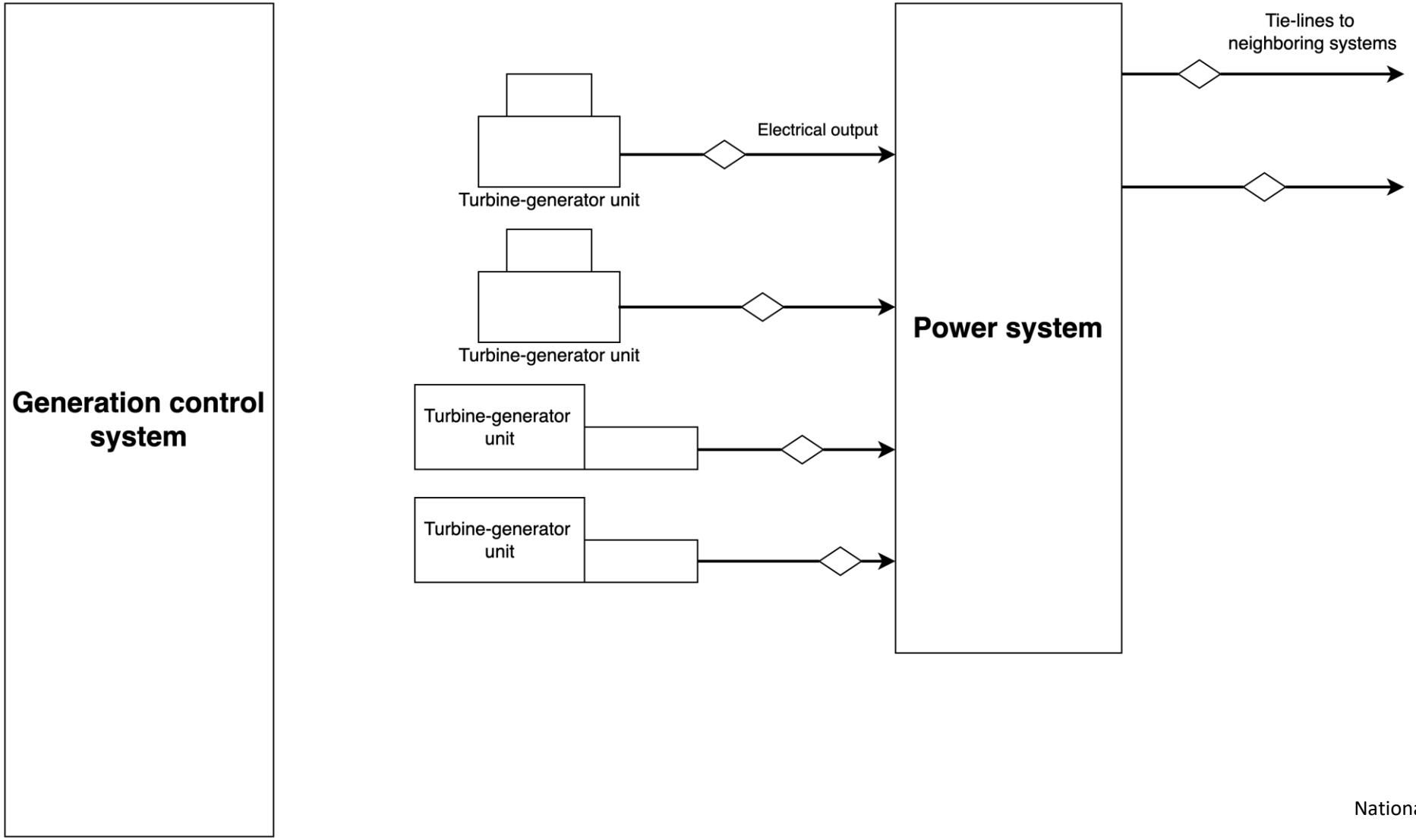
# Interconnected Operations

# Overview of Interconnected Power Systems Generation Control Problem

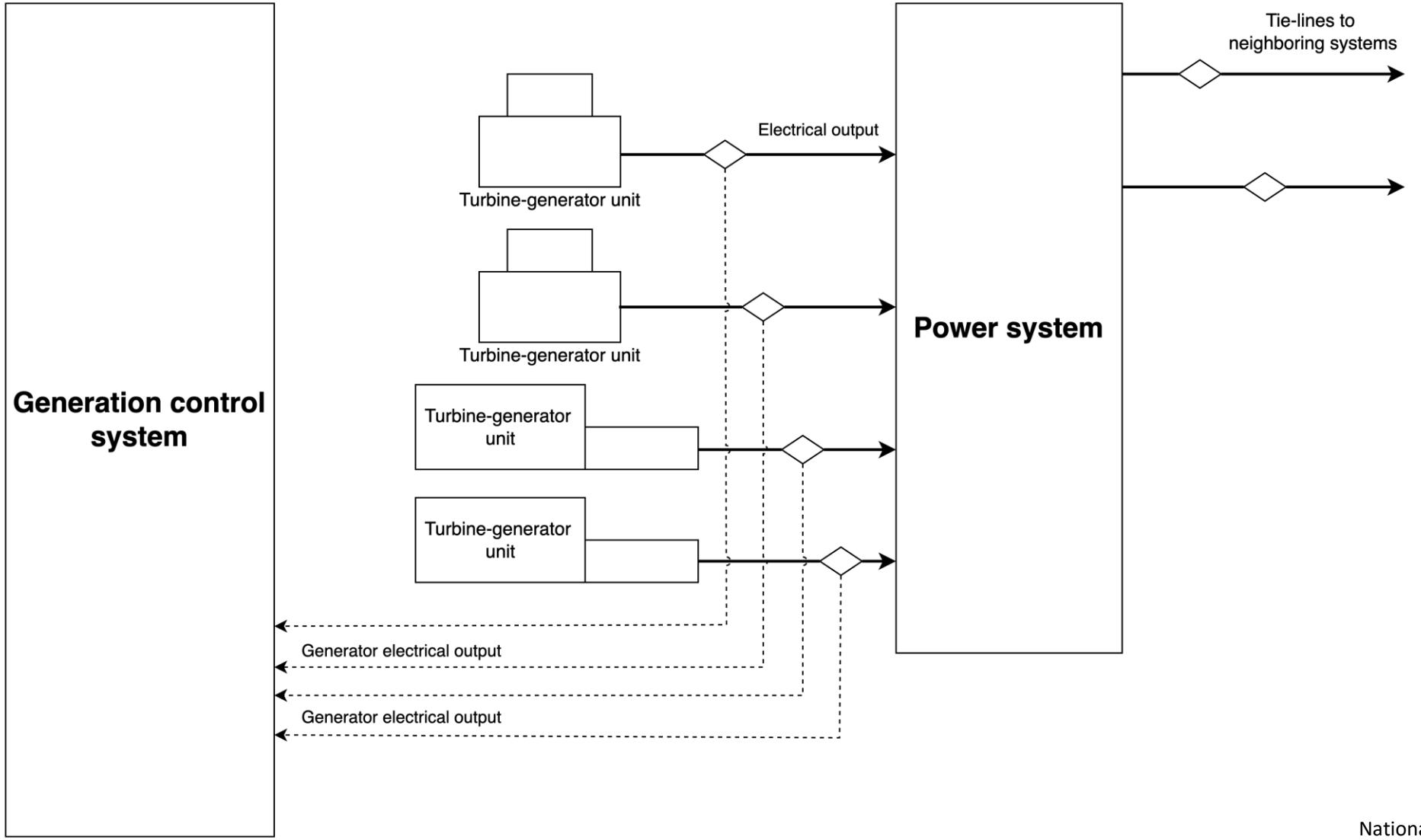



This is a "**Control Area**": An electrical system bounded by interconnectors metering and telemetry. (It controls its generation directly to maintain its interchange schedule with neighboring systems and contributes to the frequency regulation of the interconnection, controls Area Control Error [ACE] to performance targets.)

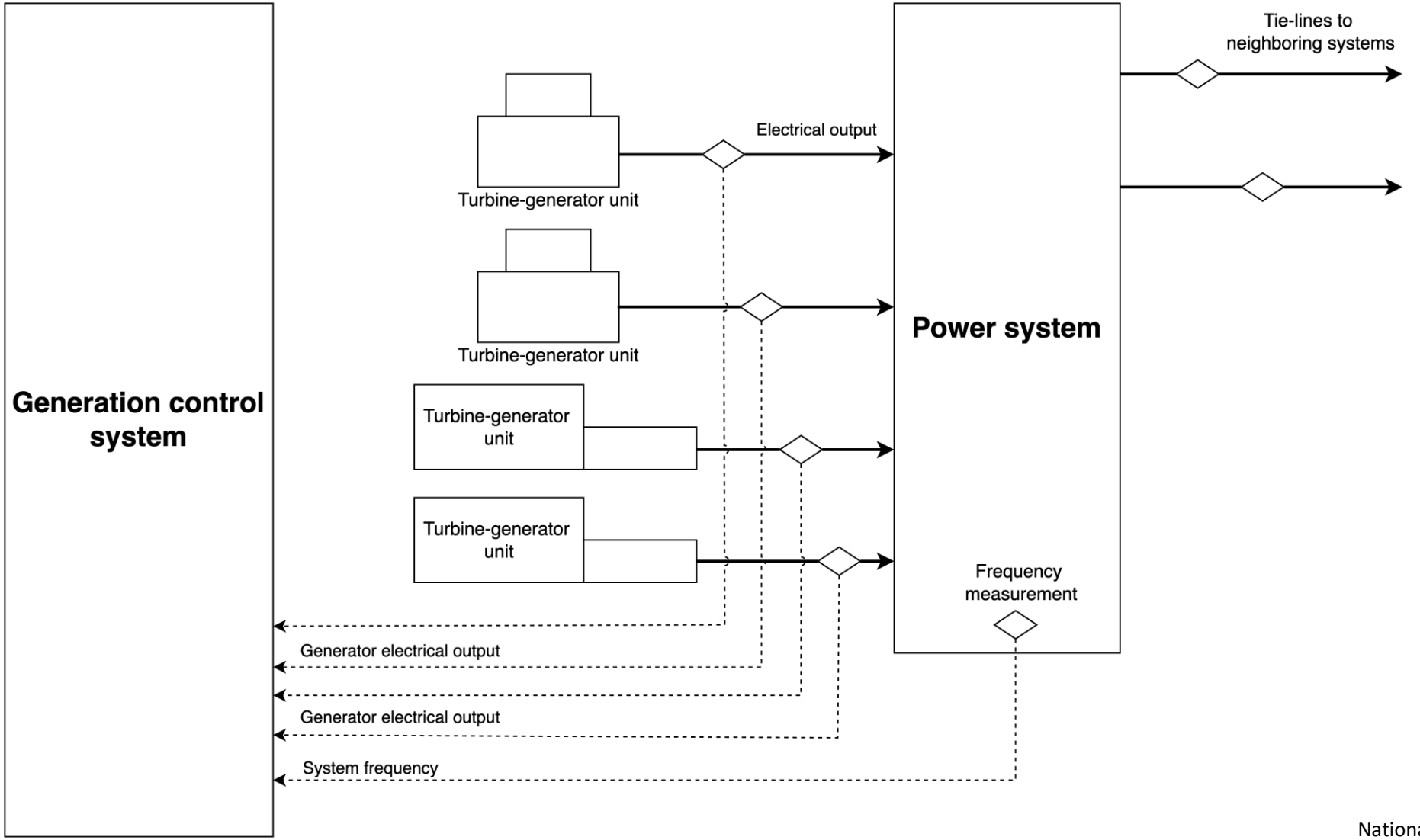
# Overview of Interconnected Power Systems Generation Control Problem



# Overview of Interconnected Power Systems Generation Control Problem



# Overview of Interconnected Power Systems Generation Control Problem



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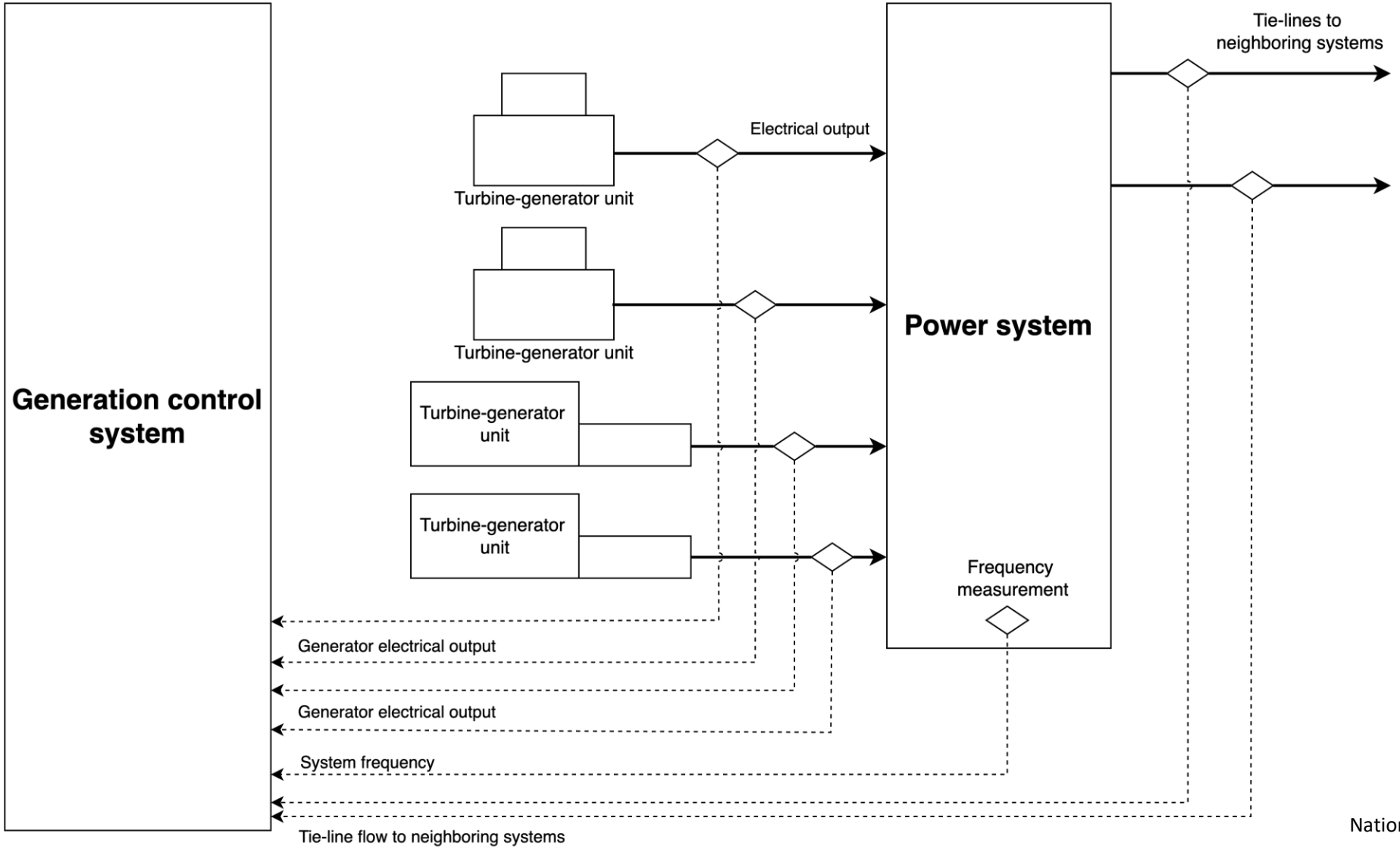
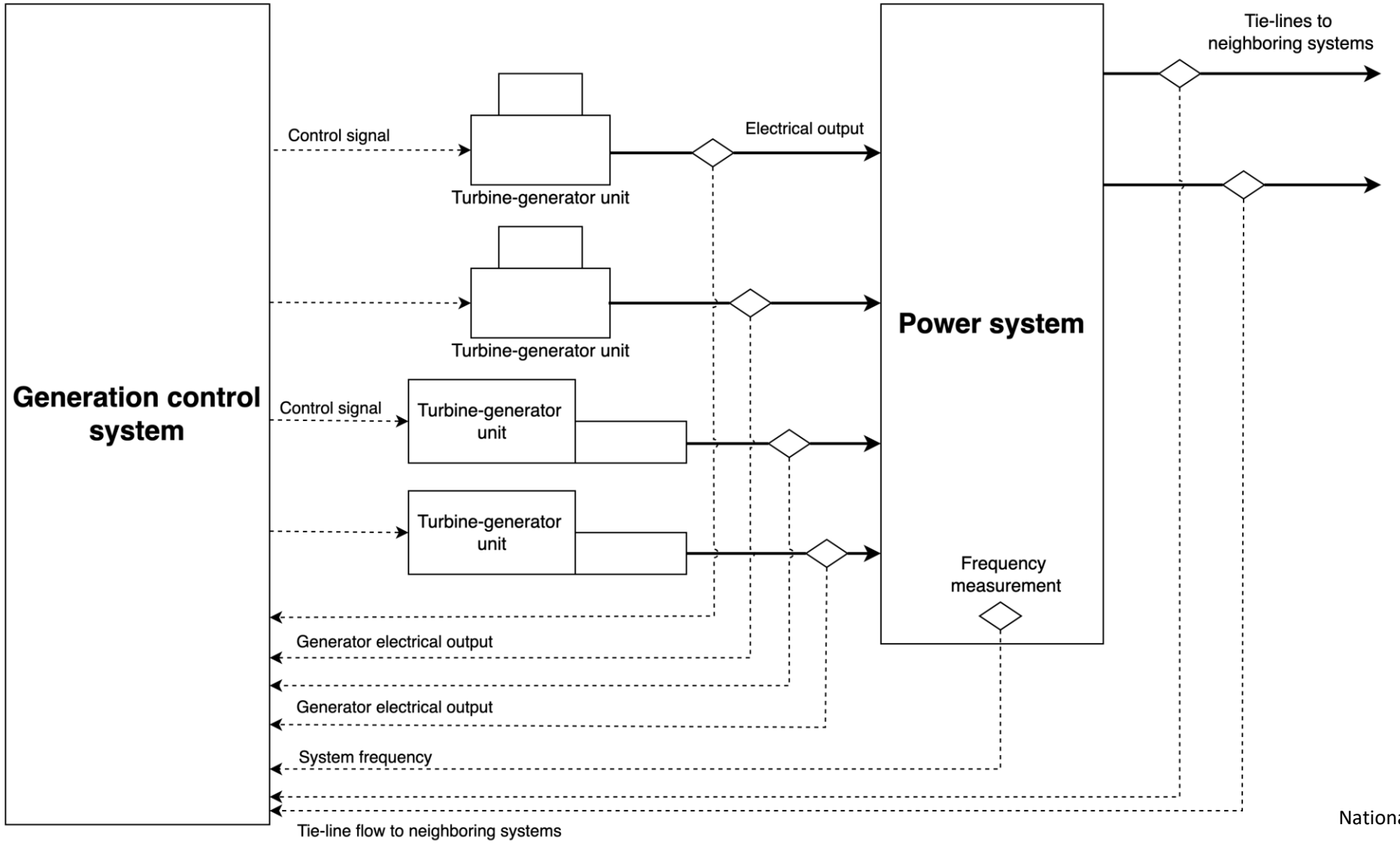
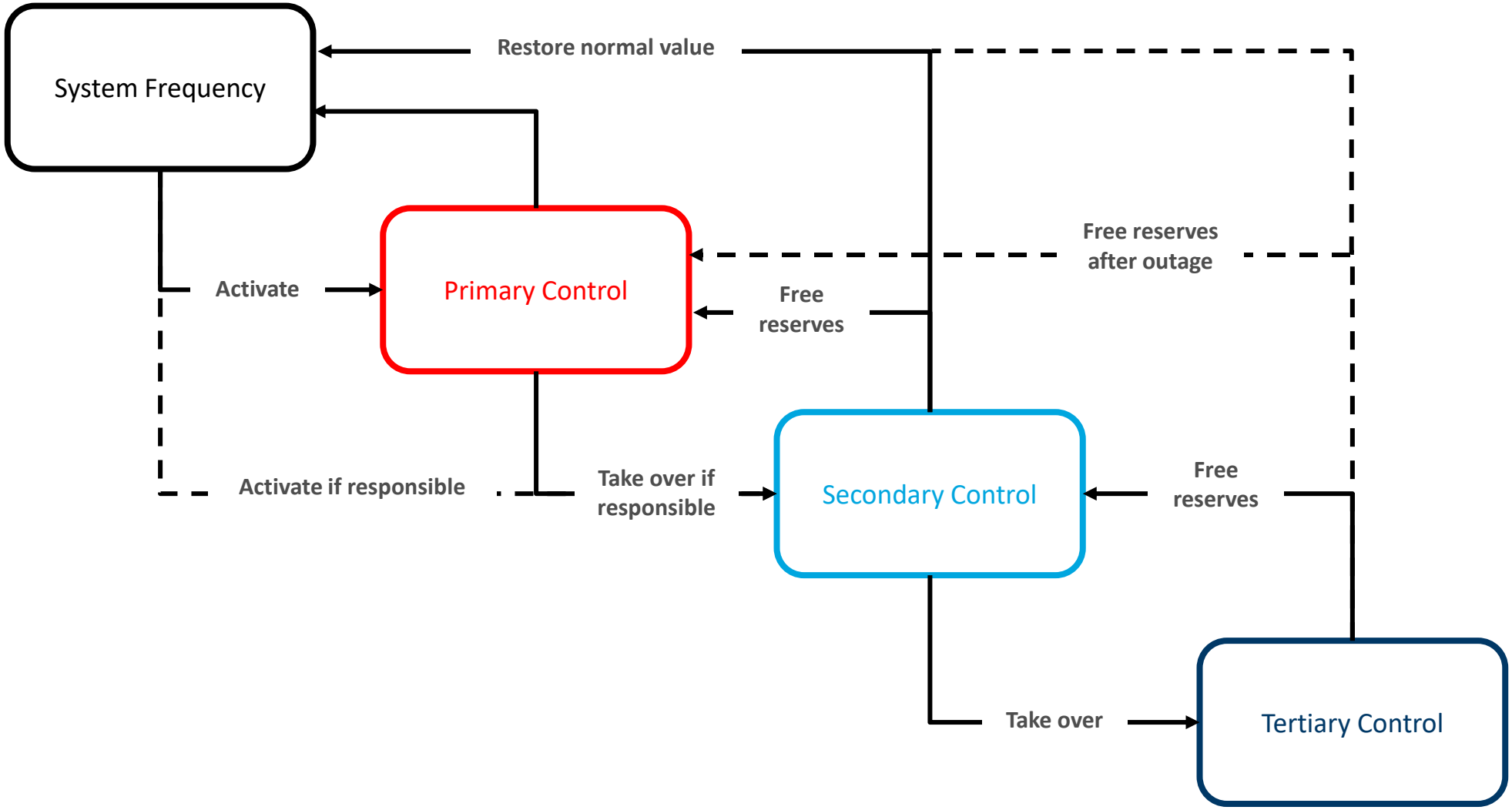


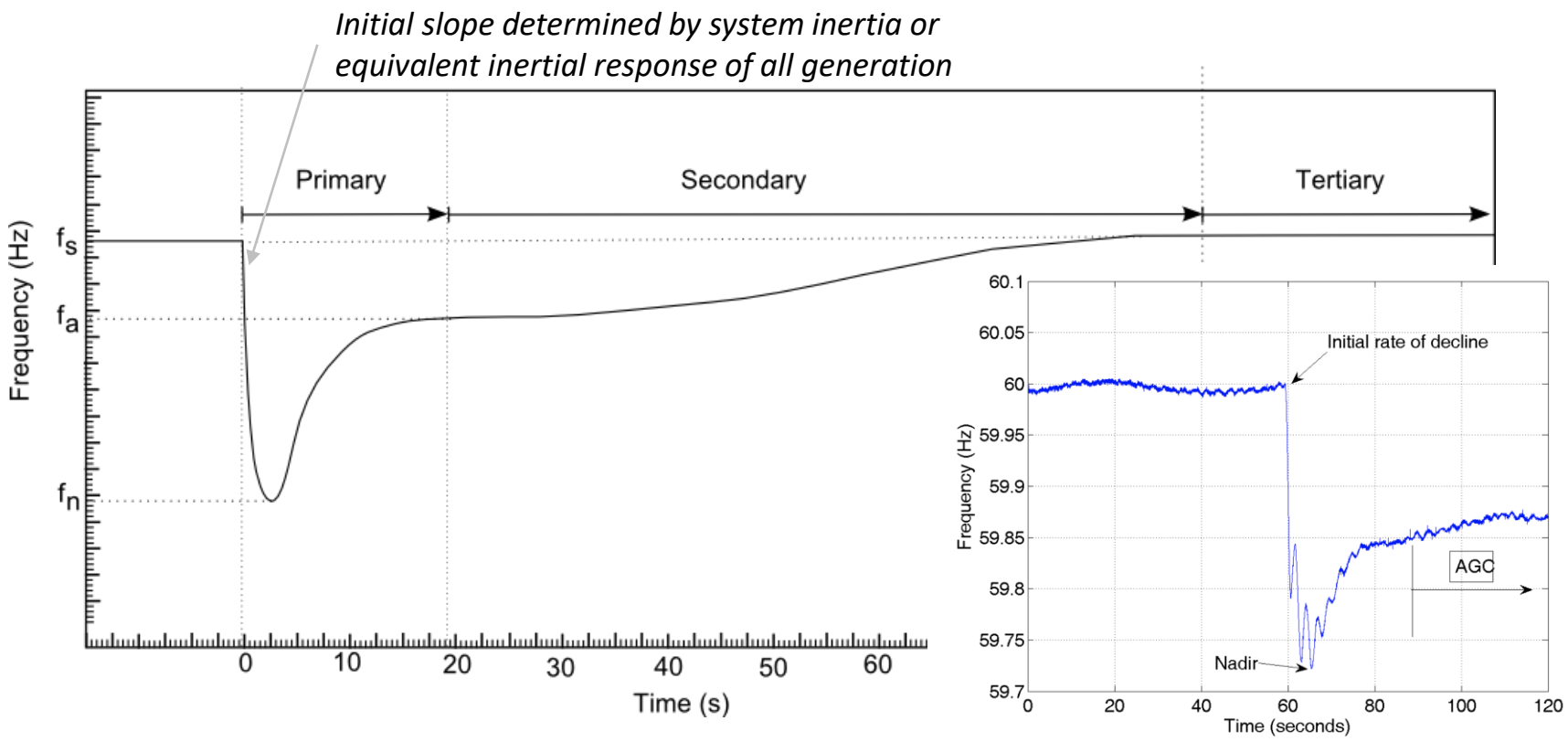
# Overview of Interconnected Power Systems Generation Control Problem



# Tiered Frequency Control Approach



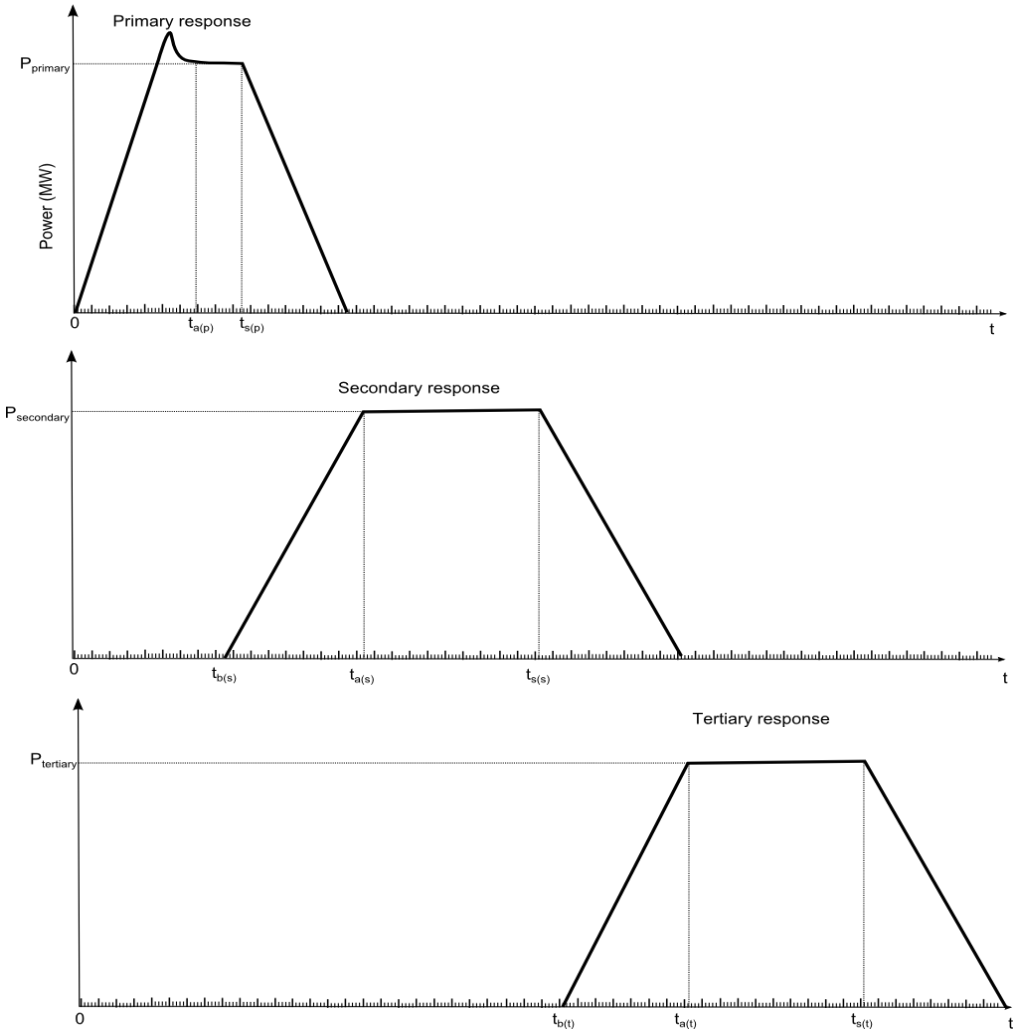
# Tiered Frequency Control Approach



# Tiered Frequency Control Approach

- **Types**
  - Primary response
  - Secondary response
  - Tertiary response.
- **Characteristics** of responses required to ensure frequency stability
  - Quantity (MW)
  - Reserve start and activation time (inherent ramp rate requirement)
  - Reserve begin time and sustain time
  - Reserve reliability level.

Demonstration of conceptual primary, secondary, and tertiary frequency response over time

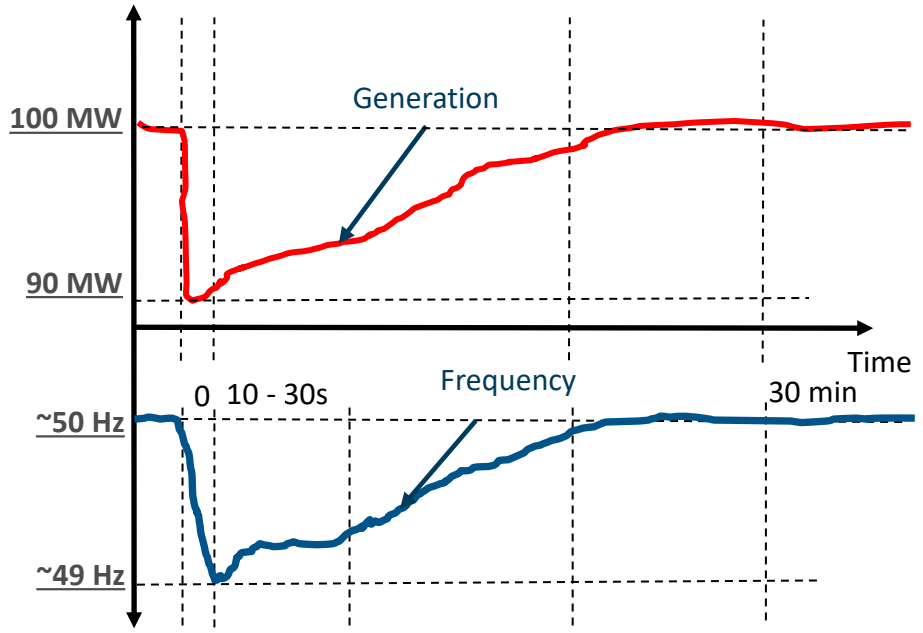


# Interconnecting Small System to a Large System

System A
1000 MW

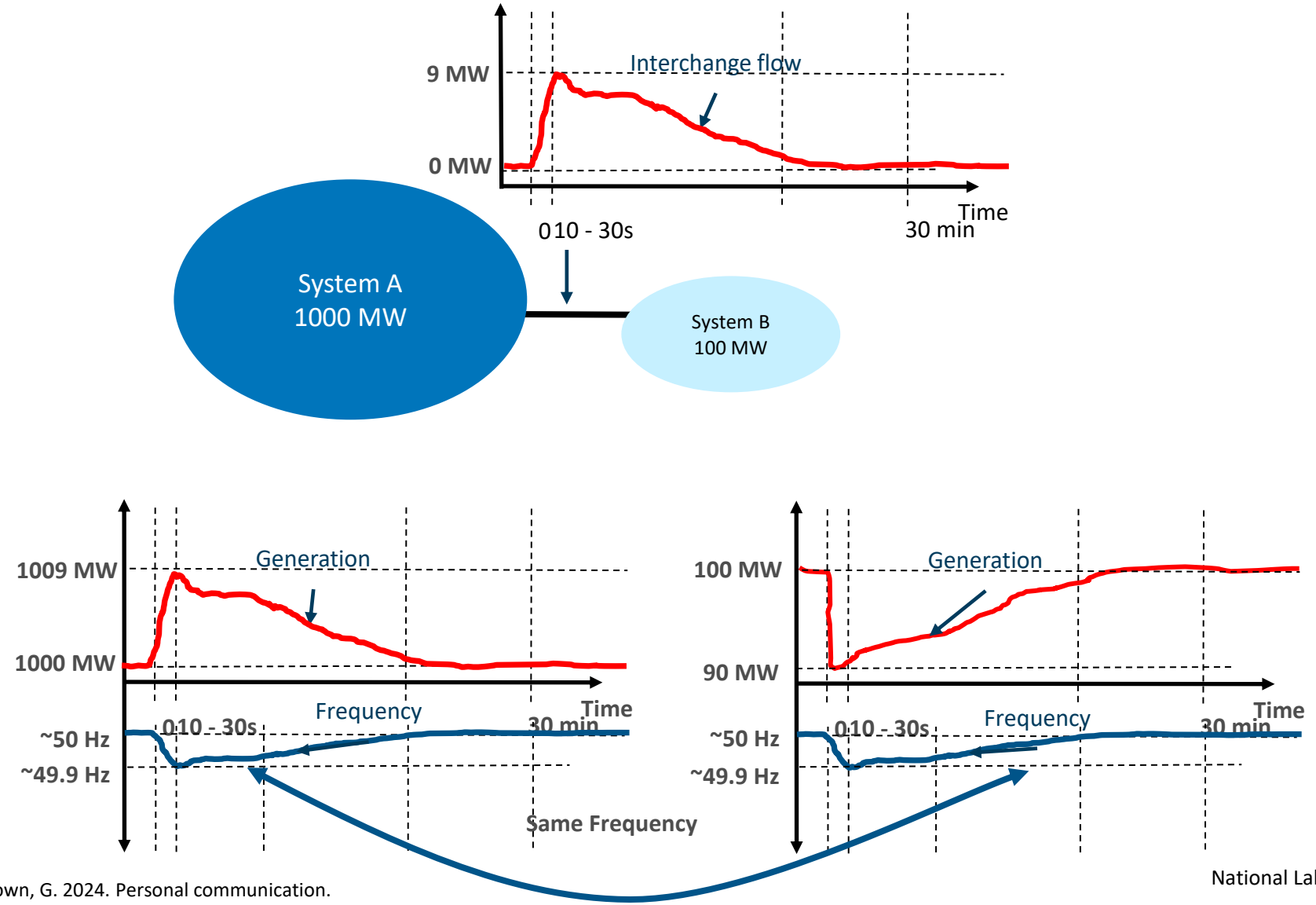
**No change in unaffected system**

System B
100 MW




Source: Derived by NLR from Chown, G. 2024. Personal communication.

# Interconnecting Small System to a Large System



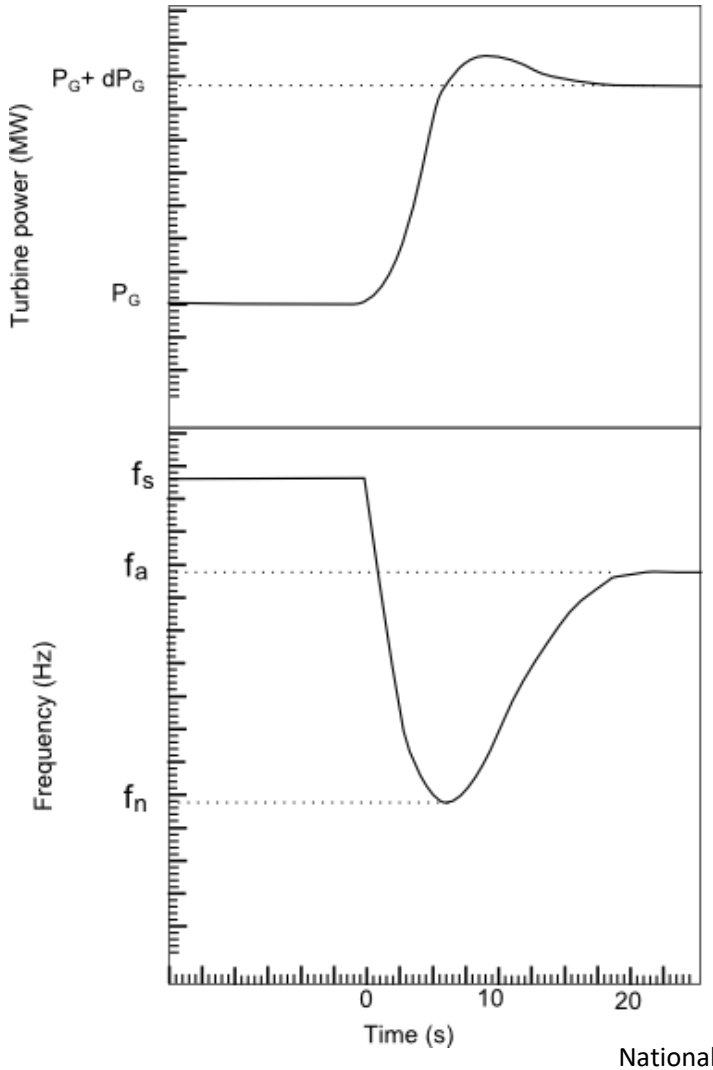

Source: Derived by NRL from Chown, G. 2024. Personal communication.

# Control Strategies: Primary Frequency Control

# Primary Response

- Automatic (governor response)
- Distributed
- Stabilizes system frequency
- Made up of a combination of:
  - » Generator droop responses
  - » Load frequency characteristic (LFC).

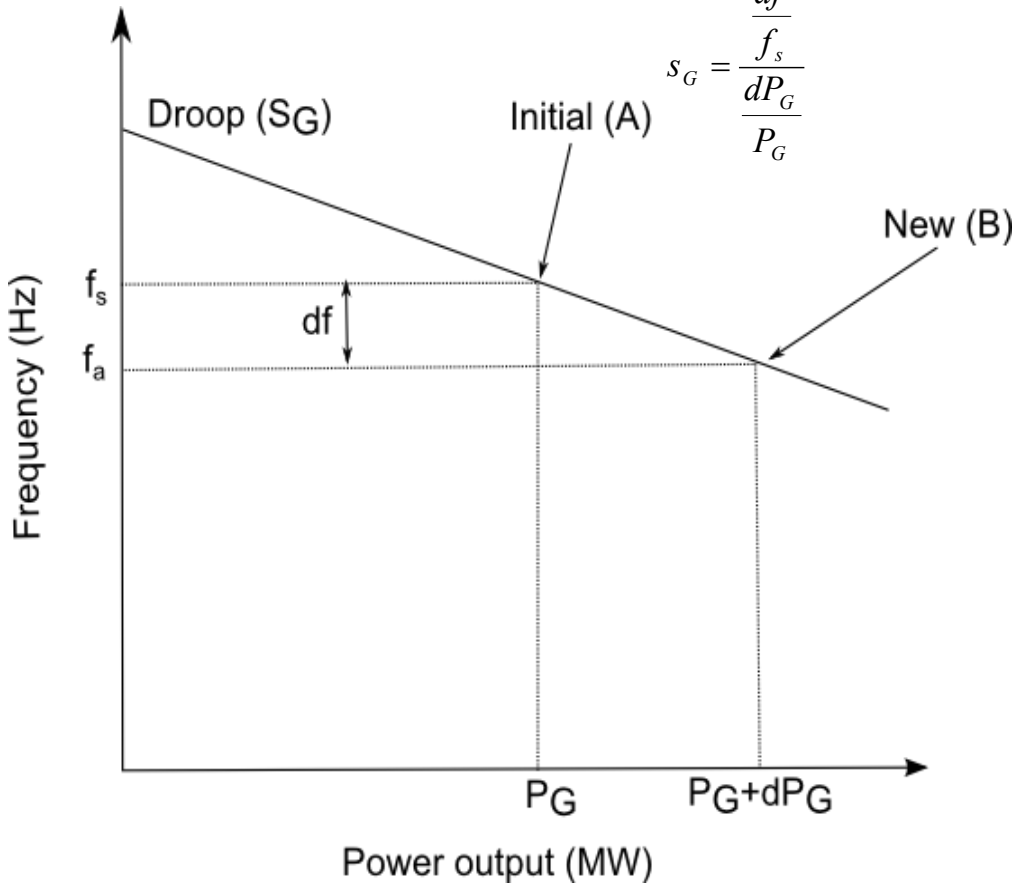
Conceptual primary frequency response following large generator contingency

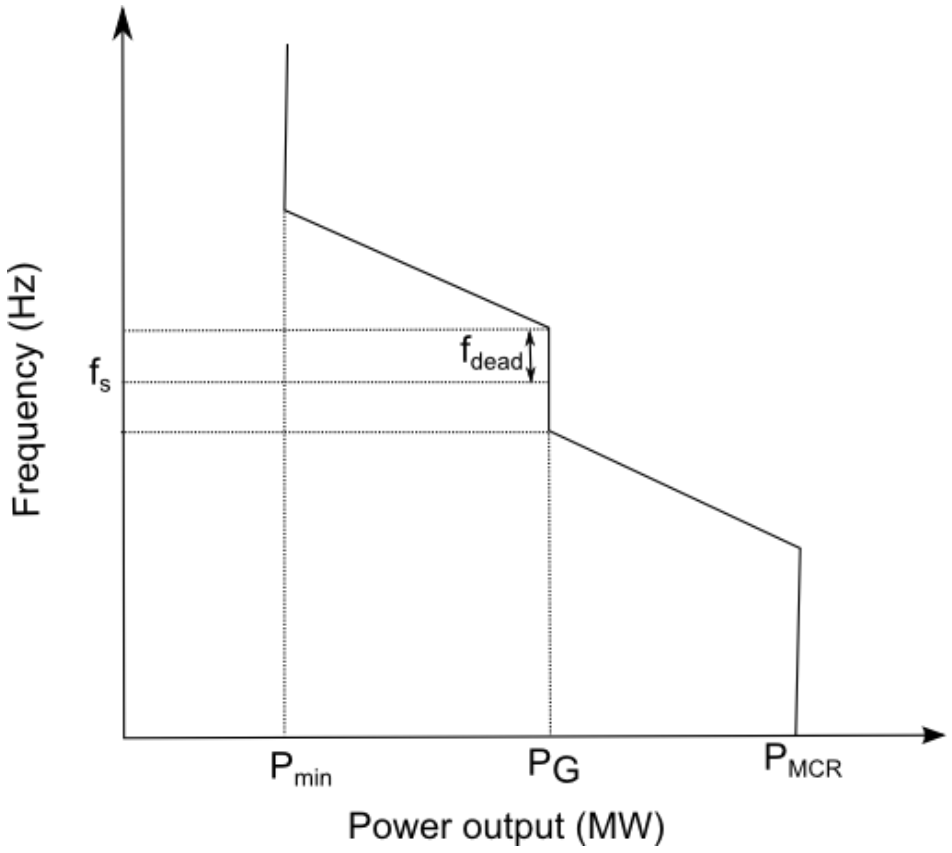


# Primary Frequency Control

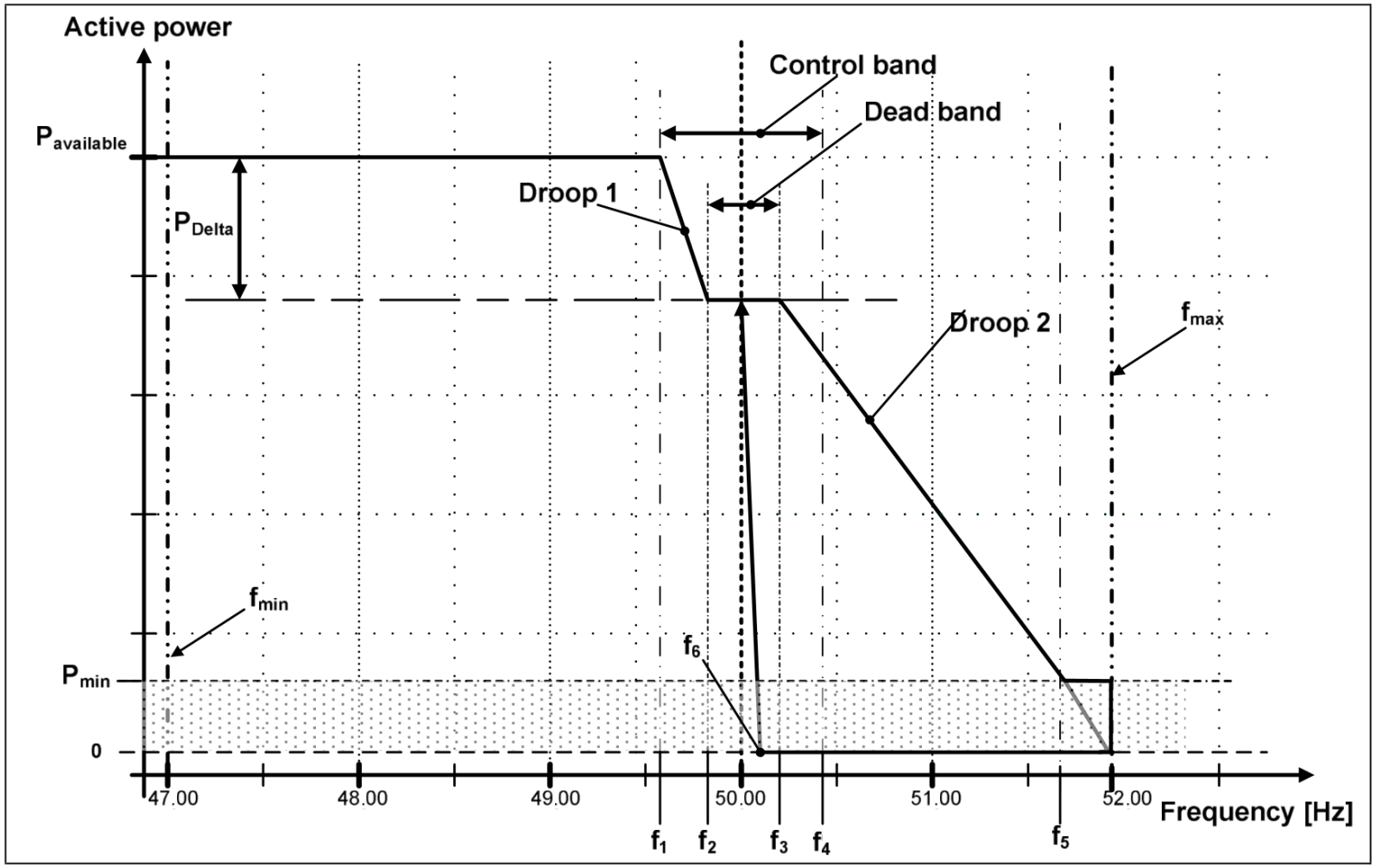
Conceptual illustration of primary response on a droop characteristic without (left) and with (right) deadband

$$s_G = \frac{\frac{df}{f_s}}{\frac{dP_G}{P_G}}$$



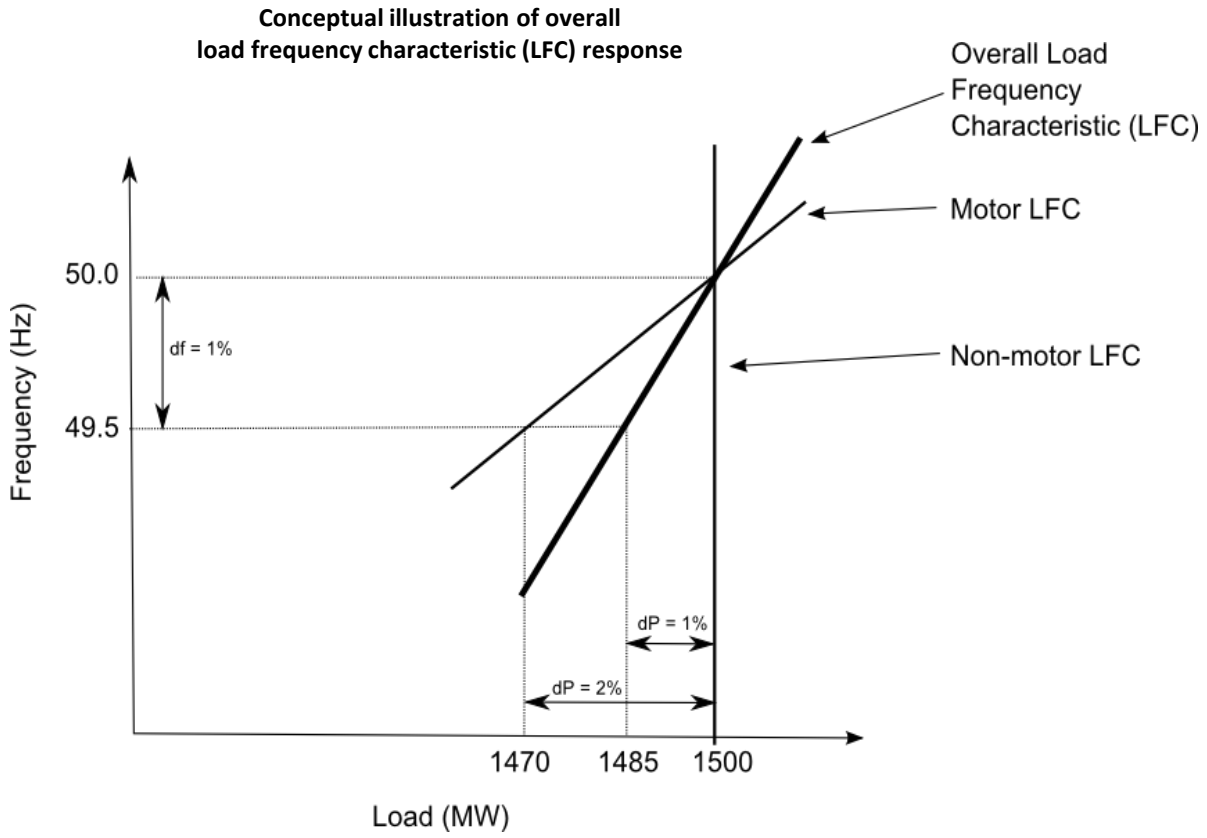
# Primary Frequency Control: Generator Droop Response




Source: Transmission Grid Code (South Africa), 2022, https://www.nersa.org.za/electricity/grid-code

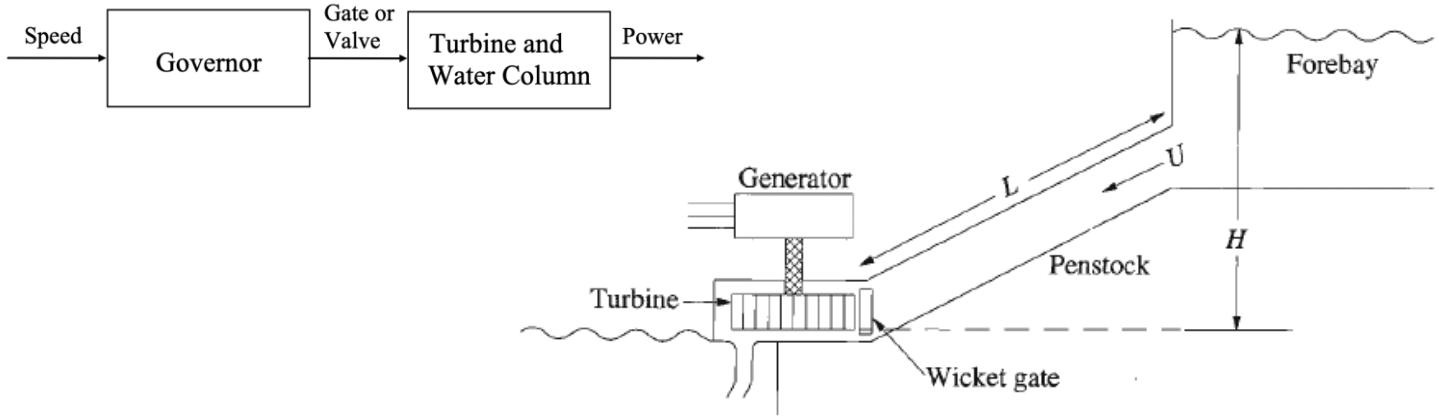
# Load Frequency Characteristic (not load frequency control)

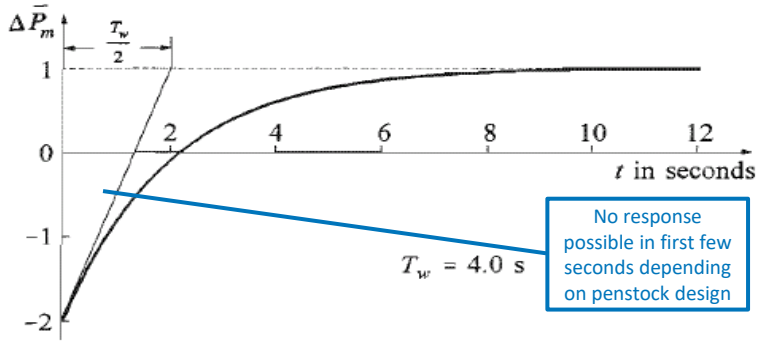
- The load frequency characteristic can be assumed to be quadratic for motor loads and no effect for non-motor loads (EPRI 1998).
- The overall effect can be linearized and assumed to be proportional to the actual demand at the time.
- The slope in the example is 1%, where a 1% drop in frequency will result in a 1% drop in load.




Source: Based on EPRI (1998), Interconnected power system dynamics tutorial

# Primary Frequency Response (Hydro Units)



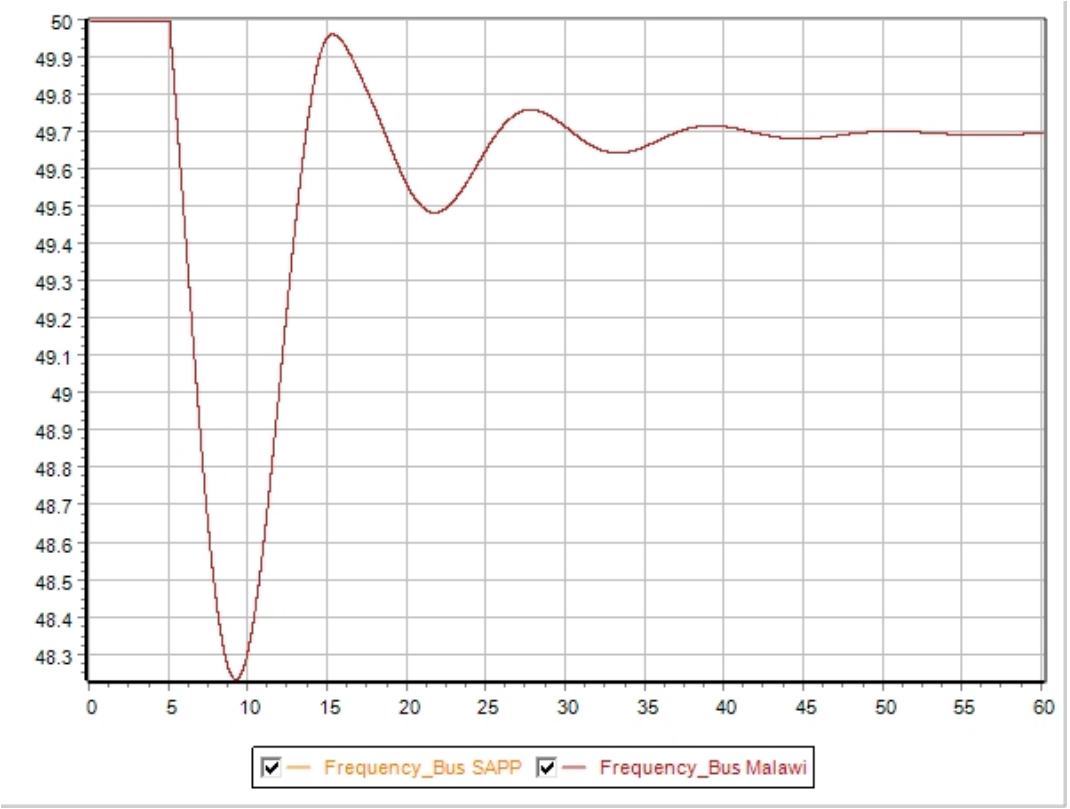



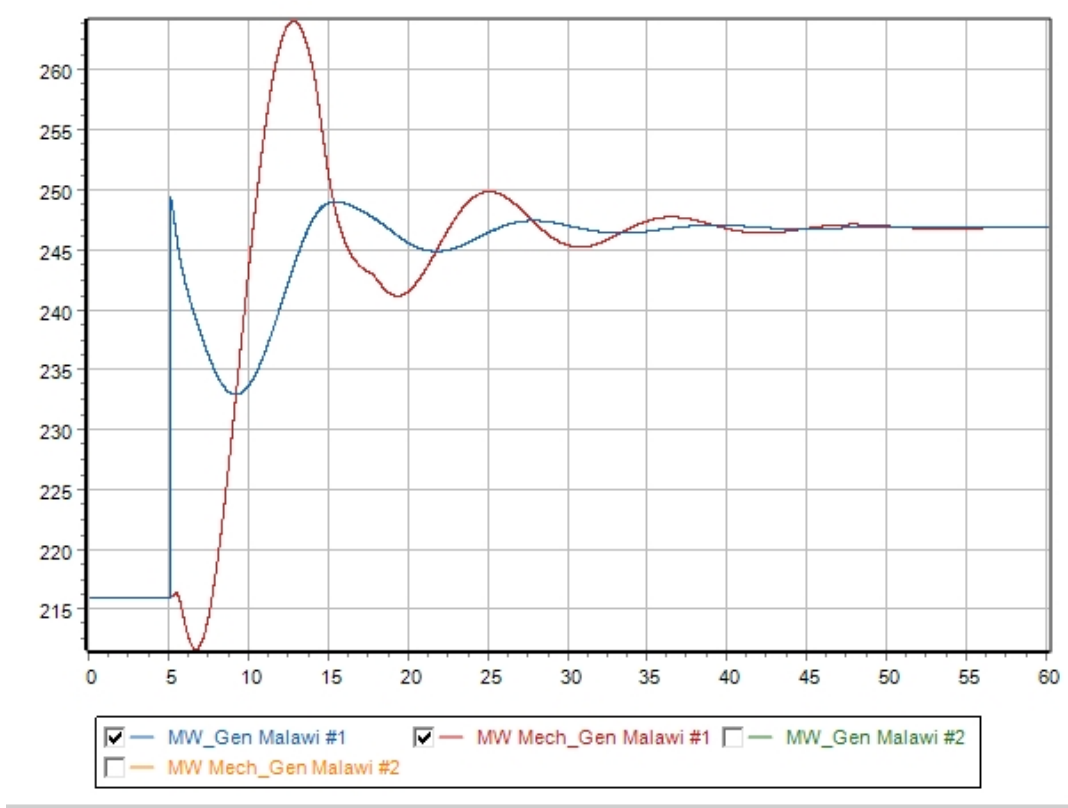

Source: Adjusted from P. Kundur. 1994. *Power System Stability and Control*. McGraw-Hill, 1994.

*Image from EGENCO Malawi (Kapichira Power Station)*

# Primary Frequency Example (Hydro Unit)

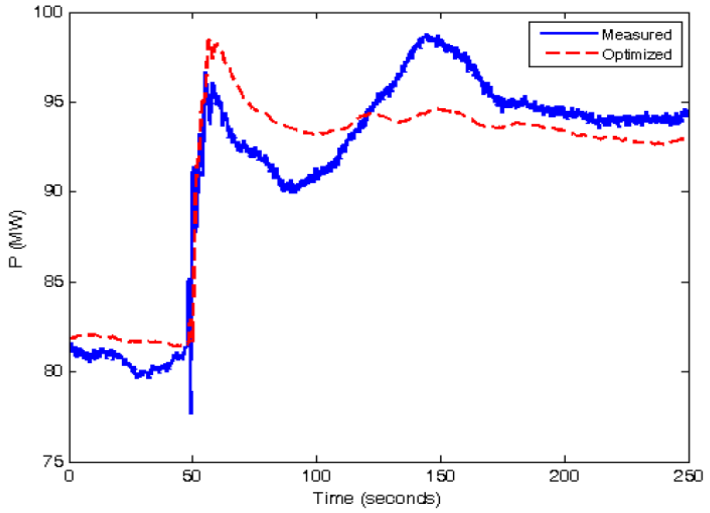
**Example primary frequency trace (left) and overall simultaneous generation response and mechanical power (right) for a generic Malawi power system model with hydro generators on a droop response**



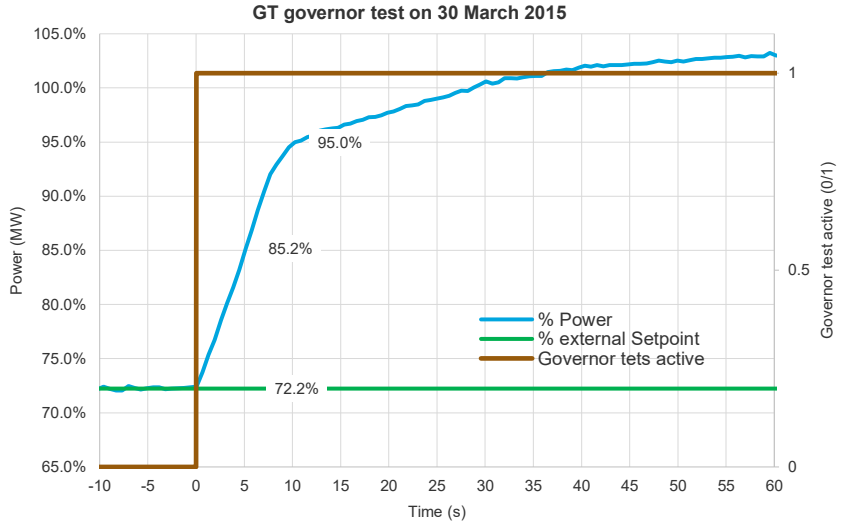
# Primary Frequency Response (Thermal Units)

**Measured response of a heavy-duty gas turbine (in a combined cycle power plant) as compared to the simulated response of the GGOV1 model**




Source: IEEE PES Technical Report PES-TR1, Dynamic Models for Turbine-Governors in Power System Studies (2013)

**Actual GT governor step test (secondary injection)**

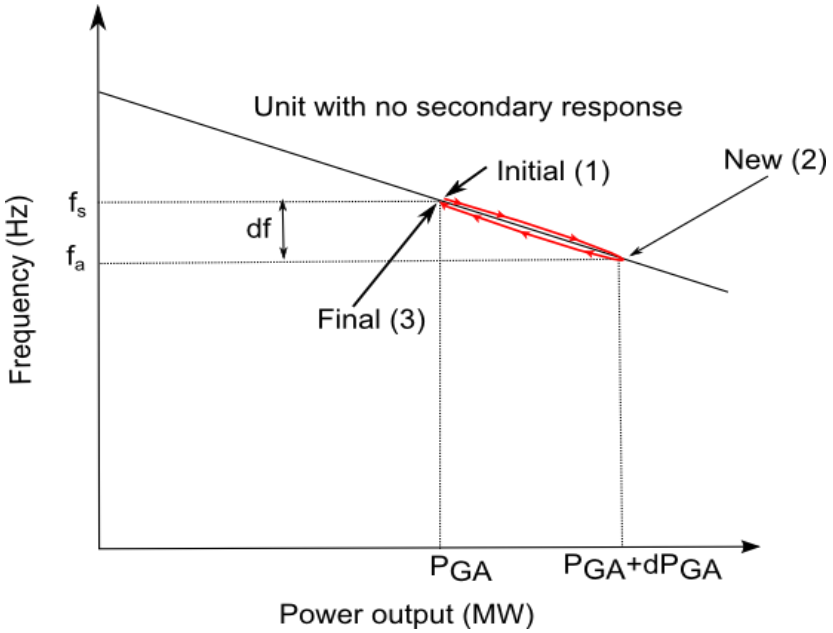


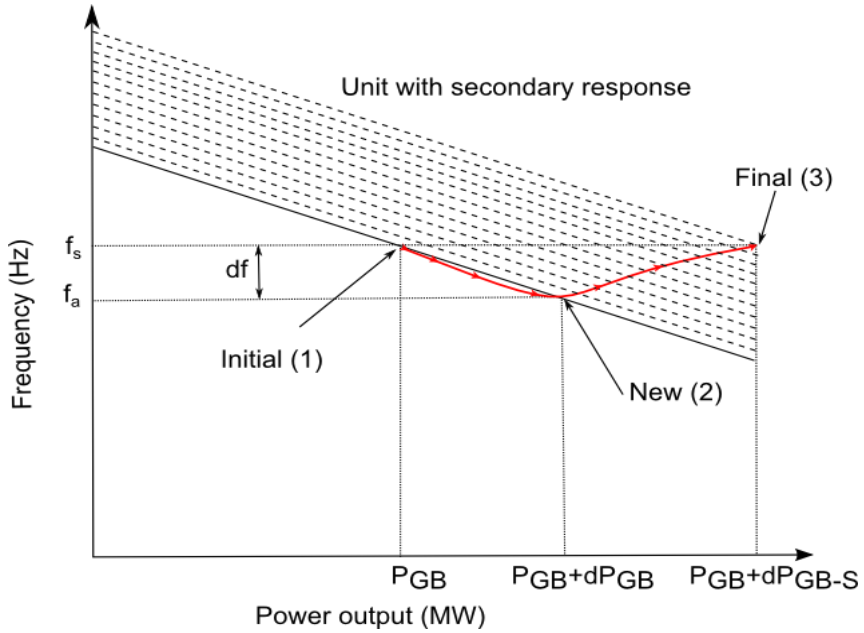

Source: Derived by NLR from Chown, G. 2024. Personal communication

# Control Strategies: Secondary Frequency Control

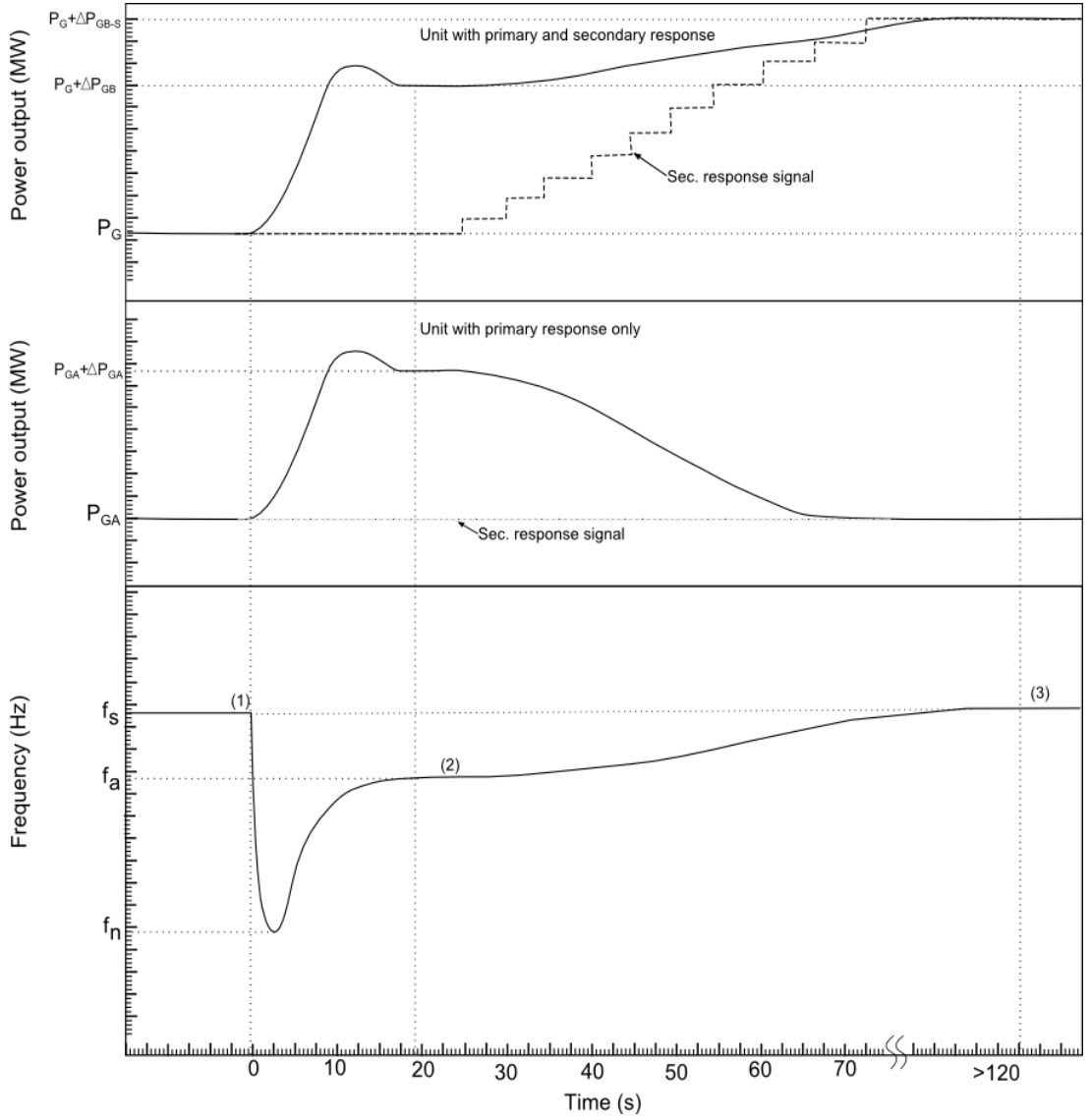
# Secondary Frequency Control

- The response required to restore tie-lines to scheduled set-point values and system frequency to within acceptable range
- Typically, centrally controlled
- Can be automatic (via automatic generation control, AGC) or manual via system operator instruction.



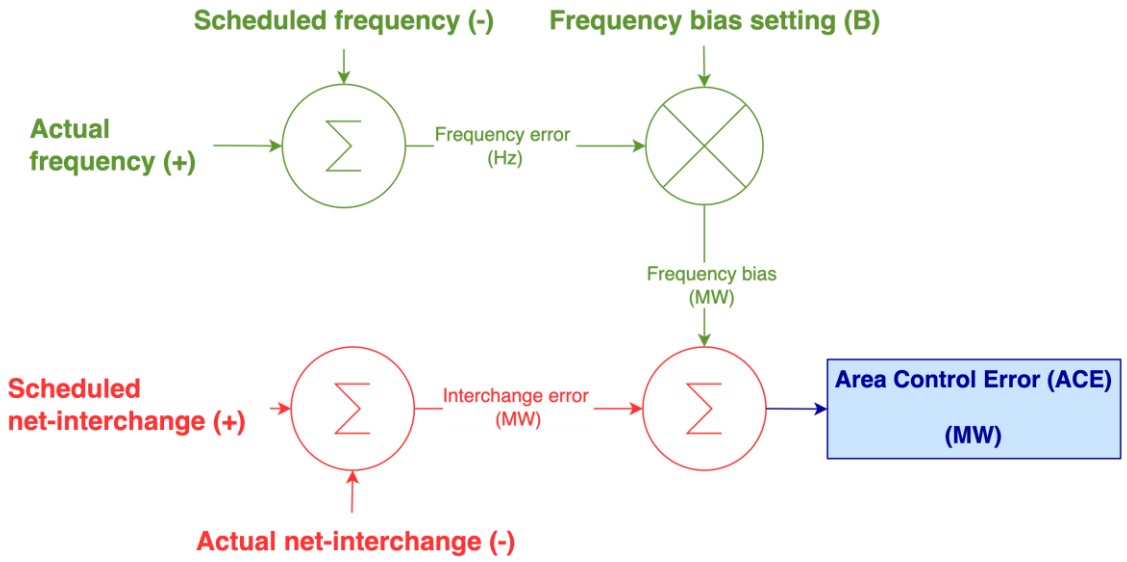
# Secondary Frequency Control



# Secondary Frequency Control (AGC and ACE)

- **Automatic generation control (AGC)** is the automated secondary frequency response tool available to SOs
  - Hold frequency at/close to nominal (50/60 Hz)
  - Maintain scheduled interchanges
  - Maintain unit generation optimally (system-wide).
- AGC operates on a control signal called the **area control error (ACE)** for a control area and is a linear combination of:
  - Deviation of frequency
  - Deviation of tie-line flows.
- ACE is **distributed to resources** through:
  - Participation factors (splitting ACE signal to generators on AGC)
  - "Raise/lower" **pulses** (~4 seconds).

Simplified illustration of AGC control using scheduled/actual frequency (green) and interchange schedule/actual (red) to establish ACE



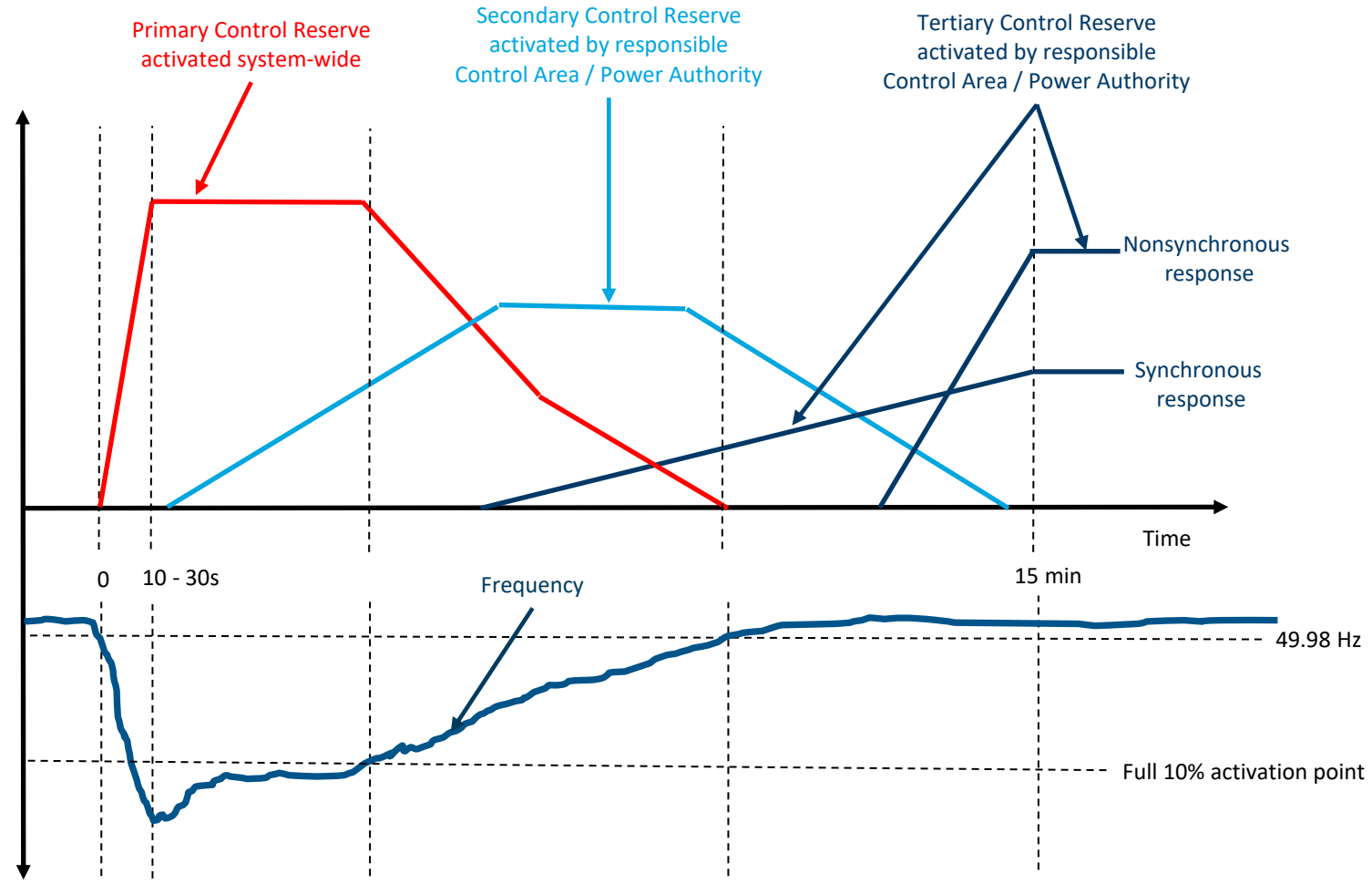

**NOTE:** AGC is a complex multifaceted topic we will not delve further into today.

# Control Strategies: Tertiary Frequency Control

# Tertiary Frequency Control

- **Quantity**
  - Required to restore primary and secondary response and to restore interconnectors back to scheduled values following large mismatches
  - Typically manual response via SO instruction (sometimes automatic via under-frequency starting)
  - Either quick start-up or quick ramp-up
  - Longer time and thus not necessarily required to be synchronized
  - Worst single contingency on own interconnected system.
- **Future**
  - With larger units or additional interconnectors carrying larger amounts of power, these may replace Kapichira as the largest unit contingency.
- **Activation and activation time**
  - Start-up times of existing thermal units and hydro units
  - Slow and thus communications with thermal plants specifically to ascertain accurate start-up and synchronize times as well as ramp-rates to provide tertiary response should be verified.

# Tertiary Frequency Control and Responses




Source: Derived by NLR from Chown, G. 2024. Personal communication.

This presentation was created for electricity sector institutions in Malawi as part of the efforts to establish the Southern Africa Battery Energy Storage Center of Excellence (SABESS CoE), which is supported by the Global Energy Alliance for People and the Planet (The Alliance). For more information about the SABESS CoE, please contact: sabesscoe@mzuni.ac.mw.

# Thank You

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