Integrating Variable Renewables onto the Bulk Power Electricity System

Joe Eto, Sascha Von Meier, and Andrew Mills

Lawrence Berkeley National Laboratory

ETA Journal Club
Berkeley, CA
October 23 and 25, 2019

The “academics” debate

PNAS

Low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes

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Edited by Stephen Polasky, University of Minnesota, St. Paul, MN, and approved November 2, 2015 (received for review May 26, 2015)

PNAS

Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved February 24, 2017 (received for review June 26, 2016)

Including allegations of insufficient power system modeling

"all loads, generation (sited before the LOADMATCH runs and placed precisely where existing generation resides), and storage are summed in a single place. Therefore, those authors do not perform any modeling or analysis of transmission. As a result, their analysis ignores transmission capacity expansion, power flow, and the logistics of transmission constraints (*SI Appendix*, section S2.6).

Similarly, those authors do not account for operating reserves, a fundamental constraint necessary for the electric grid. Indeed, LOADMATCH used in ref. 11 is a simplified representation of electric power system operations that does not capture requirements for frequency regulation to ensure operating reliability (additional details are in *SI Appendix*, section S3).

Including allegations of insufficient power system modeling, cont

"Furthermore, the model is fully deterministic, implying perfect foresight about the electricity demand and the variability of wind and solar energy resources and neglecting the effect of forecast errors on reserve requirements (25). In a system where variable renewable resources make up over 95% of the US energy supply, renewable energy forecast errors would be a significant source of uncertainty in the daily operation of power systems. The LOADMATCH model does not show the technical ability of the proposed system from ref. 11 to operate reliably given the magnitude of the architectural changes to the grid and the degree of uncertainty imposed by renewable resources."

While academics debate, grid operators are managing ever-increasing amounts of variable renewable energy on the gri

Wind breaks a new record in Southwest Power Pool

CURTIS WALTER

APRIL 26, 2019

Print

This past weekend, wind power set a new record in the Southwest Power Pool (SPP), the regional grid that covers most of the midwestern United States. On April 21, wind's share of power generation reached 66.5 percent for the region. According to SPP, wind provided 14,063 megawatts (MW) of its 21,148 MW total load.

The Midcontinent ISO (MISO) is studying how to operate with even larger amounts of variable renewable generation

MISO

Renewable Integration Impact Assessment

Finding integration inflection points of increasing renewable energy

Second Workshop *RIIA Phase 2 Interim Results November 28th, 2018*

MISO's study considers four grid integration topics

Resource Adequacy

Ability to maintain the Planning Reserve Margin (incremental capacity needed)

Energy Adequacy

Ability to operate within generator limits (ramp rate, min up/down time, min/max capacity), transmission limits (ratings), and system limits (energy balance, operating reserves)

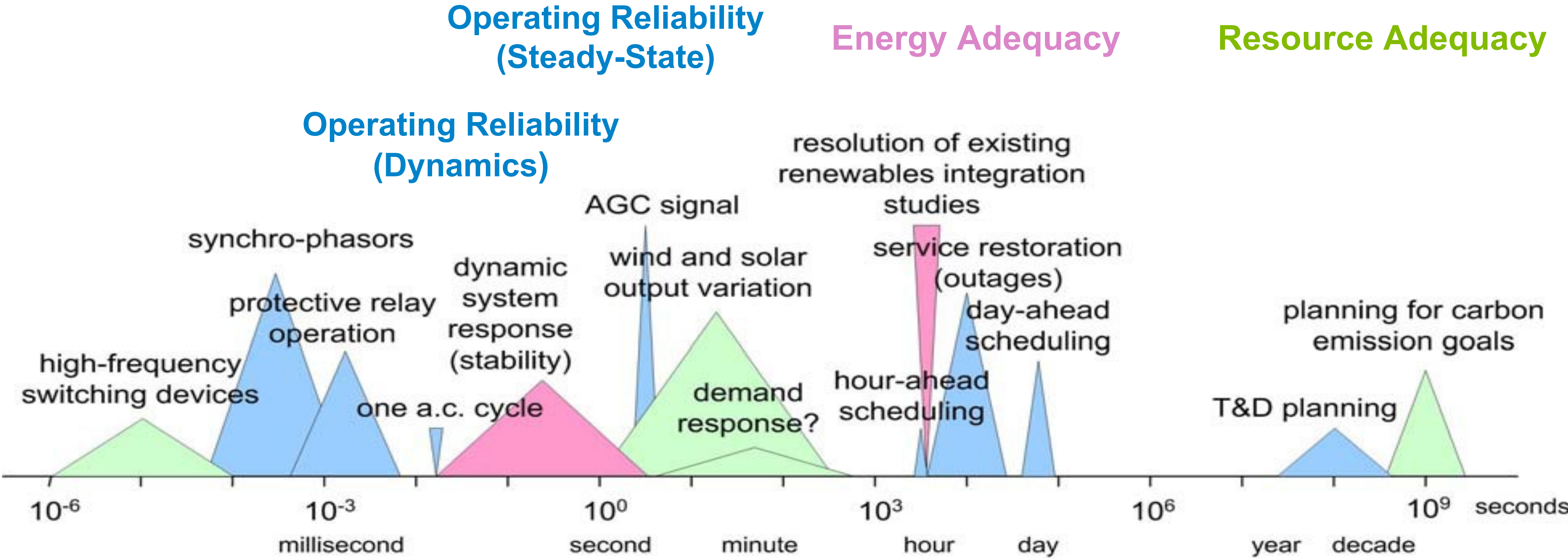
Operating Reliability (Steady-State)

Ability to operate the system within acceptable voltage and thermal limits

Operating Reliability (Dynamics)

Ability to maintain stable frequency and voltage, and meet system performance requirements

Today, we will introduce these topics
On Friday, we will describe MISO's findings



Source: A. von Meier, "Challenges to the Integration of Renewable Resources at High System Penetration," California Energy Commission, May 2014

Intro to Load Frequency Control

Alexandra "Sascha" von Meier

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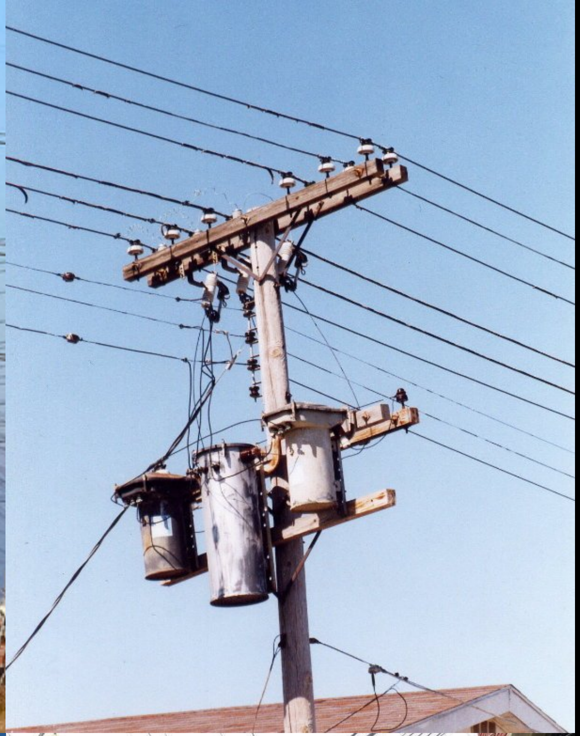


“The electric grid is a system that works in practice, not in theory.”

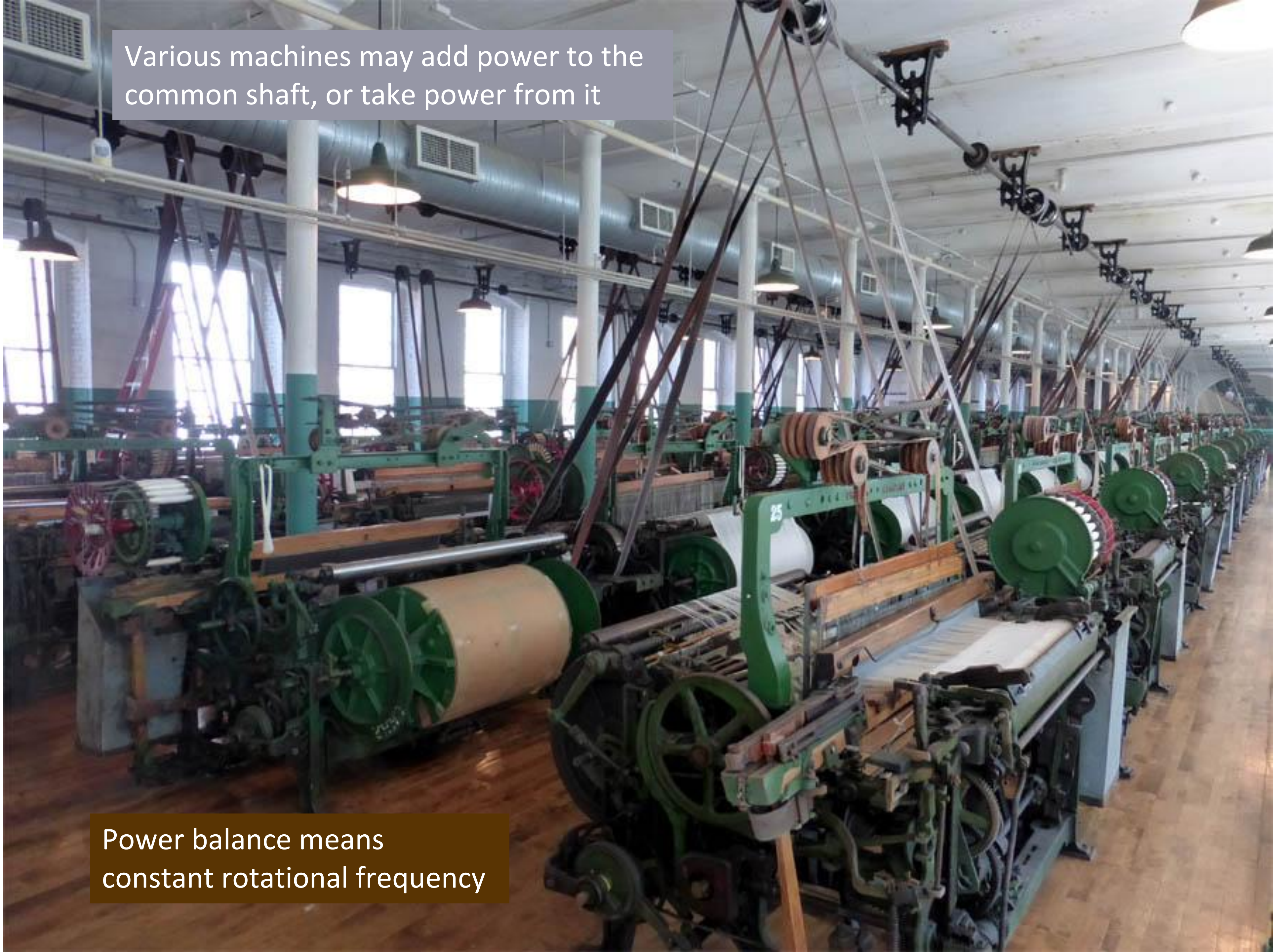
Todd LaPorte

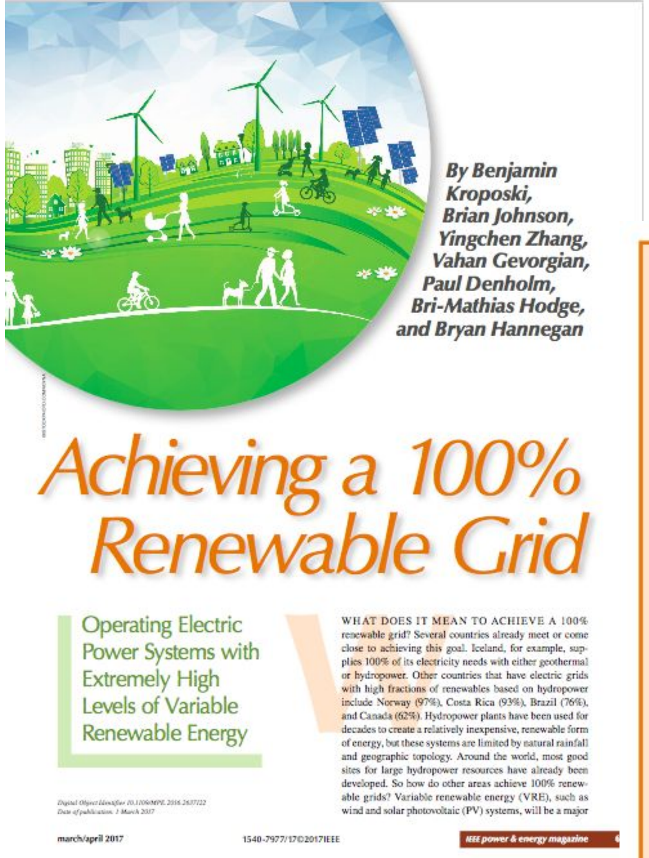
How do we keep power generated = power demanded?

Multiple time scales:

1. Economic decisions: Unit Commitment, Economic Dispatch
   Day-ahead & Hour-ahead markets
2. Fast operational decisions: Load following, frequency regulation services; Automatic Generation Control (AGC) signal
3. Built-in mechanical feedback loops: Generator droop control
4. Built-in electromechanical stability: Rotational inertia

Think about it: This had to work before there were computers, or even reliable communications…


Various machines may add power to the common shaft, or take power from it
Power balance means constant rotational frequency
25



By Benjamin Kroposki, Brian Johnson, Yingchen Zhang, Vahan Gevorgian, Paul Denholm, Bri-Mathias Hodge, and Bryan Hannegan

Achieving a 100% Renewable Grid

Operating Electric Power Systems with Extremely High Levels of Variable Renewable Energy

WHAT DOES IT MEAN TO ACHIEVE A 100% renewable grid? Several countries already meet or come close to achieving this goal. Iceland, for example, supplies 100% of its electricity needs with either geothermal or hydropower. Other countries that have electric grids with high fractions of renewables based on hydropower include Norway (97%), Costa Rica (93%), Brazil (76%), and Canada (62%). Hydropower plants have been used for decades to create a relatively inexpensive, renewable form of energy, but these systems are limited by natural rainfall and geographic topology. Around the world, most good sites for large hydropower resources have already been developed. So how do other areas achieve 100% renewable grids? Variable renewable energy (VRE), such as wind and solar photovoltaic (PV) systems, will be a major

Digital Object Identifier 10.1109/MPE.2016.2637122
Date of publication: 1 March 2017

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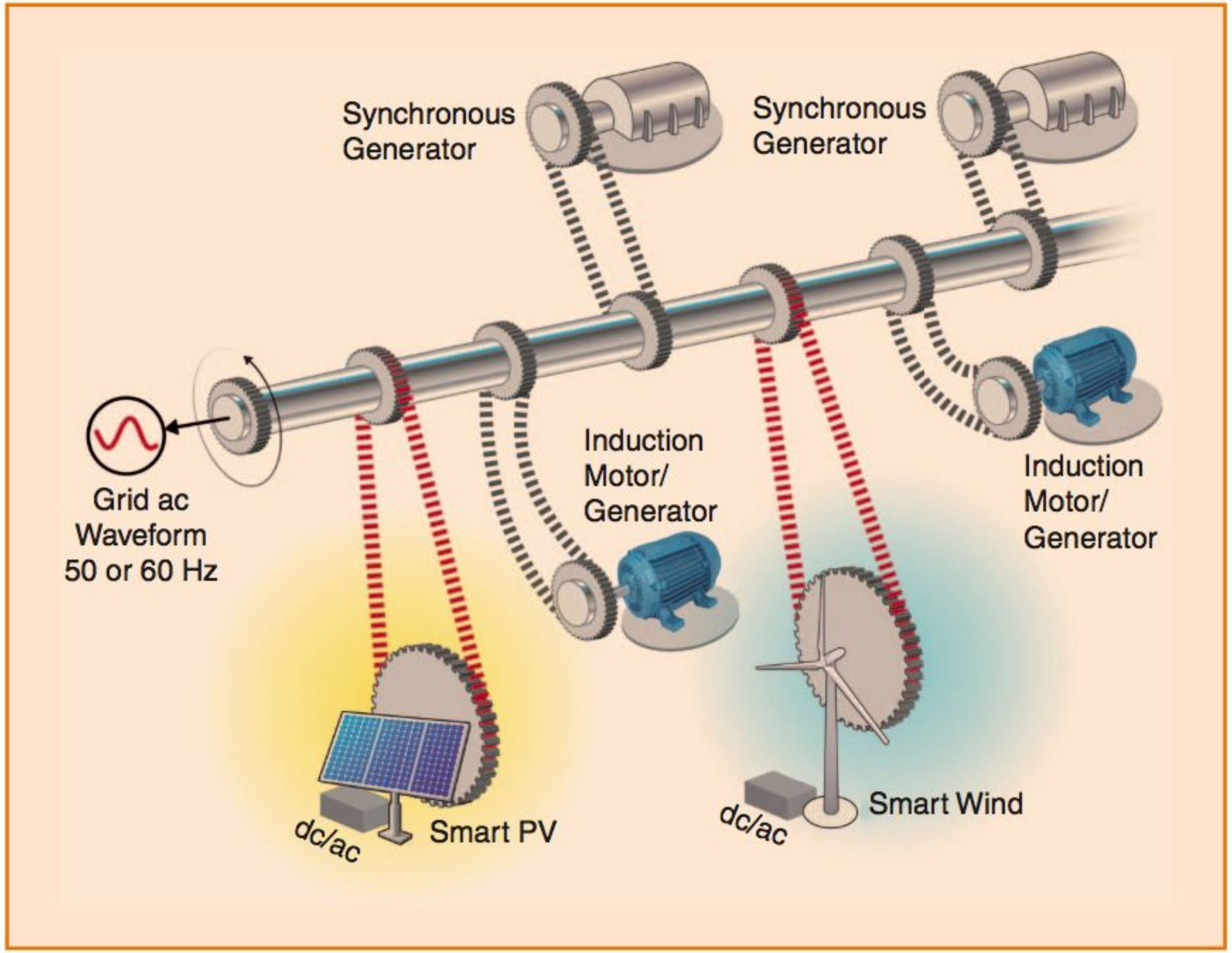
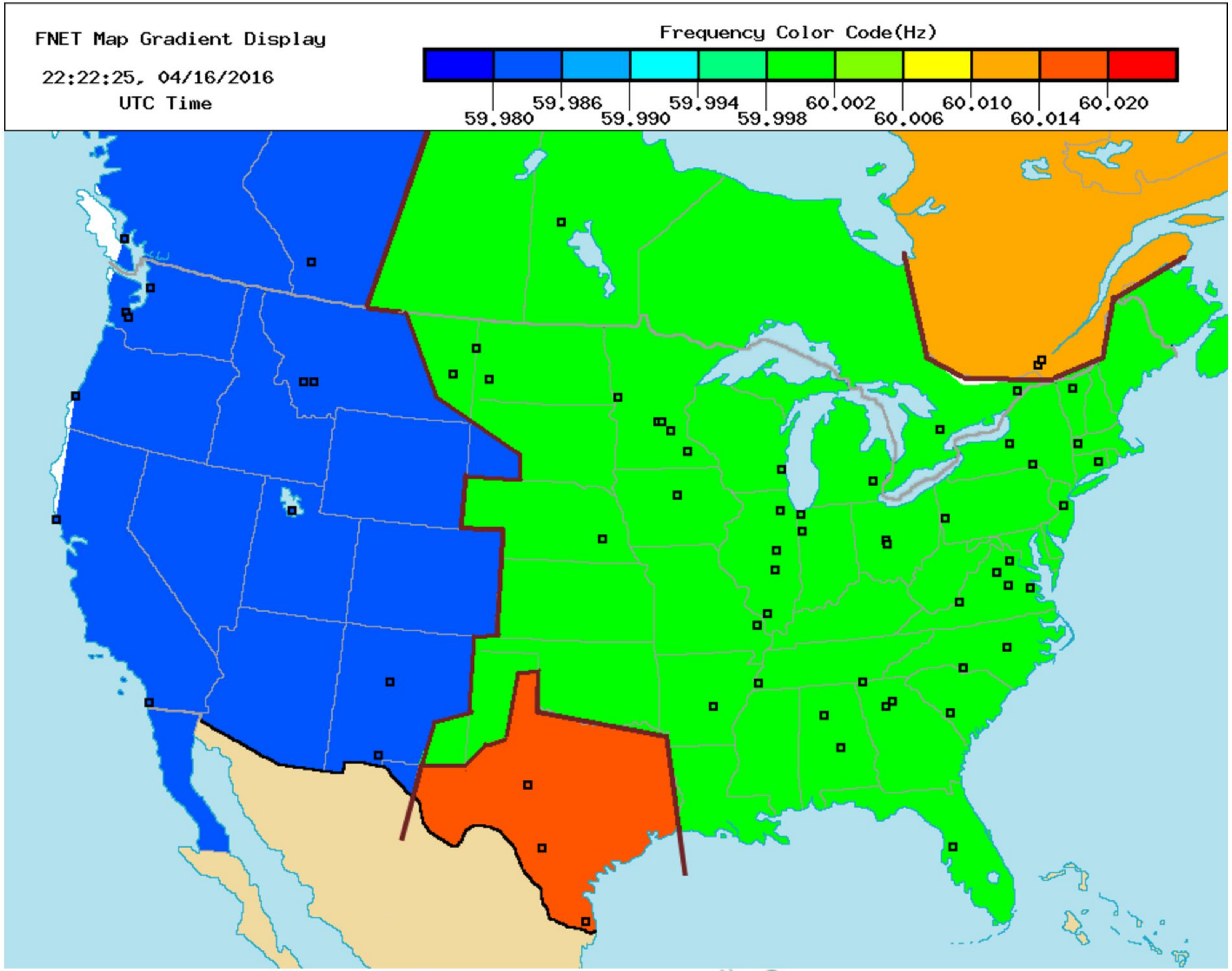


figure 6. The representation of an electric power system showing tight coupling of synchronous generators and smart VRE systems and loose coupling of induction motors/generators.



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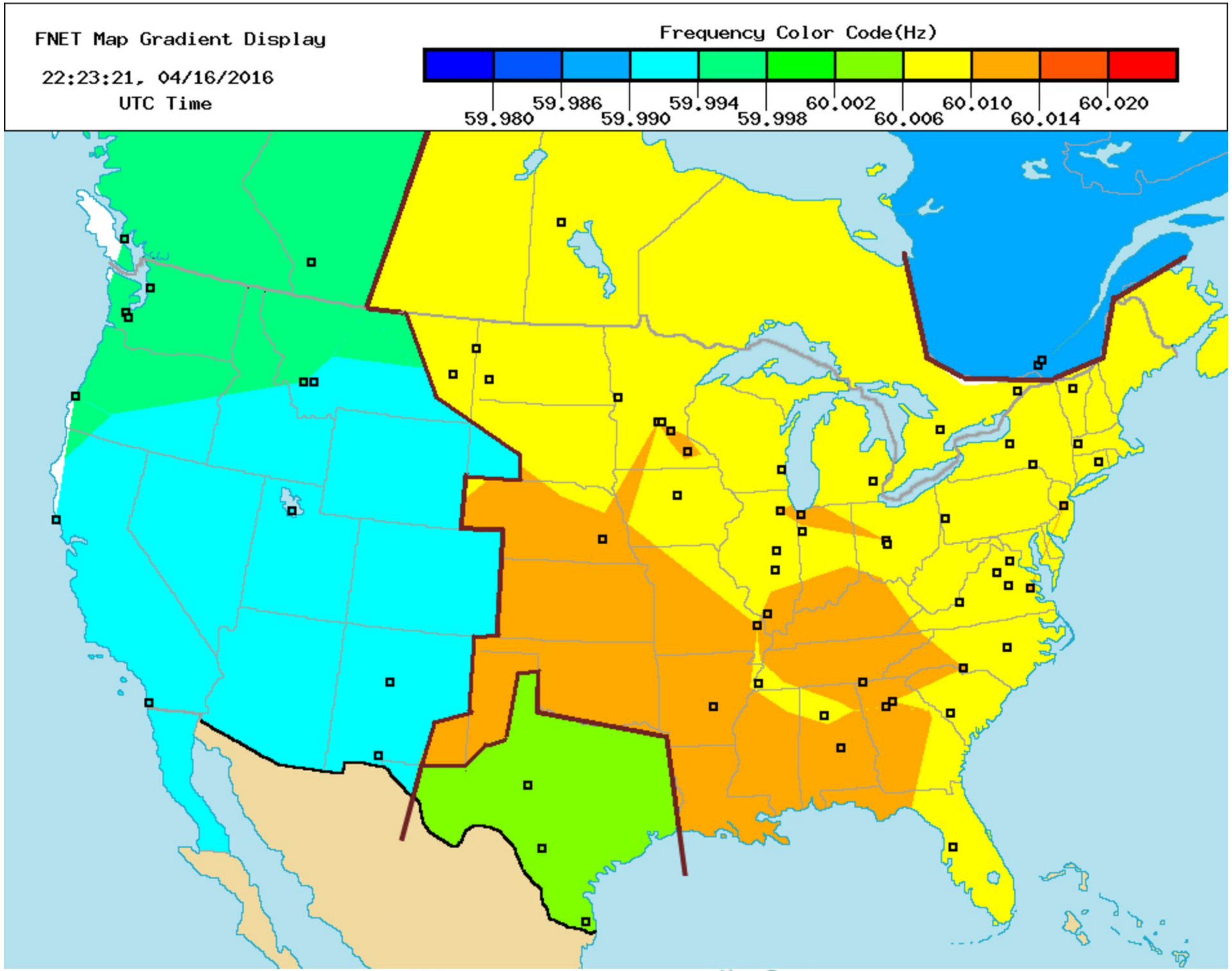


http://fnetpublic.utk.edu/


Local Forecast

Maschinenhaus:
Blick auf
den Turbosatz


Batesville (LS Power)

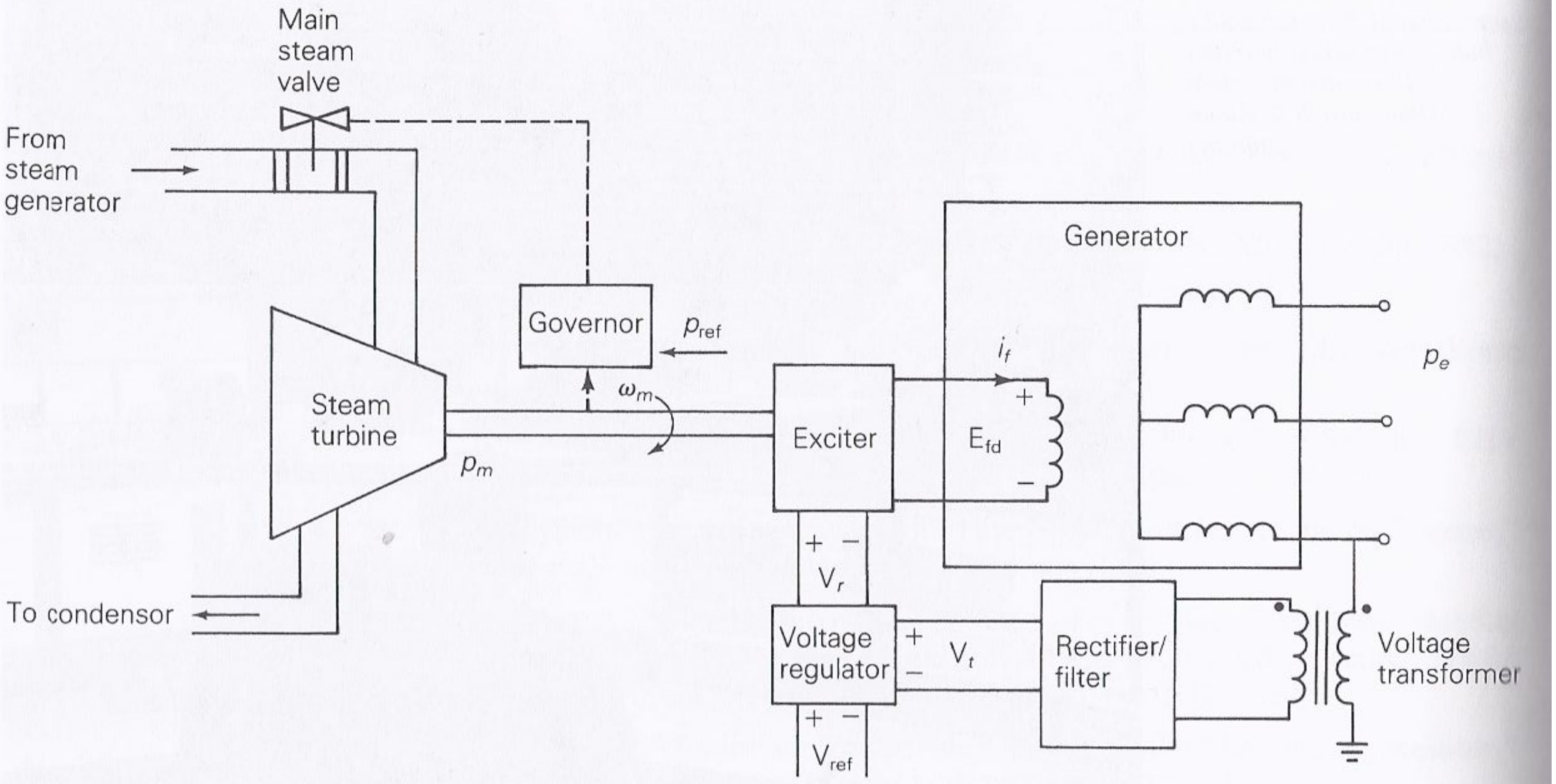


FIGURE 12.1 Voltage regulator and turbine-governor controls for a steam-turbine generator

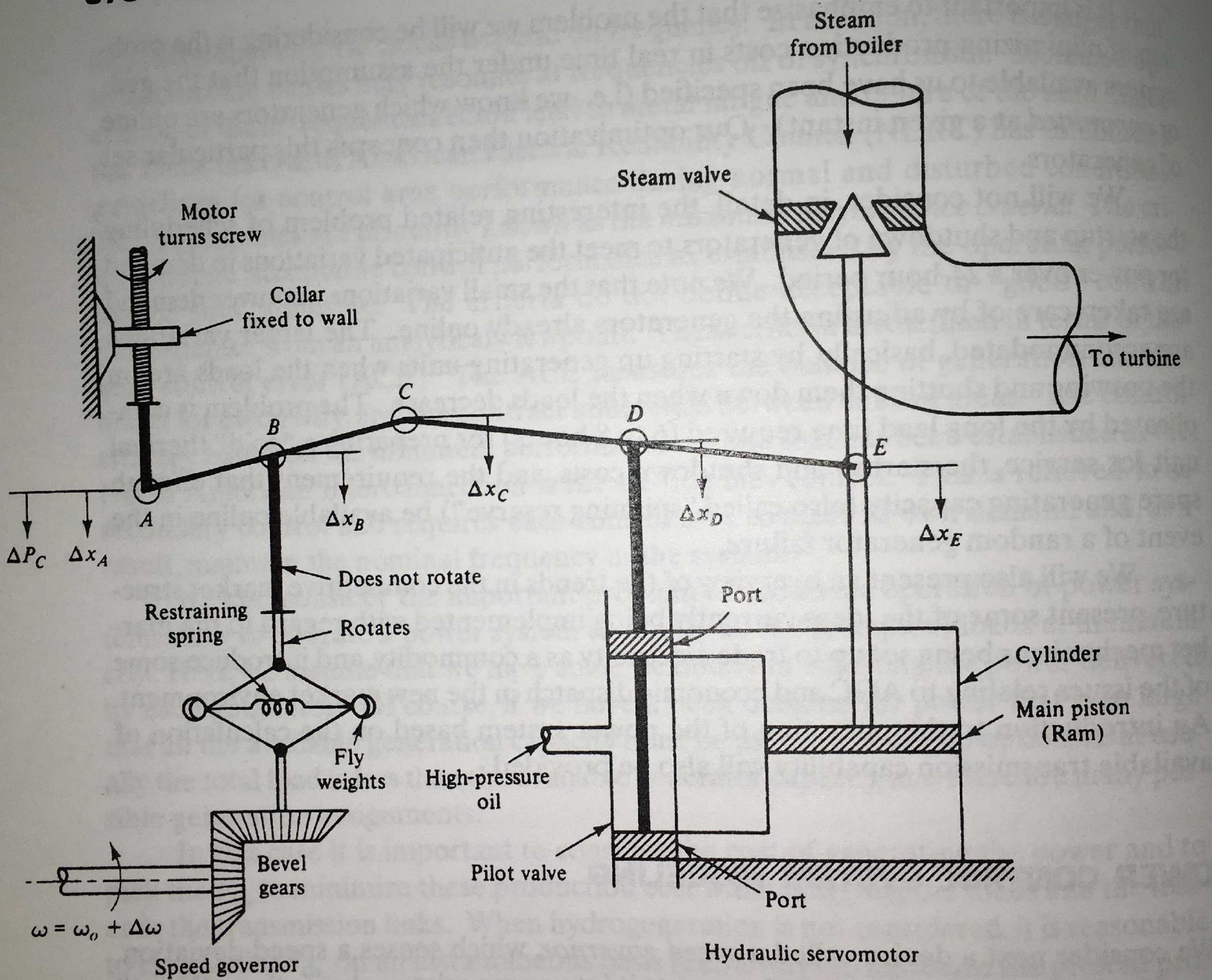


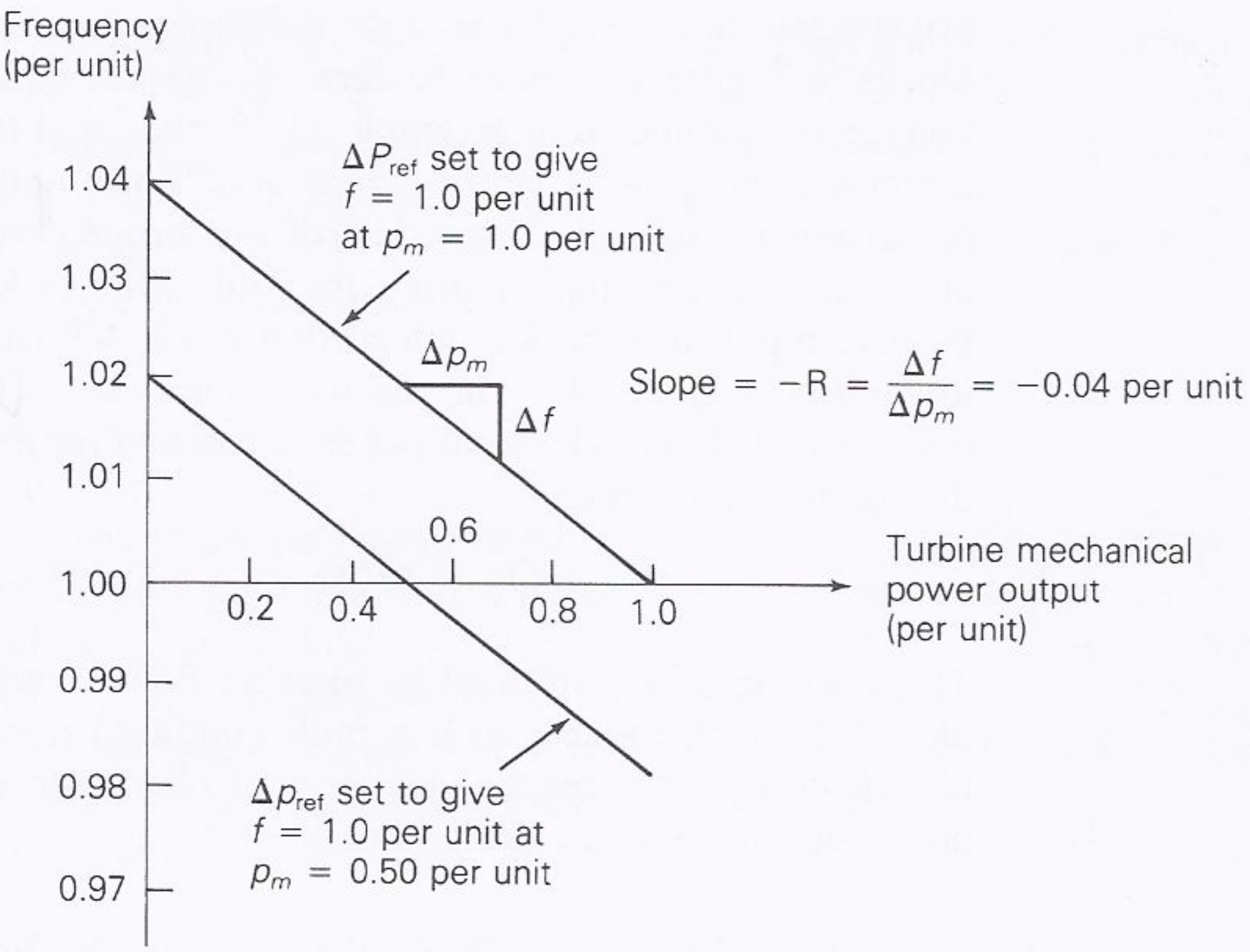
Figure 11.1 Servo-assisted speed governor.

The Droop Curve

assigns a slope and desired power setting to the generator governor
so it will increase power if frequency is slow, decrease power when frequency is high

FIGURE 12.8

Steady-state frequency–power relation for a turbine-governor



from Glover, Overbye & Sarma, Electric Power Systems Analysis

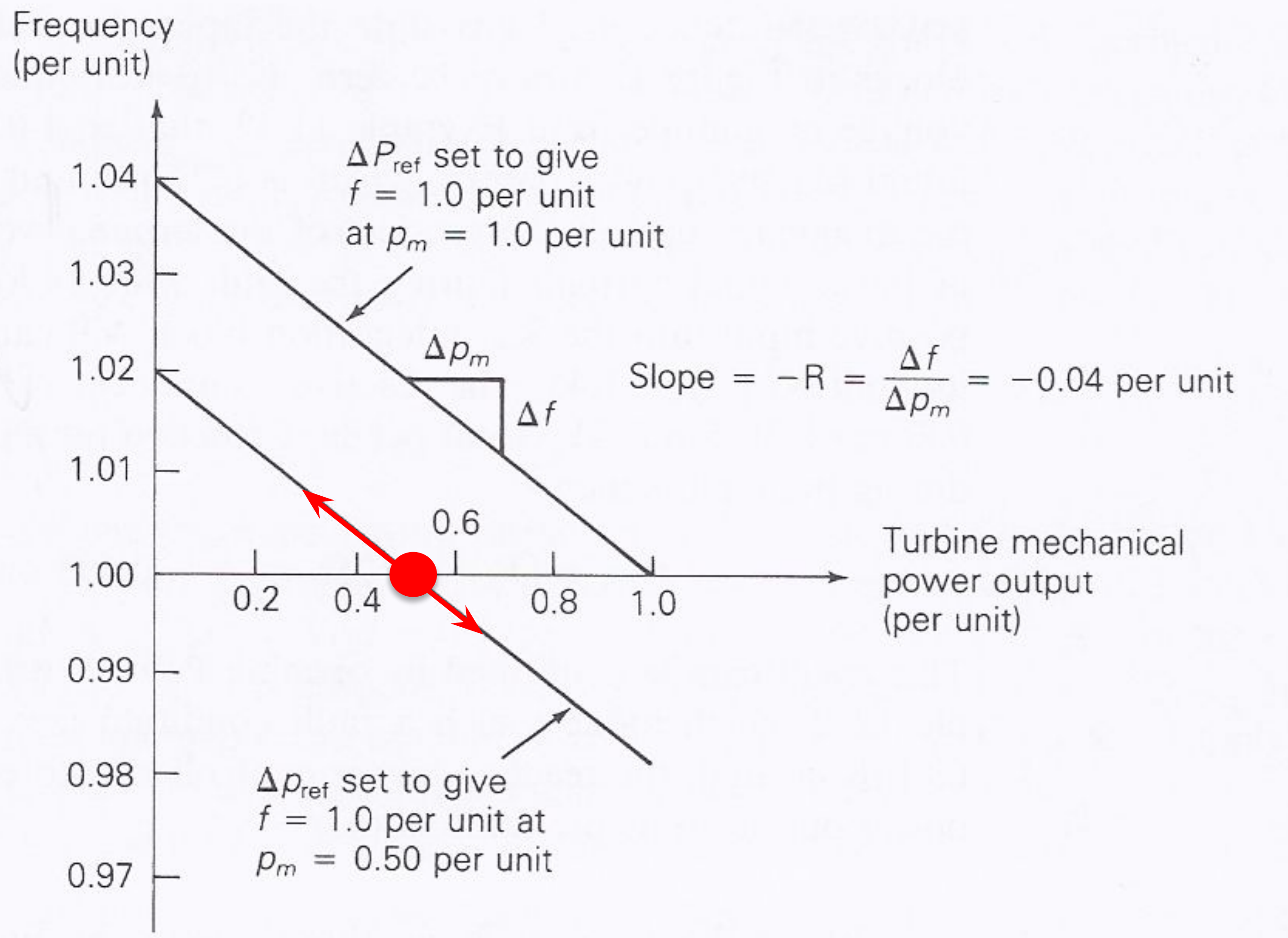
Step 1: Primary frequency control

Operating point moves up or down the droop curve

This stabilizes system frequency by making generation = load

FIGURE 12.8

Steady-state frequency–power relation for a turbine-governor



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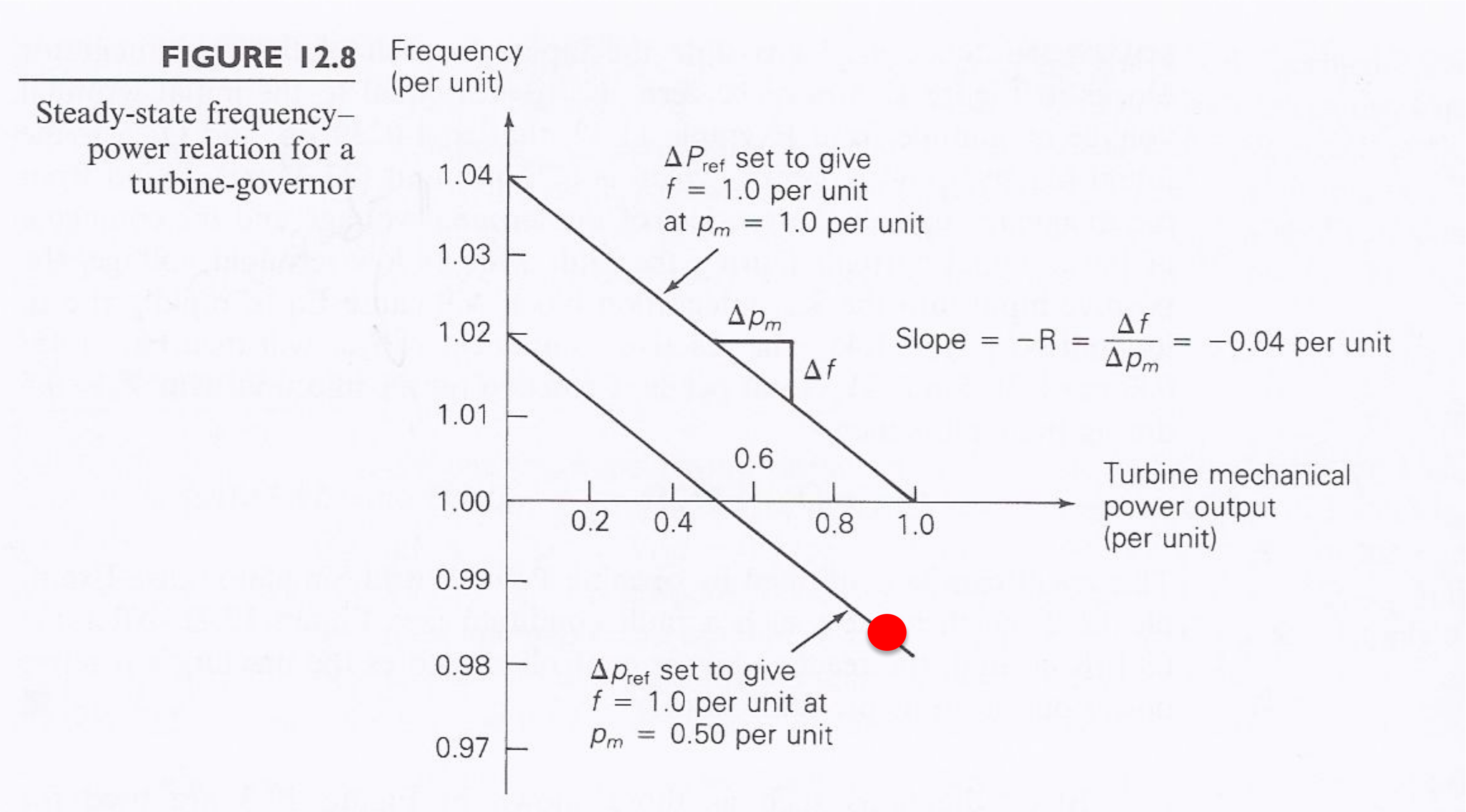

from Glover, Overbye & Sarma, Electric Power Systems Analysis

Step 2: Supplementary frequency regulation

slowly changes set-points to return frequency to nominal value while continuing to meet the new load condition

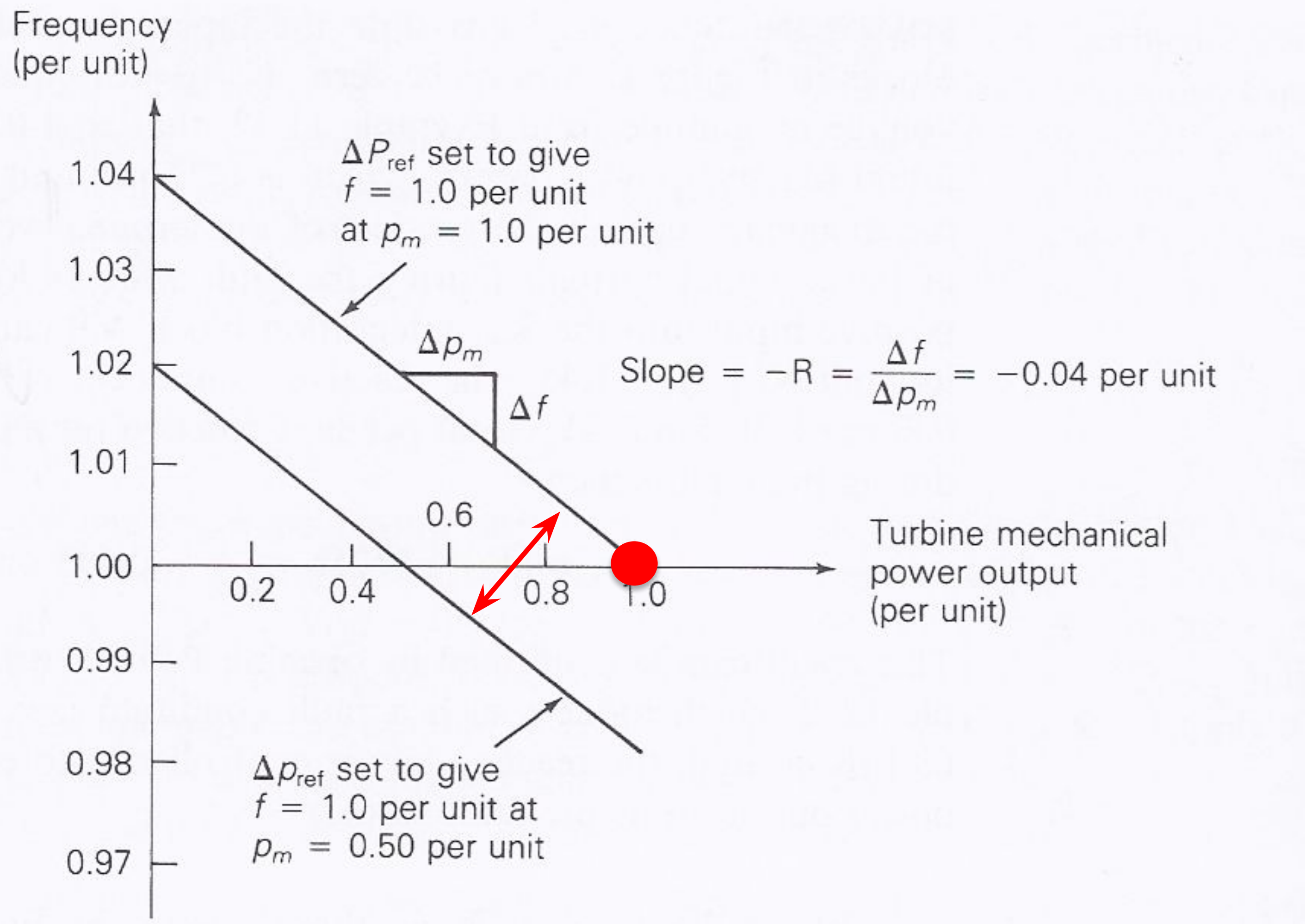

FIGURE 12.8 Steady-state frequency–power relation for a turbine-governor

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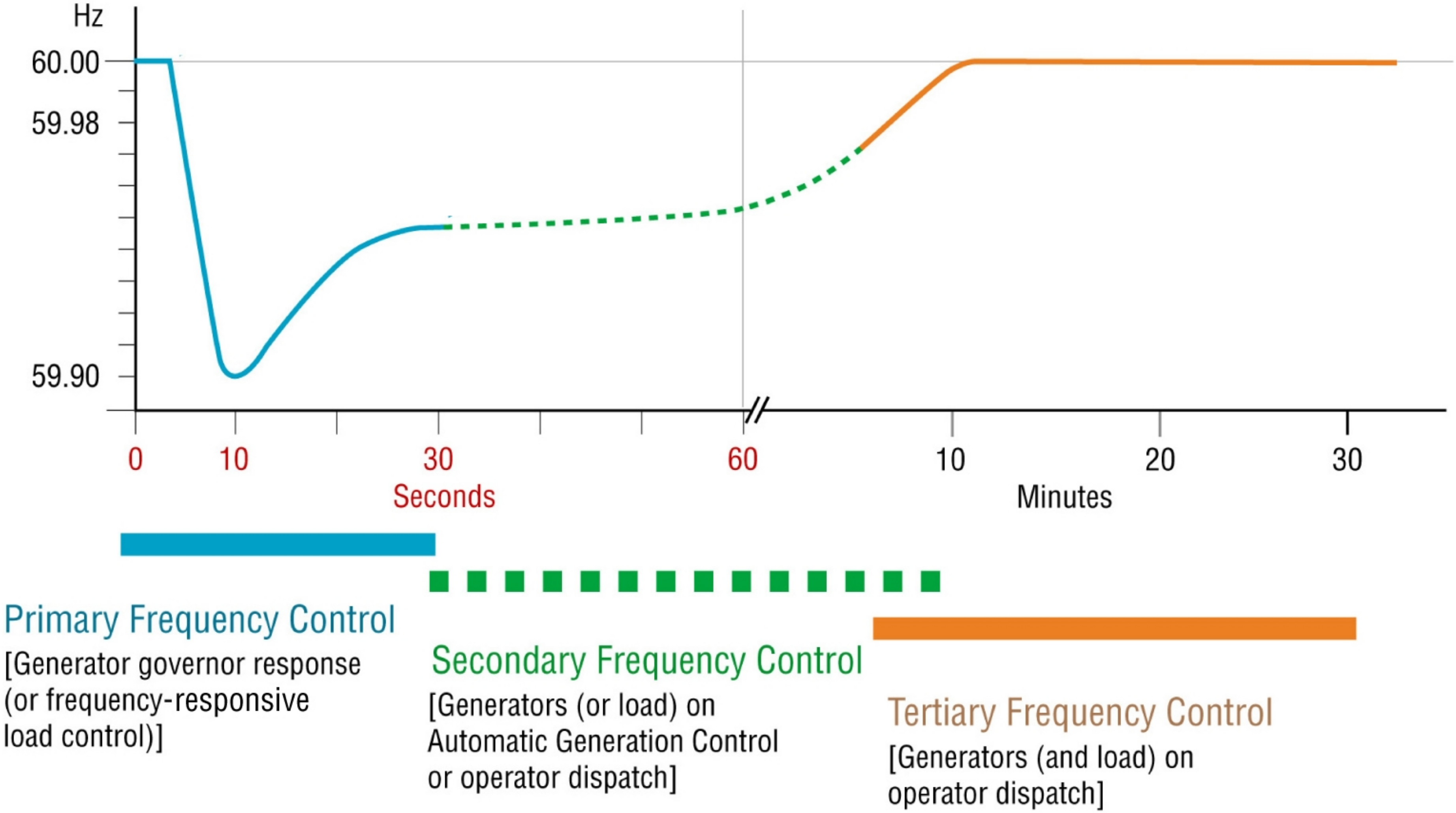

Hz
60.00
59.98
59.90
0
10
30
60
Seconds
10
20
30
Minutes
Primary Frequency Control
[Generator governor response (or frequency-responsive load control)]
Secondary Frequency Control
[Generators (or load) on Automatic Generation Control or operator dispatch]
Tertiary Frequency Control
[Generators (and load) on operator dispatch]

Load Frequency Control

How to decide what new setting to choose for each generator?

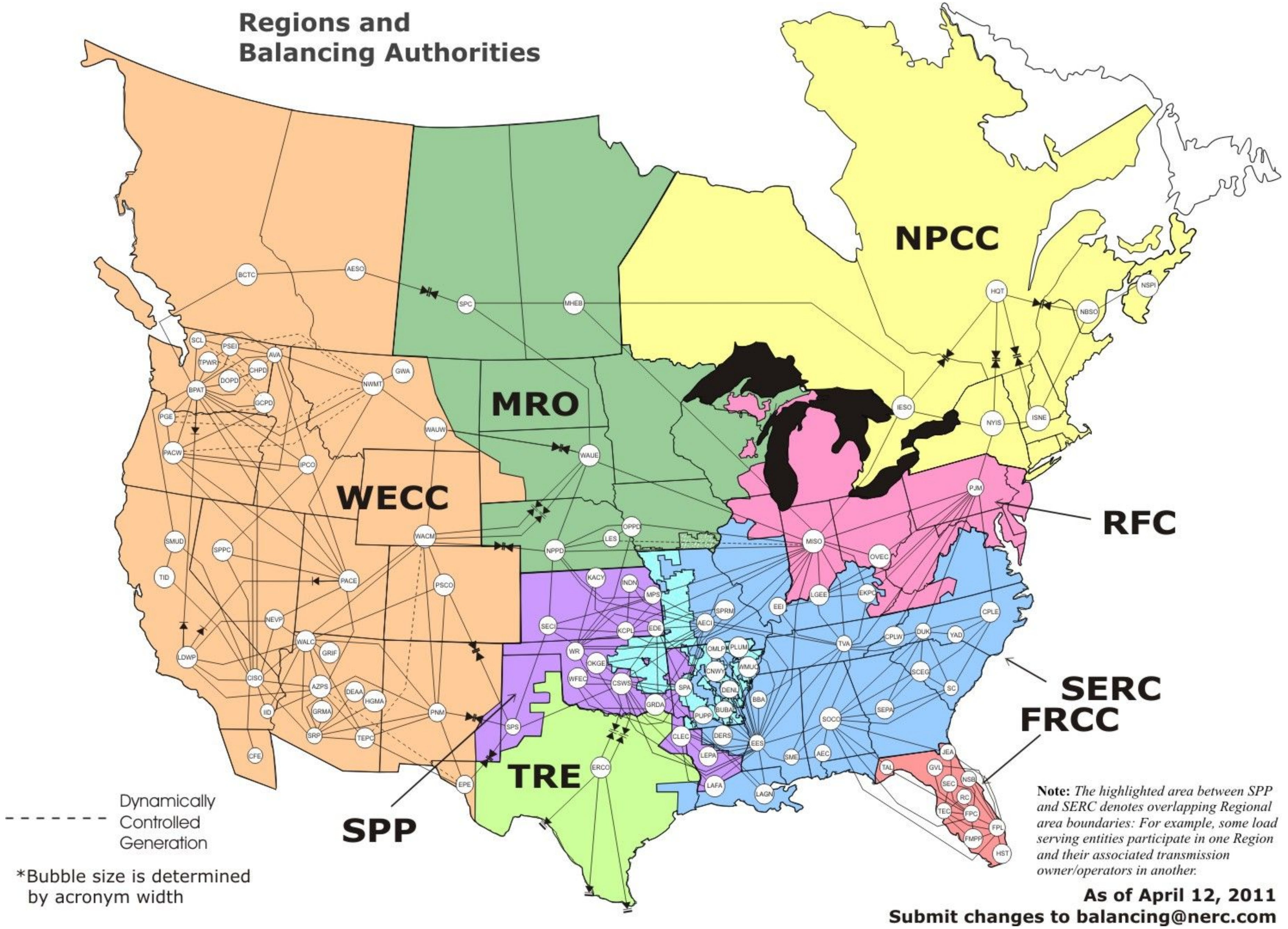
Take into account:

- how much contribution is desired from each generator based on economic considerations
- desired and undesired tie-line flows (transfers) between adjacent balancing authorities.

Can a person do this?

Not really.

Automatic Generation Control (AGC) *includes*
Load Frequency Control *and* ***Economic Dispatch****.*
AGC signals are sent to generators in several-second intervals, whether for purposes of frequency control or economics.


Regions and Balancing Authorities
WECC
MRO
NPCC
RFC
SERC
FRCC
SPP
TRE
BCTC
AESO
SPC
MHEB
HQT
NSPI
NBSO
IESO
NYIS
ISNE
PJM
MISO
OVEC
SCL
PSEI
AVA
TPWR
CHPD
DOPD
BPAT
GCPD
GWA
NWMT
PGE
WAUW
PACW
IPCO
WAUE
SMUD
SPPC
WACM
TID
PACE
PSCO
NEVP
WALC
GRIF
LDWP
CISO
AZPS
DEAA
HGMA
IID
SRP
TEPC
GRMA
PNM
CFE
EPE
SPS
ERCO
NPPD
LES
OPPD
KACY
INDN
MPS
SECI
KCPL
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WMUC
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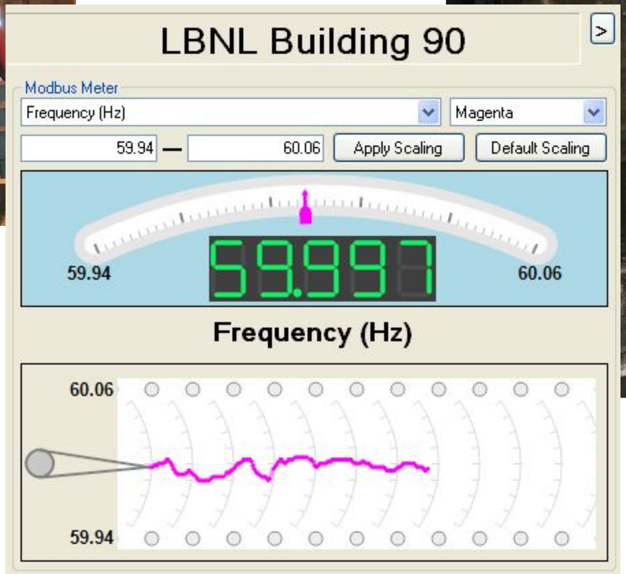
PUPP
BBA
CLEC
DERS
LEPA
LAFA
LAGN
EES
SME
AEC
SOCO
SEPA
TVA
EEI
LGEE
EKPC
CPLE
DUK
YAD
CPLW
SCEG
SC
JEA
TAL
GVL
SEC
NSB
RC
TEC
FPC
FPL
FMPP
HST
Dynamically Controlled Generation
*Bubble size is determined by acronym width
Note: The highlighted area between SPP and SERC denotes overlapping Regional area boundaries: For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.
As of April 12, 2011
Submit changes to balancing@nerc.com

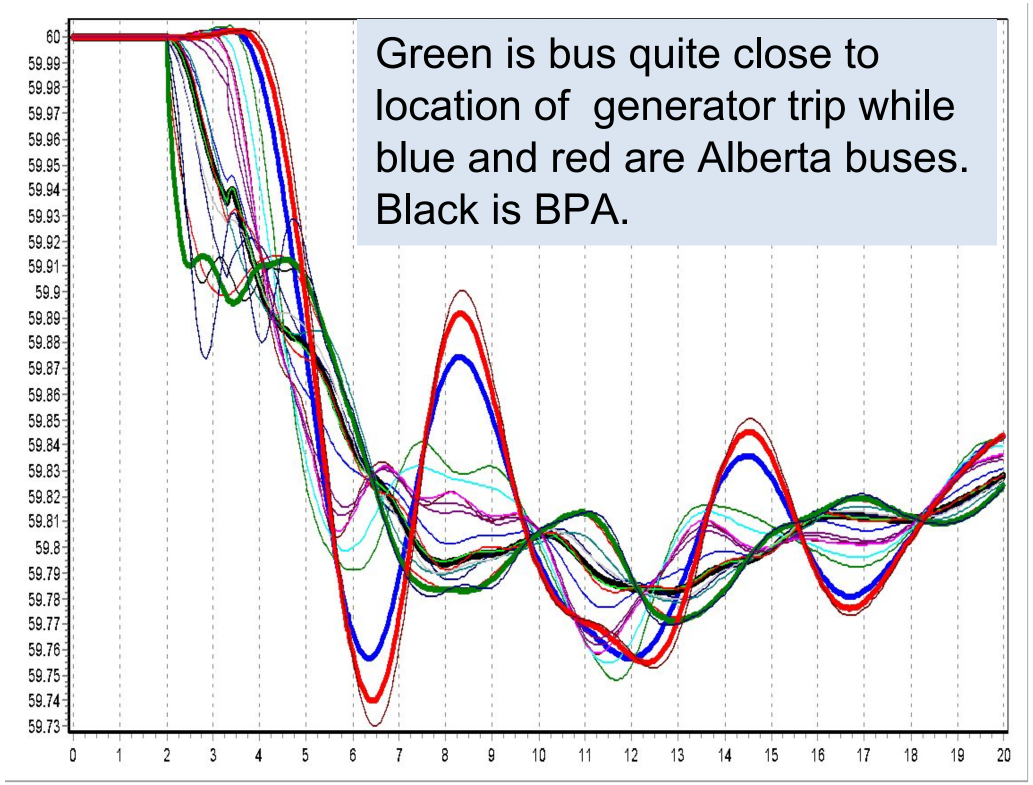
The grid is stable…

Key: Rotating mass in large generators = inertia

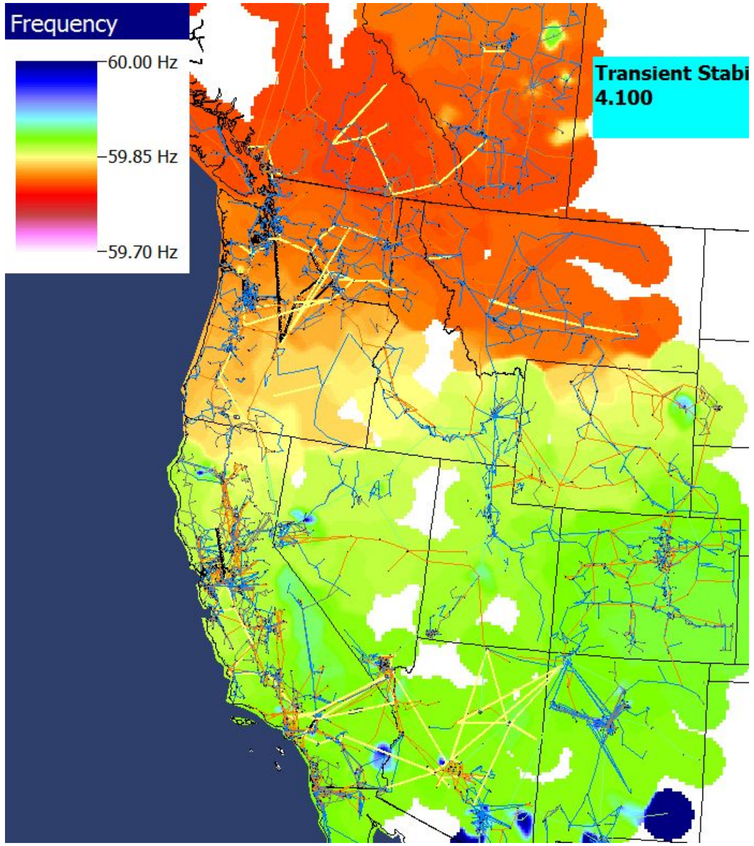


…except when it isn't

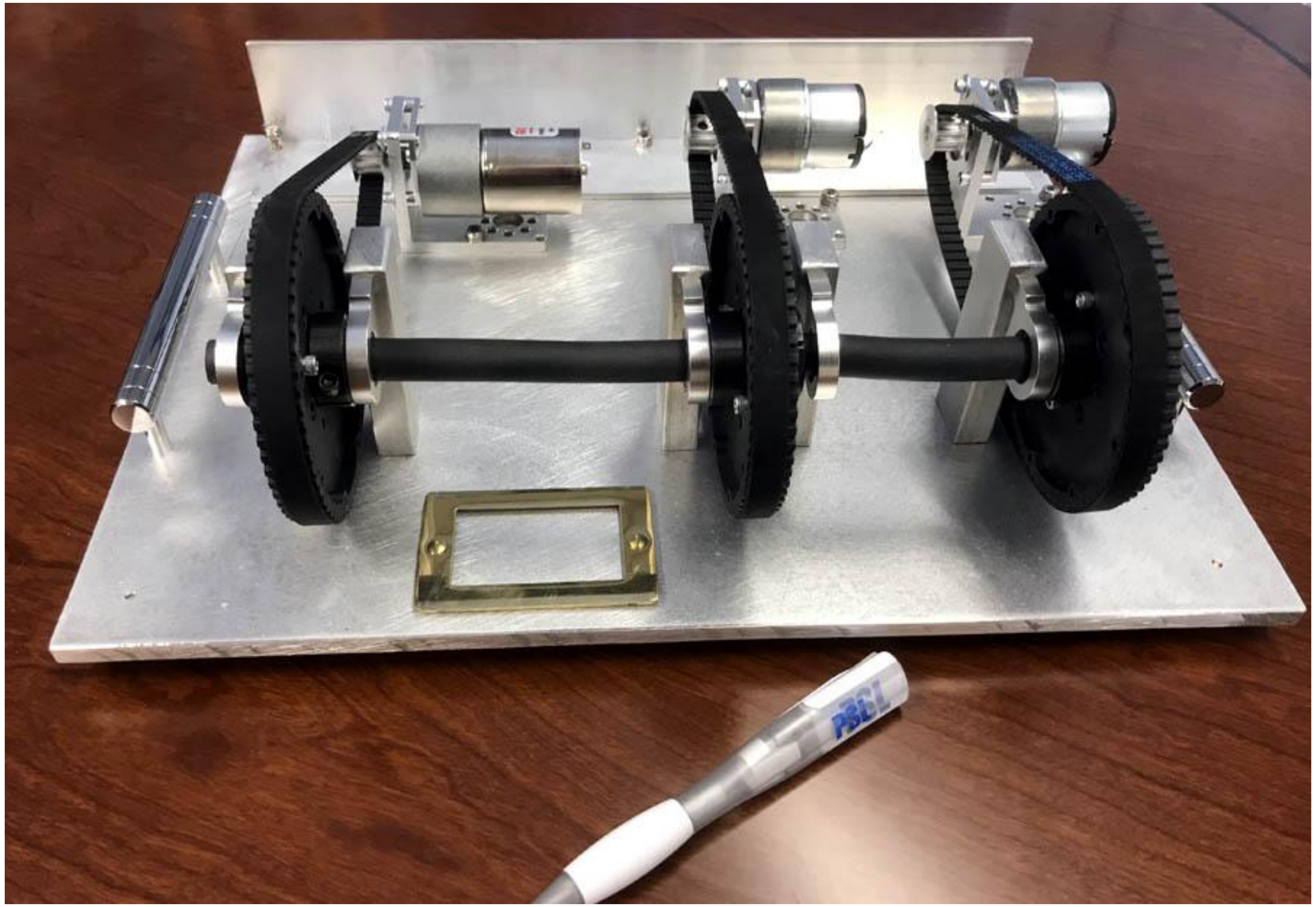
Figures show the frequency change as a result of the sudden loss of a large amount of generation in the Southern WECC



Time in Seconds

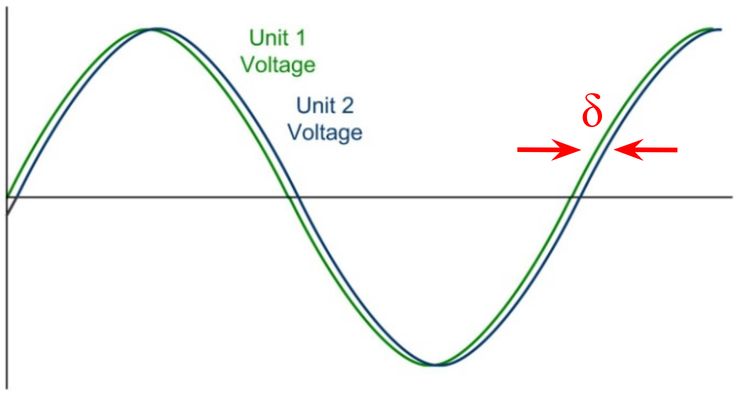


Frequency Contour



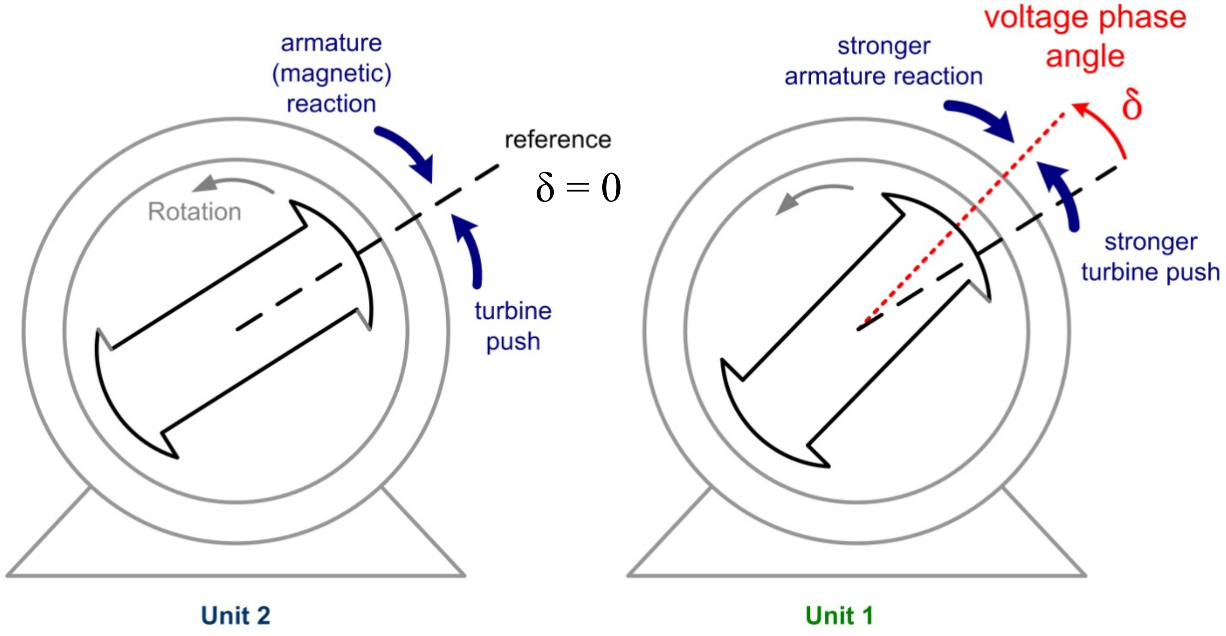
Mechanical model and photo by Alex McEachern
Rubber shaft illustrates voltage “twist” as power is transferred among motors & generators

Real power transfer between generators



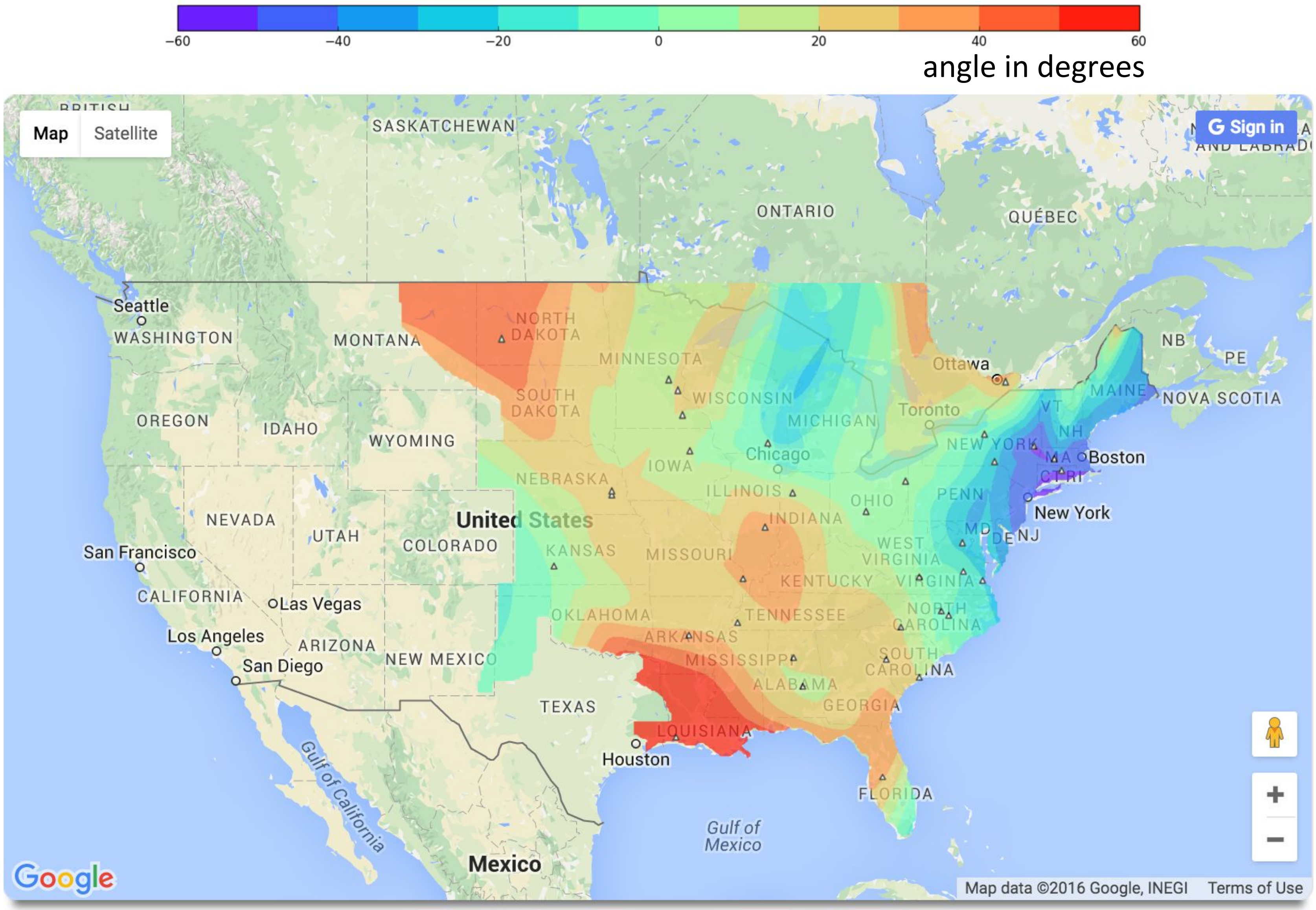
the small phase angle δ between two generator buses drives a.c. power flow

$$P \approx \frac{V_1 V_2}{X} \sin \delta_{12}$$



power flows from Unit 1 toward Unit 2

Voltage phase angle profile April 16th 2016, 10:20:37 pm



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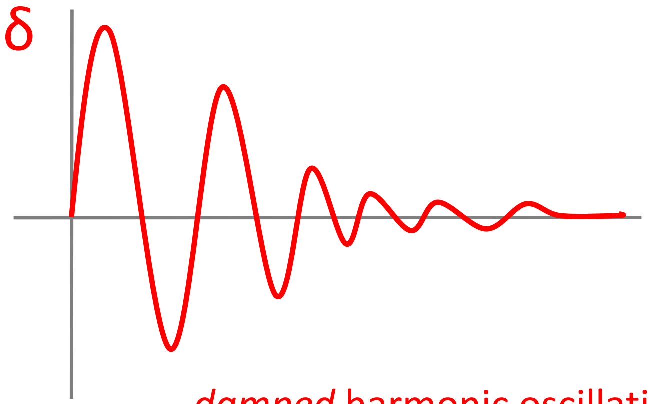
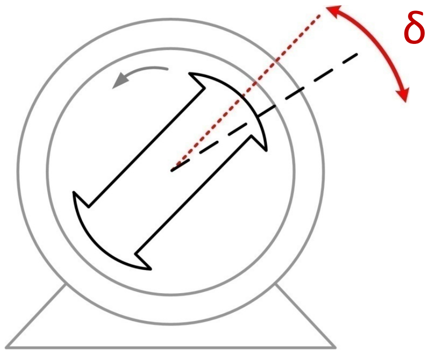
Phase angle and frequency describe stability in the a.c. grid

- load-frequency response (droop): when $P_{IN} \neq P_{OUT}$ frequency ω changes
- magnetic coupling between generators
- rotational inertia



damped harmonic oscillation
seen in voltage phase angle



generator swing equation

$$M \frac{d^2\delta}{dt^2} = P_m - P_e$$

How do we keep power generated = power demanded?

Multiple time scales:

1. Economic decisions: Unit Commitment, Economic Dispatch
   Day-ahead & Hour-ahead markets
2. Fast operational decisions: Load following, frequency regulation services; Automatic Generation Control (AGC) signal
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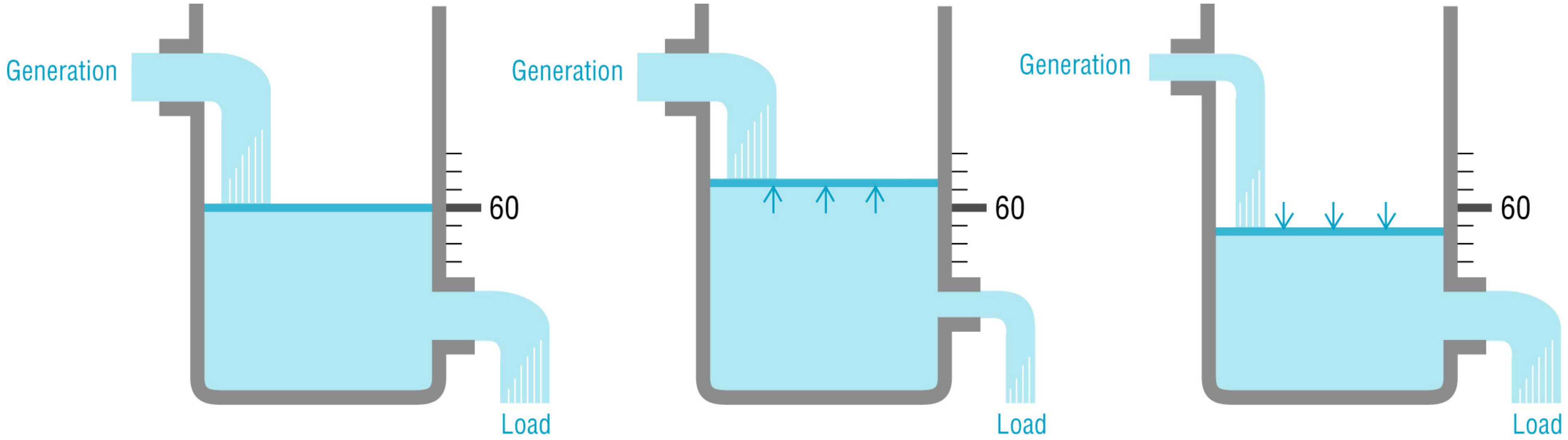
More Slides!

Balancing Authorities in California

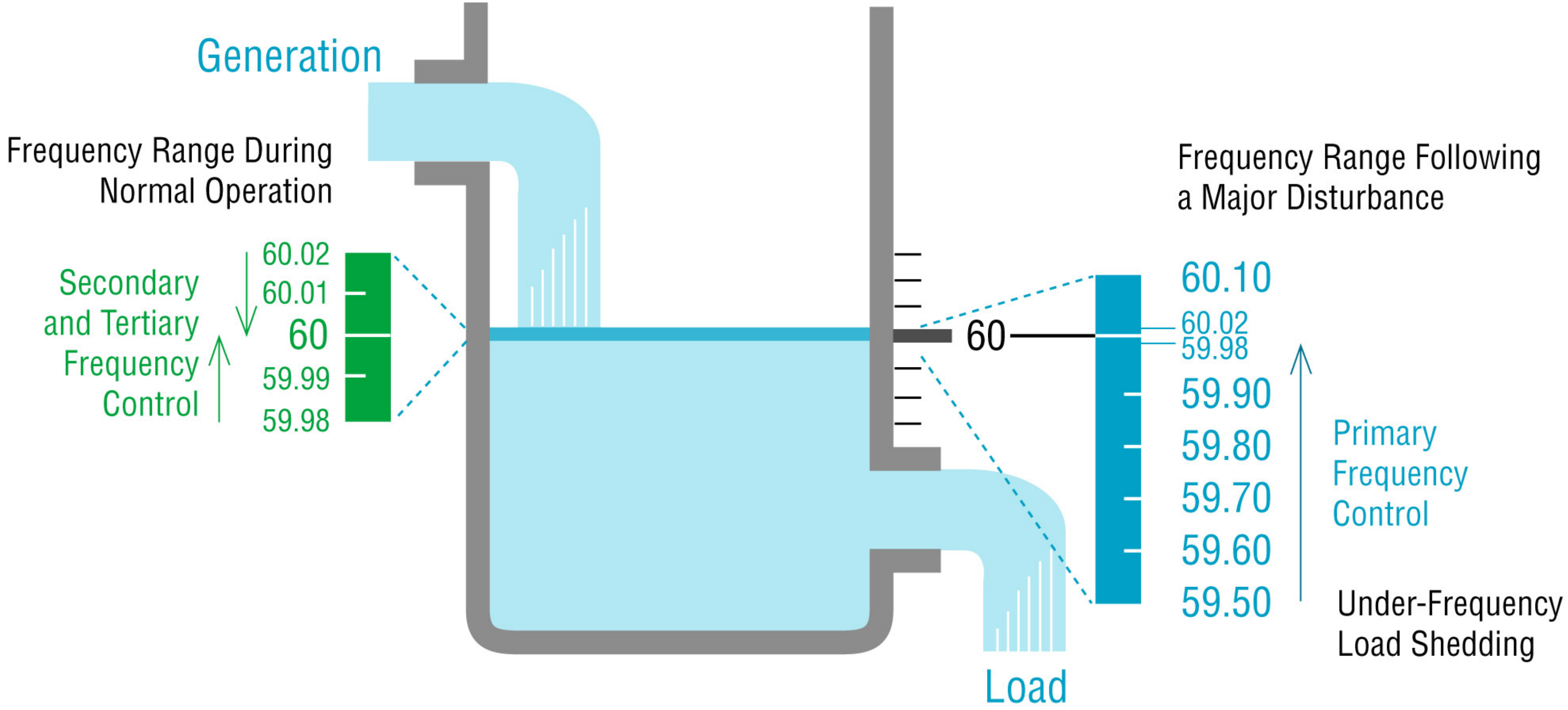
Load Frequency Control



In-flow equals out-flow, frequency stable at 60 Hz

Out-flow less than in-flow, frequency rises above 60 Hz

In-flow less than out-flow, frequency falls below 60 Hz



Primary frequency control: stop the water level from rising or falling

Secondary frequency control (supplementary regulation): return to desired level