Workshop on High Megawatt Electronics

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An Isochronous Grid Through Electronics

Colin Schauder
Satcon Technology Corporation

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The Grid is a Wonderful Thing – But …

- The US electric power grid is a modern wonder.
- We are
  - Usually it's ***<u>BENEFICIARIES</u>*** – everything is electrical
  - Sometimes it's ***<u>VICTIMS</u>*** – suffer through power outages
  - But always it's ***<u>CAPTIVES</u>*** – almost impossible to change
    - Huge capital investment in equipment and infrastructure
    - Entrenched bureaucracy and operating procedures
    - No financial incentive to do anything differently
    - Nothing changes unless legislation forces it
- Given the technology and hindsight available today, Edison and Westinghouse might come to different conclusions about how to deliver electricity.

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The Utility-Scale Electronic Generator

- A static or other electronically-controlled sinusoidal 3-phase voltage source
- *Self-commutated* (i.e. independent of ac line voltage)
- High power rated
  - Multi-megawatts to hundreds of MW
- Capable of real power flow in one (or both) directions from (or to) a real power source (or sink, or energy storage) – analogous to the “prime mover”
- Capable of connection at transmission voltage levels
- Capable of generating (and absorbing) reactive power
- High Efficiency
  - Expected power losses < 1%

Electronic Generators Arrived Quietly in the 1990's - In Disguise

- Not billed as generators, but disguised as part of other equipment types – up to 320 MVA
  - STATCOM – Static Compensator
    - Westinghouse, Mitsubishi, ABB, Alsthom – US installations TVA, AEP, PG&E, NYPA, SDG&E, VELCO, NU, Austin
  - UPFC – Unified Power Flow Controller
    - Westinghouse (Siemens) – AEP, NYPA, Korea
  - SSSC – Static Synchronous Series Compensator
    - Westinghouse (Siemens) – AEP, NYPA
  - IPFC – Interline Power Flow Controller
    - Westinghouse (Siemens) - NYPA
  - Arc Furnace Flicker Compensator
    - Westinghouse, Mitsubishi
  - Back-to-back asynchronous intertie
    - ABB – US installation at AEP
  - HVDC Lite
    - ABB worldwide

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Various High-Power Equipment Has Been Built Around Large Electronic Generators

- All of these types of equipment qualify as electronic generators as defined here.
- The power ratings achieved are comparable with moderately large utility generating units
- None of the equipment types has typically been associated with a built-in capability to produce electrical power from fuel or renewable sources or to and from bulk energy storage.
- They were designed to serve different purposes from conventional utility power generation
  - Var generation – Voltage support – Flicker reduction
  - Transmission line power flow control – Power oscillation damping.
  - Underwater and underground power transmission by cable
- But .. Connected to suitable dc power sources or energy storage the same designs could serve as very high performance ac generating units for the grid.

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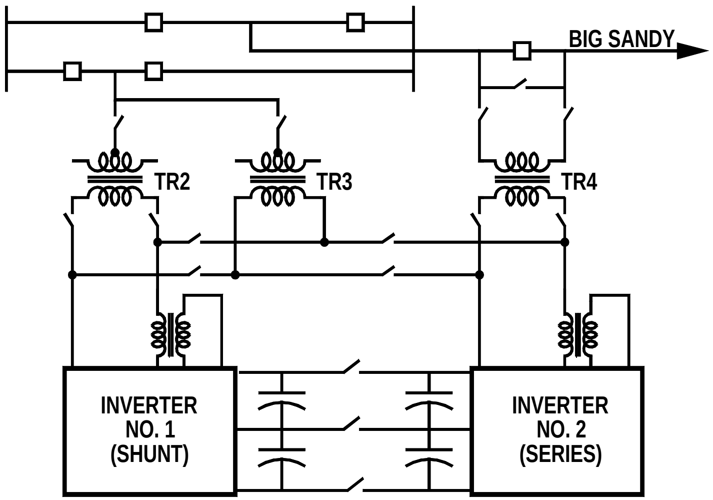
WESTINGHOUSE (SIEMENS) UNIFIED POWER FLOW CONTROLLER
AEP INEZ SUBSTATION, KENTUCKY.
320 MVA (2 x 160 MVA) INVERTER - DEDICATED JUNE 1998

- First back-to-back inverter installation
- Largest inverter installation in the world (when dedicated)
- First high power 3-level pole installation
- First demonstration of series connected inverter-based compensation
- First demonstration of UPFC with automatic power flow control



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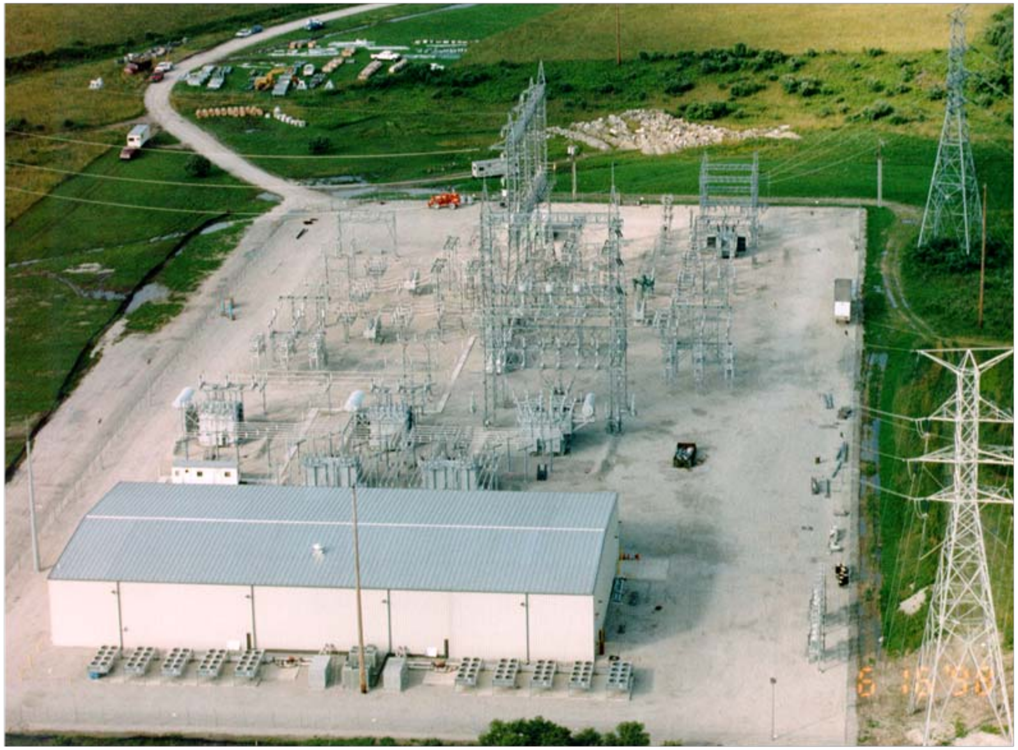

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UPFC Installation at AEP Inez Substation

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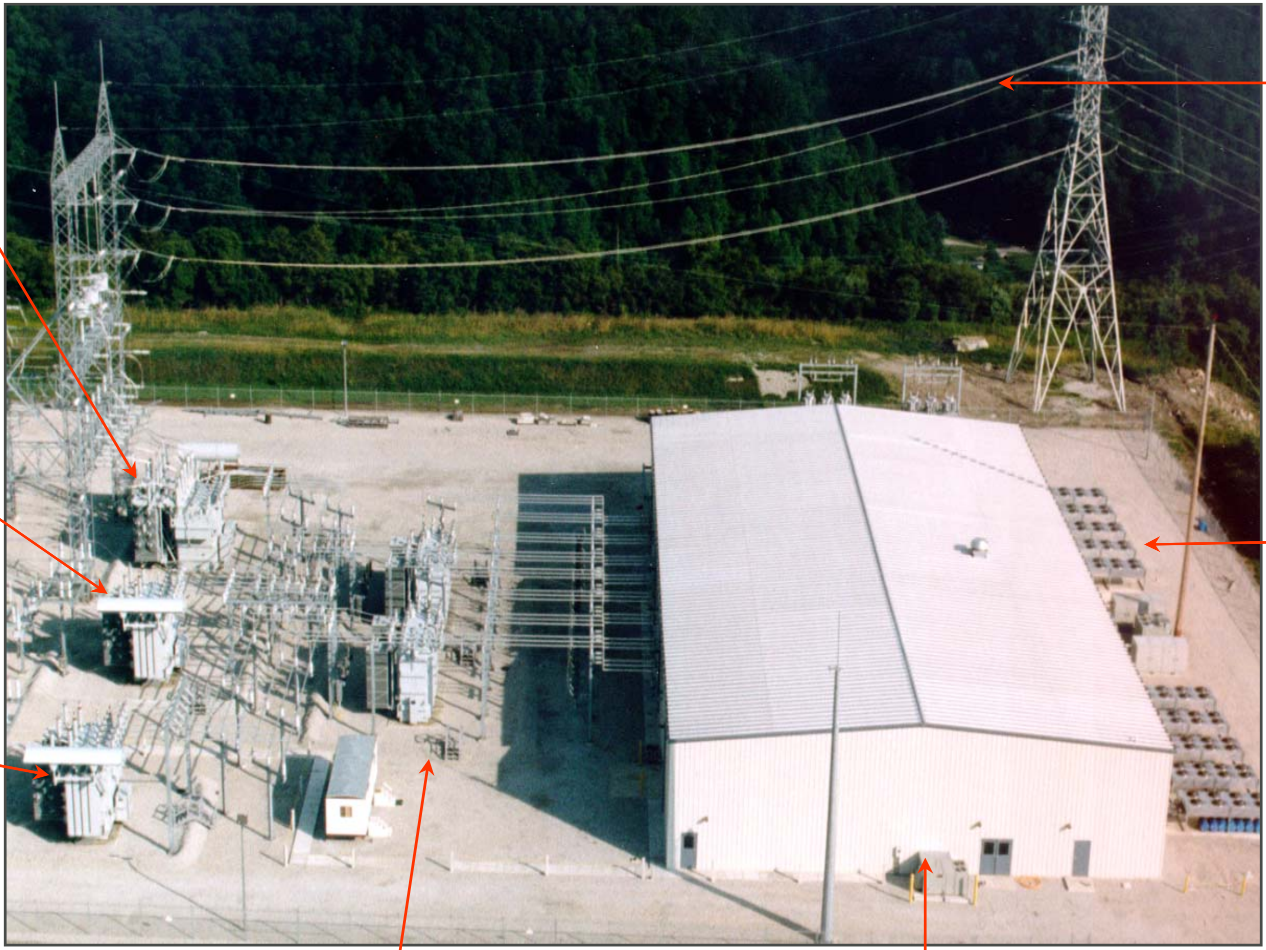

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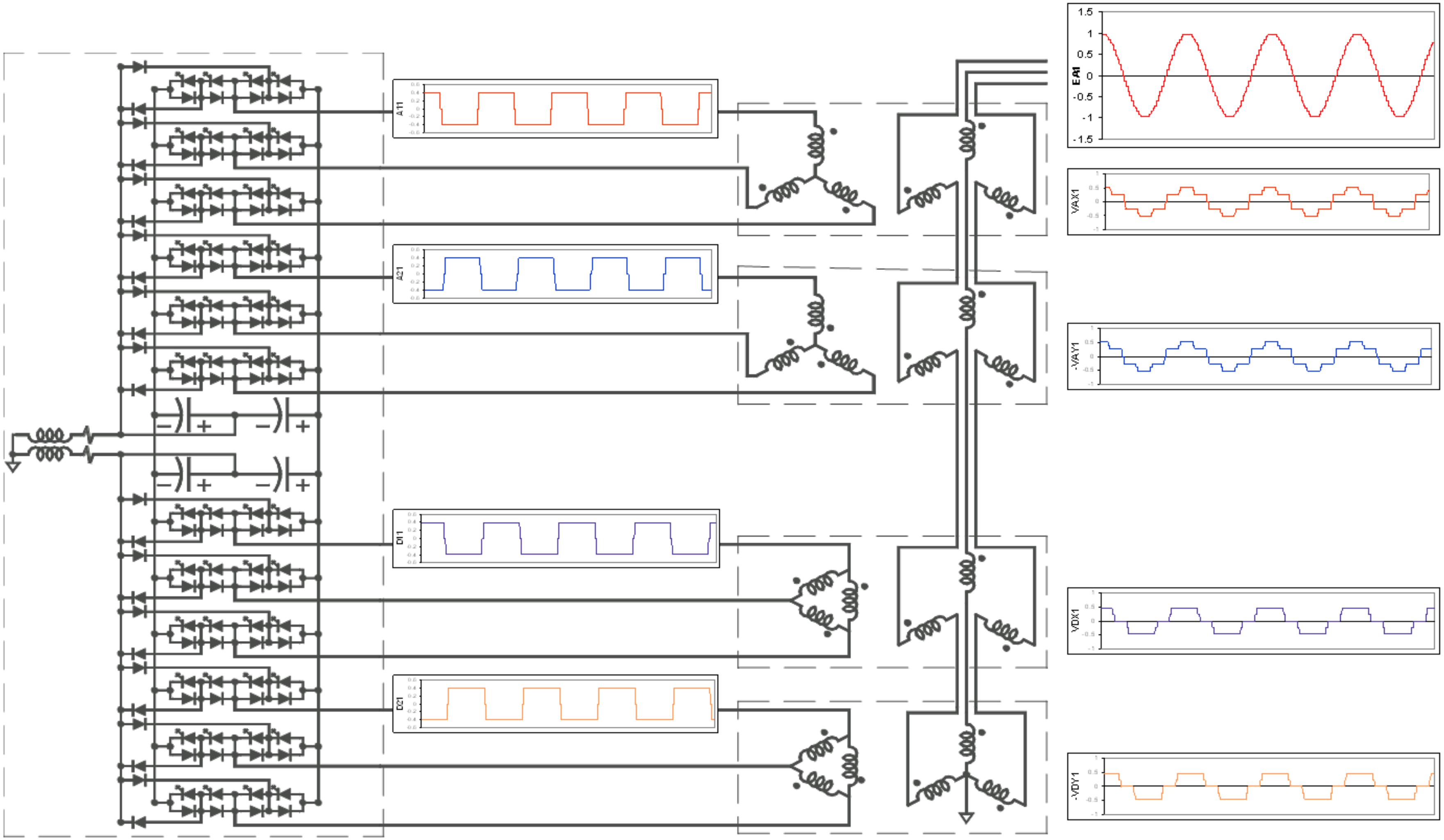
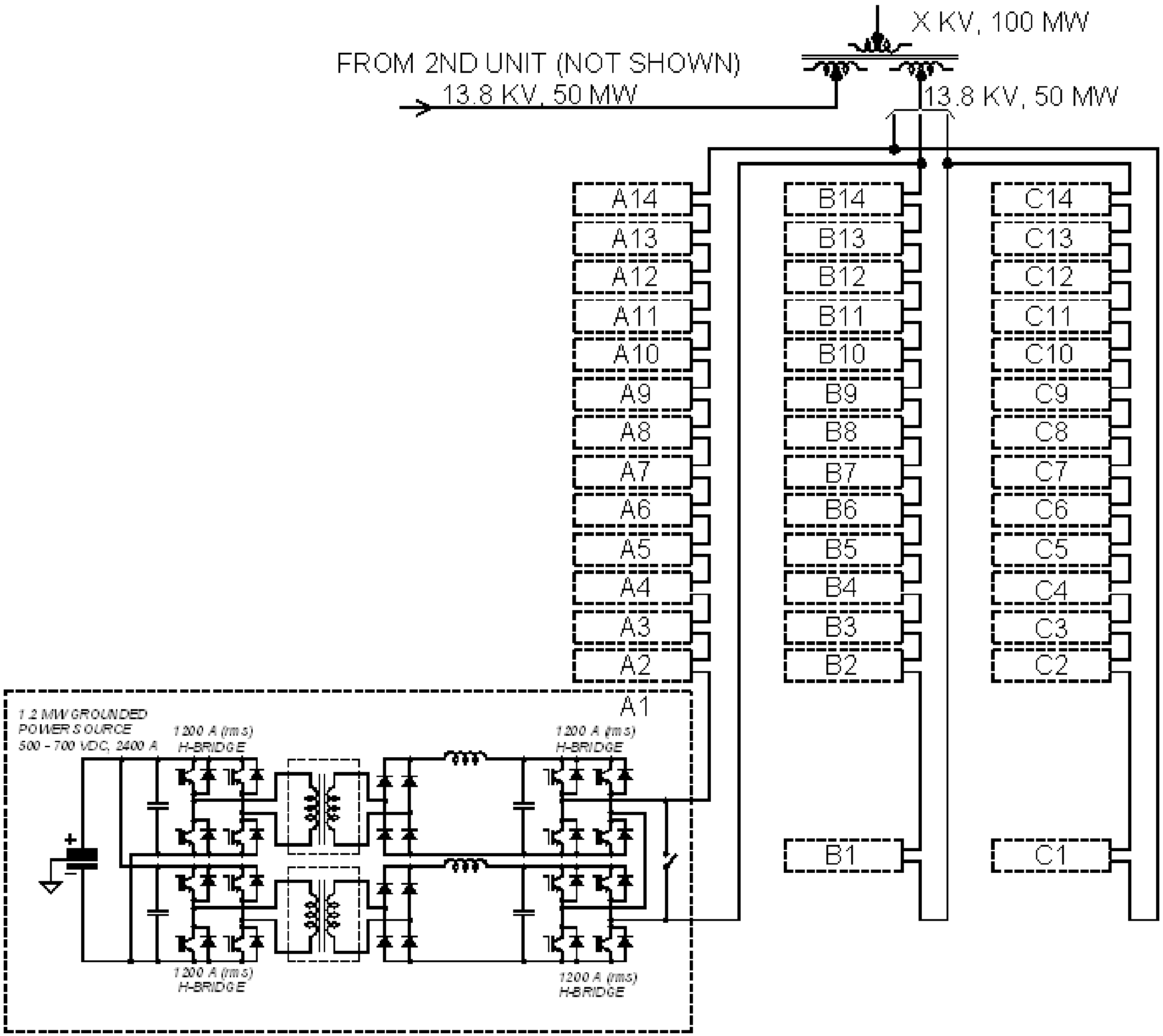
View of the 320 MVA (2 x 160 MVA) GTO-Based Inverter at AEP Inez Substation

Example of Electronic Generator Waveform Synthesis
- AC Series Cascade - 60 Hz Switching - 48-Pulse Output Voltage
- Practical Design in Service at 150 MVA



Example of a Hypothetical 100 MW Electronic Generator
- H-Bridge Series Cascade - Low Voltage IGBT's
- Multiple Grounded Power Sources



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Large-Scale Self-Commutated Electronic Generators Failed in Some Markets – Succeeded in Others

- After many successful demonstration projects established the technical viability, commercial reality set in.
  - Failed in transmission compensator market
    - Utilities prefer alternative line-commutated thyristor-based equipment for var generation - Lower performance, lower cost.
    - Little interest in power flow control or oscillation damping
  - Succeeded in underwater and underground cable transmission market.
    - HVDC Lite (ABB) (and very recently HVDC Plus (Siemens))
    - DC cable beats AC cable transmission.
    - Self-commutated beats line-commutated on weak AC bus

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Return of the Electronic Generators – No Disguise

- Electronic generators are returning to the grid, with a new raison d’être as the grid connection interfaces for renewable and alternative energy sources and storage
  - Lower unit power ratings (1MW - 3MW typical) – but sometimes aggregated to tens of MWs per site
  - Often connected to the *distribution system at MV levels* rather than a transmission bus
  - With built-in power sources / sinks:
    - Renewable energy (PV storage (x 1 MW)
    - Grid interface for wind turbines (x 3 MW DFIM)
    - Energy storage
  - Usually not owned and operated by utilities

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Electronic Generators Have Been Relegated to Menial Duty Providing an Interface with the AC Grid

- Presently electronic generators act as simple low-tech power sources connected to the grid.
  - Allowed to push current into the grid for various purposes
  - Regulate voltage at transmission buses and ride through disturbances
  - Regulate nothing on distribution buses - get out of the way during disturbances and let the big boys handle it

Control of the AC Interconnected Grid Has Evolved Around Synchronous Machine Generators

- Frequency is used as a global control variable
  - Effectively establishes a form of communication between generating units.
- Grid control *depends* on frequency change.
- Generator governor action provides a power/frequency droop characteristic that establishes equitable load sharing.
- Sudden load changes are transiently supplied from the collective stored energy (inertia) until governor action stabilizes the grid at a new frequency.
- Secondary control from a control center slowly adjusts the droop characteristics so that the load/generation equilibrium point returns to 60 Hz.

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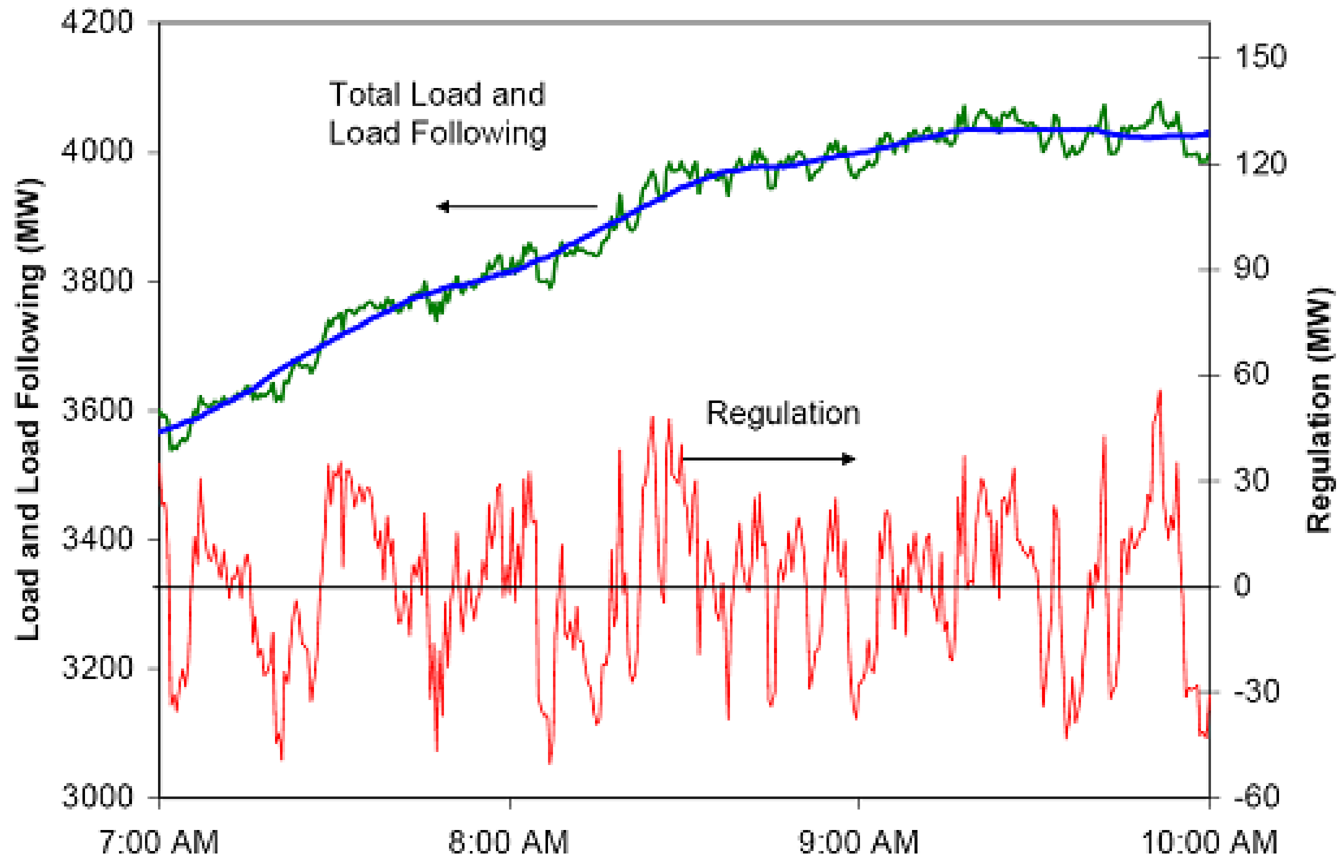
Control is Based on Frequency Deviation and Correction – Power Used For Correction is Expensive



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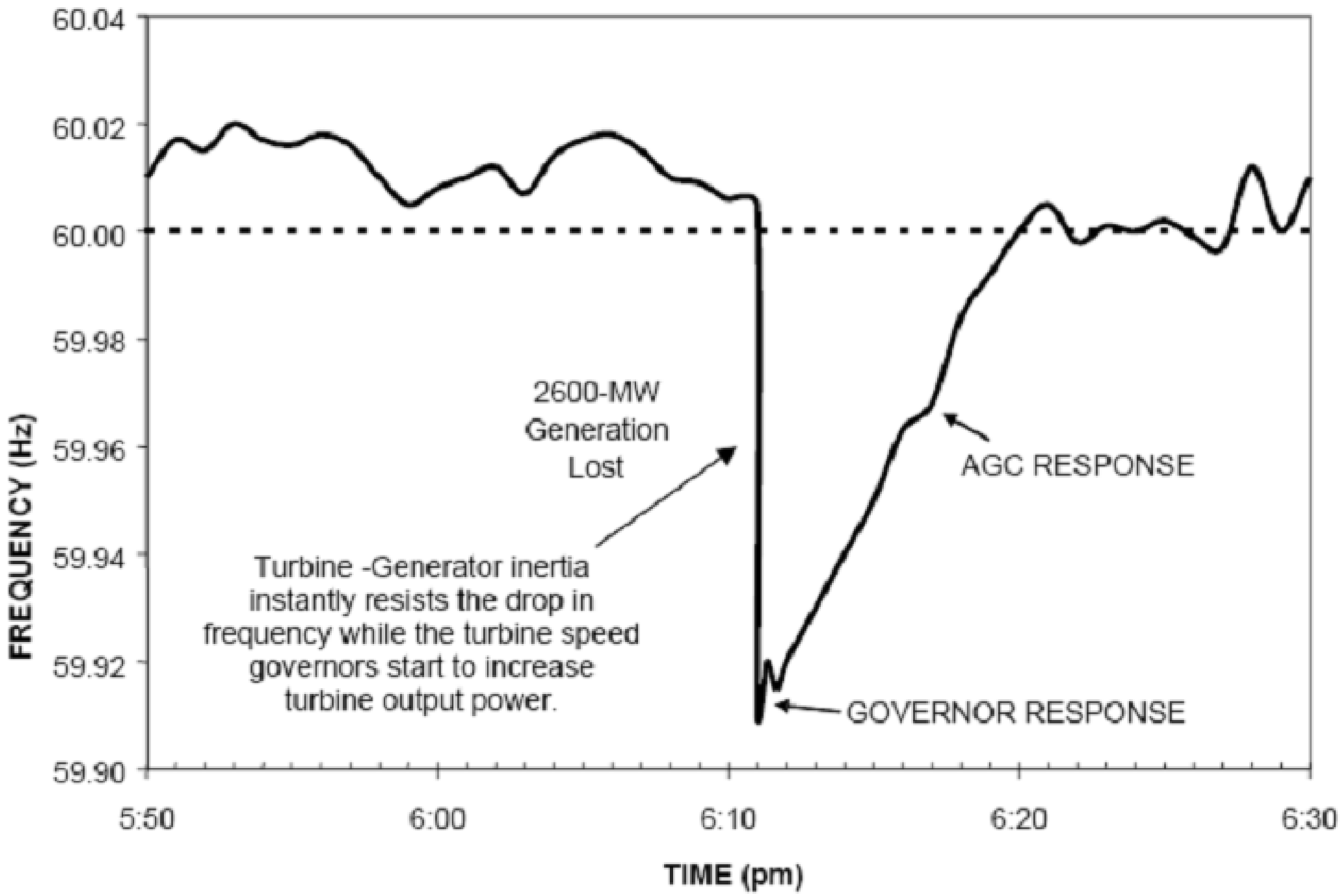
Stored Energy (Inertia) Supplies Load Excess Until Governor Action Stabilizes Frequency – AGC Corrects



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How Would You Utilize The Capability of An Electronic Generator to Control a Grid?

- Emulate a conventional synchronous machine generator in a conventional ac interconnection

OR

- Establish an isochronous ac interconnection area under electronic control

How Should Electronic Generators Be Incorporated Into A New Modern Grid Architecture?

- Electronic generators can be forced to suppress their fast control capability, and mimic the behavior of their rotating synchronous machine counterparts.
  - Frequency/Power droop with slow secondary frequency correction – Business as usual – Same power system stability issues.
  - This is the basis of the CERTS approach to microgrid control

OR

- Electronic generators can be used to
  - Maintain constant grid frequency
  - Instantaneously absorb real and reactive load/generation differences
  - Provide dc interties for stable power exchange with other ac grid segments
  - Respond rapidly to control center commands through secure high speed communications.

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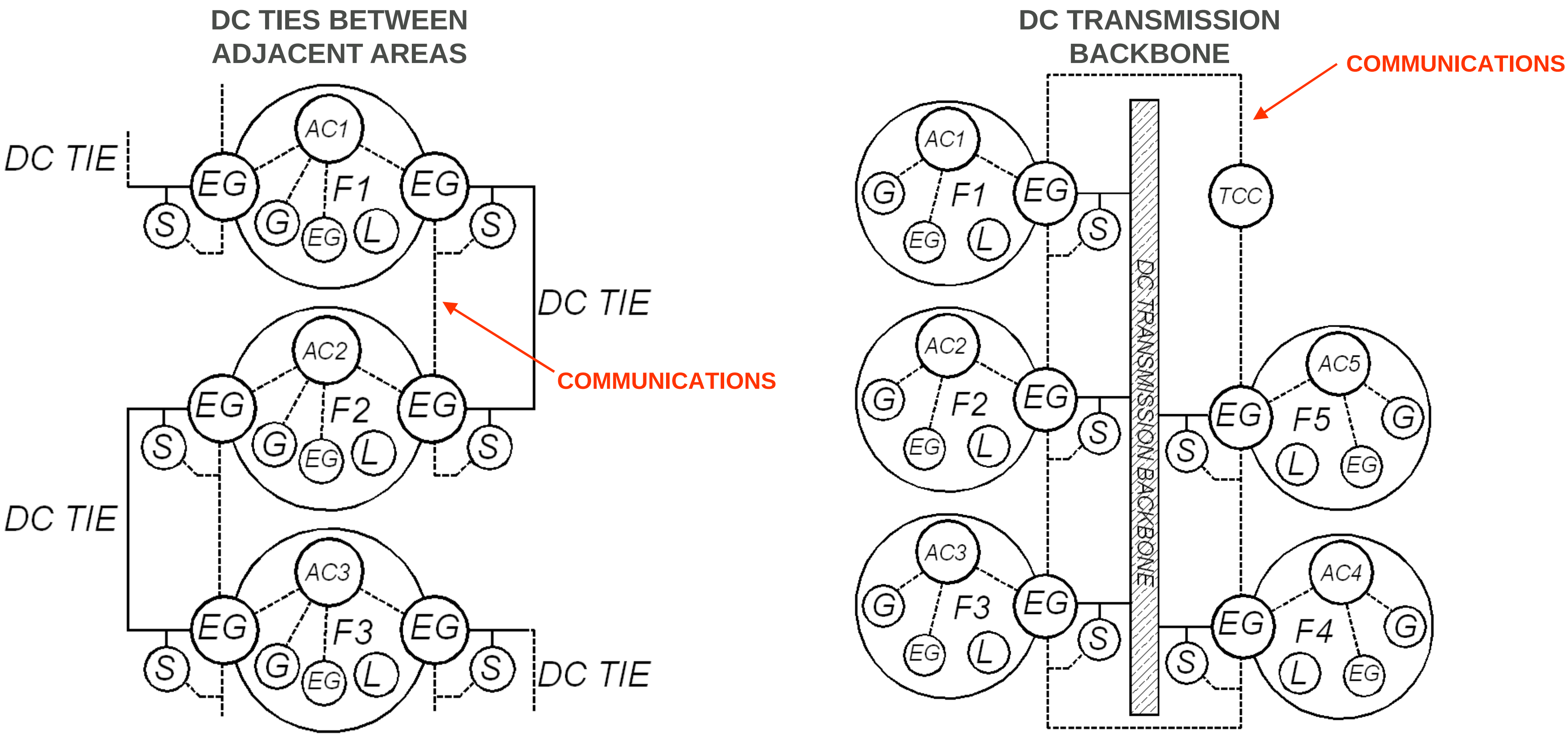
Electronic Generators Can Be More Than Just Grid Interfaces – They Can Control The Grid Frequency

- An electronic generator of sufficient rating can support a quasi-infinite ac “swing” bus, defining the frequency of the entire ac interconnection in an absolute sense.
  - An electronic generator provides a nearly ideal Thevenin voltage source behind a finite tie impedance
  - Frequency and phase of the controlled voltage source is <u>not dependent on load</u>
  - The electronic generator supplies or absorbs all of the differential real and reactive power for the grid (i.e. the difference between other generation and loads) – virtually instantaneously.

Two Hypothetical Electronic Grid Architectures



AC - AREA CONTROL
G - SYNCHRONOUS M/C GENERATION
EG - ELECTRONIC GENERATION
L - LOAD
S - ENERGY STORAGE
F - FREQUENCY
TCC - TRANSMISSION CONTROL

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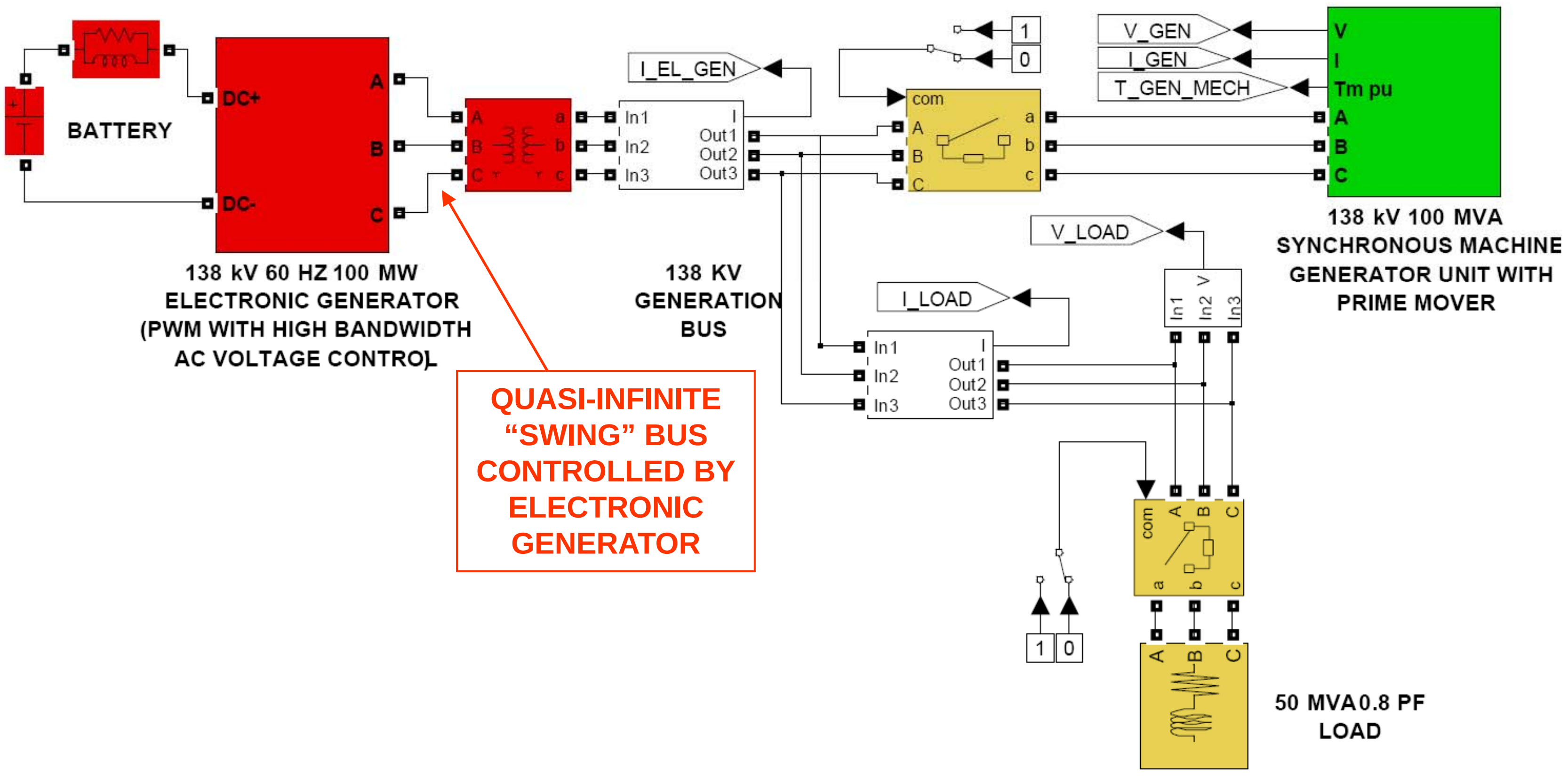
An Isochronous Grid With Electronic Generator Control

SIMULINK MODEL FOR HYPOTHETICAL GRID CONTROLLED ISOCHRONOUSLY BY AN ELECTRONIC GENERATOR
- Battery feeds electronic generator serving as isochronous swing generator , controlling voltage and frequency
  - Electronic generator supplies or absorbs transient real power and continuous reactive power as needed
- Rotating synchronous machine generator unit supplies continuous load with prime mover under dispatch control



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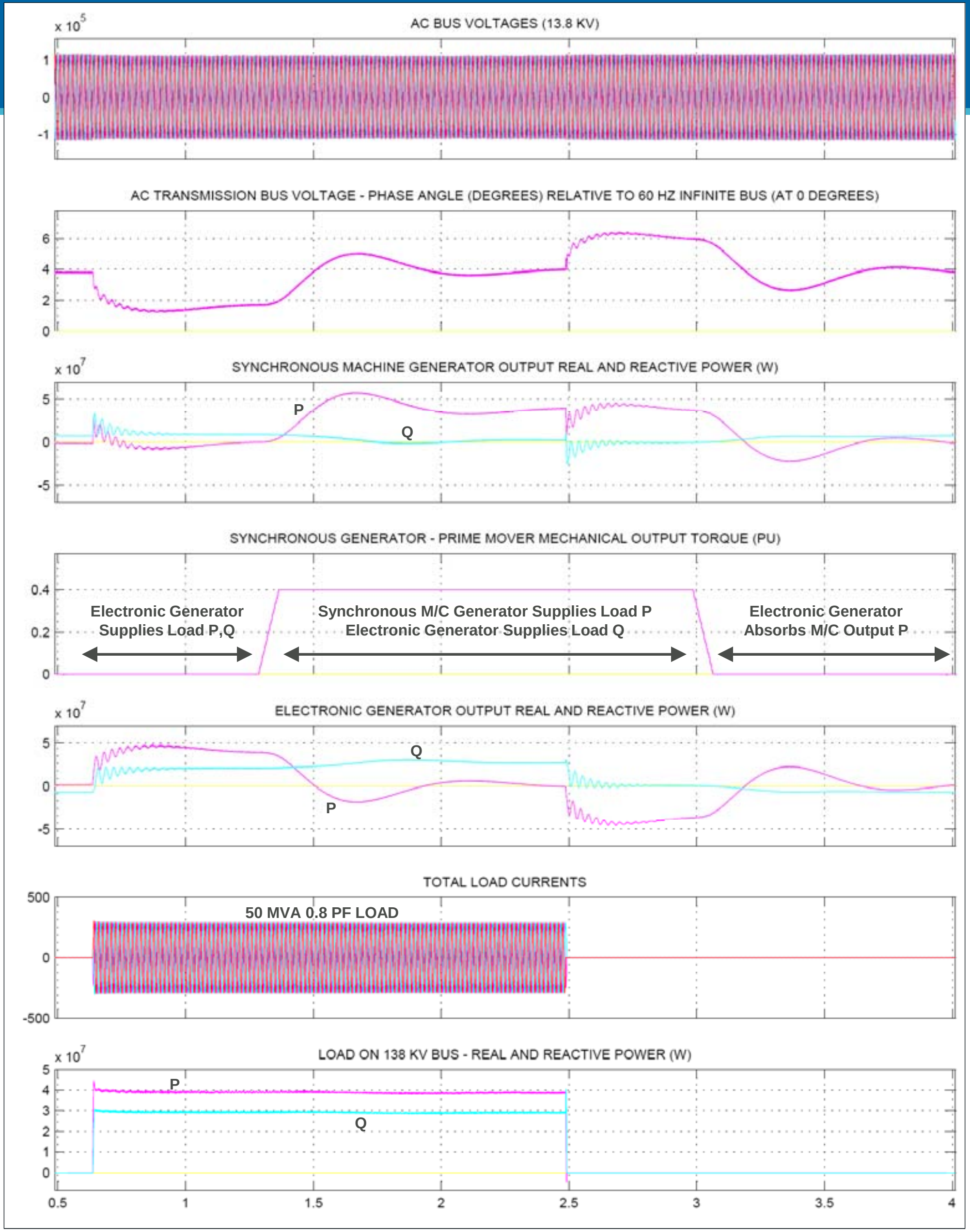
An Isochronous Grid With Electronic Generator Control

Average Frequency Constant At 60 Hz

100 MW Electronic Generator Supports Isochronous Grid With Instantaneous P and Q



100 MW Synchronous M/C Generator Supplies Real Power On Command

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The Challenges For Proponents of Utility Scale Electronic Generators

- Achieve high reliability and availability
  - Essential for equipment controlling a grid
  - Should be easier with electronics than rotating machines
- Develop/incorporate suitable energy storage (High MW – short or long term) and/or power sources to enhance the capability of electronic generators to absorb, store, and deliver energy
- Gain acceptance through large “island” grid projects incorporating synchronous machine generators
- Fight the good fight – Work to revise standards that impede the progress of new forms of generation
- Establish a sound commercial basis for the use of electronic generators – Otherwise they will disappear!

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