Electric Power 101

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NO, WE DIDN'T NUKE OUR-
SELVES BACK INTO THE STONE-
AGE. WE DEREGULATED OUR
ELECTRIC UTILITIES...
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Why Are we Here?

"Electric Power 101" - *Not* "Life, the universe, and everything"

- **Most of the concepts in electric power are relatively simple and easily understood**
- **Some of these concepts are not obvious and their implications are easy to miss**
- **Complexity comes from the numbers of devices and their interconnection/interdependence**
- **High voltages, currents, and powers limit what can be done economically**
- **Many regulatory, policy, market, and societal issues are intertwined with technical issues but they are *not* the sole province of the technical folks**

Answers First - Then Explanations

What are we looking for?

- **What is technically unique about electric power?**
- **What does this imply?**
  - **For how the system operates**
  - **For regulation**
  - **For markets**
  - **For investment**
  - **For research needs**

Electricity Moves At The Speed of Light, Gas Moves at 11 MPH, That Has To Make A Difference

- Speed matters - but not that much
  - the system is poised to withstand the next event
  - the first response is automatic
- Much more important is the lack of control and the lack of storage

Electricity Has Two Genuinely Unique Characteristics…

- Consumption and Production must be balanced continuously and instantaneously
  - there is no practical/economic storage
- There is no flow control within the transmission system
  - exceptions are DC lines, phase angle regulators, and back-to-back AC-DC-AC converters, and some FACTS devices

...With Four Natural Consequences

- Costs (prices) are inherently volatile
- System operations and transmission are communal and must be regulated
- Current operations are often restricted by preparations for the next unlikely event
- Response has value

It is important to separate inherent characteristics from historical choices

It is also important to recognize when technology changes the inherent characteristics

Basics Assumptions

Market decisions better than command and control

- **Let markets supply what they can**
  - **energy**
  - **reliability**
- **Supplier competition reduces costs**
- **System operator must be independent of financial interest in transactions**

Some Basic AC Electricity Concepts

(that explain a lot)

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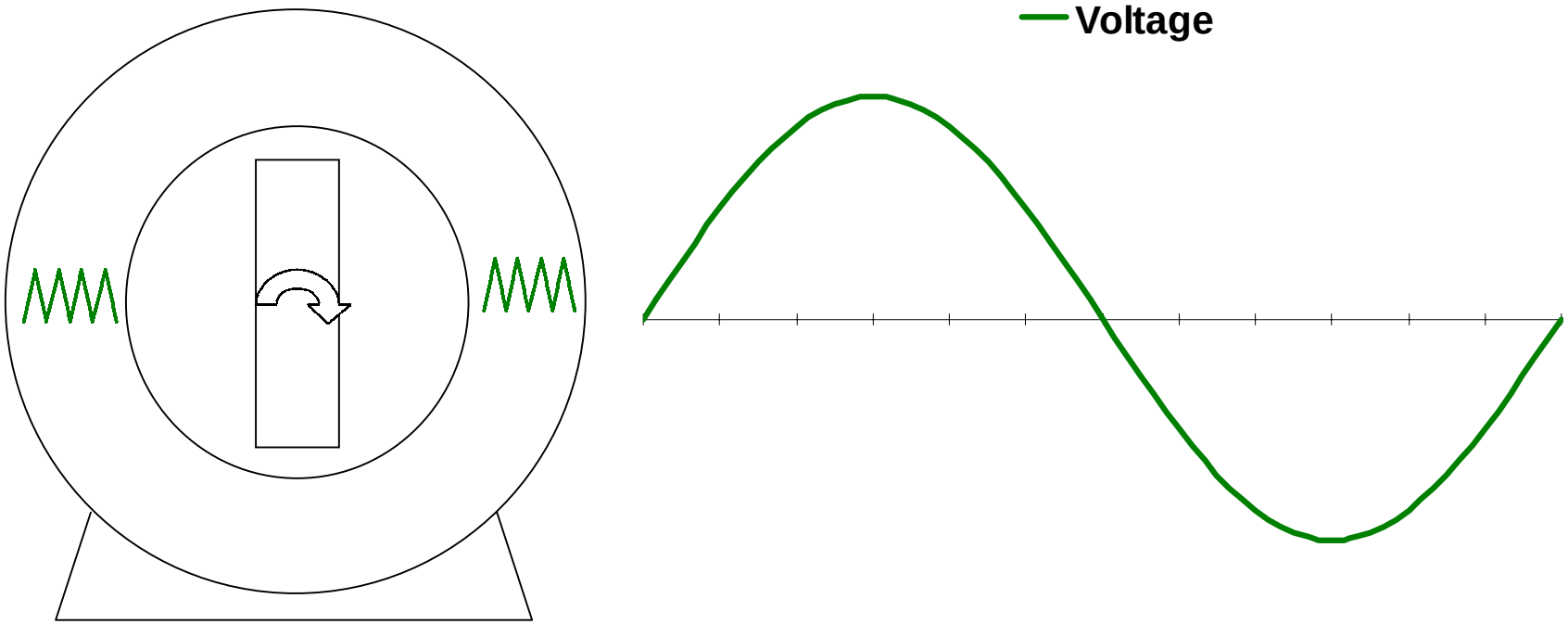
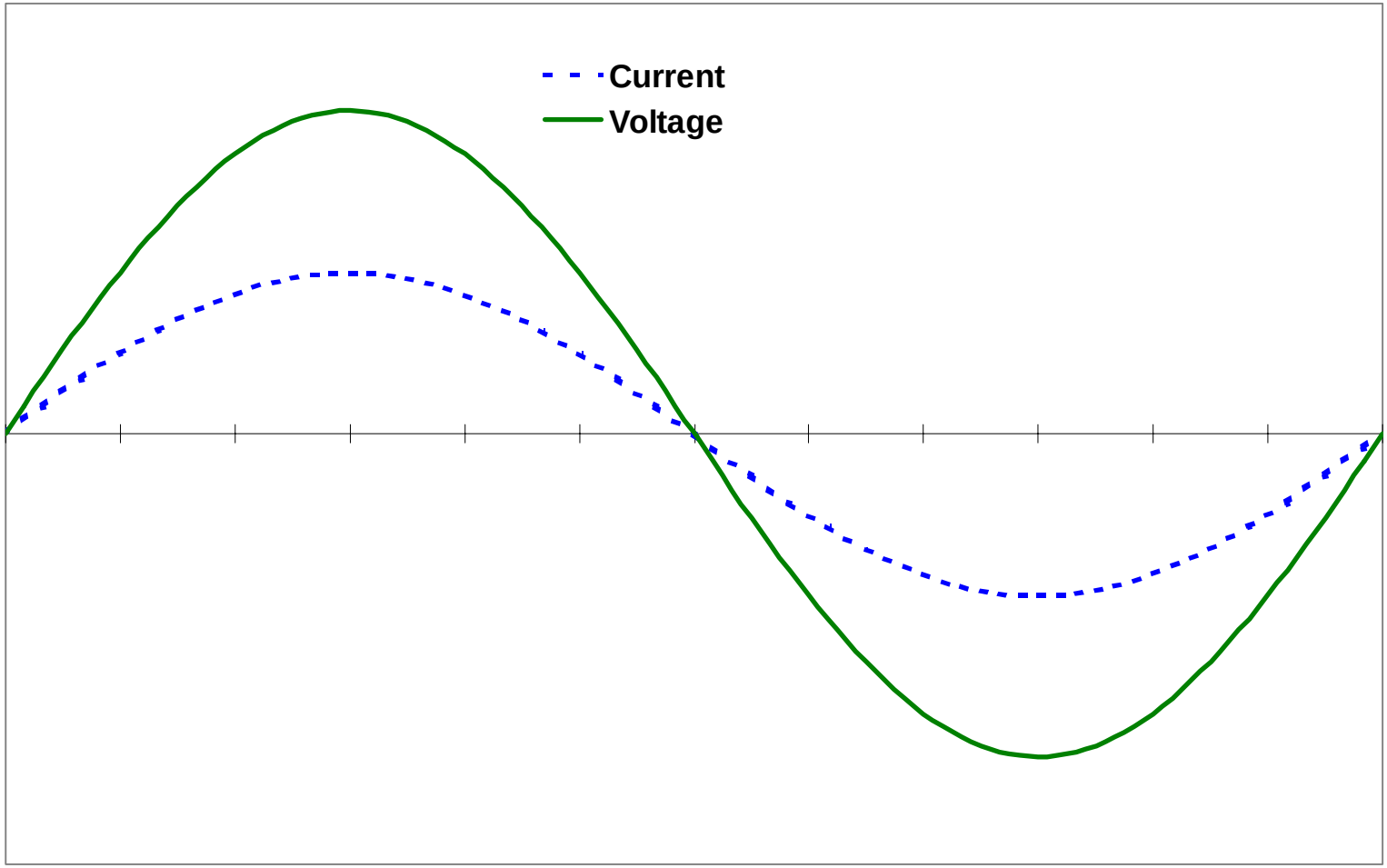
Just a Couple of Important Relationships

- Power = Force x Displacement
- Power = Current x Voltage
- Energy is the time integral of power
- Energy is guaranteed to balance
- V = I x R

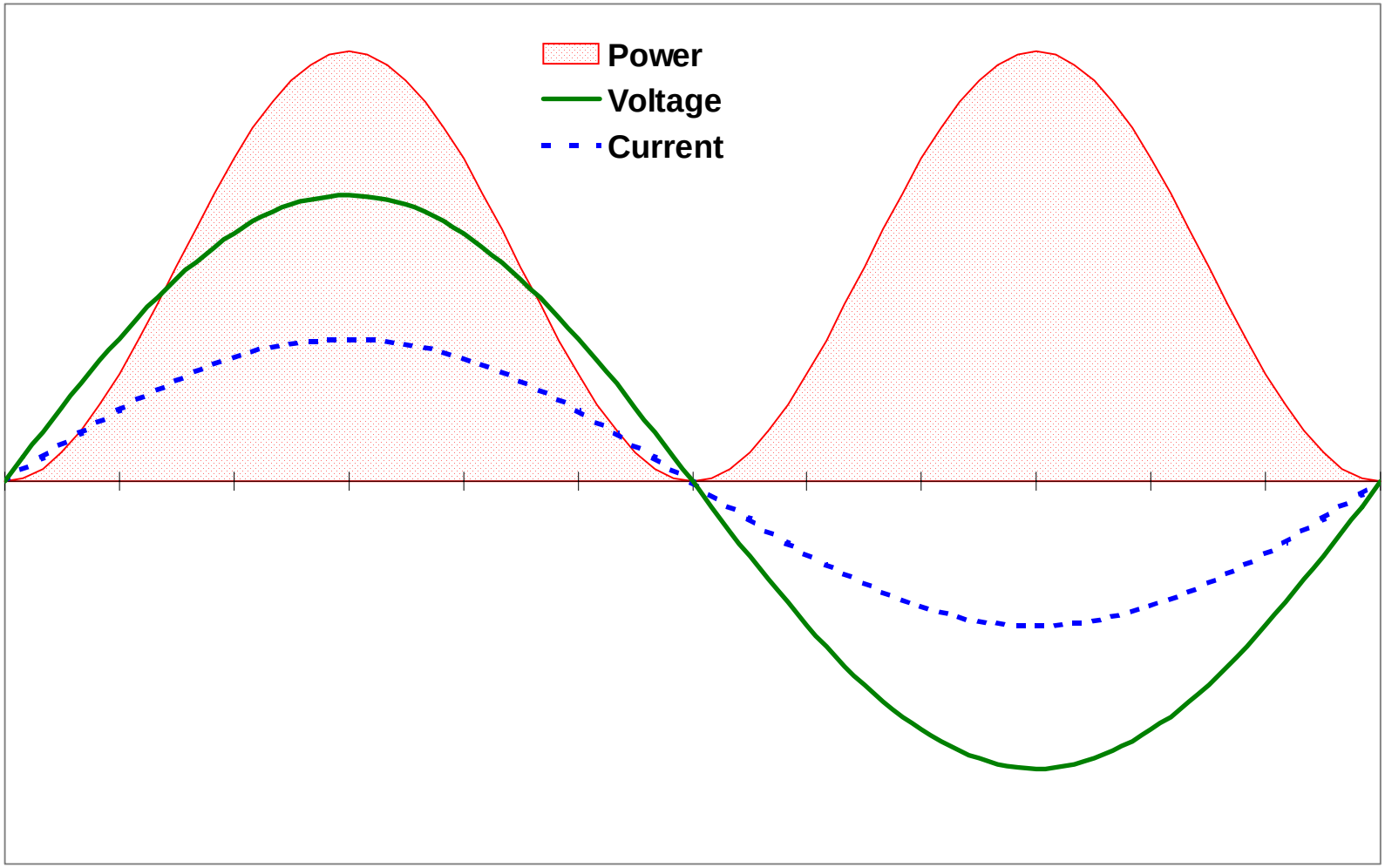
A Single Phase AC Generator



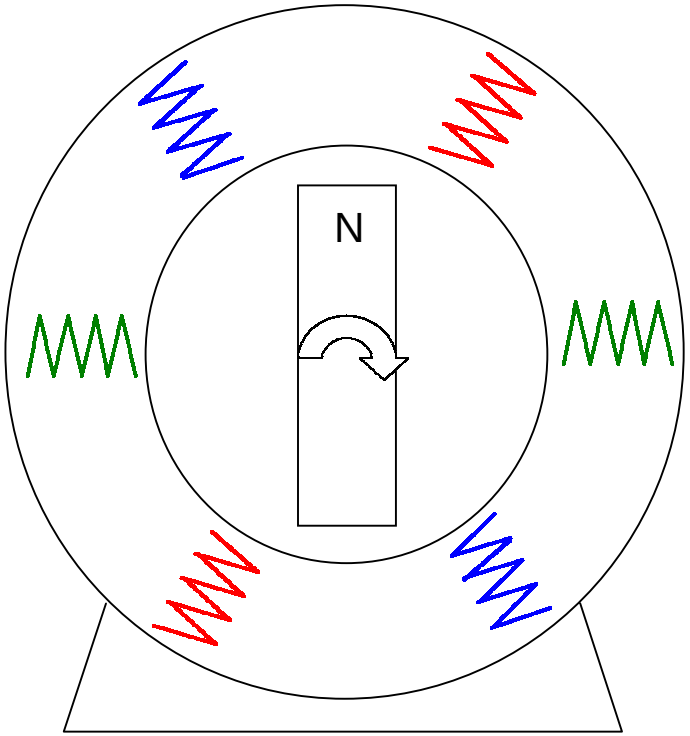
With a Resistive Load Voltage and Current are "In Phase"

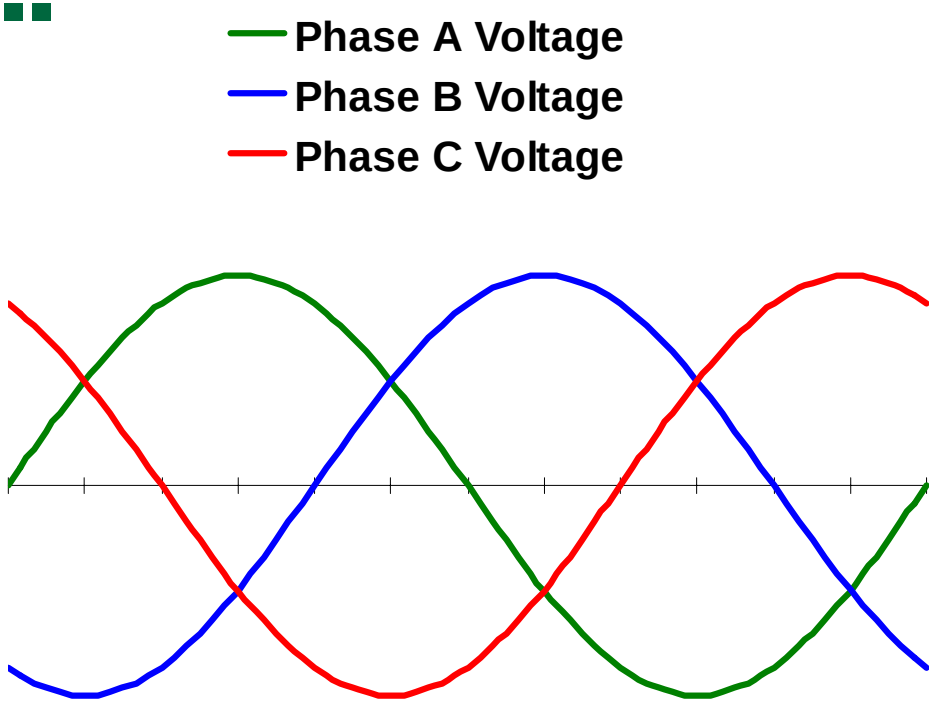


Power is the Instantaneous Product of Voltage and Current

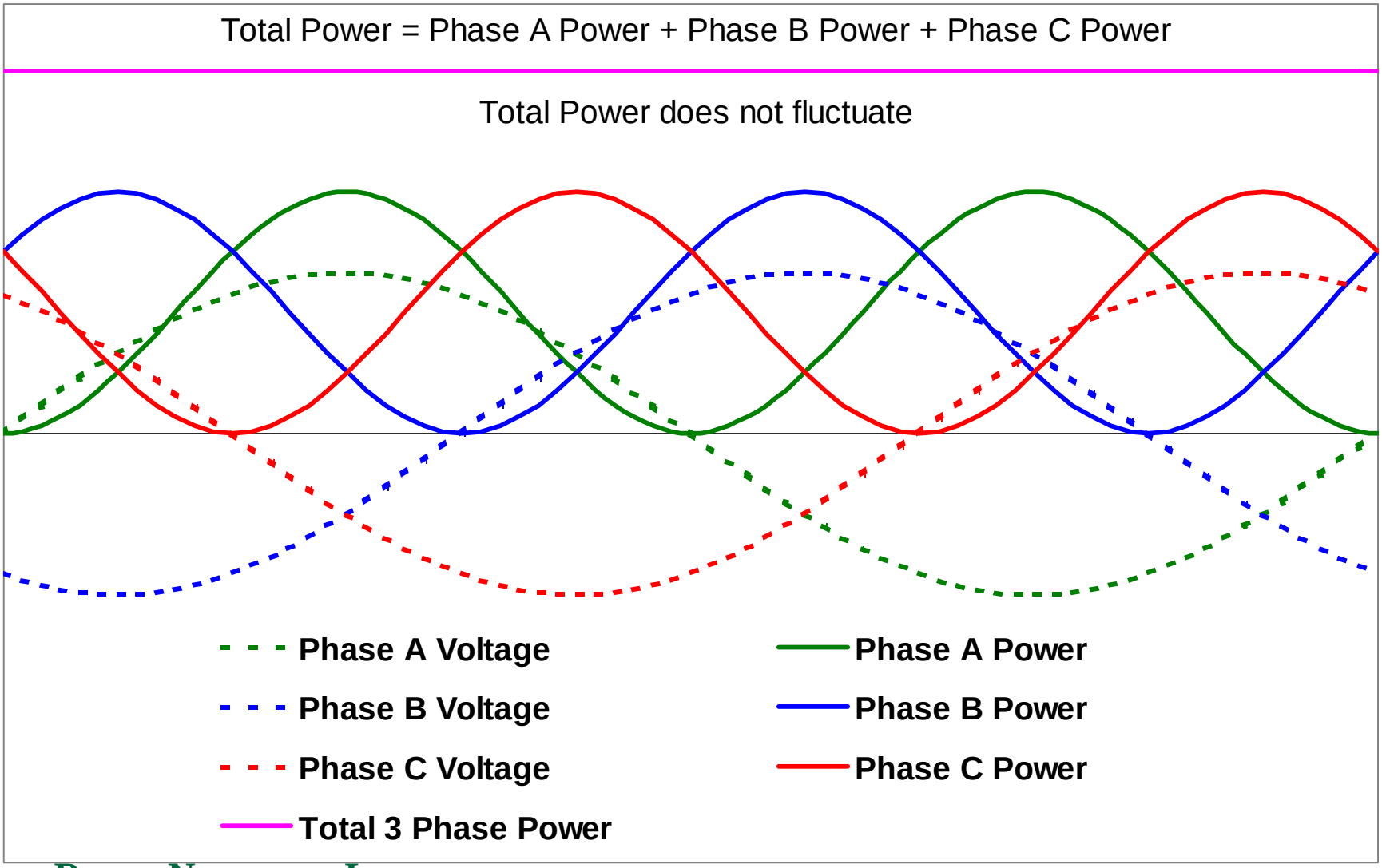


3 Phases are Distributed Around The Generator…





… With Interesting results

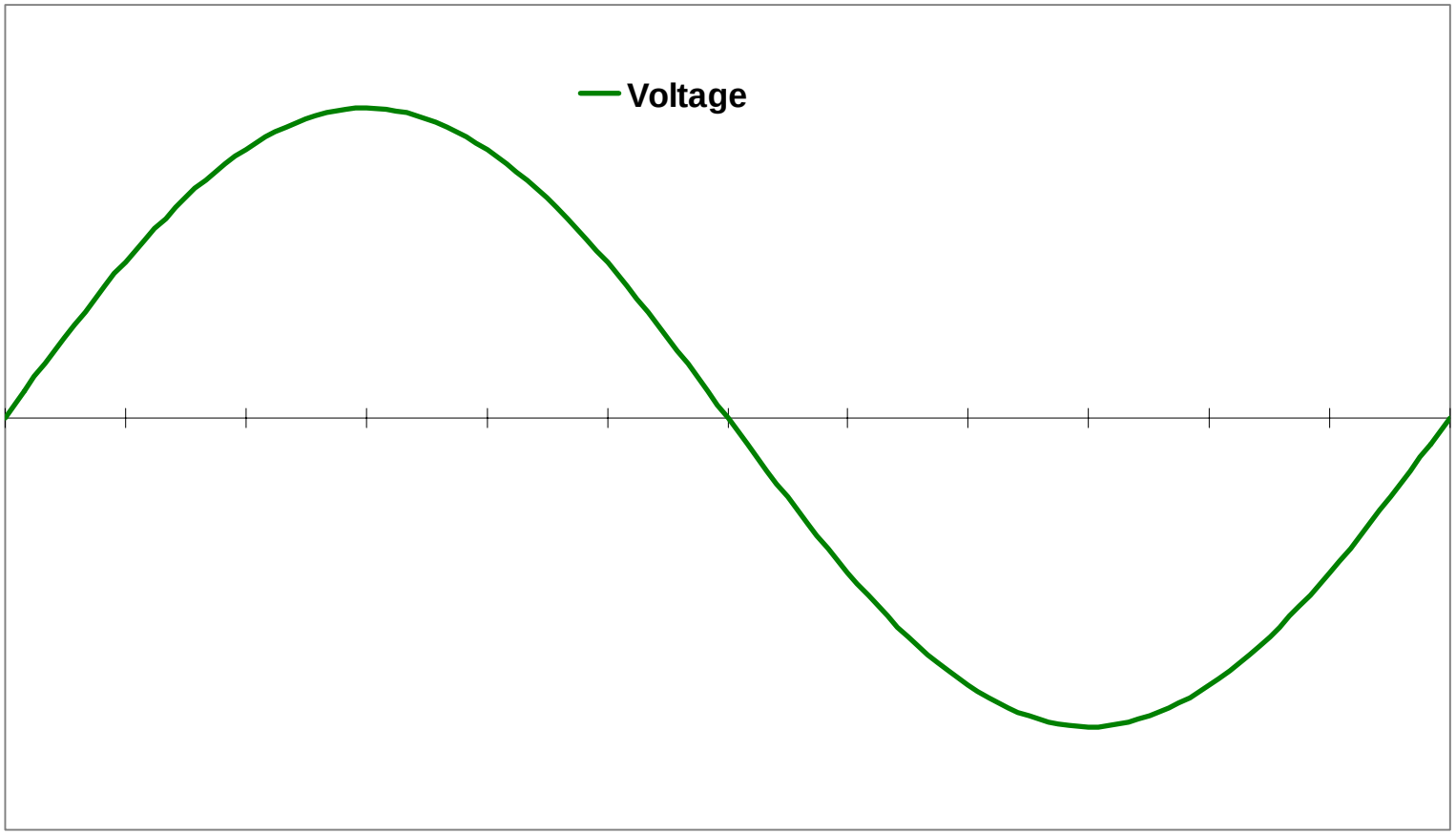


Not Much To Measure

- Voltage
- Current
- The relationship between them which results in real (MW) and reactive (MVar) power
- Frequency

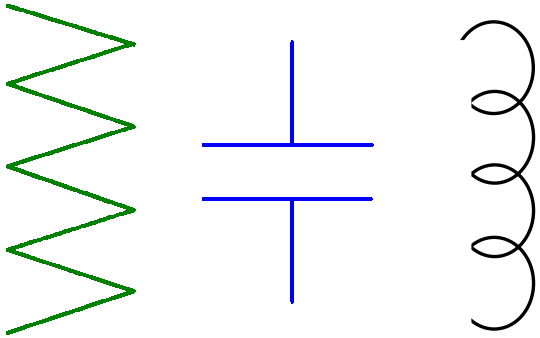
Now That We Understand 3 Phase Power and Why There are 3 Wires Lets Look at:

Power Factor

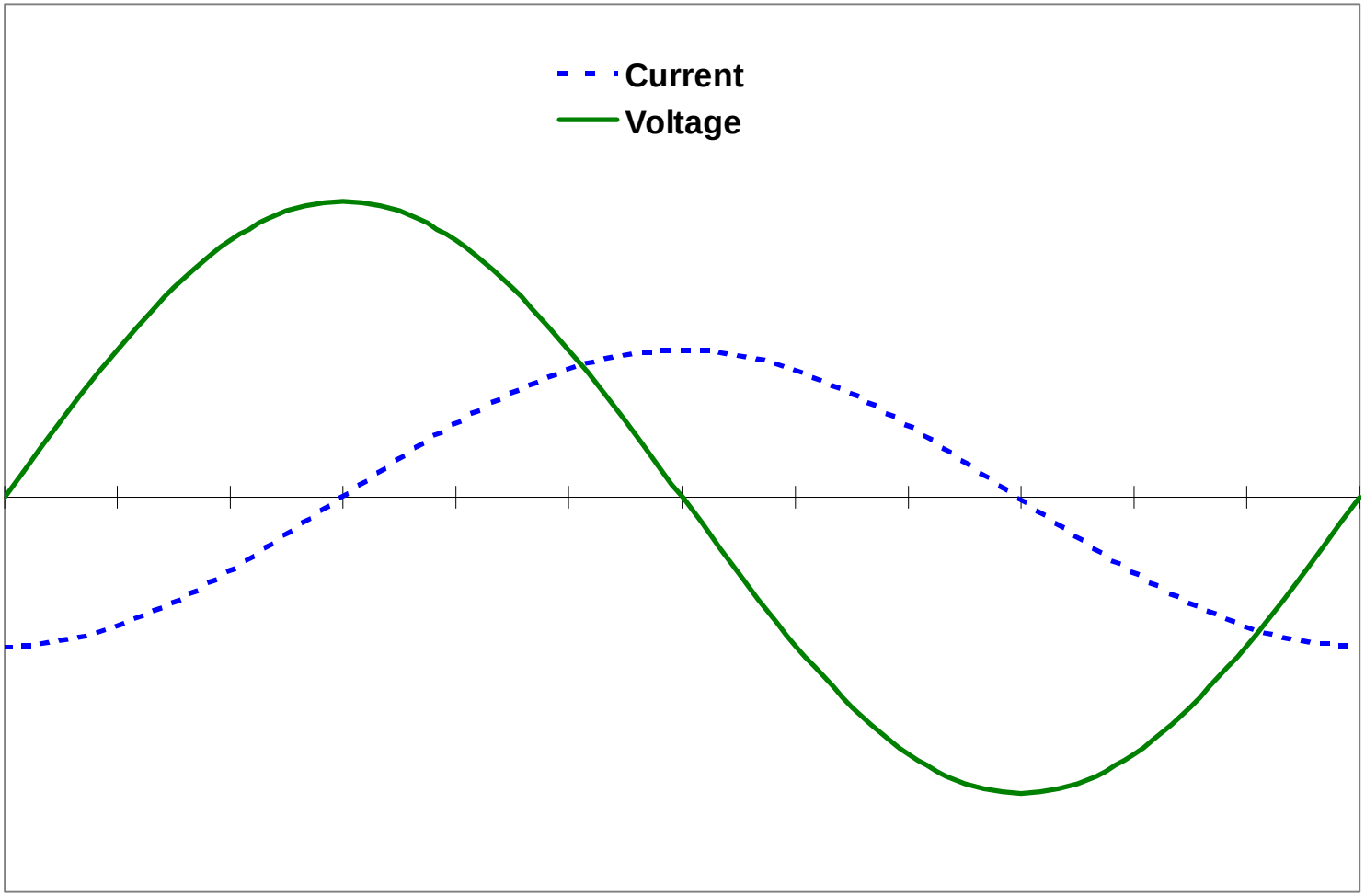


Only Three Passive Elements

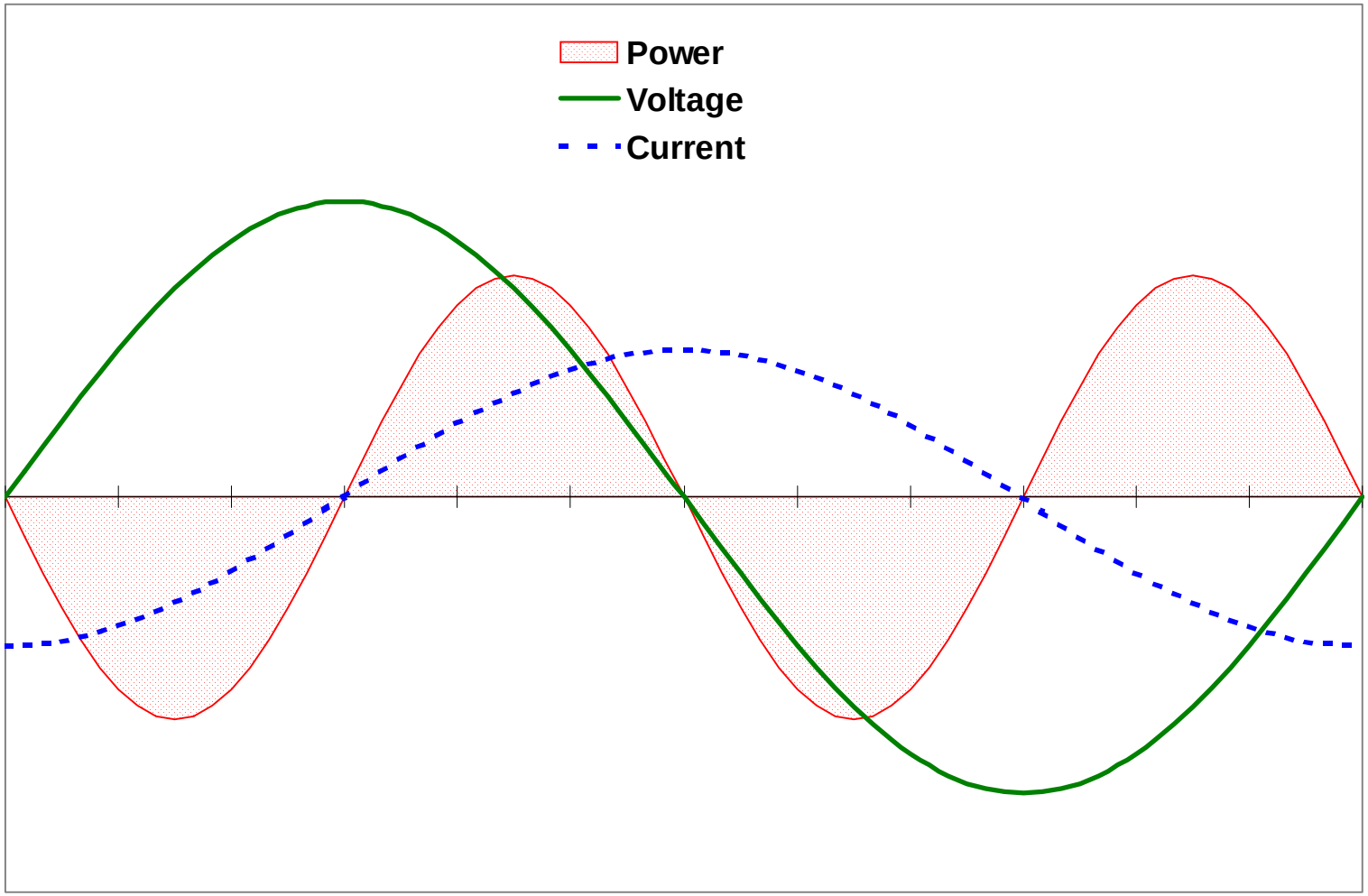
- Resistors & Resistance
- Capacitors & Capacitance
- Inductors (or Reactors) and Inductance
- All electric equipment has these three properties to a greater or lesser extent

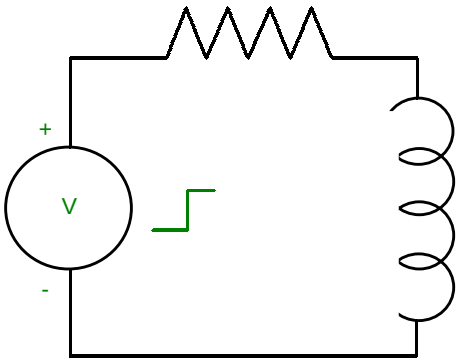


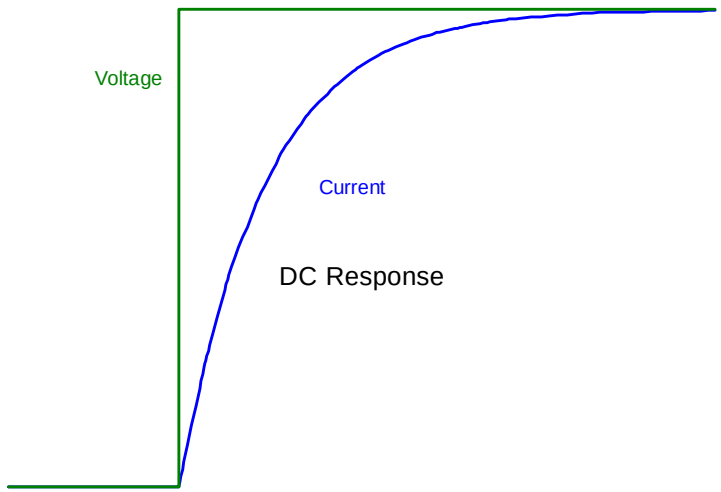
What Happens If Current Lags Voltage?

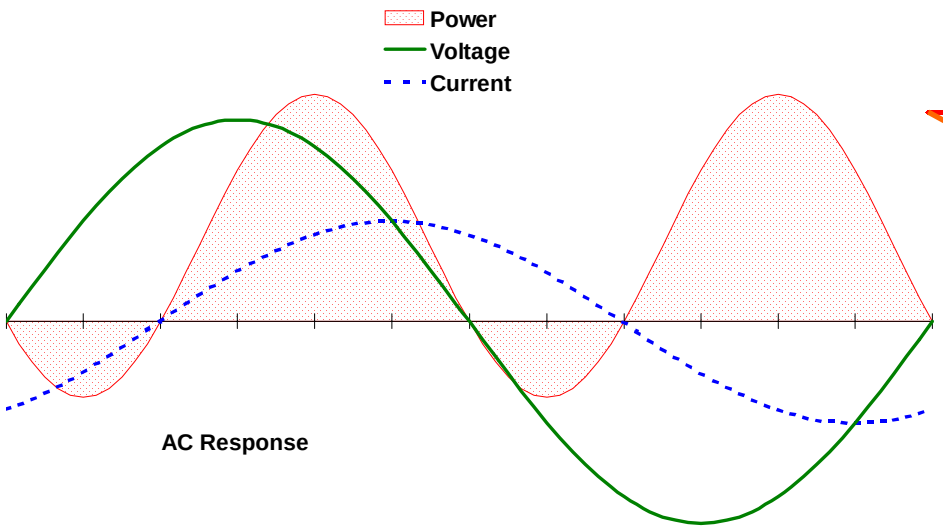


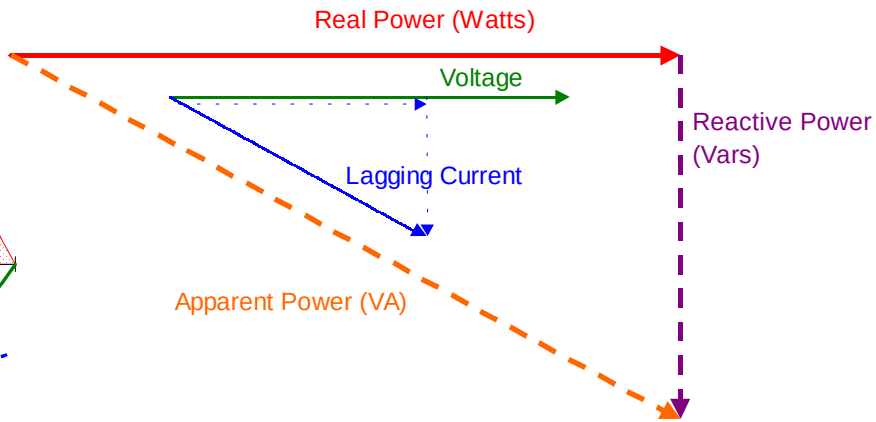
Instantaneous Power But No Net Energy

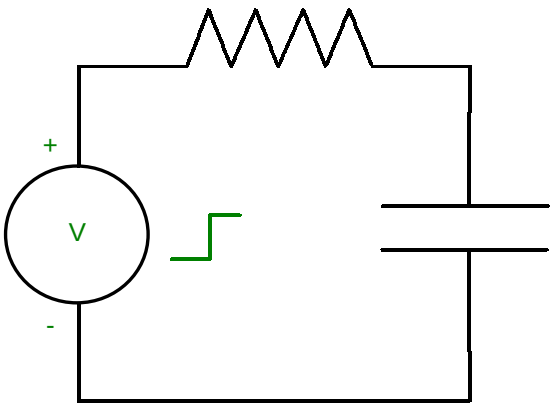



+
V
-


Voltage
Current
DC Response


Power
Voltage
Current
AC Response


Real Power (Watts)
Voltage
Reactive Power
(Vars)
Lagging Current
Apparent Power (VA)


+
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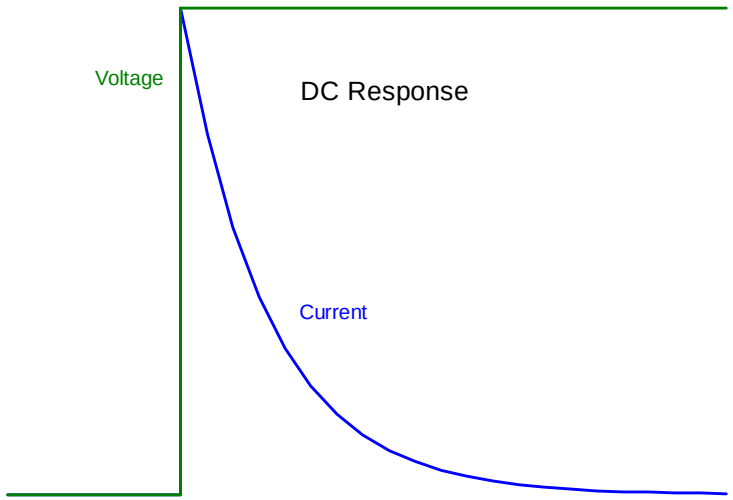
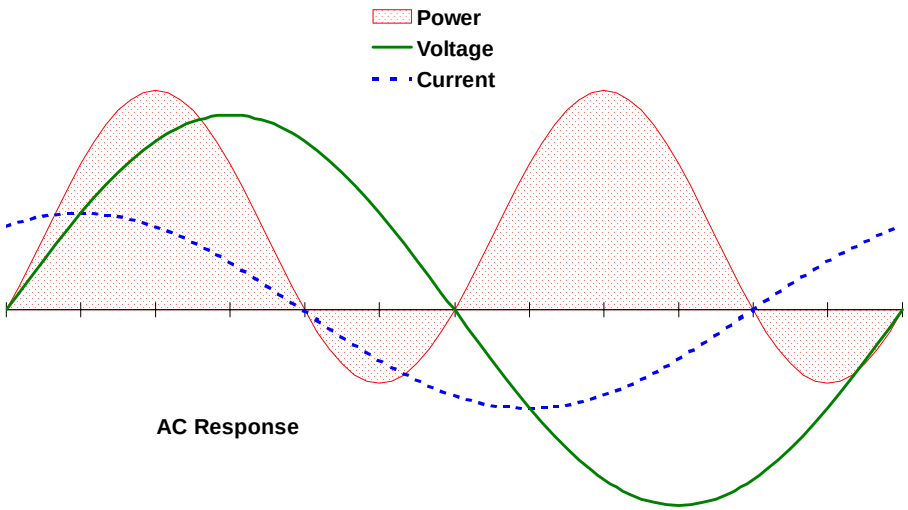
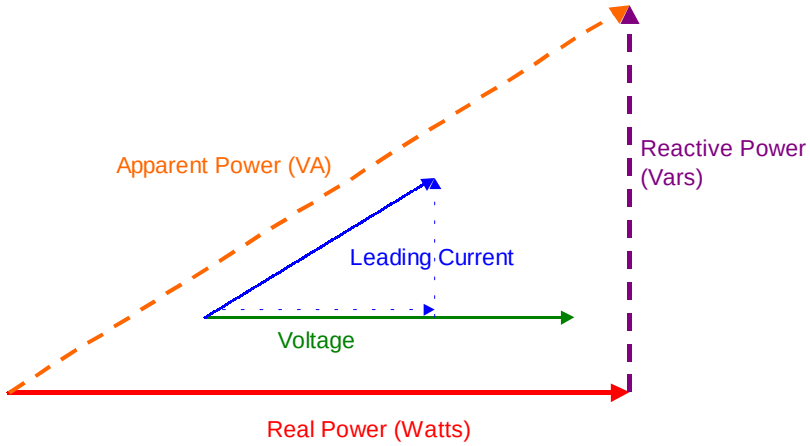
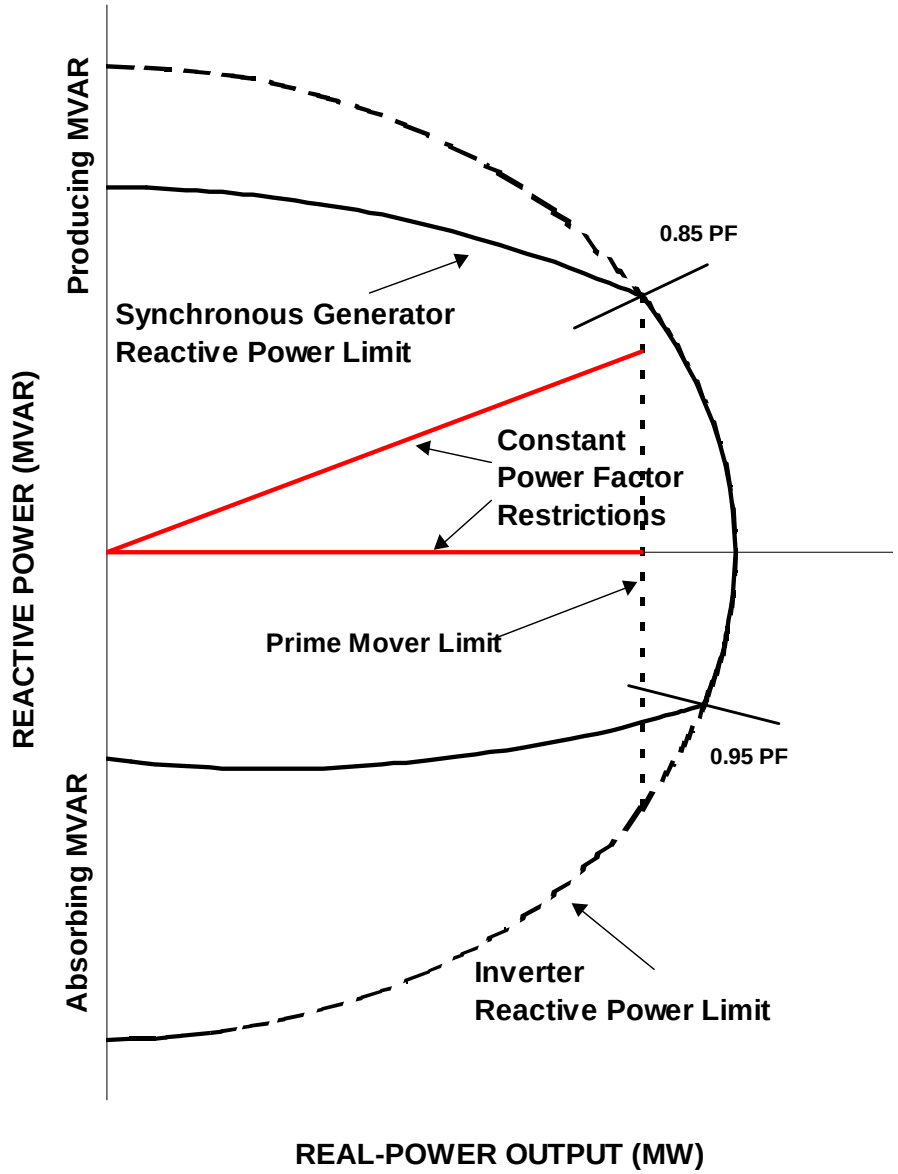

Voltage
DC Response
Current


Power
Voltage
Current
AC Response


Apparent Power (VA)
Reactive Power
(Vars)
Leading Current
Voltage
Real Power (Watts)

Generator Real and Reactive Power Capabilities Interact

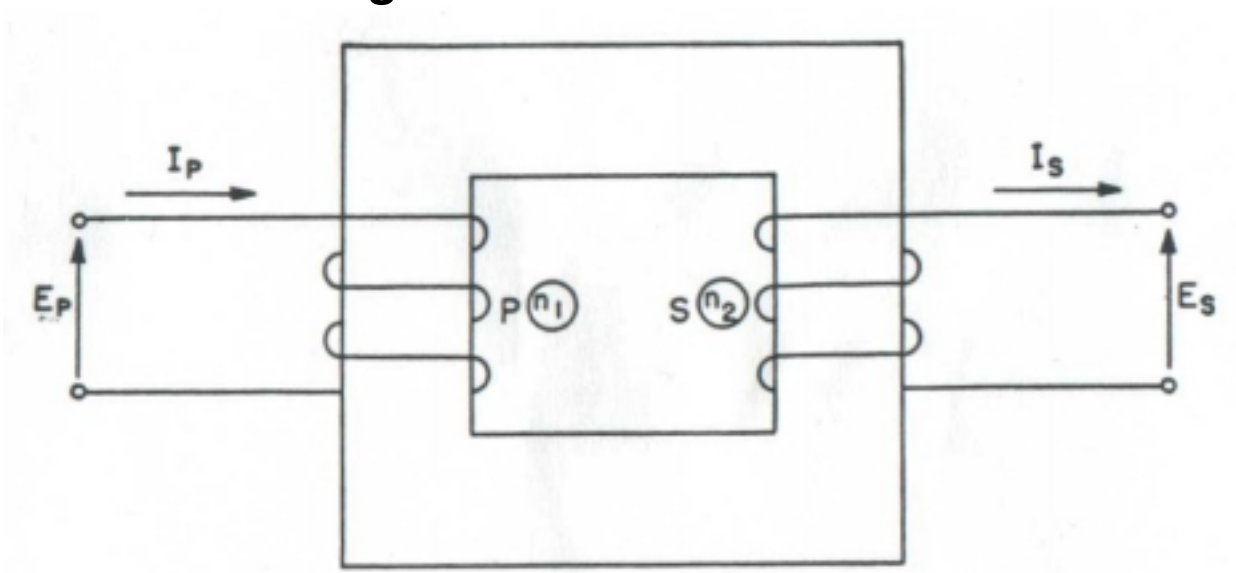


Not Many Types of Devices

- **Generators** - almost all are synchronous
- **Transformers** - only work on AC, are like gear ratios trading voltage and current
- **Transmission Lines** - overhead and underground (& undersea), AC & DC
- **Circuit Breakers** - switches that can interrupt current
- **Capacitors & Reactors (Inductors)** - control voltage
- **Unique devices** - Phase angle regulators, FACTs devices, brakes, ...
- **Assorted other parts** - switches, insulators, surge arrestors, busses, relays, instrument transformers, computers, communications, ...

Transformers Are Like Gears in a Transmission

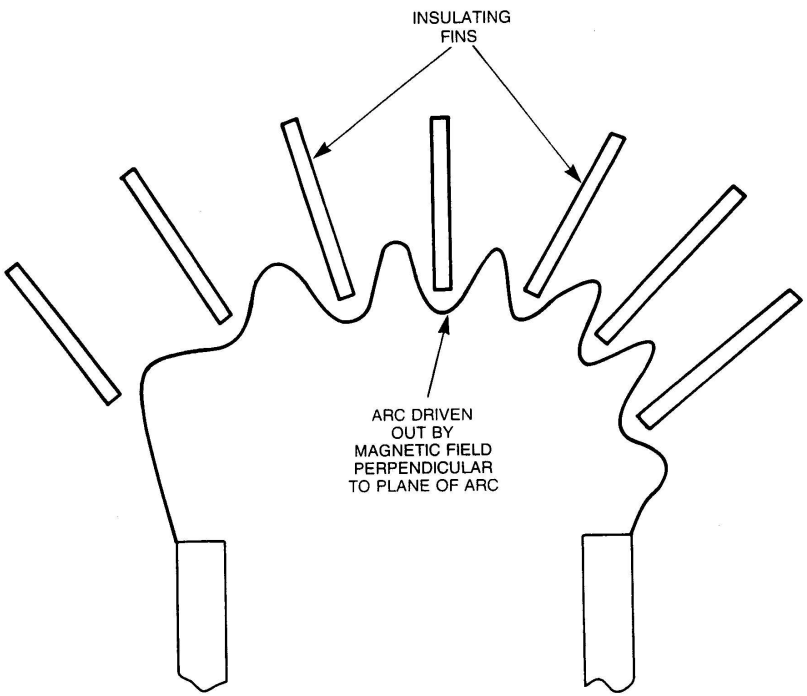
- Input energy = output energy
- They only work with AC - it is the *changing* field that interacts with the wires
- The ratio of the of the voltages is *inverse* to the ratio of the currents
- They typically raise generator voltages to make transmission cheaper and lower voltage for distribution and use



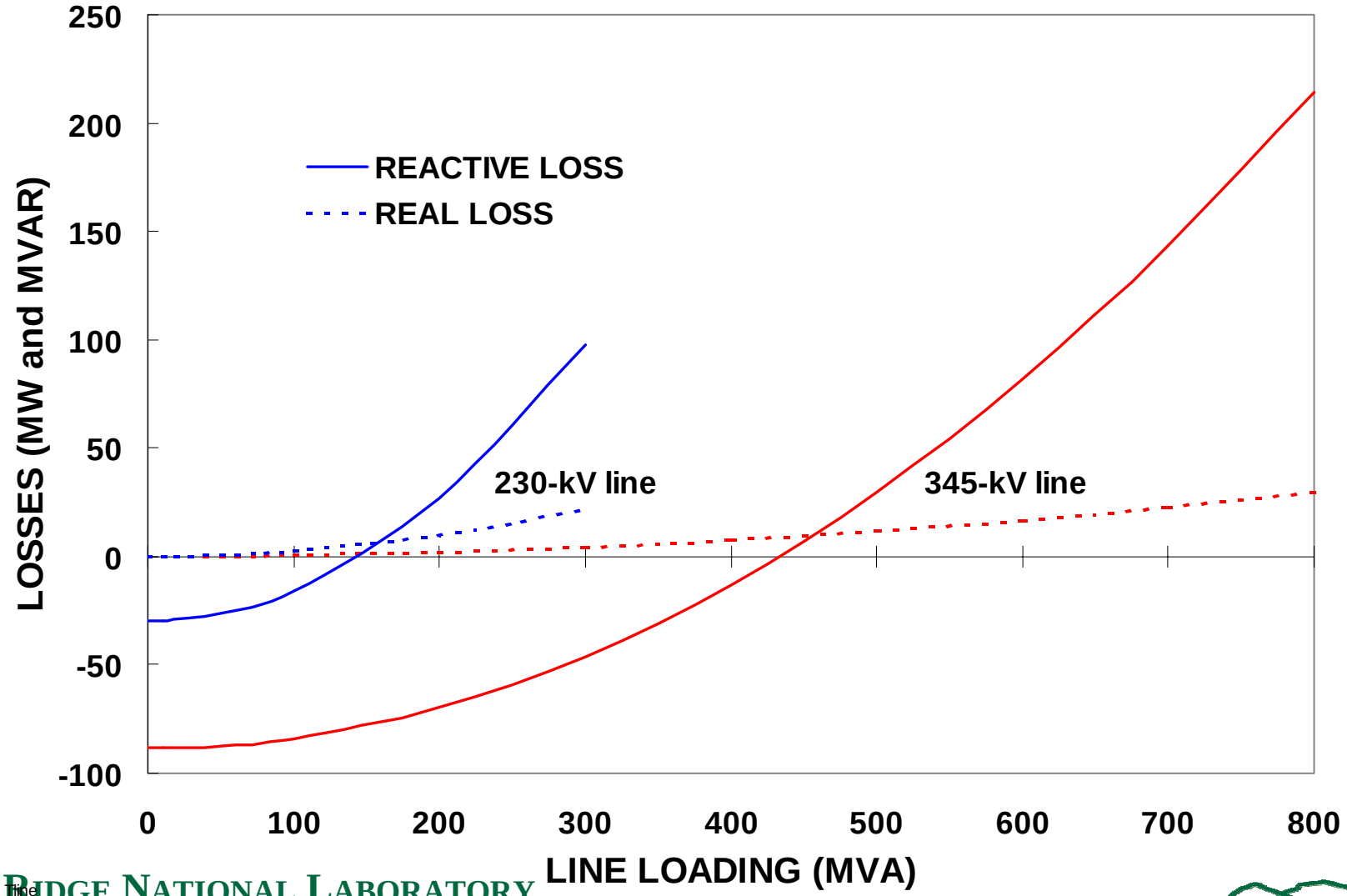
Transformers Come In Many Sizes

My Gosh, A Circuit Breaker Is Just A Switch. What's The Big Deal?

- High voltage creates arcs, extinguishing the arc takes effort
- High current compound the problem
- Circuit breakers can use air, air blasts, magnetic fields, oil, SF6, and/or vacuum
- They must operate fast, typically 3 to 8 cycles
- Failures are "interesting"



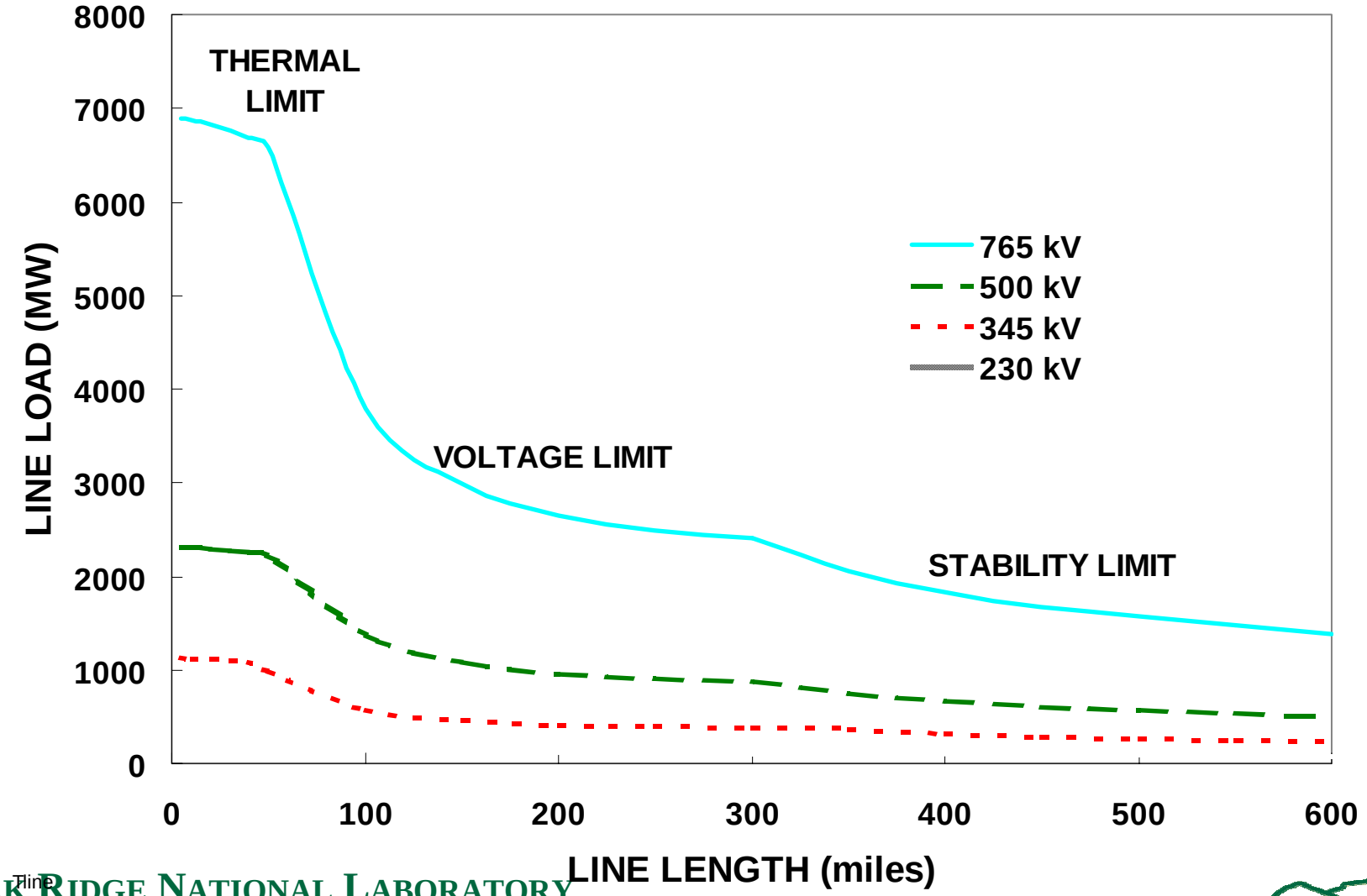
Transmission Line Inductance and Capacitance Are Much Larger Than Resistance



Voltage is a Local Issue

- The high reactive impedance and low real resistance means that watts can go a long distance while vars do not travel far
- Differences in phase angle can be seen from a long way away - and will push watts through the power system
- Differences in voltage are not visible from a great distance and var flow is limited
- You have to deal with voltage (supply vars) locally

What Limits Transmission Line Capacity?



Cost Motivates Higher Transmission Voltage

Voltage (kV)	Capital Cost (thousands $/mi)	Capacity (MW)	Cost (millions $/GW-mi)
230	480	350	1.37
345	900	900	1.00
500	1,200	2,000	0.60
765	1,800	4,000	0.45

Hirst & Kirby 2001 - Seppa 1999

The Per Unit System

- Keeping up with the many possible voltages is difficult
  - Is 310 kV too low? Is 253 kV too high?
- Keeping up with % or per unit (pu) is easy
  - 0.9 pu / 90% is too low, 1.1 pu / 110% is too high
- Nominal voltage is established
  - 138kV, 161kV, 230kV, 345kV, 500kV, 765kV
- Current and Power on equipment basis
  - normal, long term emergency, short term emergency
  - avoids the cumbersome ϕ/ϕ voltage, single ϕ current, and 3 ϕ power conversions
    - 1 pu VA = 1 pu V * 1 pu I
    - 100 MVA = 3 x 161kV/$\sqrt{3}$ x 359 amp

Why Use AC Instead of DC

(Another set of important basics)

- Transformers & high voltage transmission
- Circuit breakers
- Alternators instead of DC generators
- Induction motors instead of DC motors

What Limits Capacity?

- **Heat**
  - **everything has resistance**
  - **current going through a line or transformer heats it**
  - **heat degrades transformer, generator & cable insulation, sags overhead lines**
  - **can be an immediate failure or a long term loss of life**
  - **there are often normal, short term emergency, and long term emergency limits based on how fast the device heats up**
  - **transmission line capacity depends strongly on wind speed - wind takes away heat**

Putting The Parts Together

Now That We Have Power System Parts How Will We Serve Load?

- How to know what the load is doing?
- Smart or stiff?
- Will multiple generators work together?

First, Run Lines Between Your Generator and Your Load. Put In Transformers and Breakers at Both Ends

What Is Technically Required?

- Balance generation & load
  - normal operations
  - contingencies
- Maintain voltages
  - normal operations
  - contingencies
- Restart the system

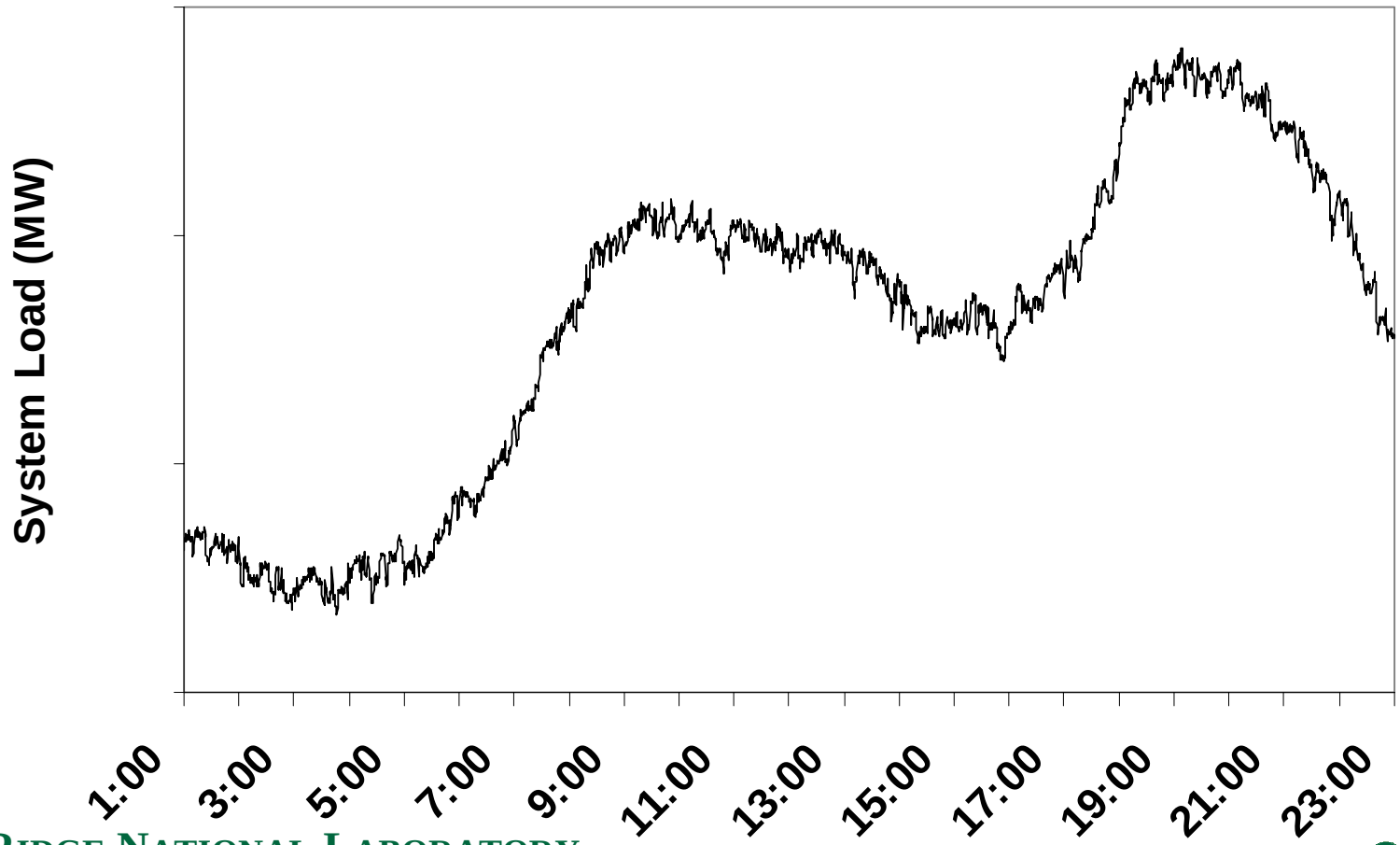
How Do You Control The Generator? Cruse Control

You have a generator & some loads. What do you do now?

- **You could monitor each load or have the owner notify you when they need more or less power**
- **Alternatively, you can watch the generator speed and voltage. No communications needed.**
  - **Changes in speed tell you to adjust the mechanical *real power* going to the generator**
  - **Voltage changes tell you to adjust the field strength (which turns into *reactive power*.)**

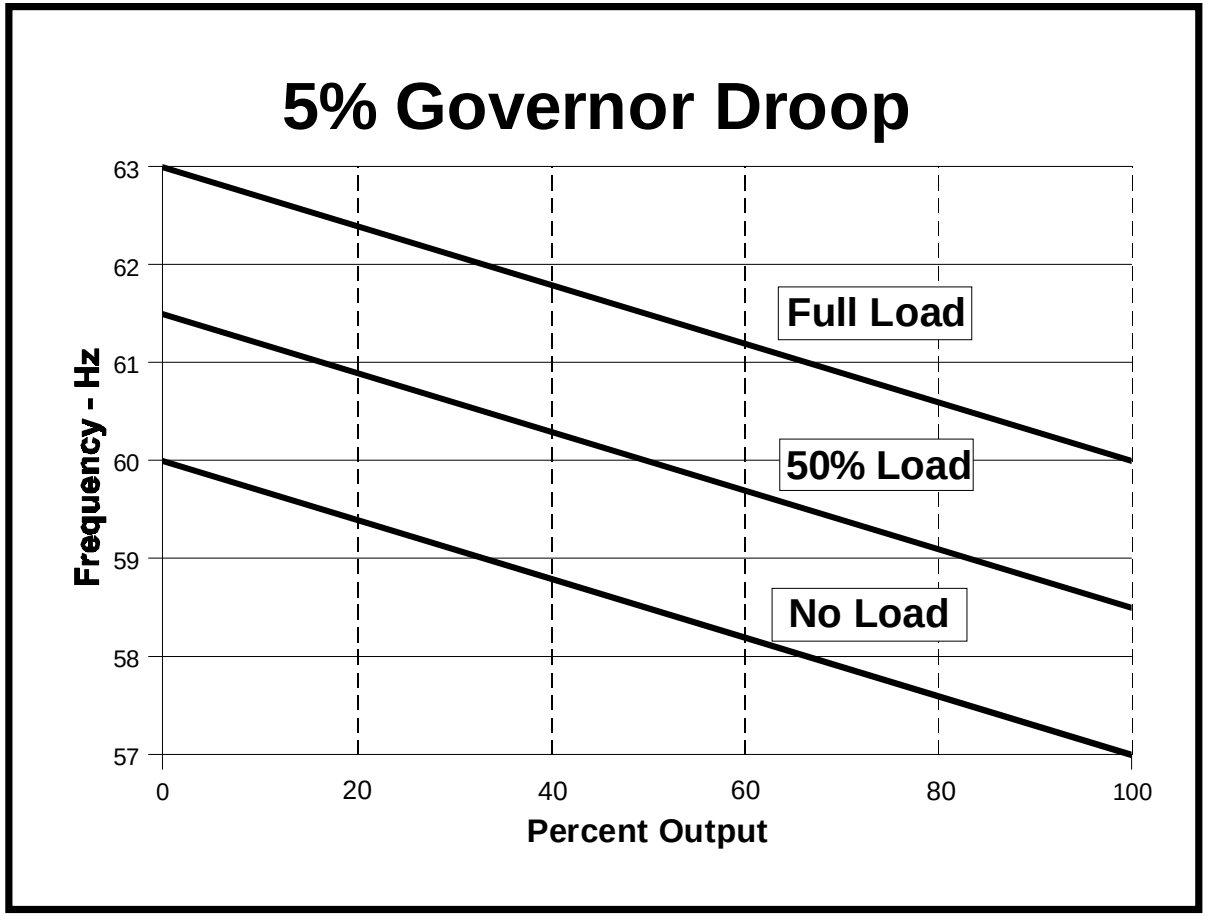
Hold constant frequency and voltage at the generator - Real and Reactive power will take care of themselves

Generators Have To Follow Dynamic Load

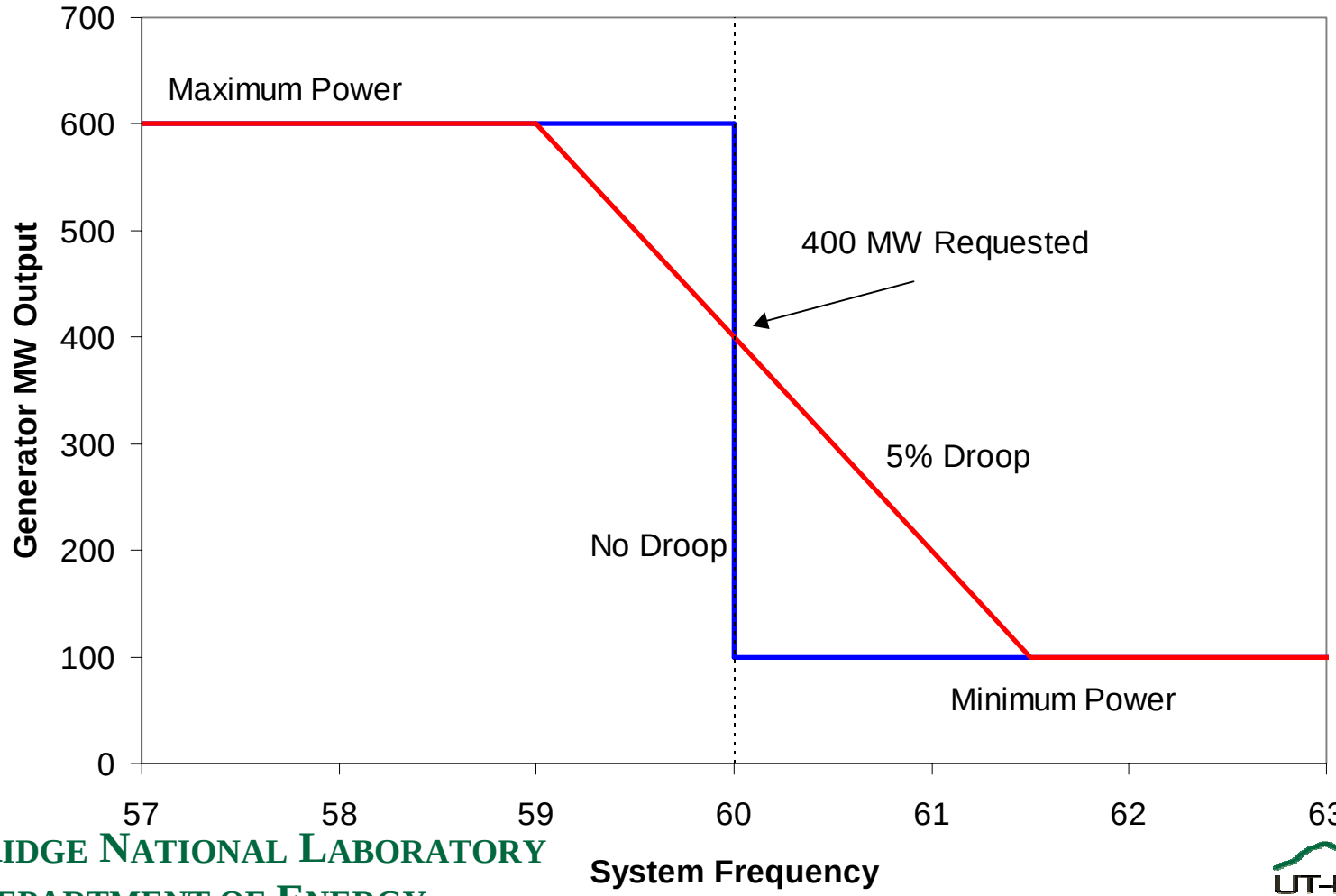


How Do You Control Multiple Generators? Cruse Control for a Wagon Team

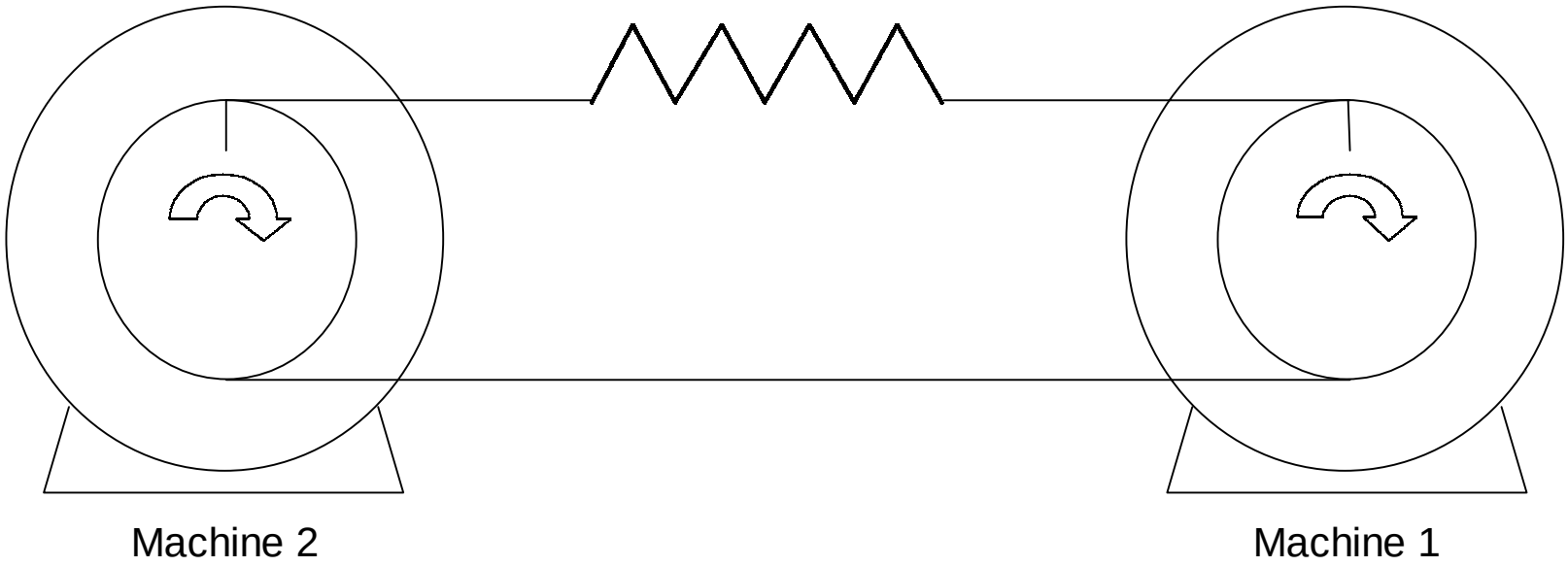
- Multiple machines trying to hold the same frequency will not share load - any slight difference in the speed/frequency sensor will send one machine to full power and the other to zero power
- You could set constant power output from most machines and let one control frequency
- Droop! Multiple machines independently share load nicely


5% Governor Droop
63
62
61
60
59
58
57
Frequency - Hz
0
20
40
60
80
100
Percent Output
Full Load
50% Load
No Load

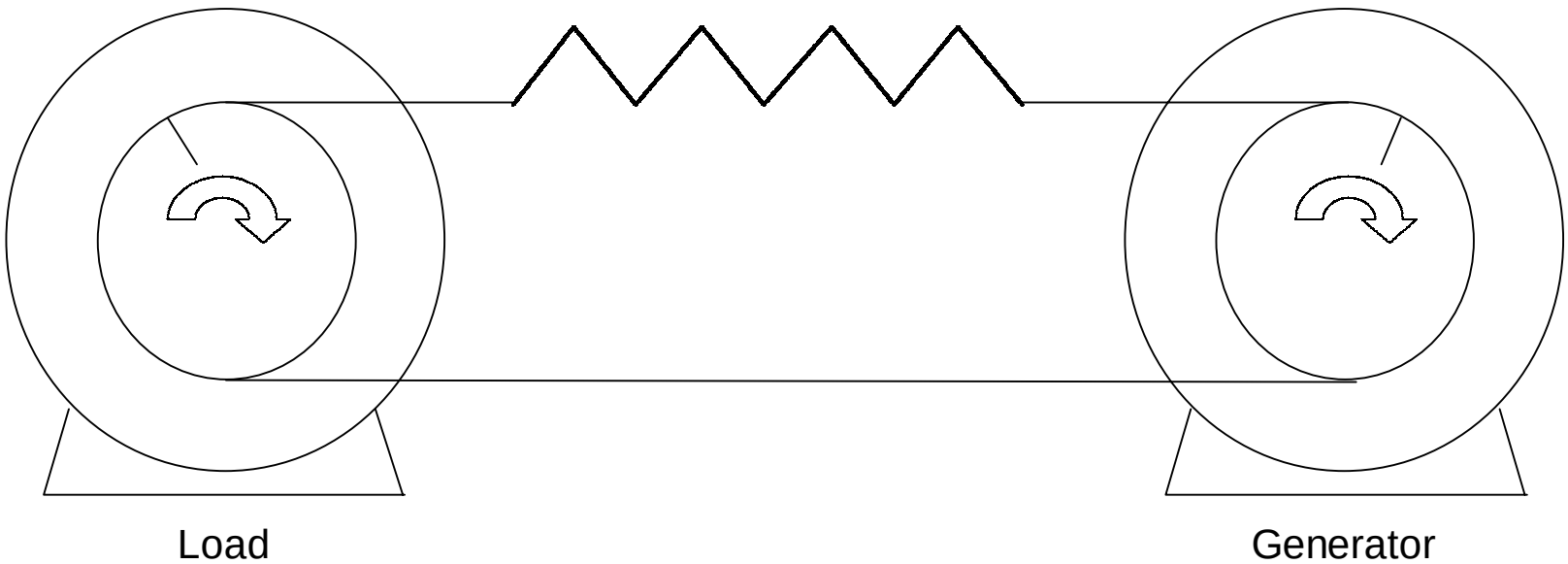
Each Machine's Droop Compensates For Small Differences in Frequency Measurement



Multiple Machines Operate In Lockstep - But They Are Coupled By Springs

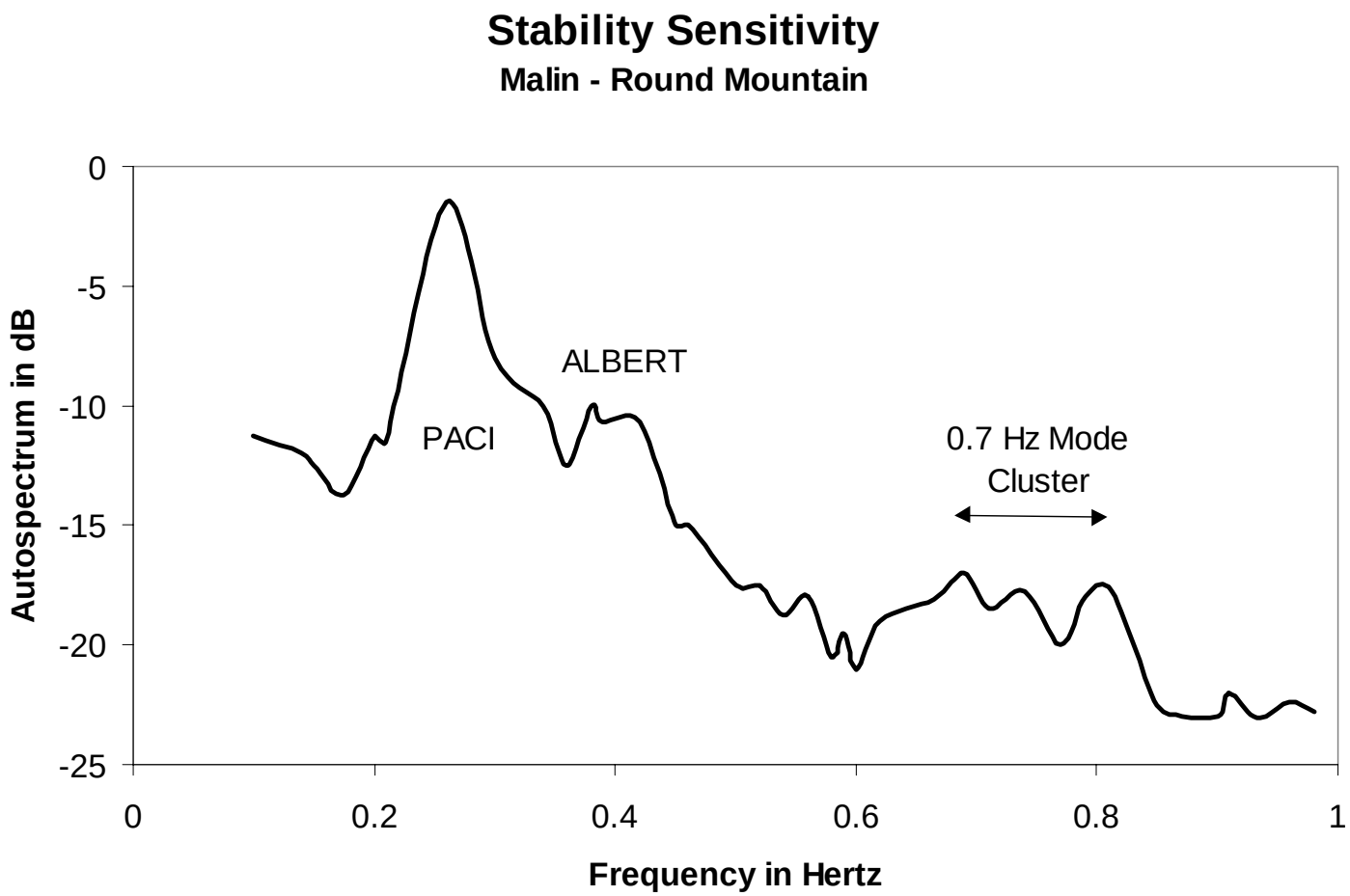


Real Power Moves By Shifts In Phase Angle



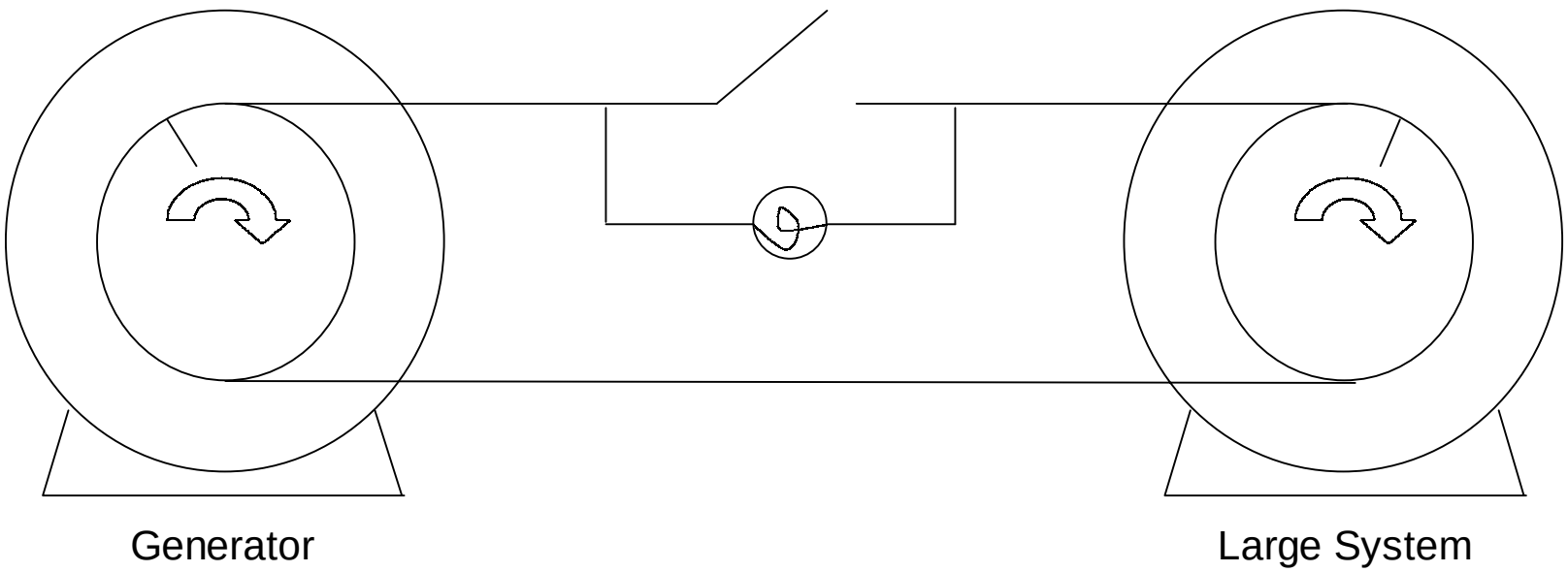
- **Too great an angle difference and the machines loose synchronization - *very* bad**
- **Dynamic stability studies examine the relative motions of multiple machines**

The Western Interconnection Resonates At Several Frequencies



Data source: Warren McReynolds - BPA

Synchronizing Generators - Not For The Faint Of Heart



- **The machines will be in lock step at the same voltage after the breaker is closed**
- **Avoid destroying the smaller machine by matching speed, phase (rotor) angle, & voltage *before* closing the breaker**

Back to Our Simple System - What Do We Watch to Control It?

- System frequency / generator speed
  - Generator real power output to make sure we are within the operating range, add and remove generators as needed
- Voltages throughout the system
  - Keep them all near 1.0 pu
- Line flows throughout the system
  - Don't burn anything up

Generators Capabilities Are Limited

- Startup time
- Ramp Rate
- Minimum on time
- Minimum off time
- Maximum load
- Minimum load
- Emissions
- …

Forecasting & unit commitment are big issues

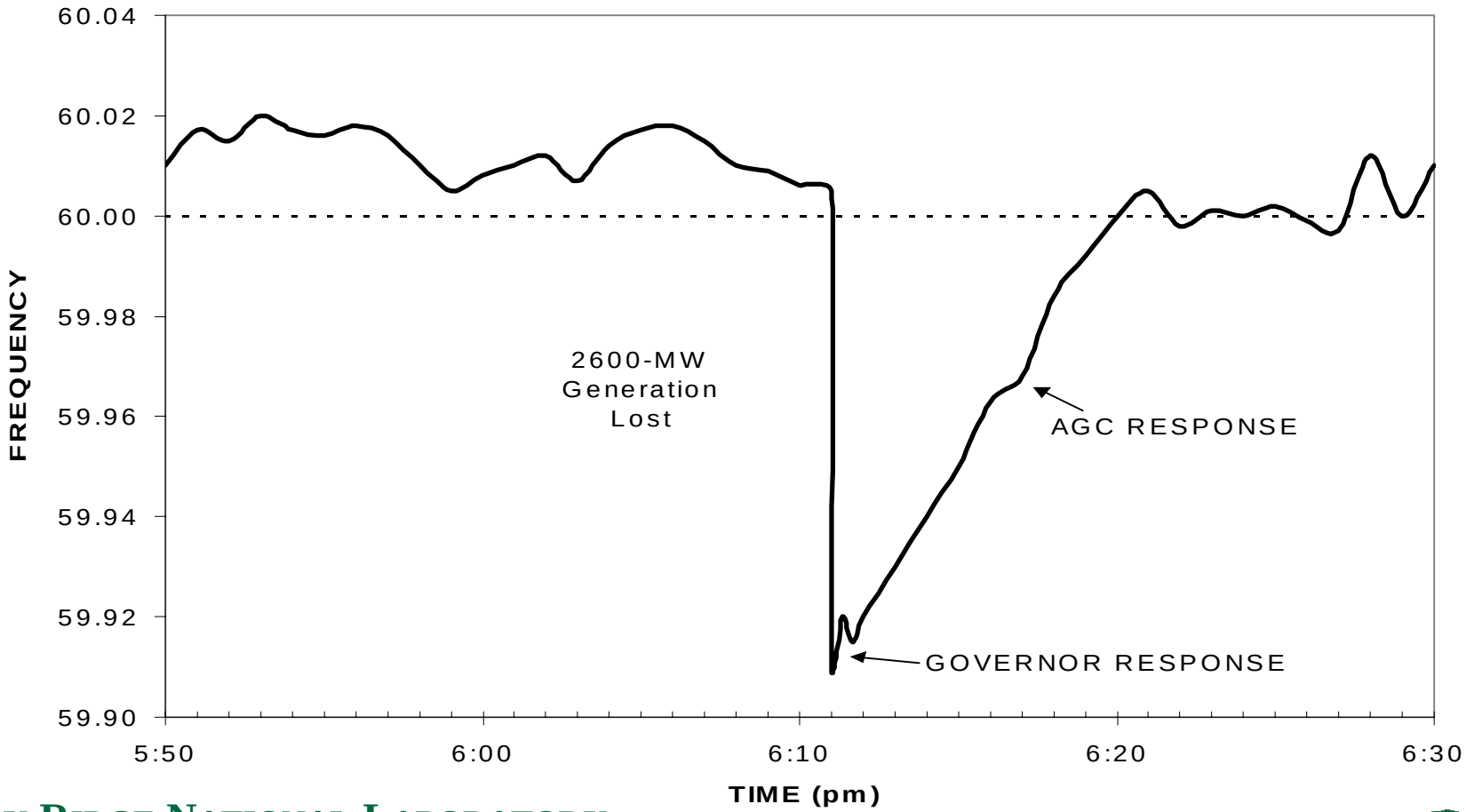
We Are Running a Hierarchical Control System

- Individual generators automatically and locally adjust output to control frequency and voltage
- Transformer tap changers and static capacitors control local voltage throughout the system
- A system operator oversees the system
  - allocates the load split between generators
  - directs generators on and off line
  - places transmission lines in and out of service

Stuff Happens - We Need To Respond To Abnormal Conditions

- Faults - Short Circuits
  - high currents cause damage - detect them & interrupt them quickly
- Recover the energy balance
  - no voltage so no energy - generators accelerate
  - load or generation may be removed when the fault is cleared
- Line & transformer flows and bus voltages will redistribute
  - correct any overloads or under/over voltages
- A range of actions are required
  - very fast relay, breaker & generator autonomous response
  - operator action to place the system back in order
  - *pre-contingency* action so the automatic actions will be successful

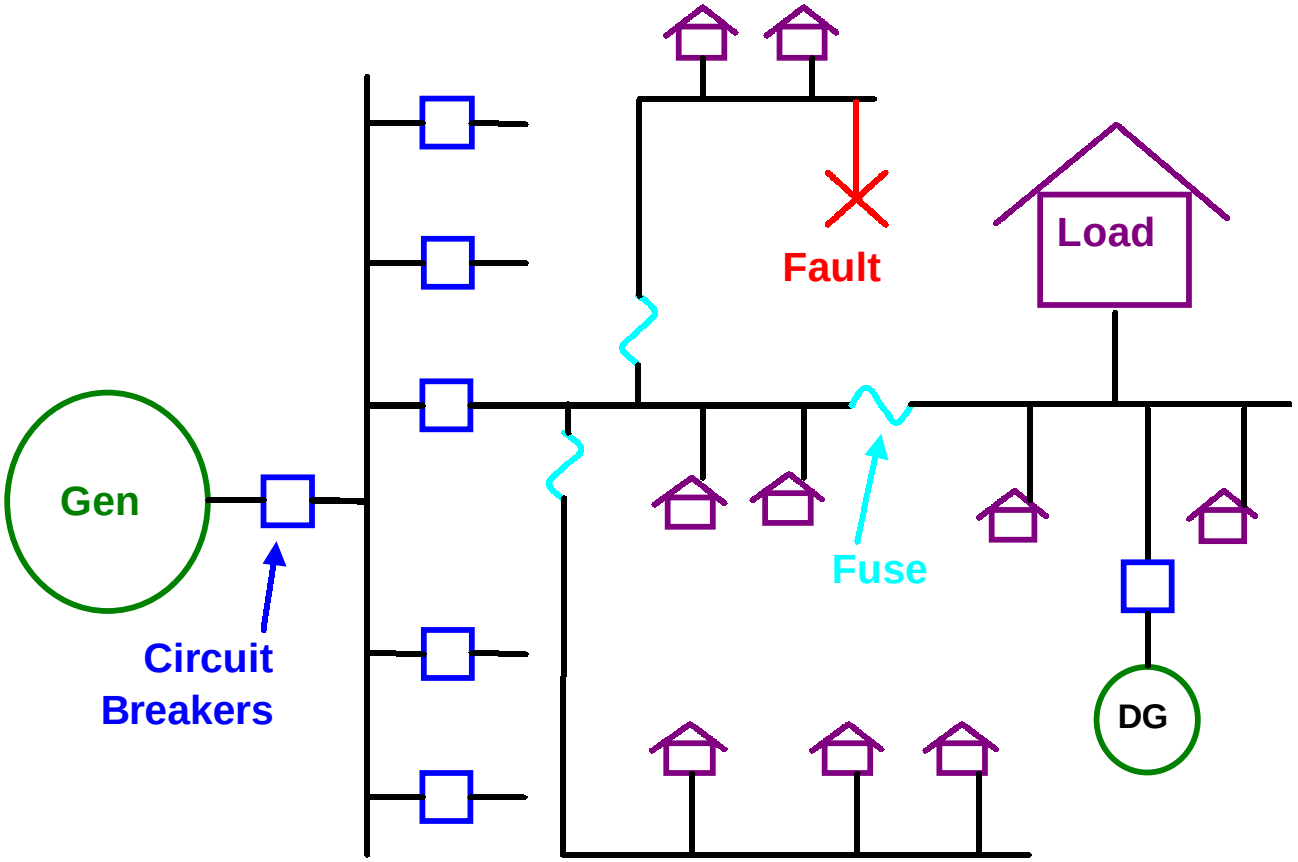
Energy Must Be R-Balanced Quickly by Adding Generation &/or Shedding Load



High Fault Currents - A Blessing and a Curse

- Stiff systems support motor starting, have little flicker
- They also have high fault currents
- Faults are detected by unusually high current
- Relay action is carefully coordinated
  - failure is grave so independent, redundant systems are used
- Most faults are temporary - automatic reclosing improves reliability but complicates distributed generation

Automatic Reclosing Saves Fuses and Minimizes Customer Outages

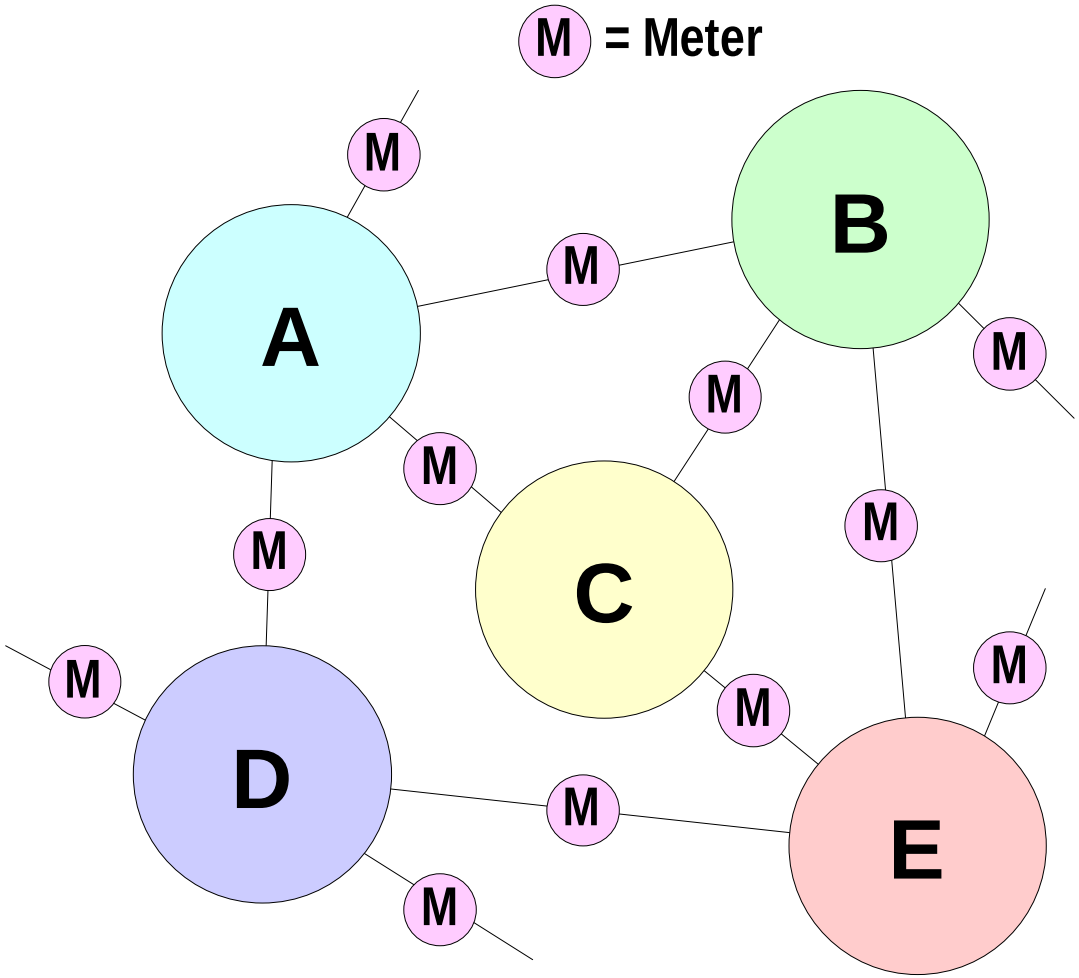


We Can Interconnect With Neighbors For Reliability and Economy

- Share reserves
- Buy and sell energy

- Don't give up autonomy!

Control Areas Meter Their Interconnections



The ACE Concept is Straightforward

Actual Interchange

- Scheduled Interchange

- 10ß (Frequency Deviation)

Area Control Error

CPS1

$$AVG_{annual}\ \{ACE_i/(-10B) * \Delta F_i\} \leq \epsilon^2$$

- ACE_i & ΔF_i are 1 minute averages
- ϵ is the 1 minute average acceptable interconnection frequency error

- **Limits average contribution to frequency error**

This is a lot simpler than it at first appears

CPS2

$$|ACE_{10}| \leq L_{10}$$

- ACE_{10} is a 10 minute average
- L_{10} is based on acceptable interconnection frequency error
- Compliance required $\geq$ 90% of time

- **Limits ACE excursions**

The Disturbance Control Standard Limits ACE After a Contingency

- **DCS - return ACE to 0 or pre-contingency within 10 minutes**
  - **applies only to 80-100% of largest contingency**
  - **failure to comply results in increased reserve requirement**

- **Assessment of individual loads & generators may have to be more deterministic - who takes the risk & who pays the consequences?**

ACE Only Concerns Net Interchange Individual Flows & Voltages Still Matter

- Lack of flow control in the network means that activities in other control areas will impact flows on your lines
- "Loop" flows are a major concern with interconnected systems
- "Contract Path" is a fiction. Unfortunately nothing better has gained acceptance
- Identifying who is causing a problem can be a major task
- The only solution is generator redispatch - transaction curtailment
- NERC's OASIS system has partly automated the process

Now That We Have A Fully Interconnected System What Do We Watch to Control It?

- System frequency / generator speed
  - Generator real power output to make sure we are within the operating range, add and remove generators as needed
- Voltages throughout the system
  - Keep them all near 1.0 pu
- Line flows throughout the system
  - Don't burn anything up
- Line flows to the neighbors (the only new one)

What Can We Control?

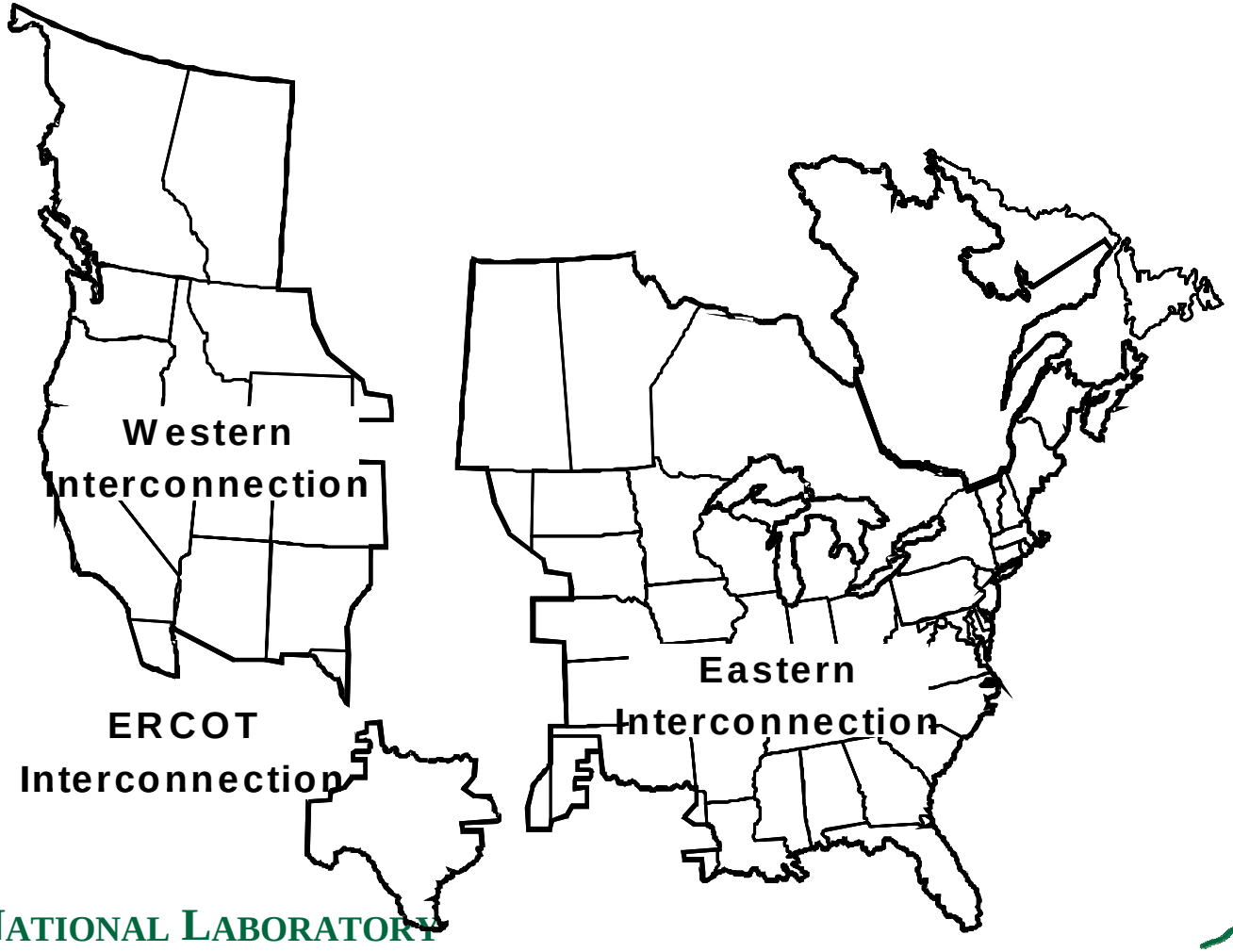
- Generators
  - Which units are on & off
  - Real power output
  - Reactive power output (to control voltage)
- Transmission system
  - Which lines are in service
  - Transformer taps (to control voltage)
  - Which capacitors are on (to control voltage)

System Control vs Revenue Metering

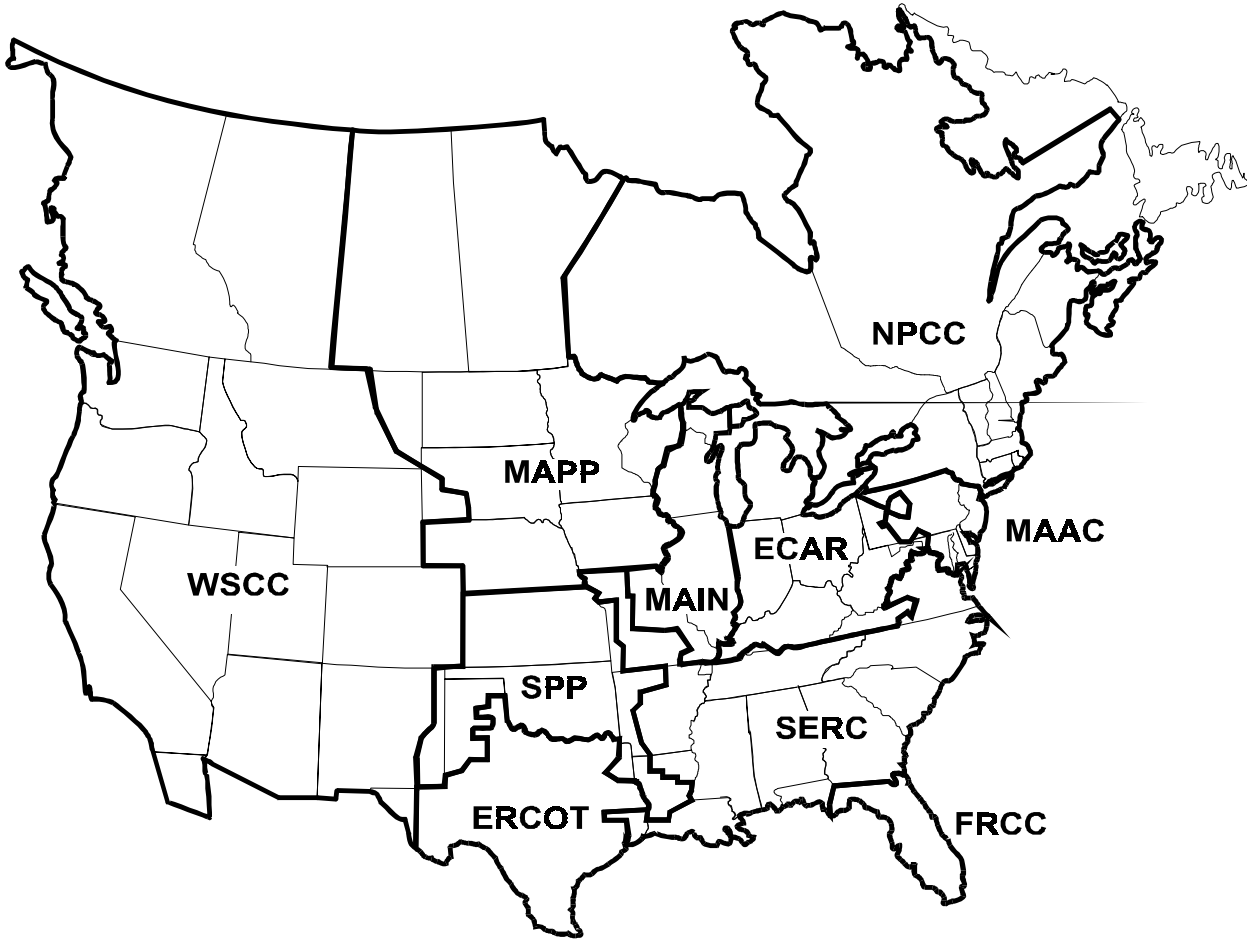
Another Interesting Insight

- **To run the system you need a good idea of voltages and flows throughout the system, generator outputs, and interconnection flows. You need to know system frequency precisely. You need to collect this information every few seconds**
- **To send bills you need continuous precise measurements of voltage, current, and the relationship between them at each customer. You only need to collect this information once per month.**
- **Revenue metering requirements are tougher. Operations communications requirements are tougher.**

Three Asynchronous Interconnections, Connected With DC Ties, Each Composed of Many Control Areas



Ten regional Reliability Councils & Over One Hundred Control Areas



NERC is Trying to Become NAERO

- North American Electric Reliability Council
  - Owned by the regional organizations which are owned by the member utilities
  - Utility membership
  - Voluntary guidelines
- North American Electric Reliability Organization
  - Owns the regional organizations
  - All stakeholders
  - Mandatory policies
- Where does its authority come from?
  - Legislation?
  - FERC?
  - Contract? (works for WSCC)
- Reliability & commerce can't be separated

The N-1 Planning & Operating Criteria

- When a contingency occurs (generator trips, lightning strikes, …) there is no time to reconfigure the system other than to isolate the broken equipment
- The system must be operated at all times such that it can withstand the next contingency
- Contingencies are enumerated
  - individual lines, transformers, generators, …
  - double circuit lines
  - any "credible" multiple contingency

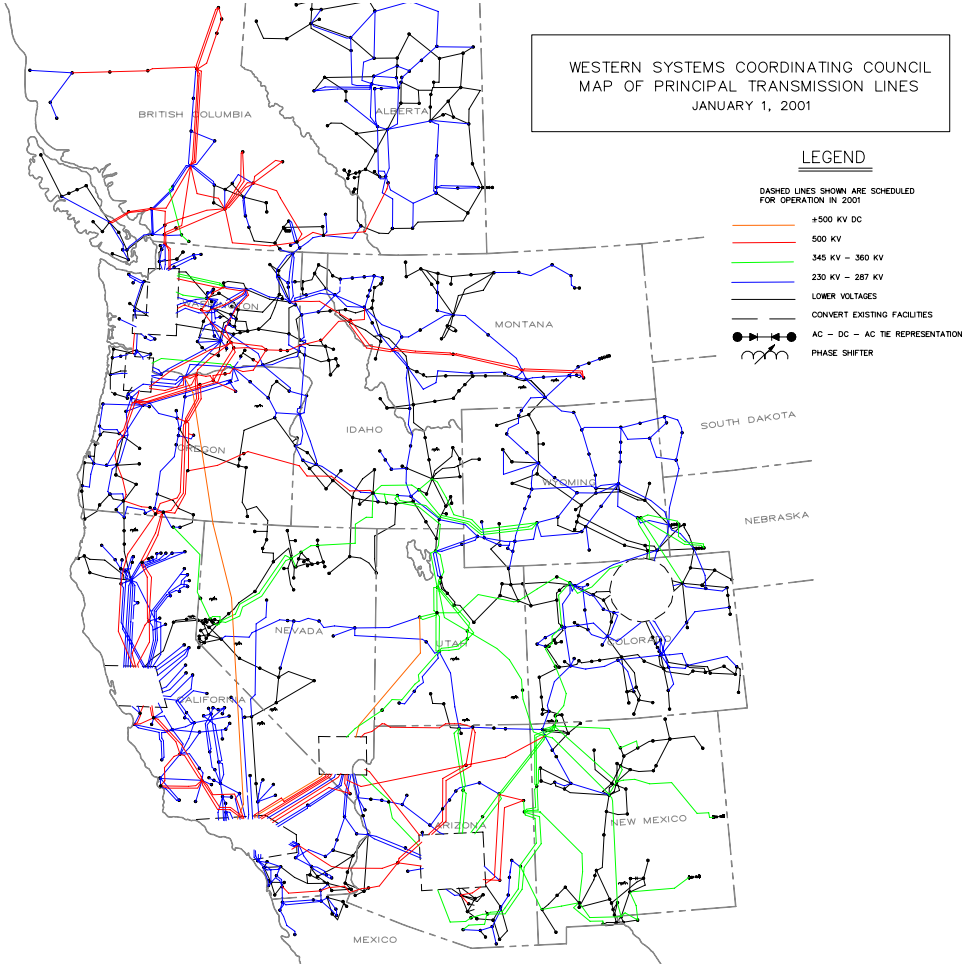
Distribution Reliability - The Lights Go Out
Wholesale Reliability - The Price Goes Up
(California Excepted)

- A contingency on a radial distribution line means someone's lights go out
  - the system tries to minimize the number of impacted customers and the outage duration
- The bulk power system is designed and operated to withstand reliability events
  - no customers should be impacted by any credible event
  - the system is continuously analyzed to assure that it can withstand the next event
  - operations are changed (mostly generators are redispatched and transactions are curtailed) when necessary
  - (it is amazing how often this actually works)

Modeling For Planning & Operations - A Critical Set of Tools

- Not as many analysis tools as you might think
- They all do about the same thing but over different time frames
- All give snapshots of defined conditions
- Complexity comes from size, not from individual calculations

WSCC Modeling - Smaller Than The Eastern Interconnection



Data Requirements Are Enormous

- Lack of flow control means that conditions on one part of the system impact flows throughout the system
  - you have to model every system you are connected to
- Data is required on every generator, line, transformer, capacitor, load, ...
  - connectivity, impedance, MW, MVAR, setpoint, capacity limits, ...

Updating Models is a Full Time Job

- Utilities are constantly updating the models of their own systems & exchanging data to create models of the interconnection
- Models are needed for current conditions and future expected conditions
  - next summer, next winter, on peak, off peak, shoulder peak, 5 years, …
- Data is harder to obtain in a competitive world

Load Flow

- Steady state calculation of buss voltages & line flows
- Can calculate transformer taps, capacitor switching, generator vars, to control voltages
- Re-run hundreds - thousands of times to check each contingency
- Identifies overloaded equipment and unacceptable voltages
- Modeler must then find alternatives that are acceptable

Load Flow Variations

- State estimator
  - uses current data to verify model
- On-line contingency analysis
  - tests current system
- Optimal power flow & security constrained dispatch
  - optimizes generators real power output

Dynamic Analysis

- Requires more data on generators and loads
- Models changing voltages & flows over a few seconds in response to a short circuit, line trip, …
- Results typically converted into line loading limits and generator operating restrictions
- Several models
  - EMTP - very fast transients
  - Transient stability - large disturbance response
  - Steady state stability - small disturbance response

Short Circuit Analysis

- Calculates the maximum fault current at each bus
  - less data required on most elements, more generator data required
  - used to specify circuit breaker requirements

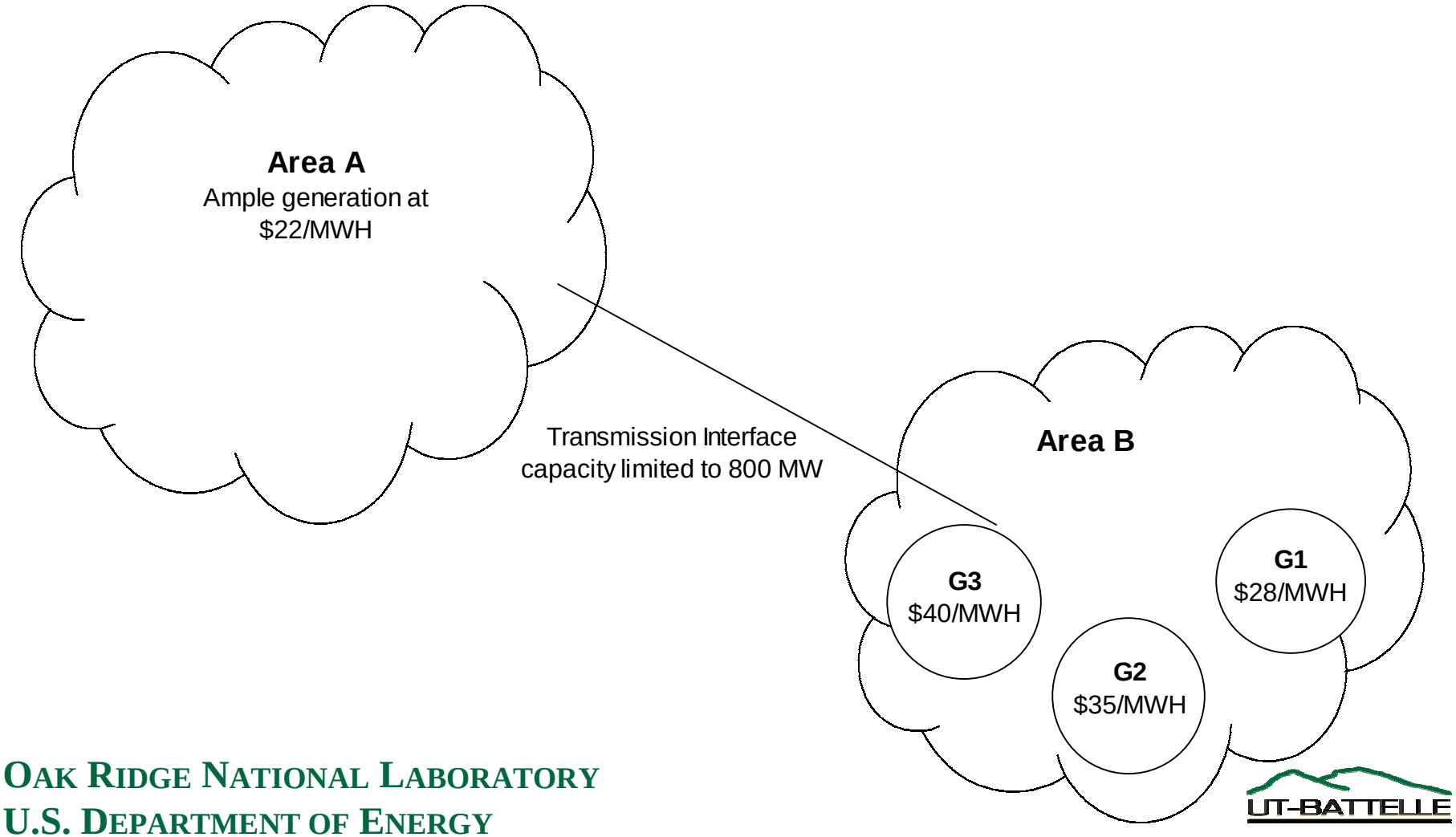
Transmission Congestion

- Desire to move more power from A to B than can be allowed
  - the line is at its load limit or a contingency would put it there
- Prices (or marginal costs) diverge
  - price at A goes down, price at B goes up
- Congestion pricing is as good as physical transmission rights ownership
  - line revenue = ($B/MWH - $A/MWH)*MW capacity

Congestion Pricing (continued)

- **Critical that the system operator does *not* receive the congestion payment**
  - **that provides an incentive to create congestion**
- **Congestion pricing *allocates* scarce transmission**
  - **sell the rights in the market (it does not matter who gets the initial sales revenue)**
- **Congestion pricing *does not* motivate transmission investment**
  - **when capacity is adequate the price goes to zero**

Congestion Pricing Generates Revenue



Reliability In A Restructured Industry

OAK RIDGE NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY

UT-BATTELLE

Electric System Reliability Has Two Aspects

- *Adequacy* **- The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled out-ages of system elements.**

- *Security* **- The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.**

Reliability and Commerce Can Not Be Separated

It is tempting to think that FERC is concerned with Comparability and Commerce, NERC is concerned with reliability, and the two can operate independently

- Reliability and commerce are inseparably intertwined
  - Reliability and commerce can often be interchanged
  - Reliability can be used to restrict commerce
  - Commerce can help or hurt reliability

What Is Technically Required?

- Balance generation & load
  - normal operations
  - contingencies
- Maintain voltages
  - normal operations
  - contingencies
- Restart the system

Restructuring Is More Clearly Defining The Reliability Services
(Ancillary Services)

- Getting the rules right is incredibly important (the regulator can no longer simply say "make it work")
- Contracts and market forces can be more effective than generation ownership
- Examining what is fundamentally required, rather than how a function was historically provided, opens new opportunities

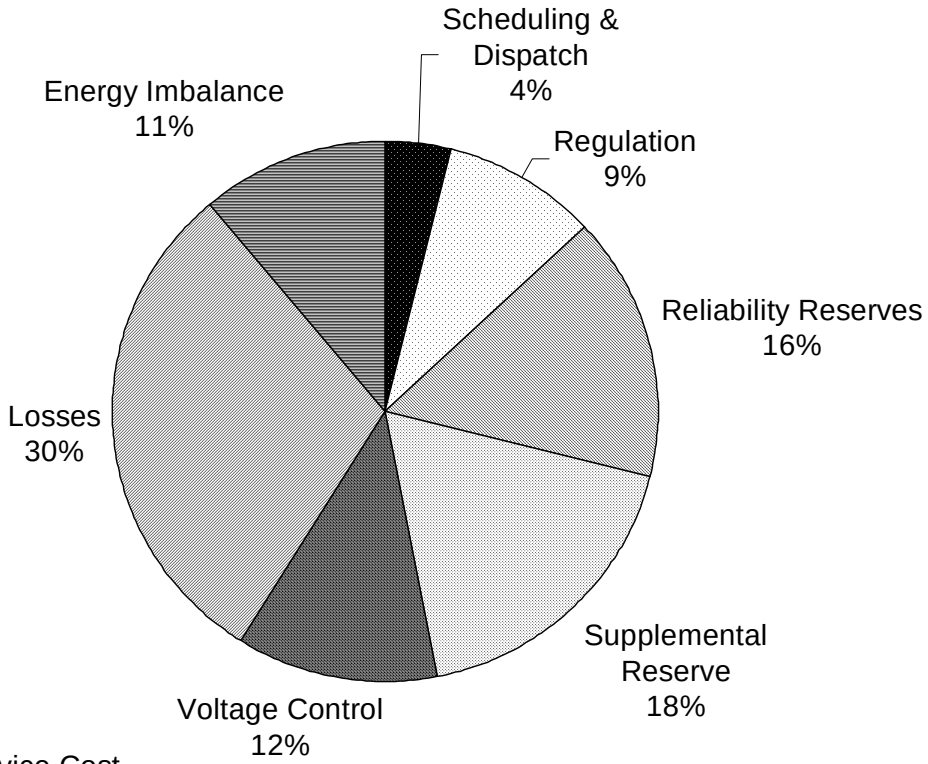
How Many Ancillary Services Are There?

- System control
- Voltage control
- Regulation
- Operating reserves
  - Frequency responsive
  - Supplemental
- ✚ Energy imbalance
- Load following
- ✚ Loss replacement
- ✚ Backup supply
- ✚ Dynamic scheduling
- System black-start
- ✚ Network stability

Why Create Competitive Markets for Ancillary Services?

- The cost of some ancillary services are not trivial
- Loads differ in their ancillary service requirements
- Generators differ in their capabilities and requirements
- Markets allow diverse individuals to balance value
- This may increase load participation in supplying services

Imbedded Cost Based Averages Provide an Estimate of the Size of the Ancillary Services Market



Total Ancillary Service Cost
$12 billion/yr, $4.10/MWH

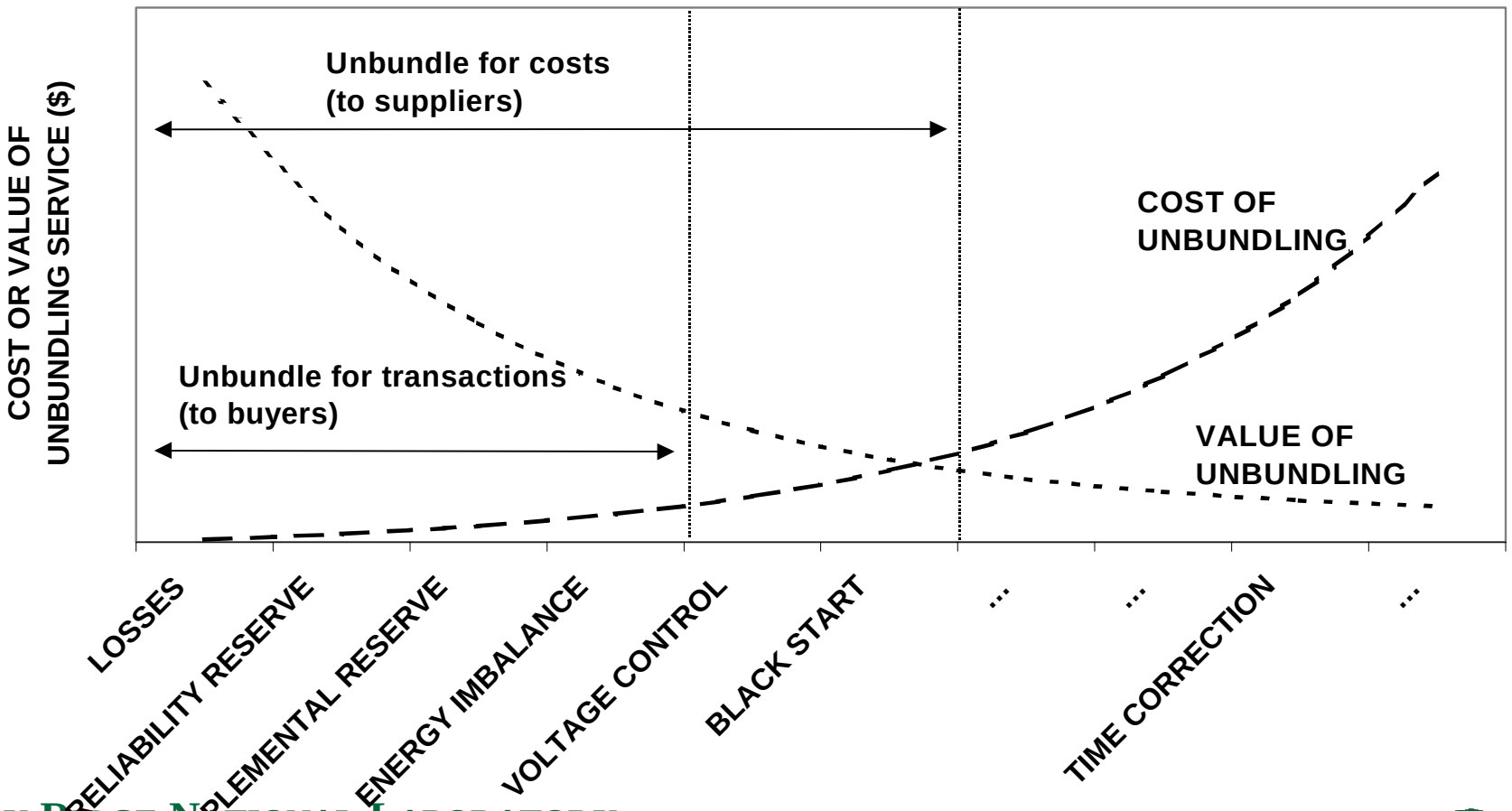
This is Not New Technology

Utilities have been performing these functions for decades, but as vertically integrated regulated monopoly organizations.

A structure with multiple competitive parties require clearer definitions, measurements, requirements rules, and operating policies

We need to think about the power system in new ways

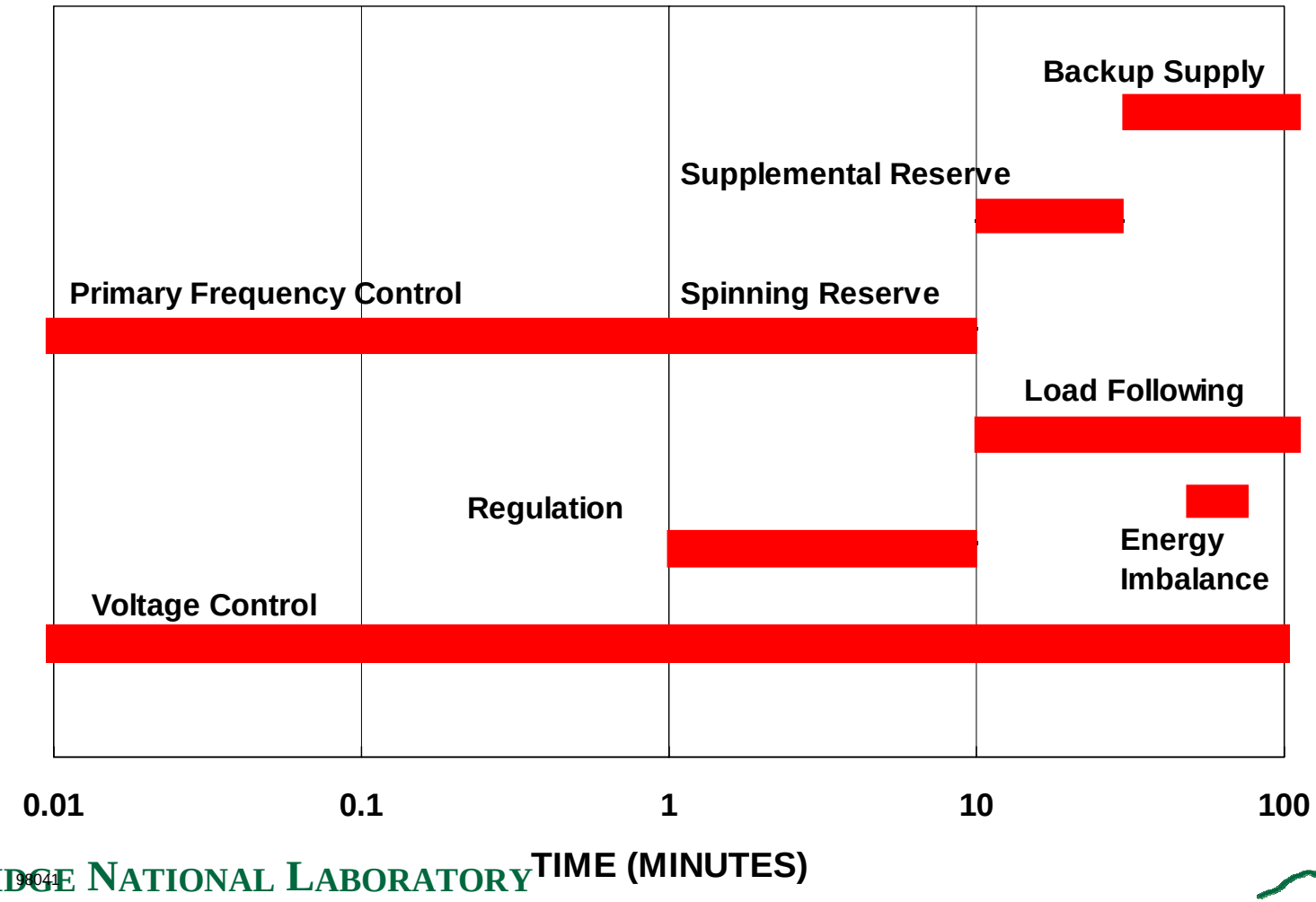
Degree of Unbundling Should Depend on Cost and Value



Response Time Dictate Some Characteristics

- Fast (less than 1 minute) it is automatic, local response
- Intermediate can have coordinated response from a fleet of resources under central control
- Commercial markets can respond in ~1 hr

Ancillary Services Have Different Time Scales



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Economic Efficiency

- Generally there are multiple ways to provide each service
  - Generation
  - Transmission
  - Customer facility
    - Provides the service
    - Using alternatives
- Price signals communicate worth
- Knowing both the cost of providing the service and the value of the service facilitates making economic choices
- Direct research & investment to expensive services

Most Services Needed For Commerce Also

- Three services required *only* for commercial transactions
  - Load following or Energy imbalance
  - Backup supply
  - Dynamic scheduling

Services Well Defined but…

No agreement yet on

- quantifying provision or consumption
- measurement
- pricing

NERC draft Policy 10 offers limited clarification

- "details" left to the Operating Authority

Service Reliability Assured By Contract Rather Than Franchise

- The old paradigm of holding the utility rate-of-return hostage to the regulators satisfaction does not work with multiple competitive parties
- Customer satisfaction is important when there is a clear relationship between customer and supplier

Normal Conditions

Regulation

Load Following

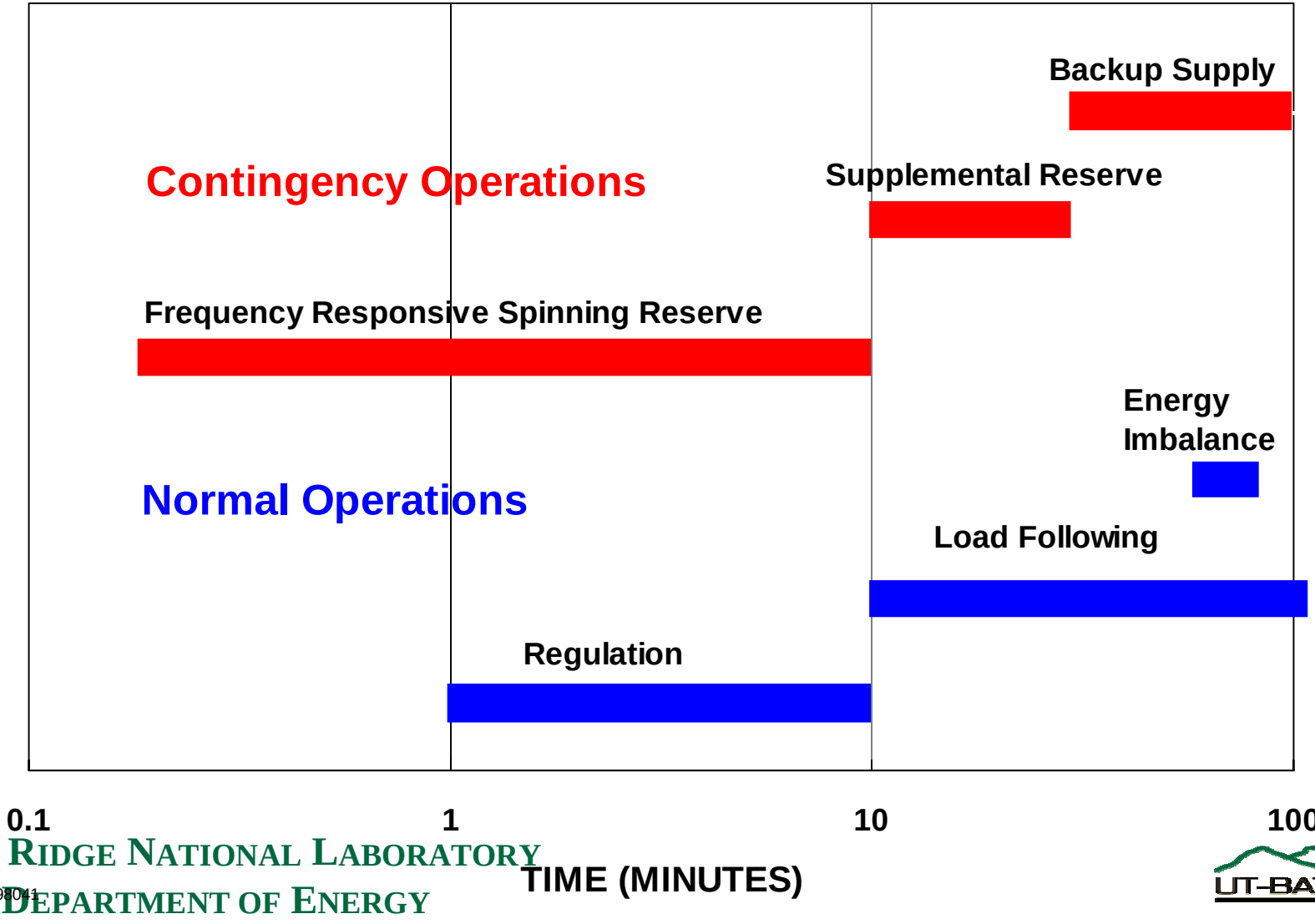
Aggregation Benefits

Control Area Performance Criteria

- Concerned with impacts on frequency & unscheduled flows
- Statistical measures for control areas
  - CPS1 limits annual average of 1 minute deviations
  - CPS2 limits 10 minute excursions

- Assessment of individual loads & generators may have to be more deterministic

Time Scale for Real Power Services



Regulation & Load Following

- Both address the time varying characteristic of balancing generation and load under normal operations
- The "system" only has to compensate for the aggregation
- The aggregation is composed of individual loads and generators with *diverse* characteristics

Regulation Matches Generation To Load, Minute-to-minute

- **Regulating units**
  - **Online**
  - **Not fully loaded**
  - **Not at minimum loading**
  - **With automatic generation control**
  - **With ability to move rapidly (MW/minute)**

- **Heterogeneity**
  - **Customer use of service (load volatility)**
  - **Volatility of non-AGC generator outputs**
  - **Supplier provision of service**

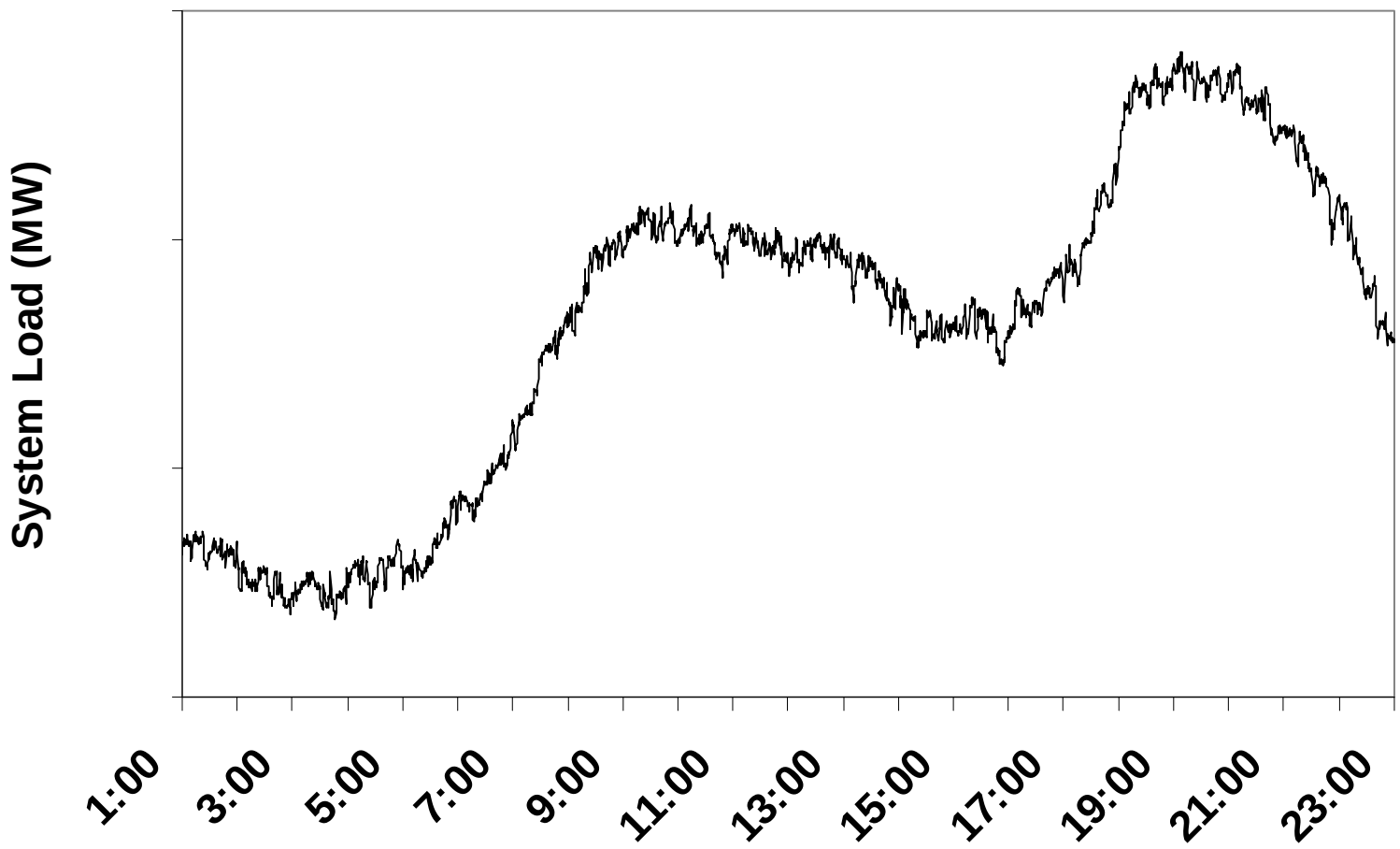
Load Following Is Longer-term Analogue To Regulation

- Use of generation to meet hour-to-hour and daily variations in load
- Occurs over 10 minutes to hours
- FERC did not require in Order 888 tariffs
- Competitive provision and pricing feasible and desirable

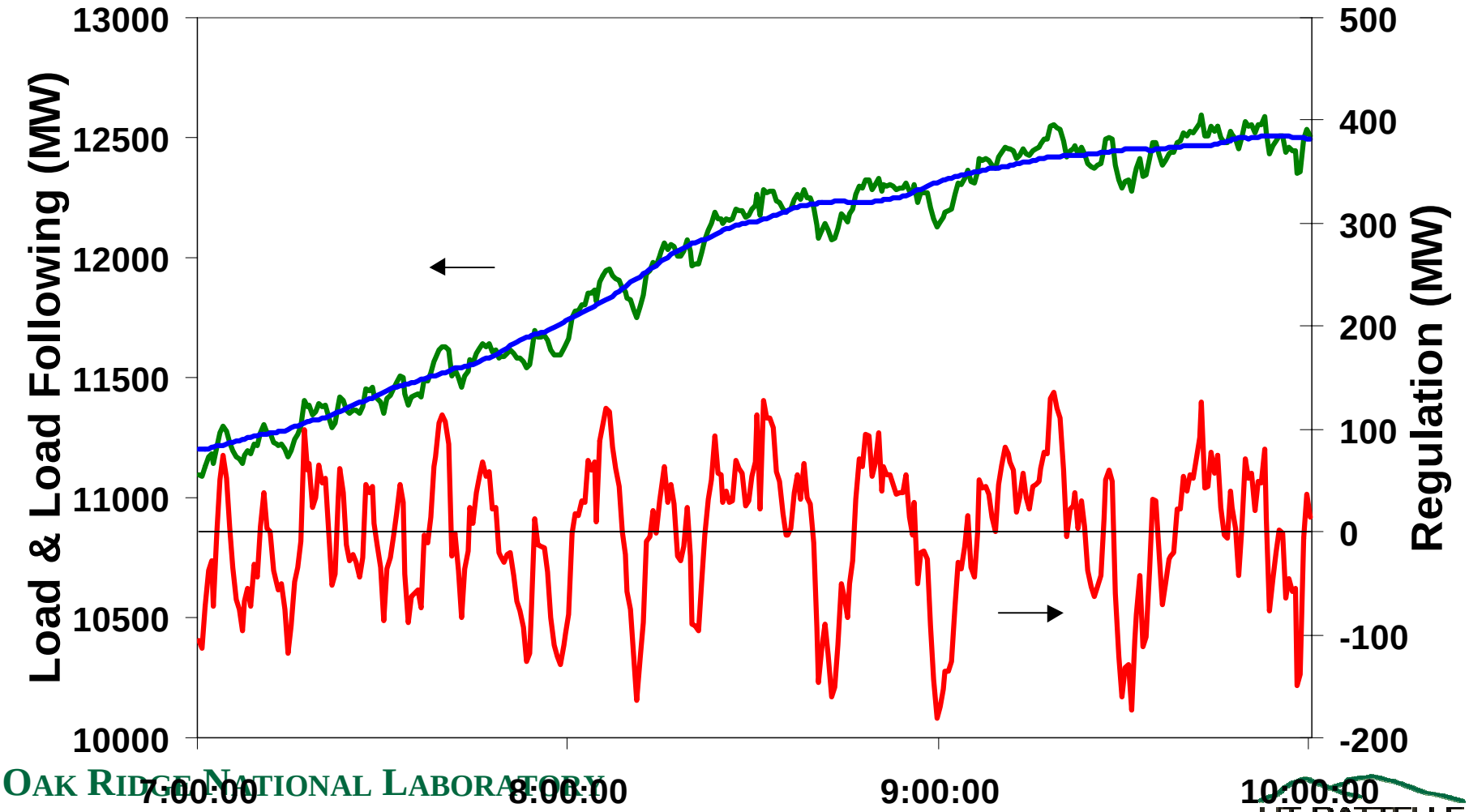
Regulation And Load Following Differ

	REGULATION	LOAD FOLLOWING
Patterns	Random, uncorrelated	Largely correlated
Generator control	Requires AGC	Manual
Maximum swing (MW)	Small	10 – 20 times more
Ramp rate (MW/minute)	5 – 10 times more	Slow
Sign changes	20 – 50 times more	Few

Typical System Load Data



Regulation and Load Following Balance the System Under Normal Conditions



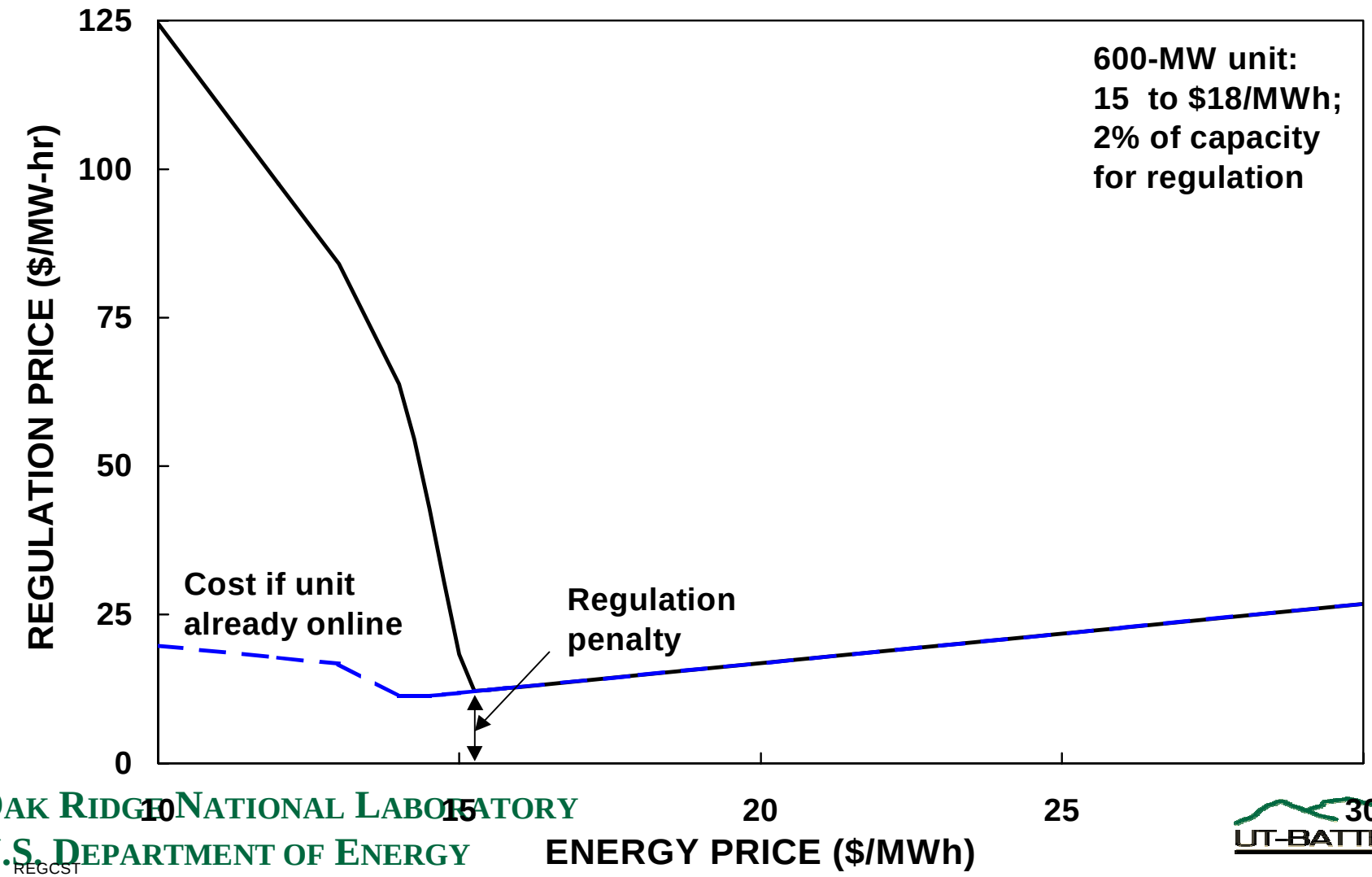
Regulation Cost Components

- Heat-rate penalty
- Unit commitment
- Opportunity cost
- Increased O&M
- Shortened lifetime

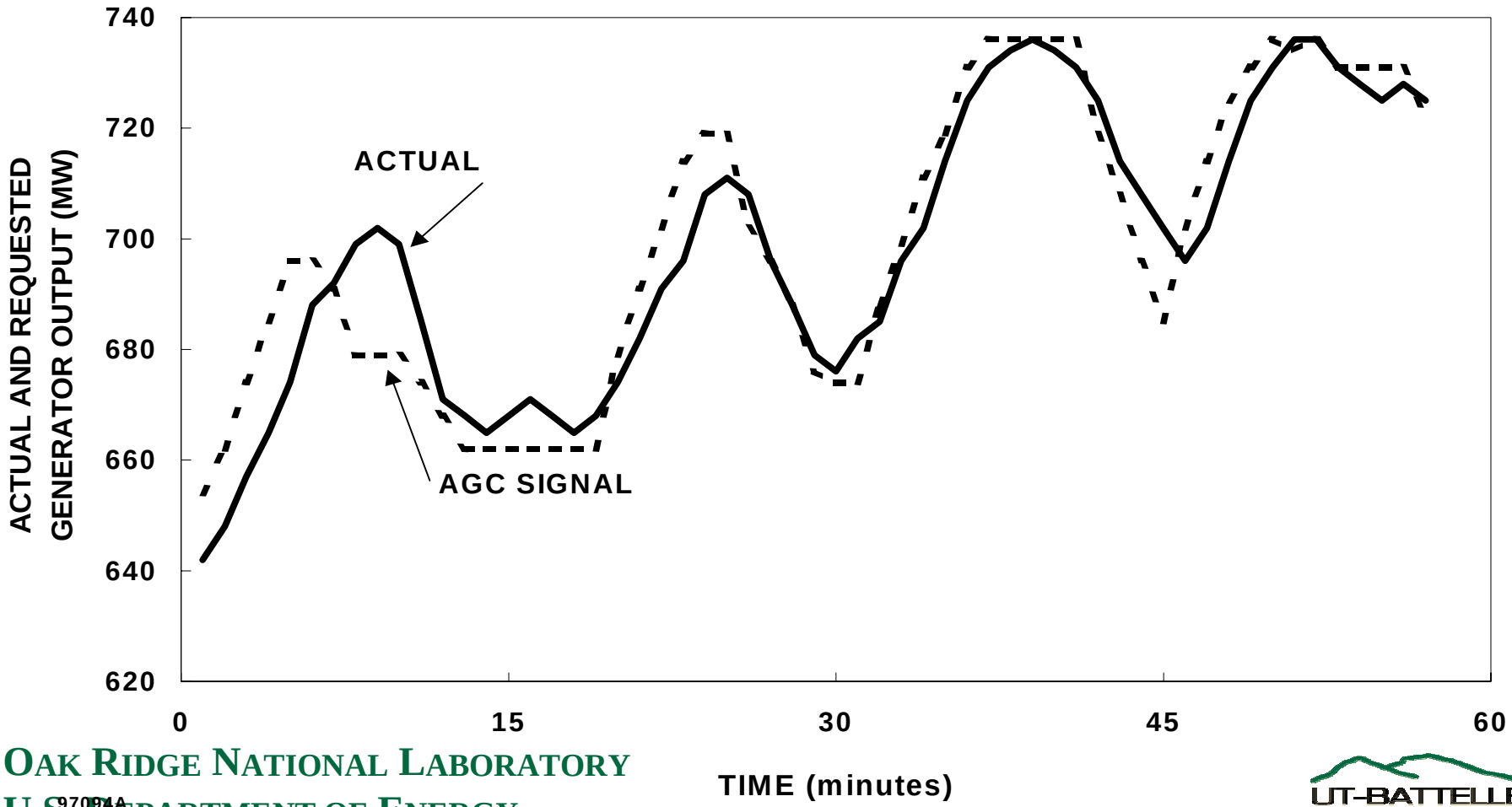
Consider Both Direct and Indirect Costs

- Direct cost of unit providing service (extra fuel, increased O&M)
- Opportunity cost of unit providing service
- Opportunity cost of other units redispatched to provide service
- Assign all three cost categories to ancillary service, not to energy

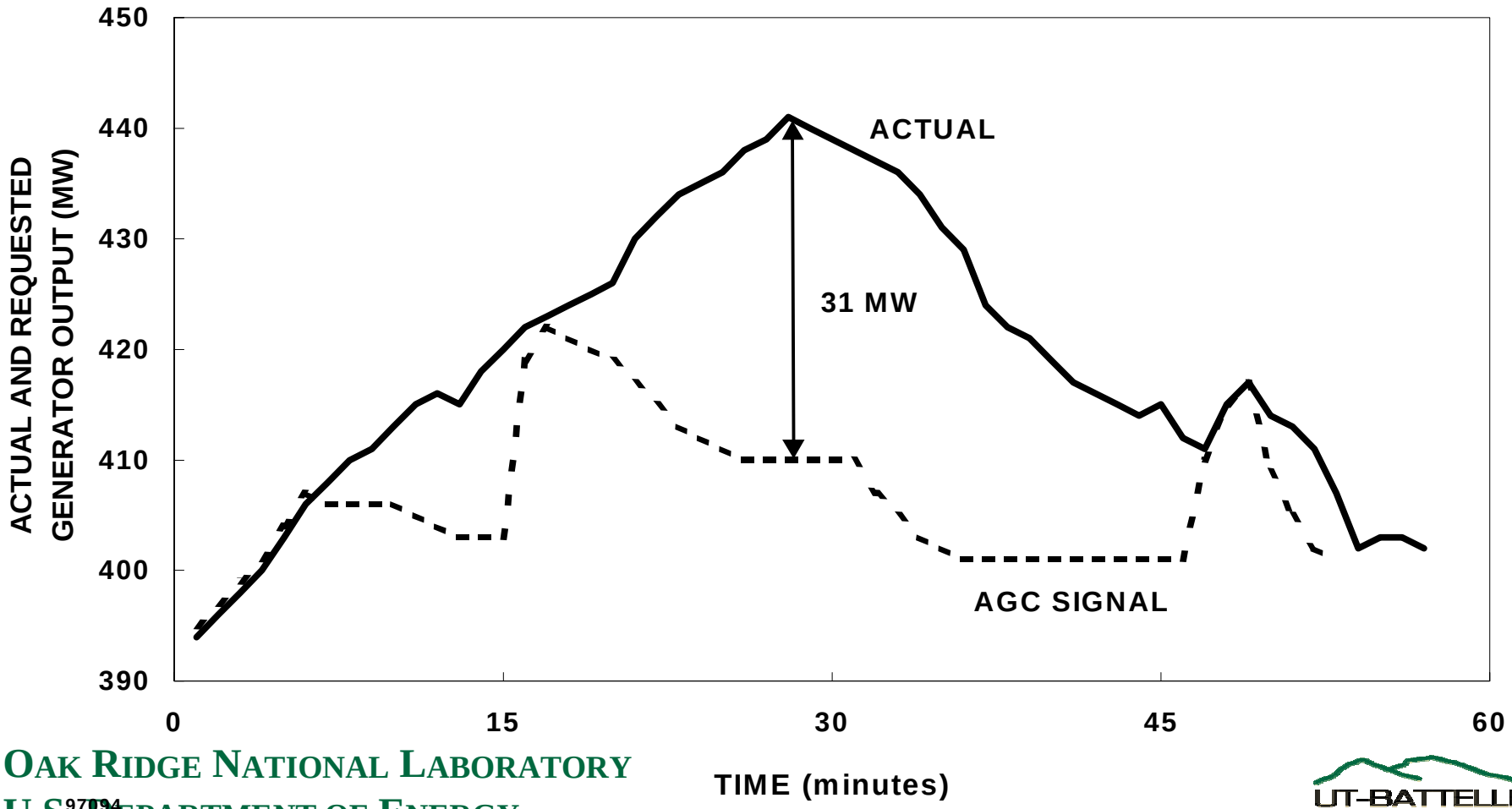
With Competition, Regulation Price Depends on Spot Energy Market



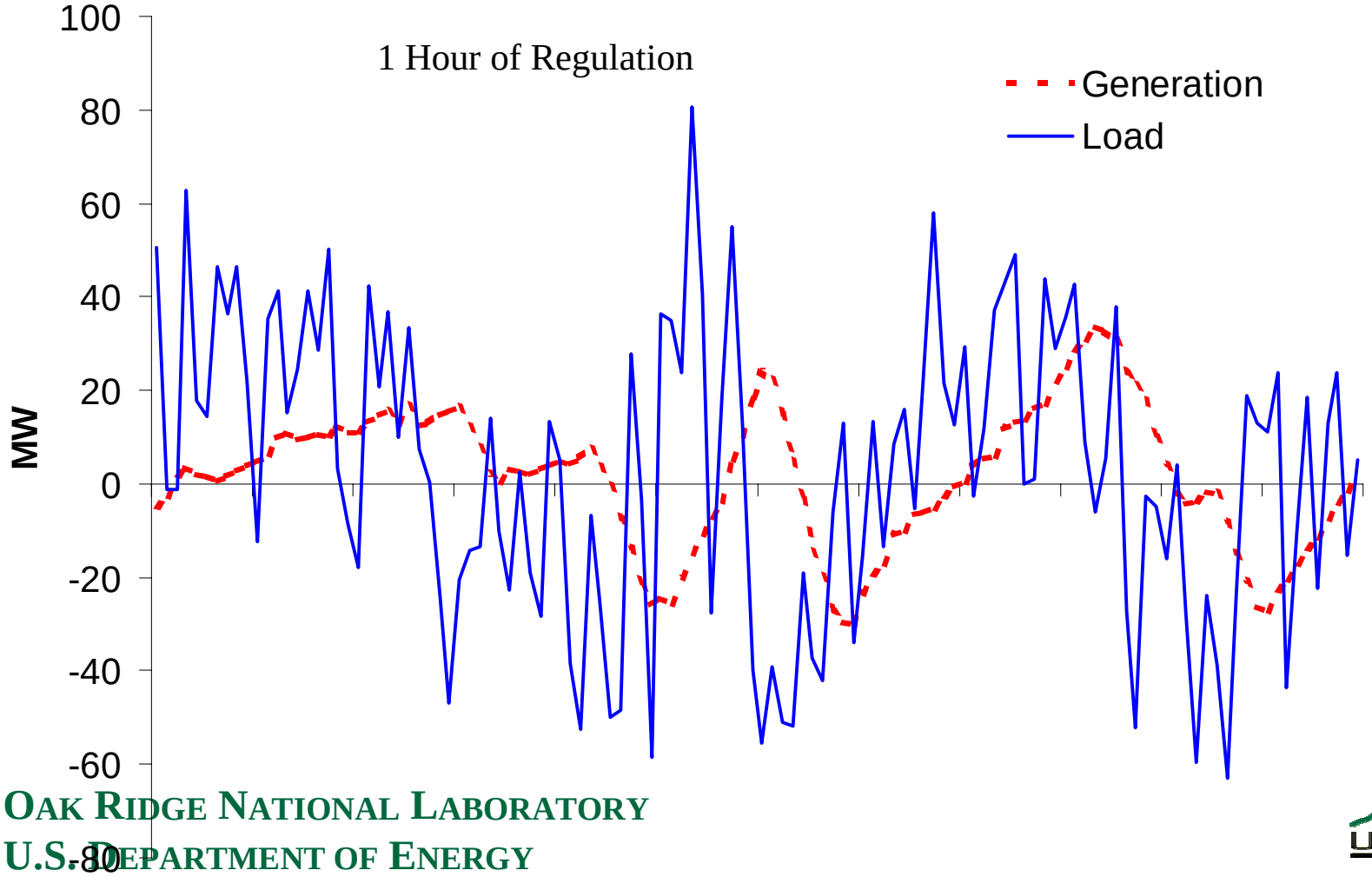
This Unit Regulates Well



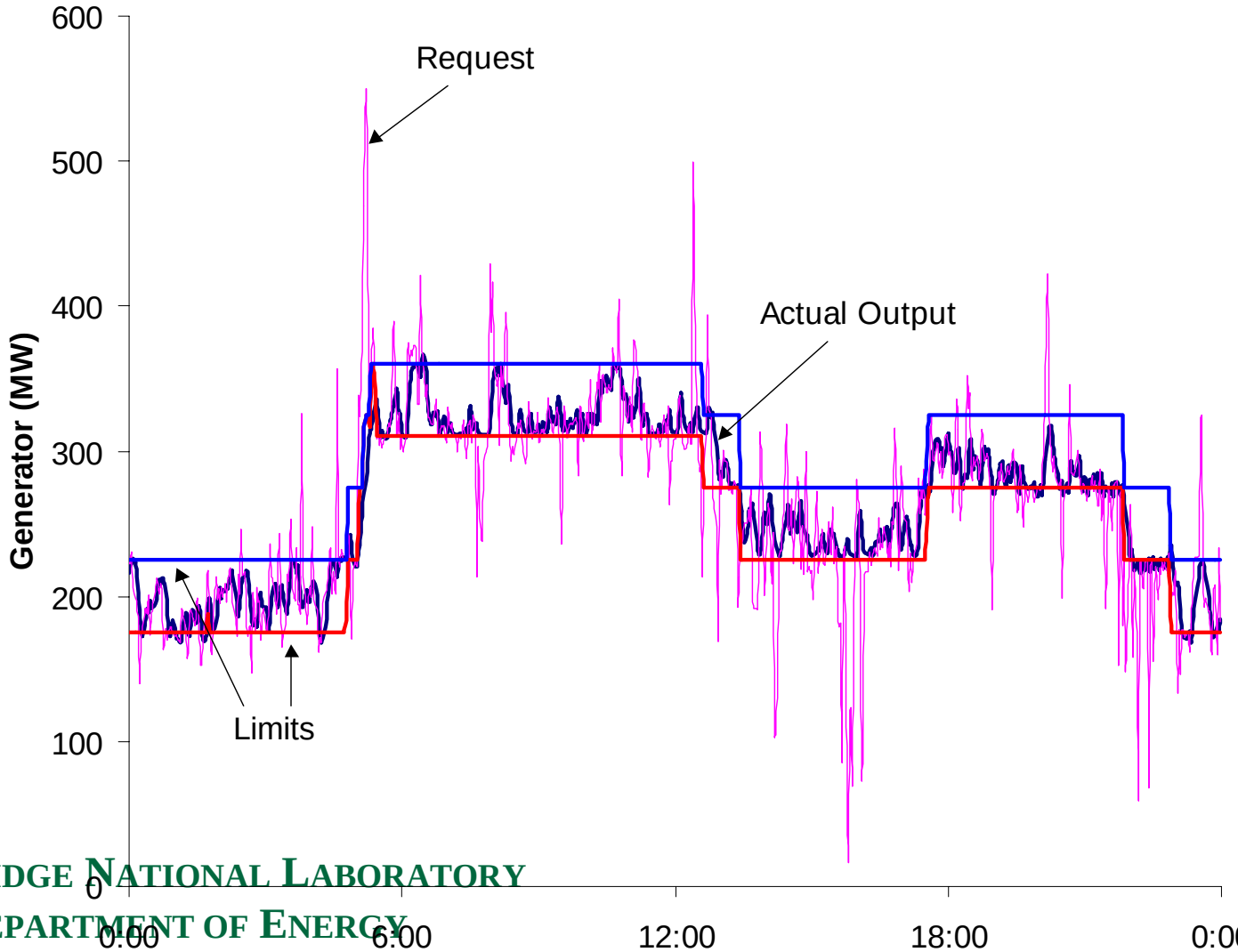
Poor Regulation Increased ACE by 31 MW During Hour



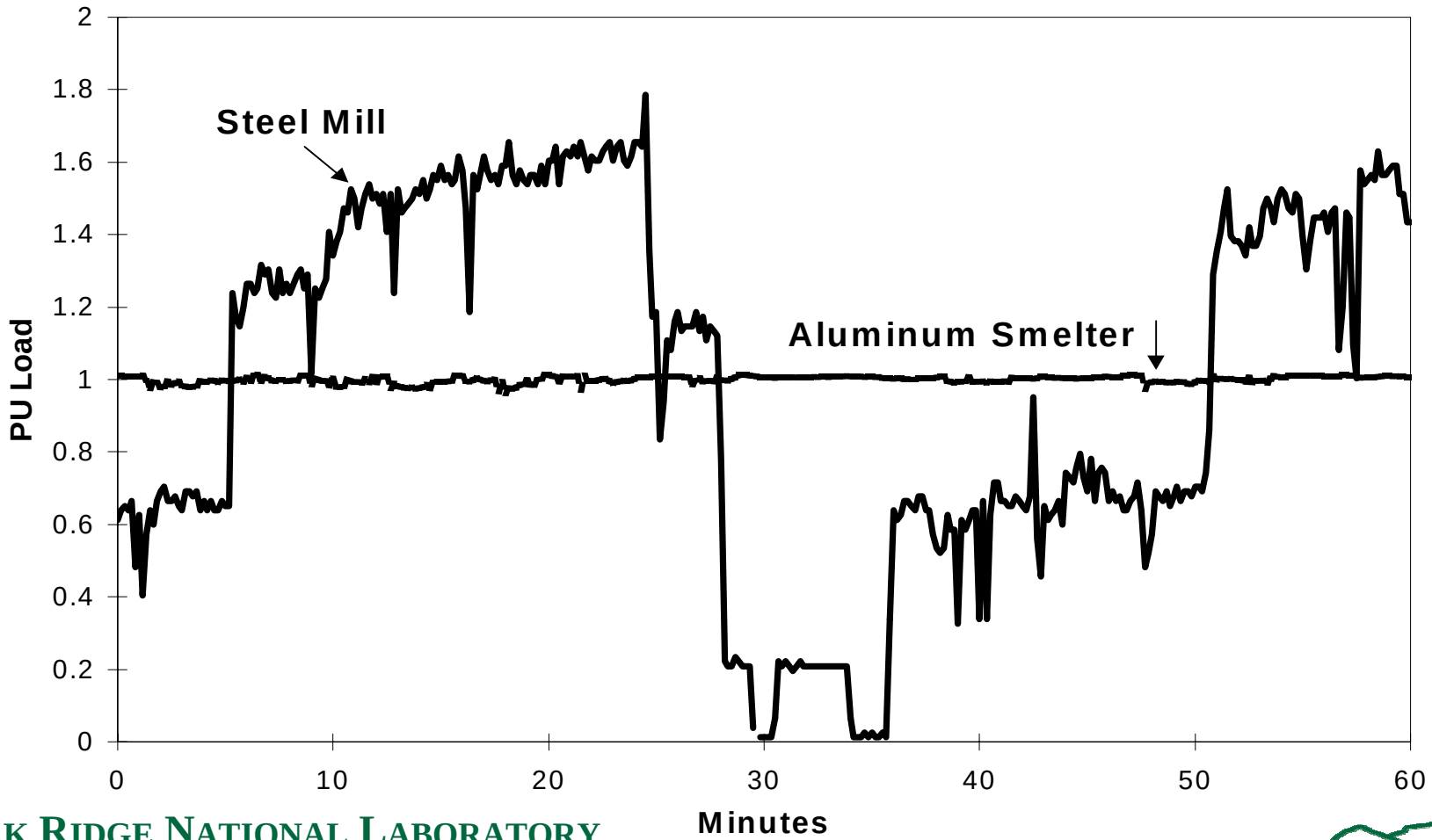
Thermal Generation Does Not Always Follow Load Closely



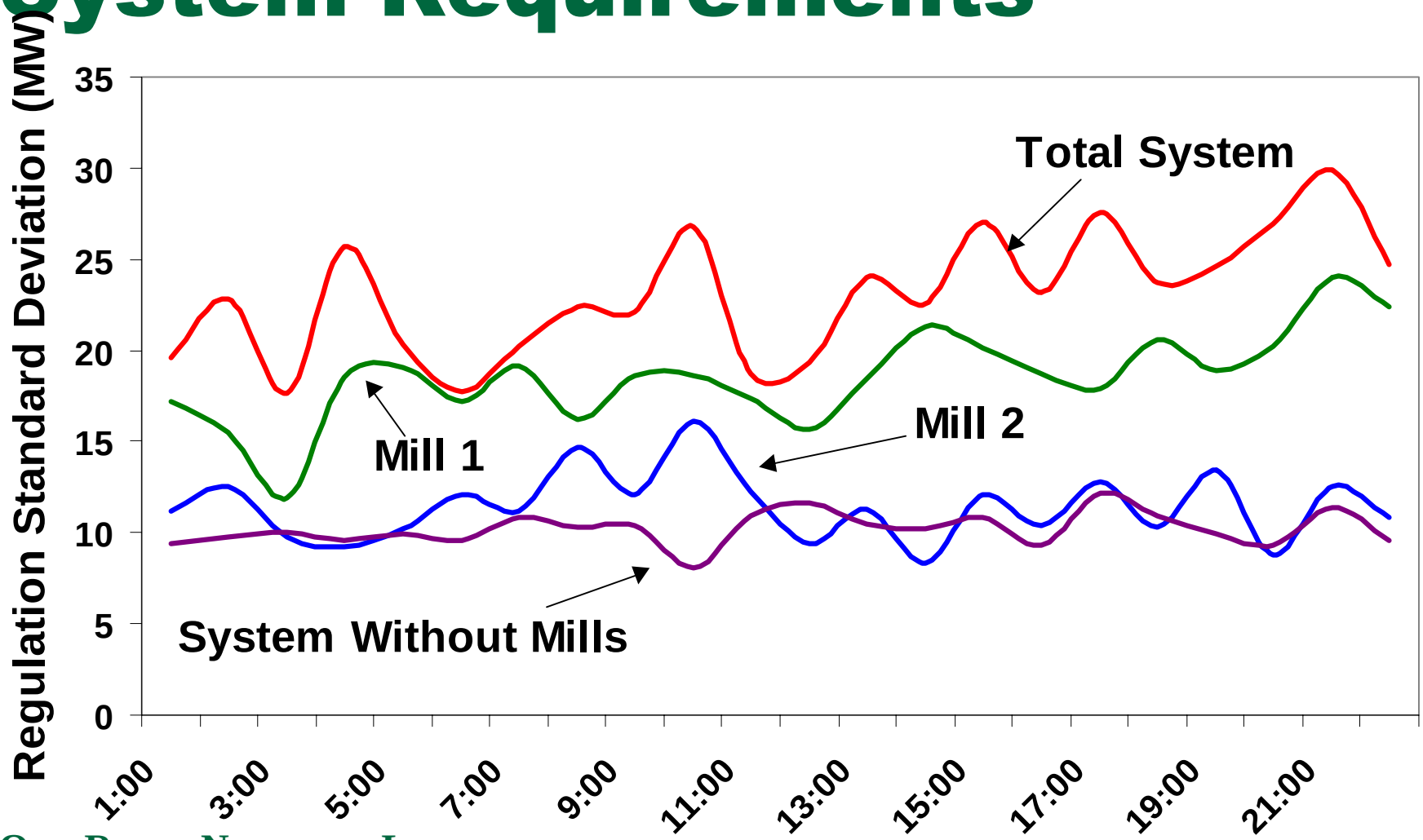
Thermal Generation Does Not Always Follow Requests Closely



Diversity in Regulation Demand



Individual Loads Impact System Requirements



Some Individual Loads Impose Large Ancillary-Service Costs

	Percentage of Total		
	Energy	Regulation	Load-Following
Control Area "A"			
Nonindustrials	66%	7%	42%
Industrials	34%	93%	58%
Control Area "B"			
Nonindustrials	97%	56%	90%
Industrials	3%	44%	10%

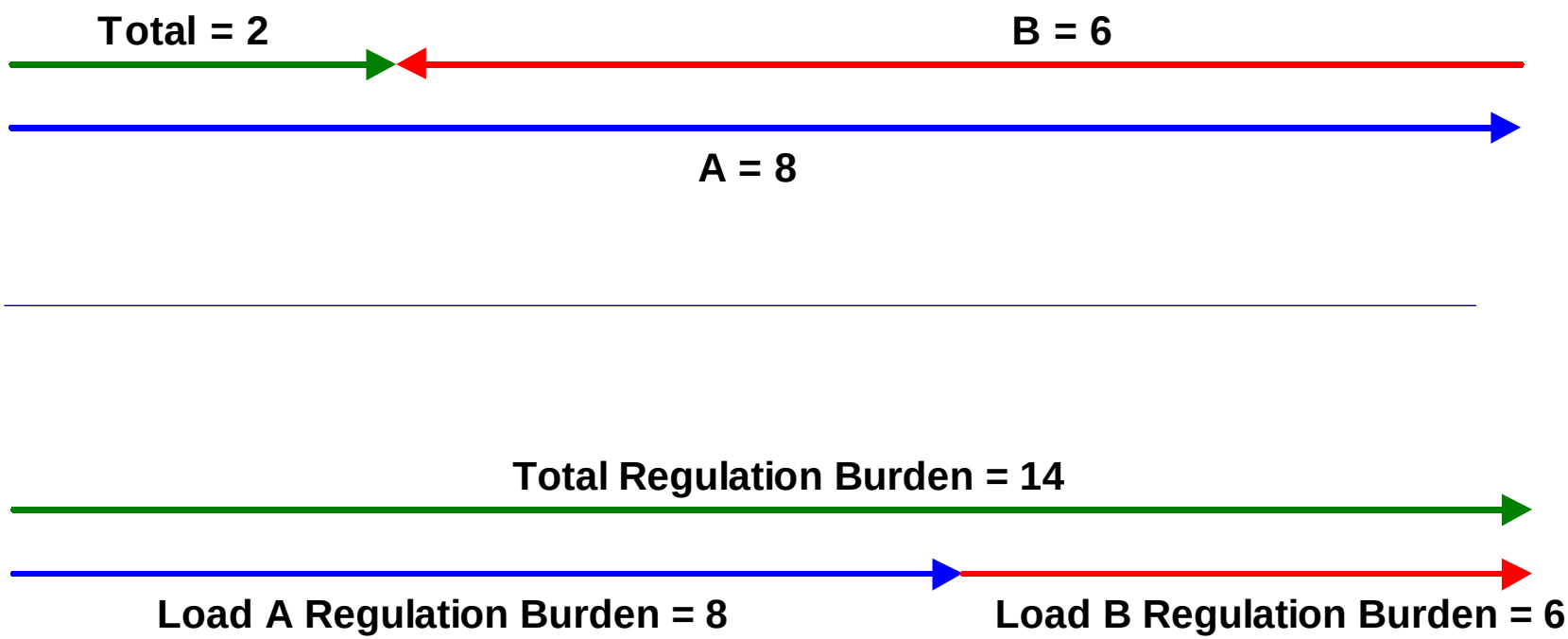
Individual Loads Differ In Their Ancillary Service Requirements

	Percentage of Total		
	Energy	Regulation	Load-Following
Nonindustrial	65.7	7.2	42.3
Total Industrial	34.3	92.8	57.7
Industrial #1	13.5	52.6	32.7
2	1.7	9.0	6.6
3	3.9	20.5	9.2
4	0.5	1.7	0.6
5	0.5	9.2	8.5
6	14.1	-0.2	0.0

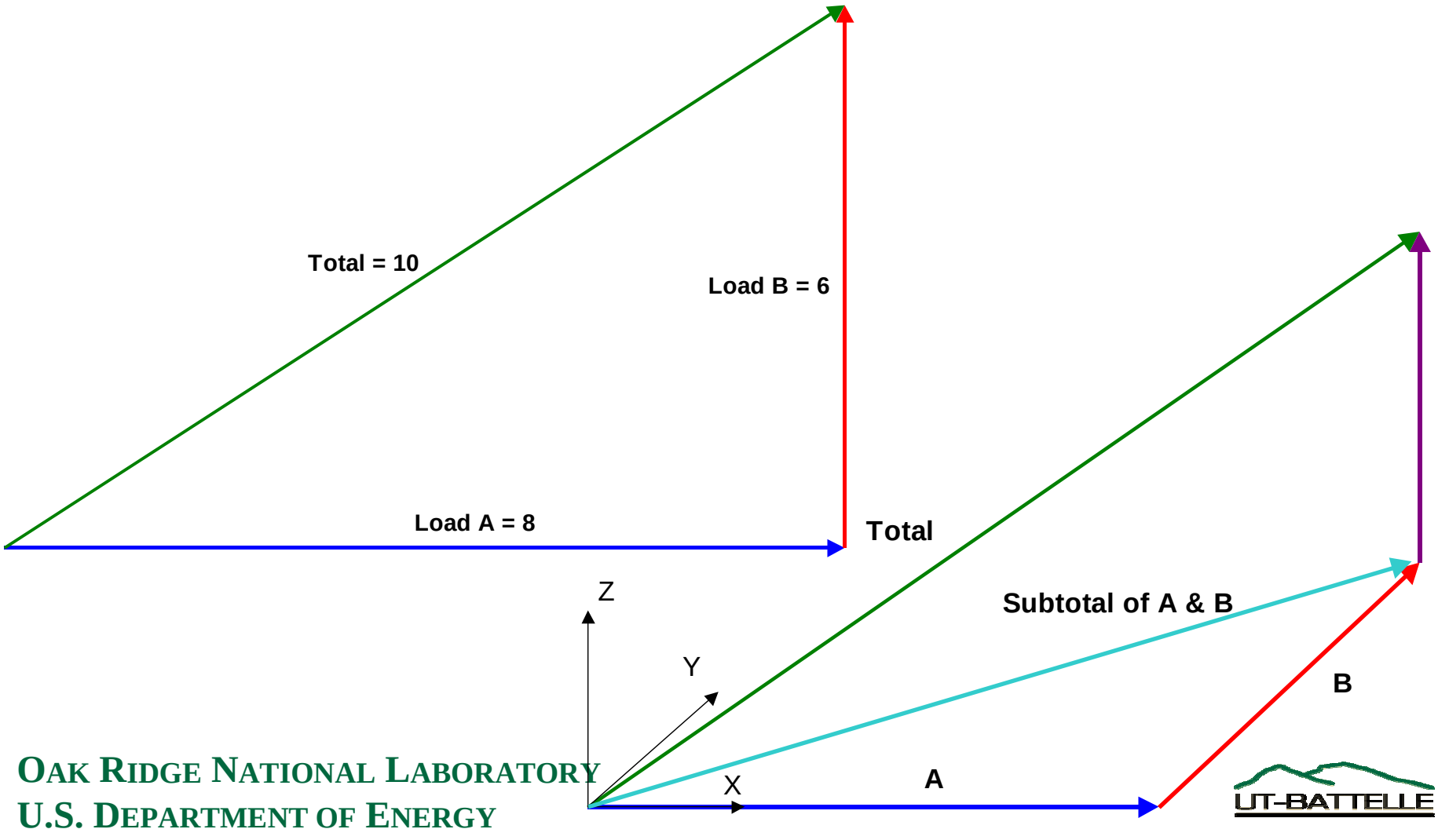
Allocation Method Should Meet Key Objectives

- Recognize positive and negative correlations (pay loads that reduce total regulation)
- Independent of subaggregations
- Independent of order in which loads added to system
- We developed a Regulation Vector Allocation Method that meets these objectives

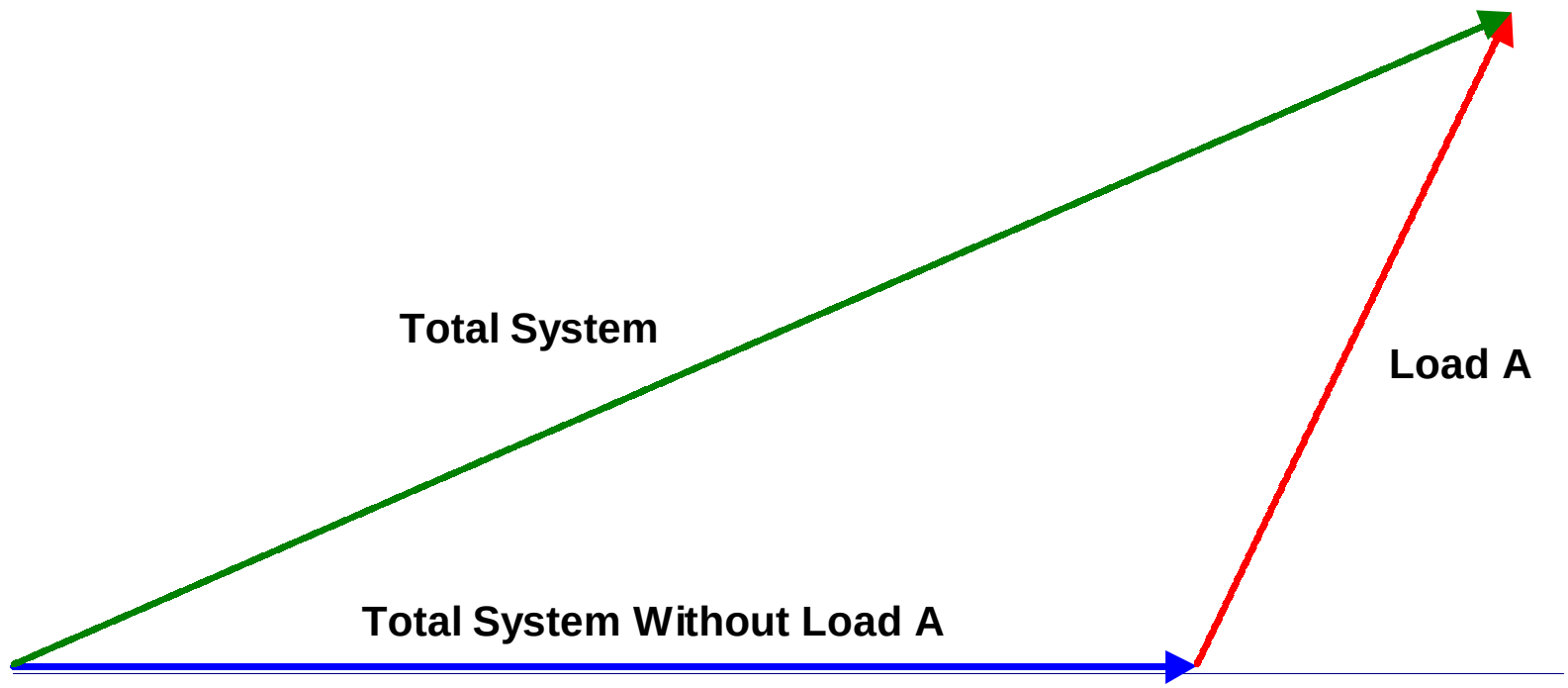
Allocation Simple When Burdens Are Correlated



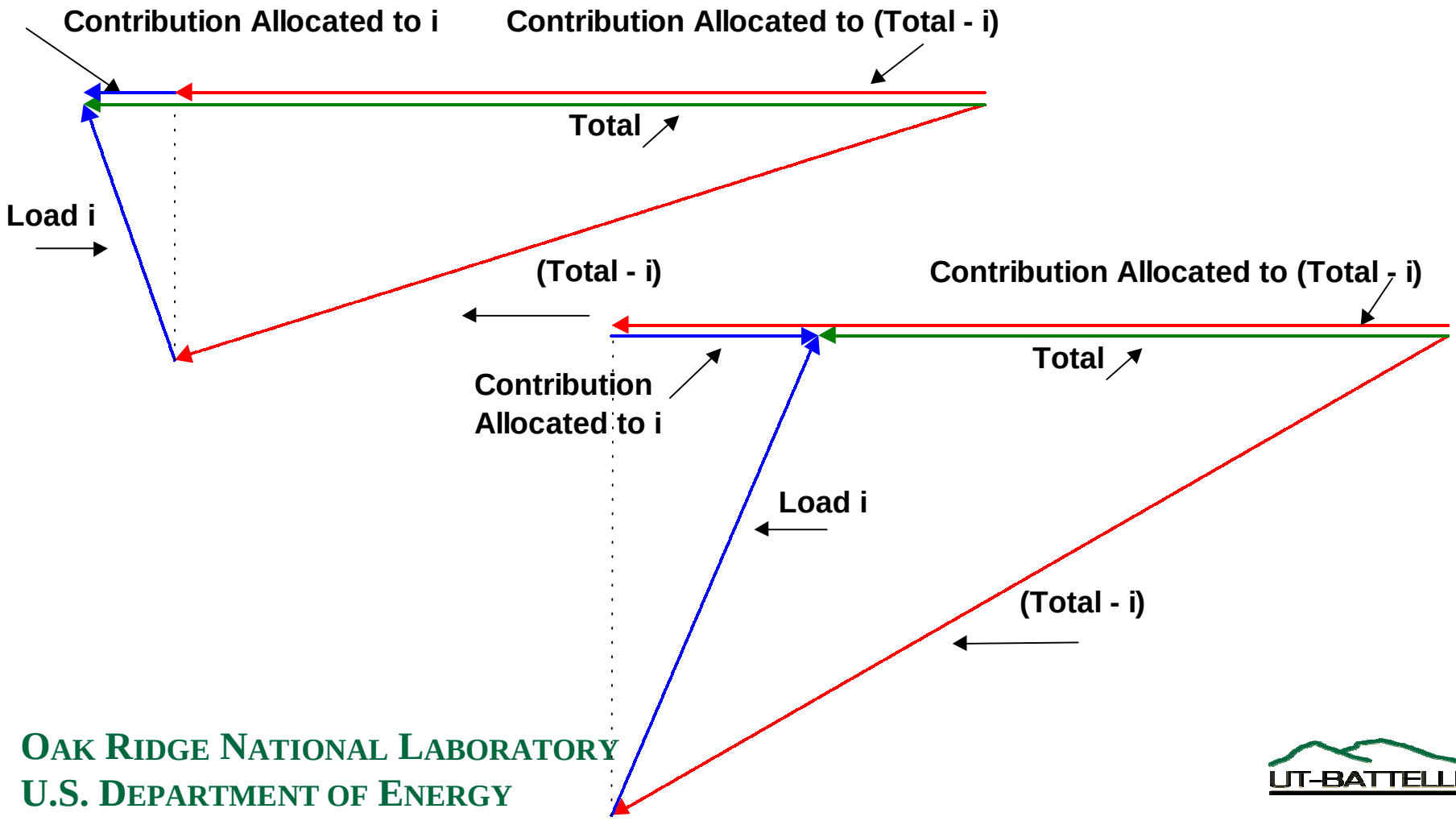
Allocation Also Simple When Burdens Completely Uncorrelated



Vector Allocation Method Generalizes To Any Correlation



Method Treats Positive Or Negative Correlations

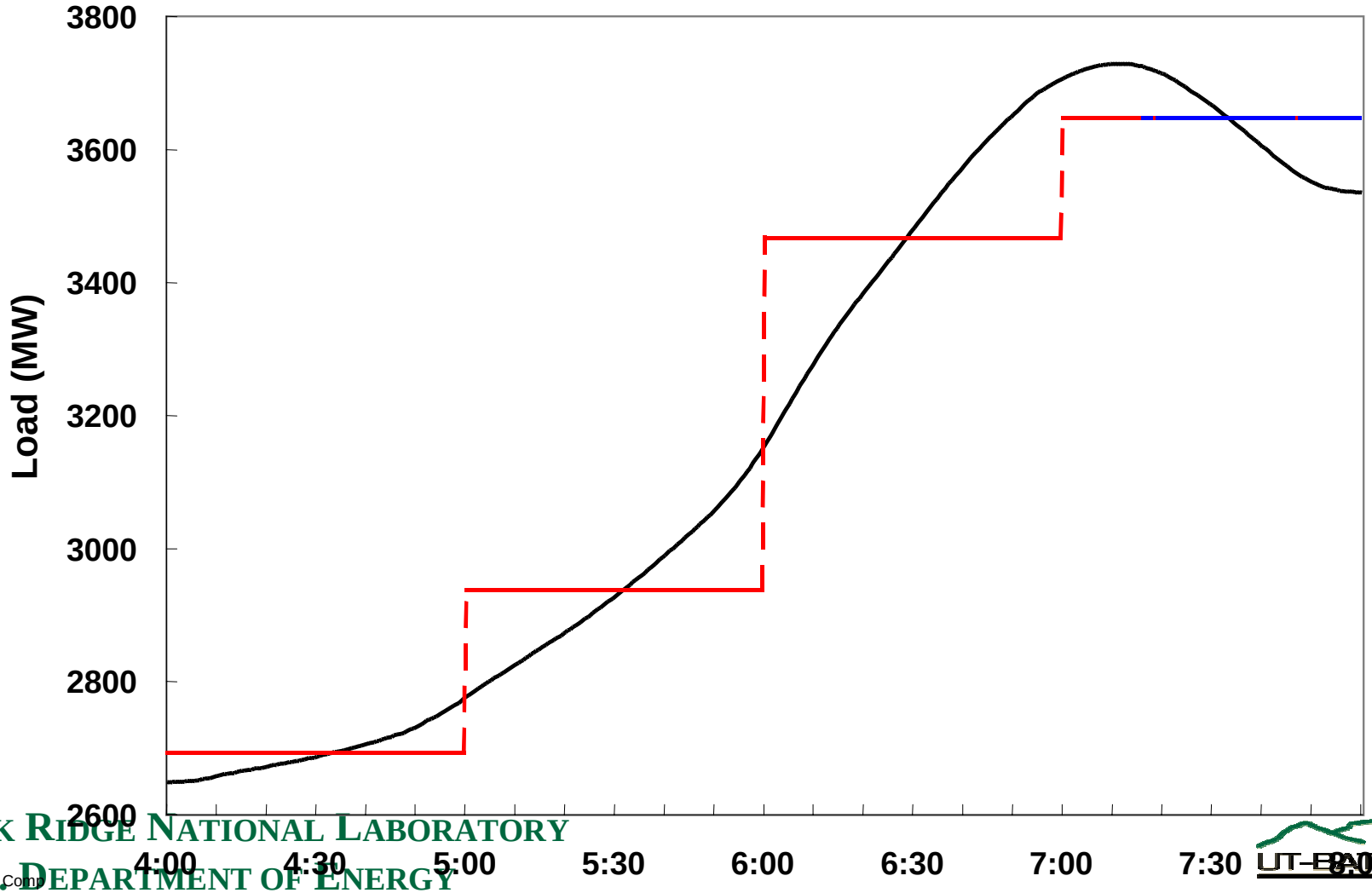


Numerical Implementation Of Vector Allocation Method Straightforward

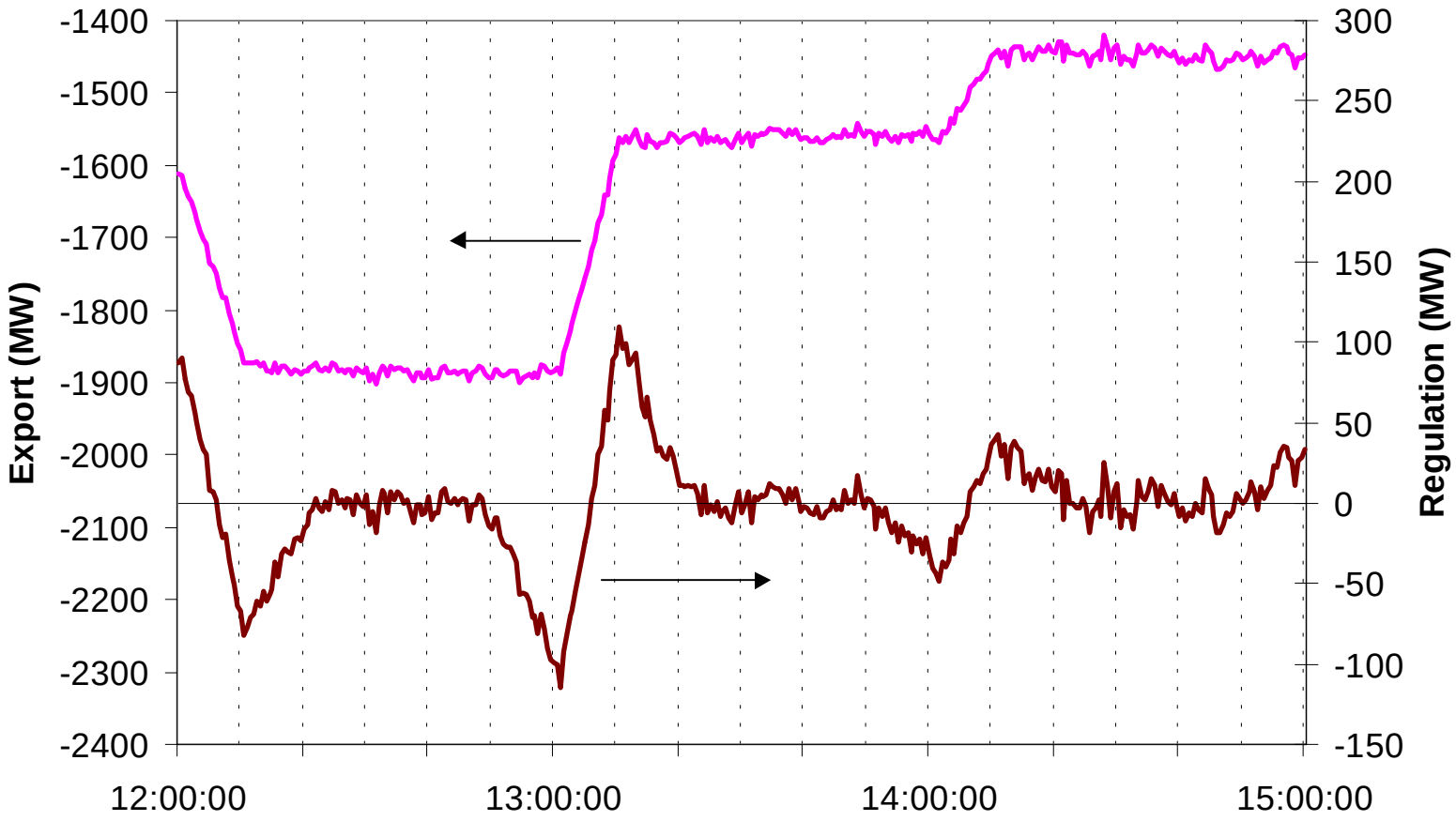
$$\sigma_{i_allocation} = \frac{\left(\sigma_{Total}^{2} + \sigma_{i}^{2} - \sigma_{Total-i}^{2}\right)}{2 * \sigma_{Total}}$$

- Handles correlated and uncorrelated components
- Independent of sub-aggregation
- Independent of order
- Disaggregate as many (few) components as desired

Block Schedule vs Continuous Requirement



Block Schedules *Create* "Regulation" Burden



Aggregation Benefits Regulation

Individual load intrahour fluctuations are generally uncorrelated

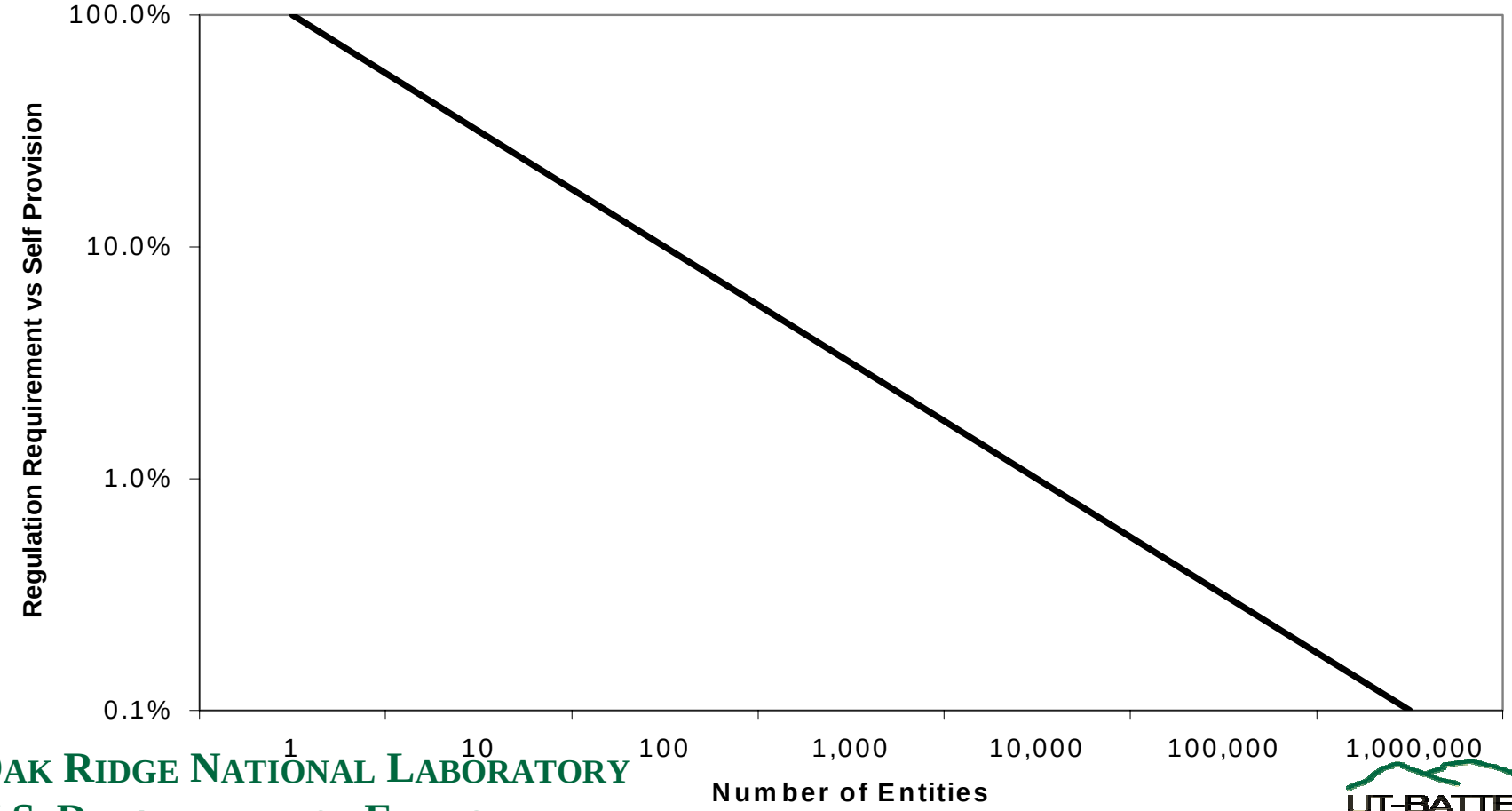
- **Energy requirement**

$$\mu_{SYSTEM} = \sum \mu_{INDIVIDUAL}$$

- **Fluctuations**

$$\sigma_{SYSTEM} = \sqrt{\sum \sigma^2_{INDIVIDUAL}}$$

Regulation Requirement per Transaction Drops With Aggregation of Similar Transactions



Charging Each Customer Based Upon Its Marginal Contribution Might be Reasonable

Requires knowledge of the standard deviation of each transaction

$$\sigma_{MARGINAL-j} = \sqrt{\Sigma\sigma^2} - \sqrt{(\sum\sigma^2 - \sigma_j^2)}$$

$$\sigma_{MARGINAL-j} / \Sigma\sigma_{MARGINAL} = [\sqrt{\Sigma\sigma^2} - \sqrt{(\sum\sigma^2 - \sigma_j^2)}] / \sum_k [\sqrt{\Sigma\sigma^2} - \sqrt{\Sigma\sigma^2 - \sigma_k^2}]$$

Aggregation of 2 Entities

	Size	σ	Regulation
A	1000	20	60
B	1000	20	60
Total	2000	28	85

Allocation Choices

- A & B share requirements equally
  - Reserve A = 42
  - Reserve B = 42
- B "joins" A and provides "full compensation"
  - Reserve A = 60
  - Reserve B = 25

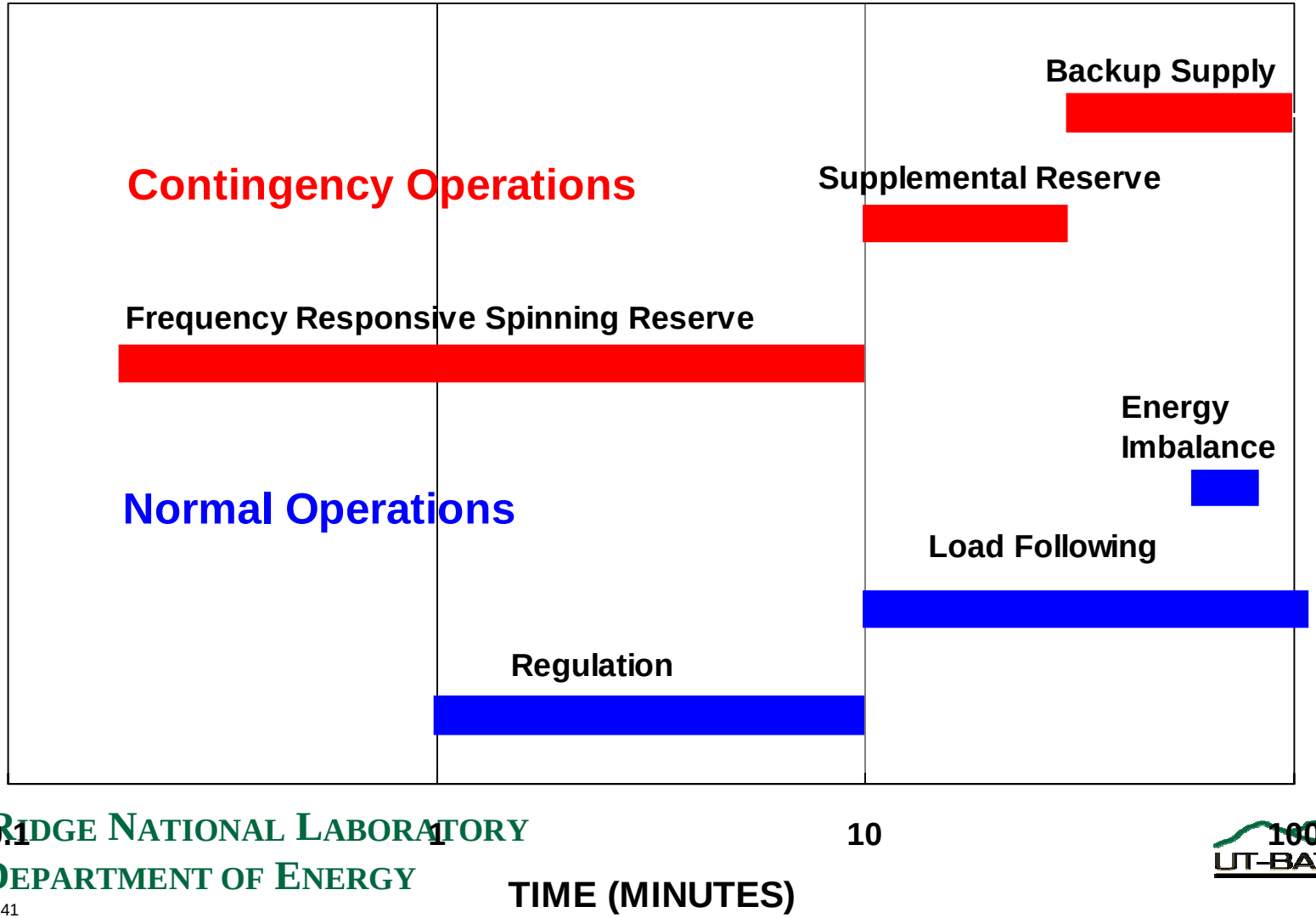
Contingency Conditions

Frequency Responsive

Supplemental

Backup Supply

Time Scale for Real Power Services



Operating Reserves

- Originally defined to compensate for:
  - forecasting errors
  - equipment unavailability
  - forced outages
  - maintenance schedules
  - regulating requirements
  - load diversity

- FERC defined operating reserves to compensate for unplanned events such as loss of generation

Contingency Reserves

- Sudden, unplanned failures of generation and transmission are unavoidable
  - N-1 criteria
- Physical requirement
  - restore generation/load balance
  - arrest frequency decay (obligation to system)
- Insufficient time for market response
- Problem addressed on a control area or wider basis

Sharing reserves greatly reduces costs

Contingency Reserves Characteristics

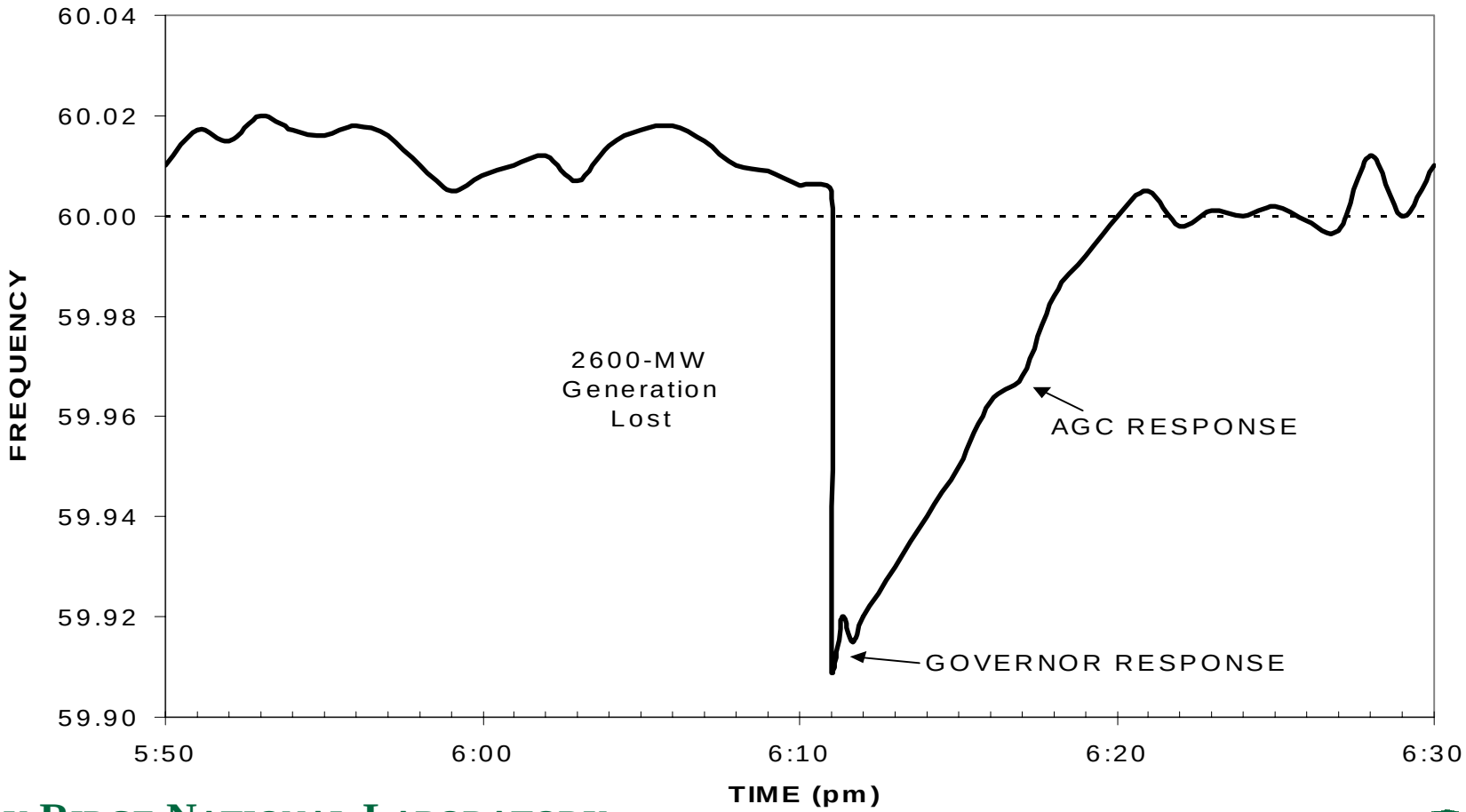
- **Frequency responsive**
  - **fast, autonomies response**
  - **coordinated droop & deadband**
- **Supplemental**
  - **fully available in 10 minutes**
- **Backup supply**
  - **return to commercial operation**
  - **restore reserves**

Control Area Performance Criteria

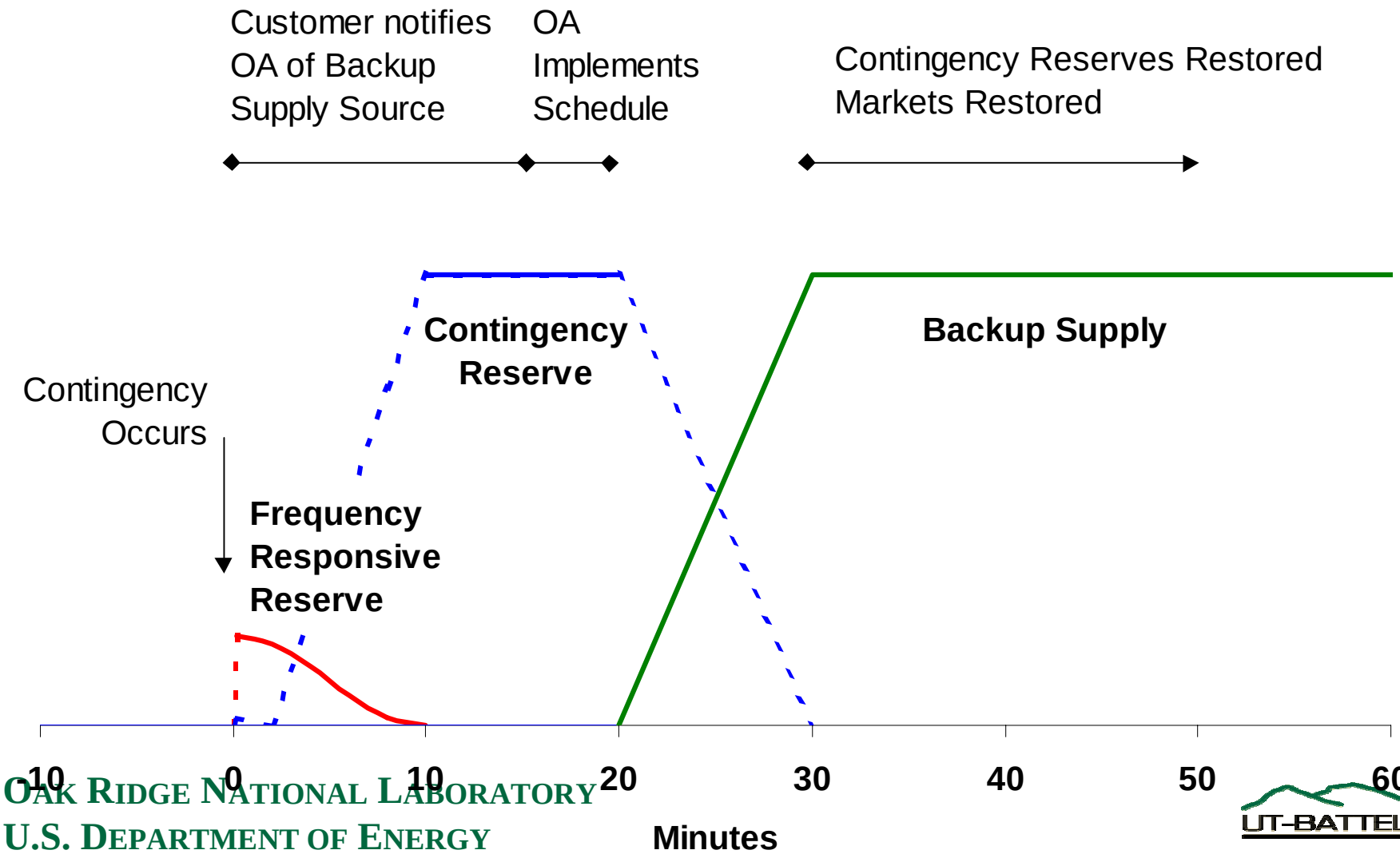
- DCS - return ACE to 0 or pre-contingency within 10 minutes
  - applies only to 80-100% of largest contingency
  - failure to comply results in increased reserve requirement

- Assessment of individual loads & generators may have to be more deterministic - who takes the risk & who pays the consequences?

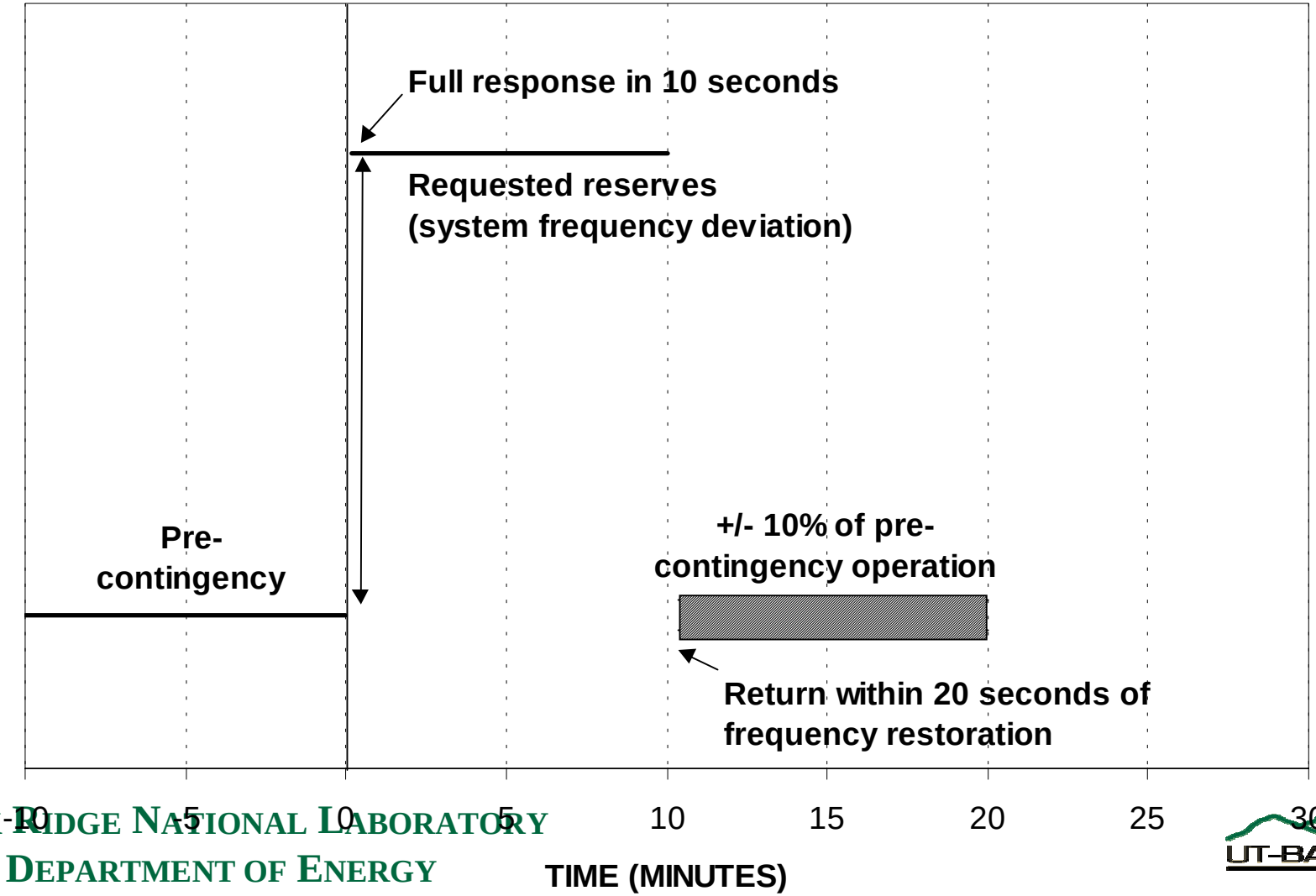
Response to a Major Generation Failure



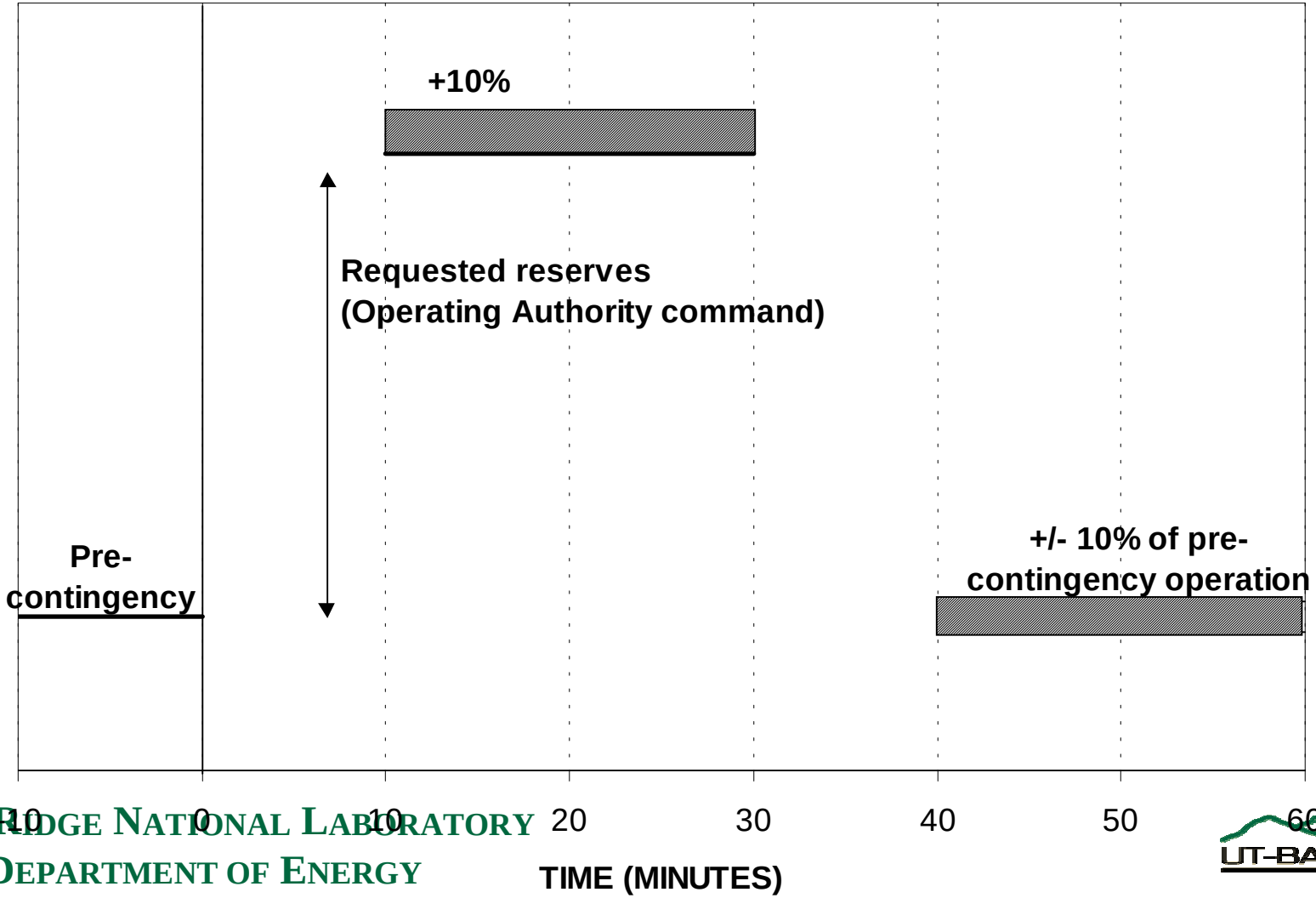
Ancillary Service Coordinated Contingency Response



Frequency Responsive Reserve Required Performance



Supplemental Reserve Required Performance



Underfrequency Load Shedding and Frequency Responsive Reserve Differ

- Underfrequency load shedding is not optional (you were going to be cut off anyway)
- Moves into the governor control frequency band - So it deploys more often
- SILOS - Shed In Lieu Of Spin

Reliability Councils Set Minimum Operating-Reserve Requirements

- Requirements based on NERC disturbance control standard to restore system within 10 minutes
- Requirement based on
  - Largest unit online
  - Absolute MW value (ERCOT = 2300 MW)
  - Projected daily peak
- Rules not based enough on data and analysis
  - Reliability of individual generators
  - Probabilistic as well as deterministic analyses
- ✻ Allocation often <u>not</u> based on unit size or performance

Contingency Reserve Resources

- Load or generation
- Post event concerns
  - restoring reserves
  - returning to pre-event schedule
- "Fleet" response
- With or without real-time metering
  - post-event metering
  - statistical metering
  - testing

Backup Supply

- **After the system deals with a contingency:**
  - **operating reserves must be restored to cover the next contingency**
  - **the commercial generation / load balance must be restored**
- **Timing must be coordinated with operating reserve duration & commercial markets**
  - **timing is related to the risk the *system* takes of not being able to respond to the next contingency**

Backup Supply Implementation

- Backup supply can address:
  - generation
  - load
  - both
  - be pre-arranged
  - use spot markets
  - vary from time-to-time
- Restore the commercial gen/load balance
  - new supply must be technically feasible under existing conditions

Voltage Control and Reactive Power Supply

Voltage Control and Reactive Supply

- Voltages throughout the power system must be maintained within a narrow range
- Reactive power consumption and production must balance in real time
- Reactive power can not be moved as far as real power

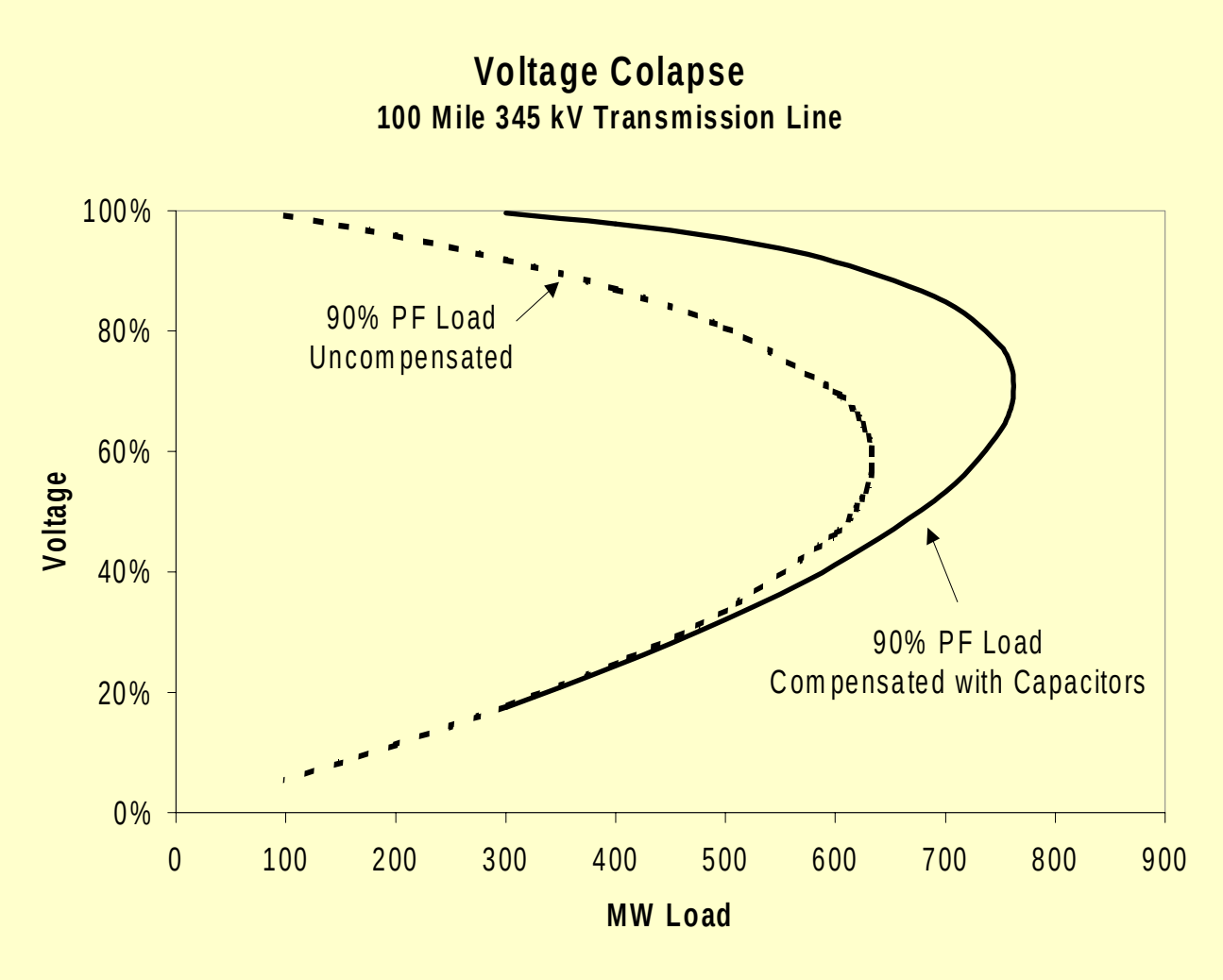
System Reactive Power Requirements

The power system itself is a consumer and producer of reactive power

- Dynamic
- Change with contingencies
- Depend on:
  - transmission system configuration
  - generation dispatch
  - load magnitude and pattern

Supply resources under system operator control

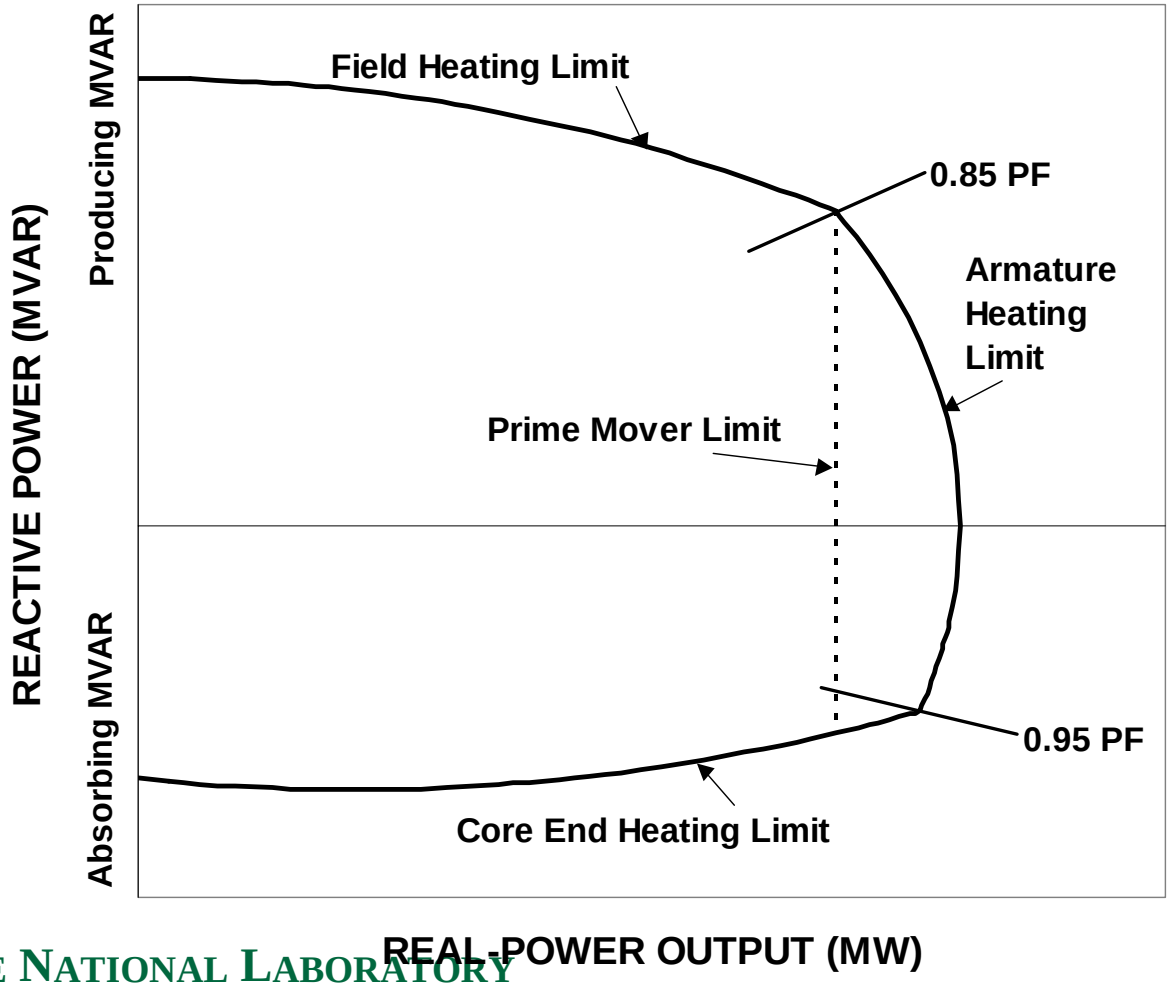
Voltage Collapse



Reactive Support Generation & Transmission

- Generator
  - fast response, output rises with V drop
- Capacitor
  - switched response, output drops with V^2
- Reactor
  - switched response, output drops with V^2
- SVC
  - fast response, output drops with V^2
- STATCOM
  - fast response, output drops slowly with V

Generator Reactive Limits



Voltage Control Requirements

- Maintain acceptable voltages throughout the system
- Dispatch transmission and generation resources
- Manage reserves to handle contingencies

- Difficult to allocate voltage control burden among customers

Black Start

System Black Start

Unique Characteristics

- **No system power for: unit start, auxiliaries, communications, or control**
- **System condition unknown**
- **Rapidly changing configuration**

This is a policy issue that hides behind technology - society takes the risk

More Than a Generator Service

- System black start requires
  - Generators that can start themselves
  - Transmission-system people, controls, and communications
  - System-control people and communications
  - Other resources returning to service
- Everything needed to run the system under normal conditions
  - Economic constraints relaxed

System Requirements

- A Plan & *Flexibility*
- People
- Communications
- Control
- Information
  - current conditions
  - capabilities & requirements
- Generation resources

Black Start Units

- Location
  - topography
  - technical capability
- Capacity
  - real & reactive
  - min & max
- Stability
  - unloaded, loading & loaded
- Control
  - real & reactive
  - frequency & voltage
  - accuracy & speed
  - local & remote
- Black start capability
  - within required time

Next Start Units

Restoration requires generators return to service

- **each unit goes from being a load to requiring load**

Terry Volkmann, NSP, suggests:

	# hours it takes to Synchronize		
# of hours it takes for the T. Provider to provide power to the generating unit	Unit 1	Unit 2	Unit 3-N
1 Hour	4	5	6
2 Hours	6	8	10
3 Hours	10	14	18

Energy Imbalance

- **Results from mismatches between energy schedules & delivery**
- **Physical power system must be balanced in real time**
- **Basically an accounting function - assigns costs after the fact**
- **Can get complex when accounting for the energy components of several ancillary services**

Looks a lot like Inadvertent Interchange

How to Price Energy Imbalance

- **Out-of-pocket costs**
  (fuel plus variable O&M)
- **Embedded cost of generation**
  (including capacity costs)
- **Penalty provisions to prevent abuse**
  - **encourage forecasting**
  - **encourage purchase of standby service**
- **Spot market provision**

Dynamic Scheduling

Real-time monitoring, telemetering, etc. required to electronically move load or generation real energy services from a Host Control Area (CA) to another CA

- Data collection & communications at SCADA rate
- Dynamic signal put in both CA's ACE
- Consume physical interconnection capacity

Intermediate CA's need to be aware of the transaction

Costs, Prices, Tariffs, & Market Interactions

Many Reliability Services Can Be Provided Competitively

- Competition feasible
  - Regulation
  - Load following
  - Contingency reserves
  - Backup supply
  - Loss replacement
- Competition uncertain
  - Voltage control
  - Black start
  - Network stability

How Price Signals Are Given Is Important

Interruptible rates continuously compensate customers who then hope to never reduce load

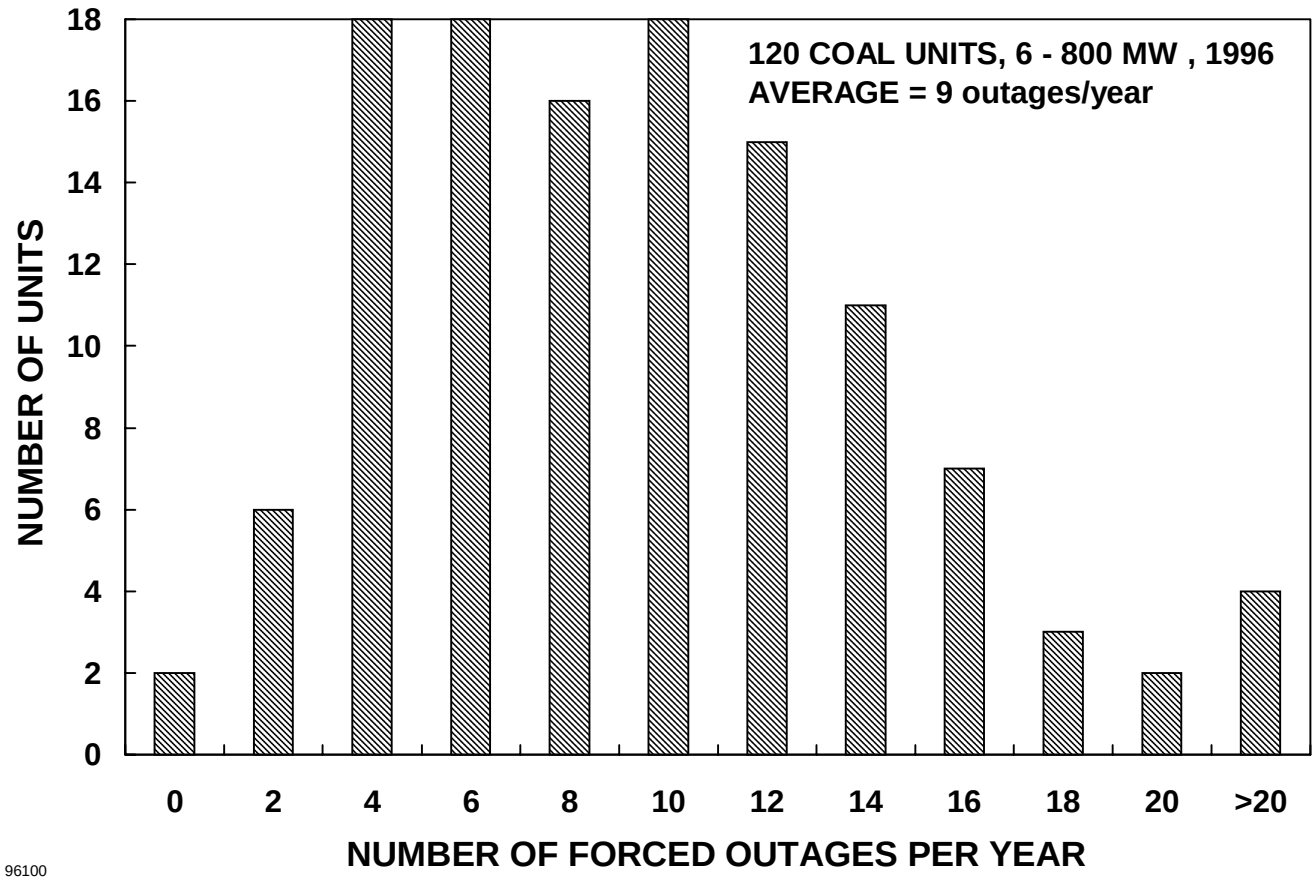
Real-time-prices allow customers to choose when it is more economic for them to continue to consume and when it is economic to curtail

Implementation Details are Important

- California runs sequential ancillary service markets
- NY collects performance data from all suppliers and optimizes overall ancillary service provision

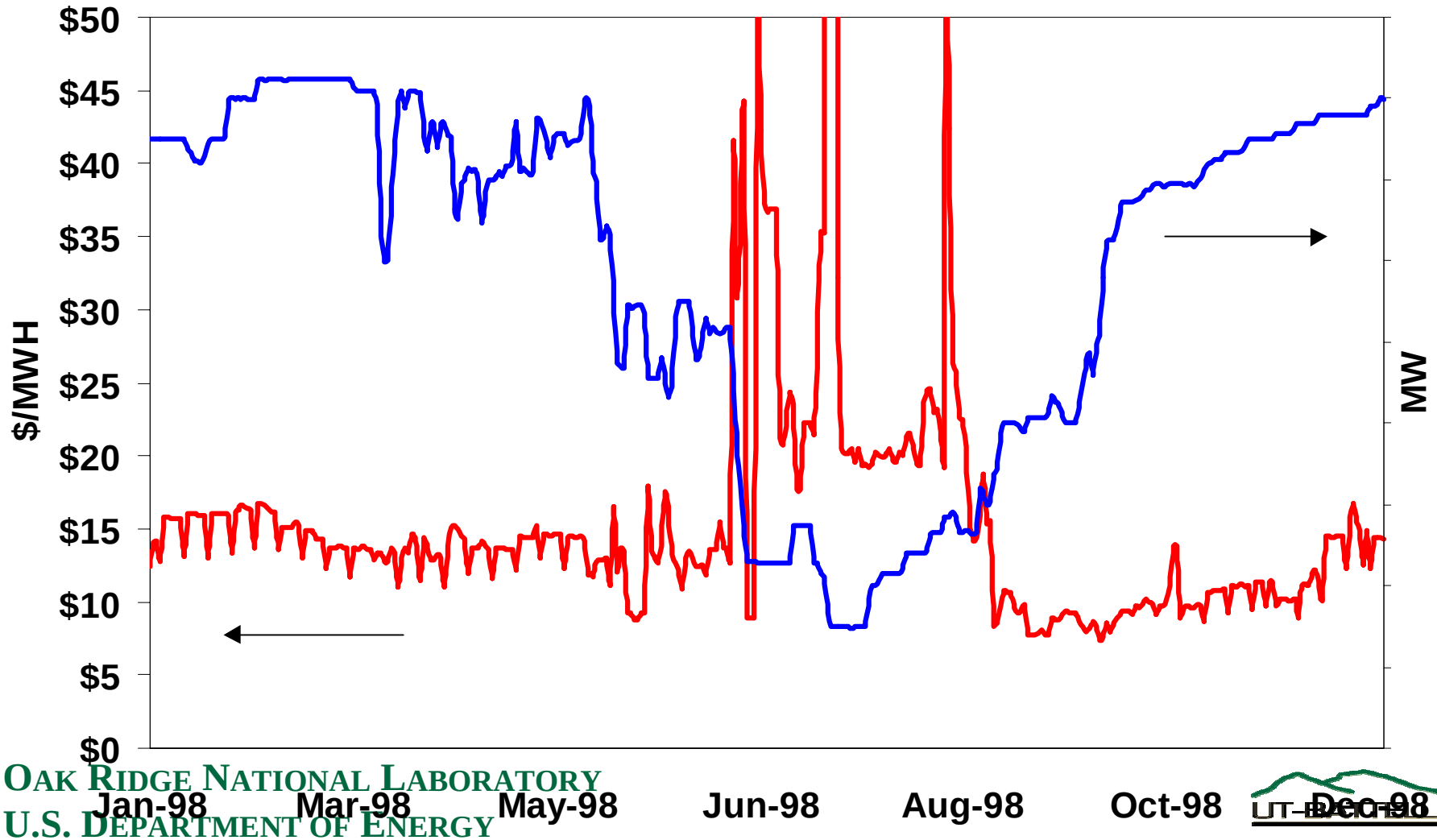
Markets interact, suppliers maximize profits, and unintended consequences abound

Outage Frequency Differs Substantially Among Generators

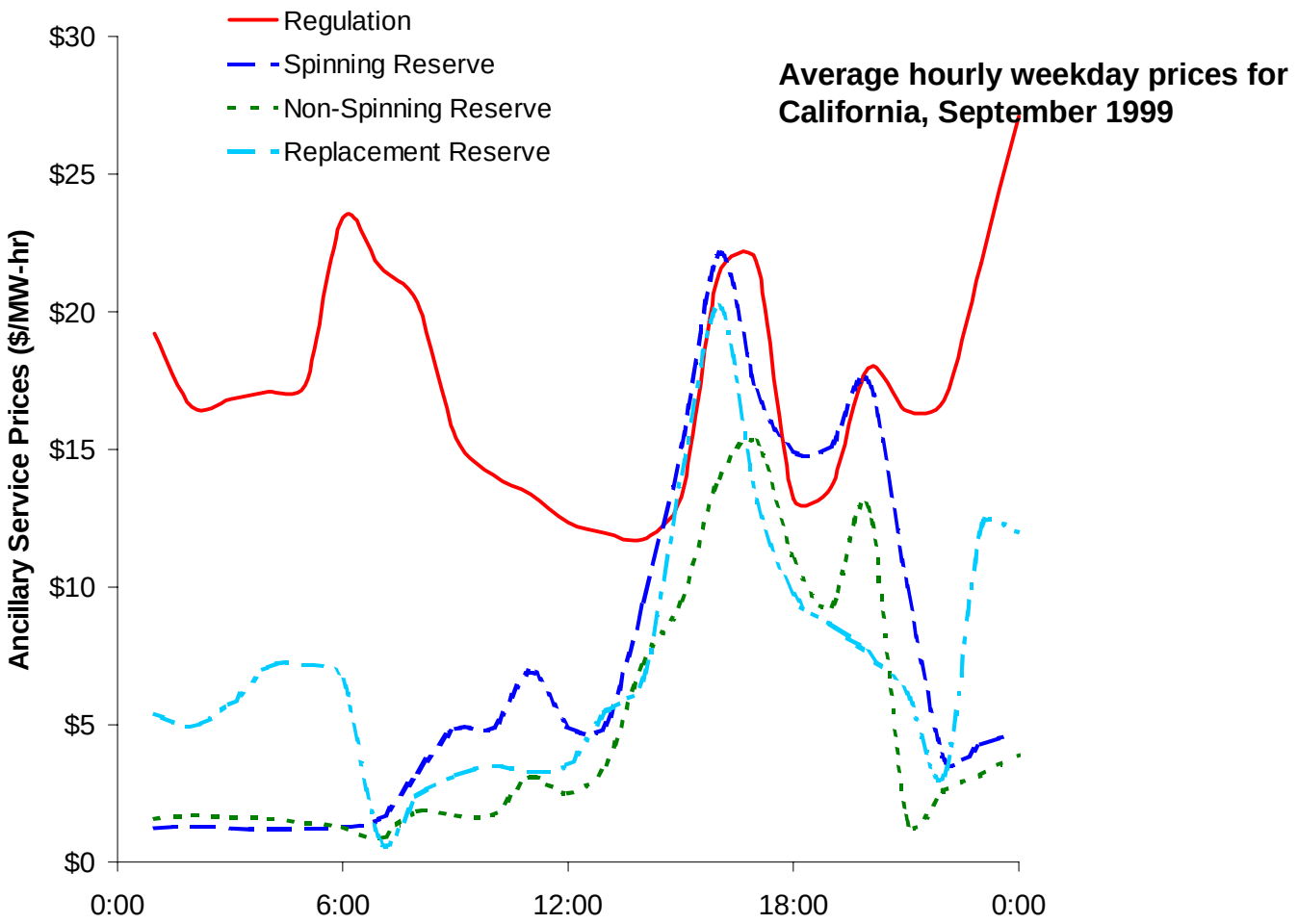


Price Responsive Load

Daily Averages



Volatile Ancillary Service Prices Add To The Quantification Need



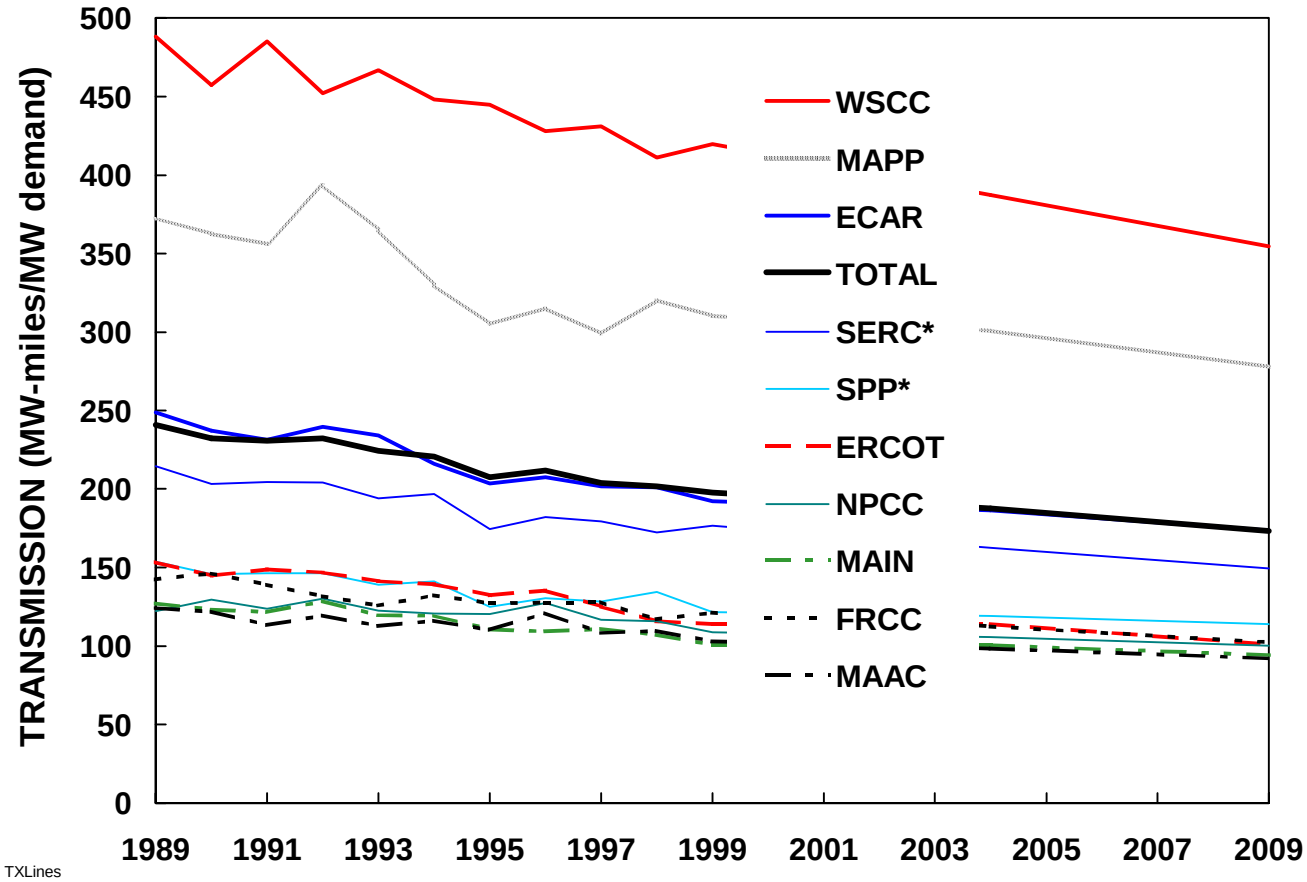
Current Ancillary-service Tariffs Unrelated To Markets

- Prices usually based on average load, not on customer use of service
- Prices usually fixed, do not vary from hour to hour
- True self-provision (including customer supply) limited
- Quantities tied to customer load, not to system requirements
- These problems provide profitable opportunities to beat the averages

Policy Issues With Technical Underpinnings

- We have already looked at several
  - System protection, contingency reserves & risk
  - Black start
  - Regulation allocation
- Transmission investment is another
  - Lack of control forces transmission to be regulated
  - Congestion pricing can *allocate* scarce transmission and can *illuminate* investment needs but it does not *motivate* investment

Transmission Capacity Declining Relative to Generation and Load



Market Impacts & Shared Risk

- **All of the reliability rules, CPS, DCS, contingency reserves, Black Start, … impact market opportunities (prices) and quantify the *communal* risk**
  - **Congestion typically results from *contingency* flows, not *actual* flows. This curtails commerce and reduces economic efficiency**
  - **Cheating on reserve requirements exposes the system to risk of collapse for the benefit of the cheater**

Technology is Helping

- Power electronics
  - flow control
  - stability
  - FACTS
  - HVDC & HVDC Light
- Storage
- Superconductivity
  - high density transmission
- Distributed Energy Resources
  - distributed generation
  - responsive load
  - local storage
- Sensors & Controls
- Communications
- Intelligent Agents

Distributed Resources in a Restructured Power System

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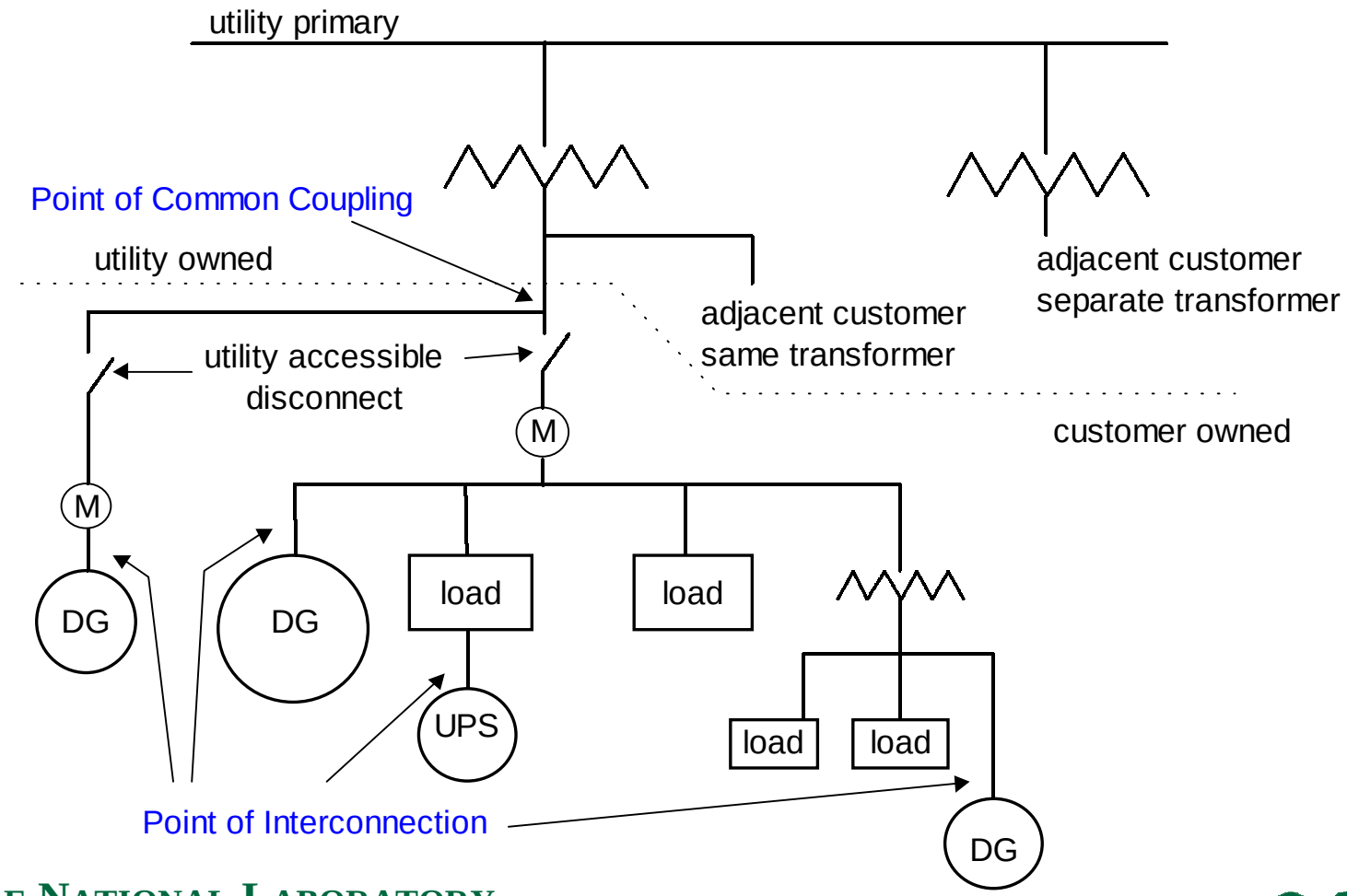
Distributed Generation Can Be Connected in a Number of Ways



Impediments to Distributed Resource Deployment

- **Interconnection requirements/standards**
  - vary from utility to utility
  - everything "depends" - each case must be studied
  - utility is both guardian of the communal power system and a competitive supplier of energy
- **Communications & control**
  - energy is not the only (or most valuable) commodity to sell
  - markets require different control signals
- **Metering**
  - you can't sell what you can't measure

Existing Utility Requirements

- **Based upon requirements for large units**
- **Often require expensive studies**
- **Generator pays all costs (studies and modifications), up front**
- **Detailed facility requirements**

"From the electric system perspective, the challenges posed by any given parallel generator connection do not diminish significantly with reduction in generator size. For this reason, each specific connection must be studied with respect to its size, its type, and the nature of the electric system at the interconnection point." - Niagara Mohawk

Interconnection Standards Address:

- **Safety**
  - **protect the general public and utility personnel**
- **Equipment protection**
  - **prevent damage to other customer & utility equipment**
- **Power Quality / Continuity of Service**
  - **prevent outages or power quality problems for adjacent customers or jeopardize the power system**

Basic Concerns

- Faults
  - **Disconnect for faults**
  - **One-phase fault detection in three-phase case**
- Islanding
  - **Prevent islanding beyond the point of common coupling**
  - **Prevent re-energization of system beyond point of common coupling**
  - **Detect loss of electric power system**

Basic Concerns
(continued)

- Power Quality
  - **Prevent out of range voltages, frequency, harmonics, power factor, …**
  - **Limit voltage flicker induced by the distributed resource**
  - **Prevent disruptions on the utility system**
- Other
  - **Prevent magnification of transients**
  - **Limit DC injection**
  - **Provide needed isolation**
  - **Integrate with existing ground system(s)**
  - **Synchronization signals**
  - **Control directional power flow (some cases)**

Characteristics of Concern: Islanding

- The ability of the distributed generator to support an isolated portion of the grid
- Primary concern is with personnel safety
- Also concerned with utility liability if voltage or frequency is out of the required range (damage to other customers equipment)

Islanding is possible with synchronous generators, inverters, and induction generators

It is also possible to build anti-islanding controls

Islanding

- Isolated, intentional islands are good
- Unintentional islands that include a portion of the grid are seriously dangerous
- Intentional islands that include a portion of the grid offer benefits but require great care

Emergency Generators

- All utilities are vulnerable to customer use of emergency generators and backfeeding
- Entergy addresses through customer education (throw the main breaker)

Additional Concerns

- Harmonics
- DC offset
- Flicker
- Aggregation - it is the total, not the individual

Generator Characteristics

Characteristic	Type of Conversion Technology			
	Generators		Inverters	
	Synchronous	Induction	Self-comutating	Line-comutated
Fault current	High	Very low	Low	Low
solated operation	Yes	No	Yes	No
Anti-islanding	Requires special relays		Requires deliberate design	
Voltage control	Most	No	Yes	No
Examples	Engine-driven, hydro, a few microturbines	Wind turbines, small hydro, engine-driven	Fuel cells, most microturbines, photovoltaics, some wind turbines	

Feeder Reclosing

- Common technique to increase reliability
  - removes temporary faults (lightning, limbs)
  - minimizes area of permanent fault
  - occurs within 12 cycles on some systems
- Distributed generator can interfere
  - maintain arc
  - prevent fault detection
- Current solution is automatic removal of DG
- Better solution is protection coordination

Interruptible Load and Load Shedding Have Been Around for Years. What's Different Now?

- The old structure sent the wrong signals
- Market Structures
  - Interruptible rates continuously compensate customers who then hope to never reduce load
  - Real-time-prices allow customers to choose when it is more economic for them to continue to consume and when it is economic to curtail
- Communications and control technology
  - New capabilities
  - Lower prices

Distributed Resources Ideal Ancillary Service Providers

- Fast response
- Fast deployment
- Redundancy
- Distributed throughout system
- Close to load

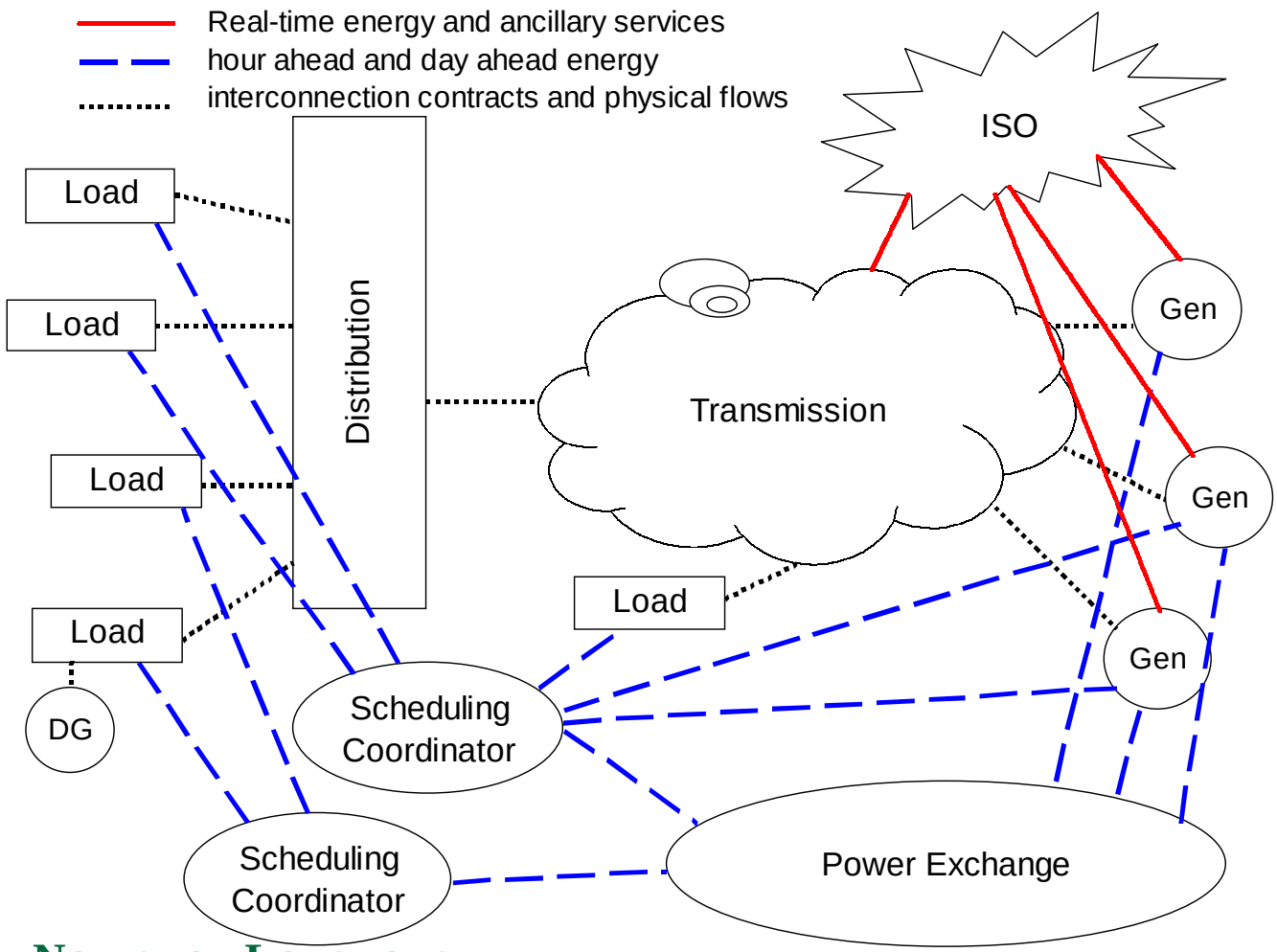
- Reduce requirements for new generation, transmission, distribution

Which *Should* a System Operator Prefer to assure reliability:

- A few large generators
  - failure of even one presents serious concerns
- 1000's of small resources
  - no common mode failure

- 10's MW of directly controllable load
- 1000's MW of price responsive load
  - responds as fast or faster
  - individual response is statistical, >90%, & uncorrelated

Loads And Distributed Generation Are Typically Excluded From Real-time And Reliability Markets



“I Have Good News - The Flight is Oversold…”

Reliability = Security + Adequacy

- **Airlines have learned how to address adequacy with real-time price response and demand elasticity**
- **They also flatten the load profile (maximize resource utilization) with price responsive demand elasticity over a range of time horizons**

System Operator's Risk/Reward Calculation

- RISK: Public humiliation with thousands of innocent people siting in the dark.
- REWARD: A certificate of appreciation in a handsome plastic frame.

Aggregation and Communications Are Obstacles

System operators are not used to dealing with small resources

- many refuse to believe loads can, will, or want to modify performance in response to price signals

- Aggregators can provide real value
- System Operator could "broadcast" control requests and monitor system performance
  - individual performance monitored after the fact
  - stricter resource certification required

Real Time Decision Support

- Fast - market response required in seconds to minutes, depending on the transaction
- Automatic & Easy - users do not have the time or interest in becoming power system experts
- Consider current customer economics as well as real-time power and ancillary service prices
  - current plant conditions
  - opportunity costs
  - current power & ancillary service prices

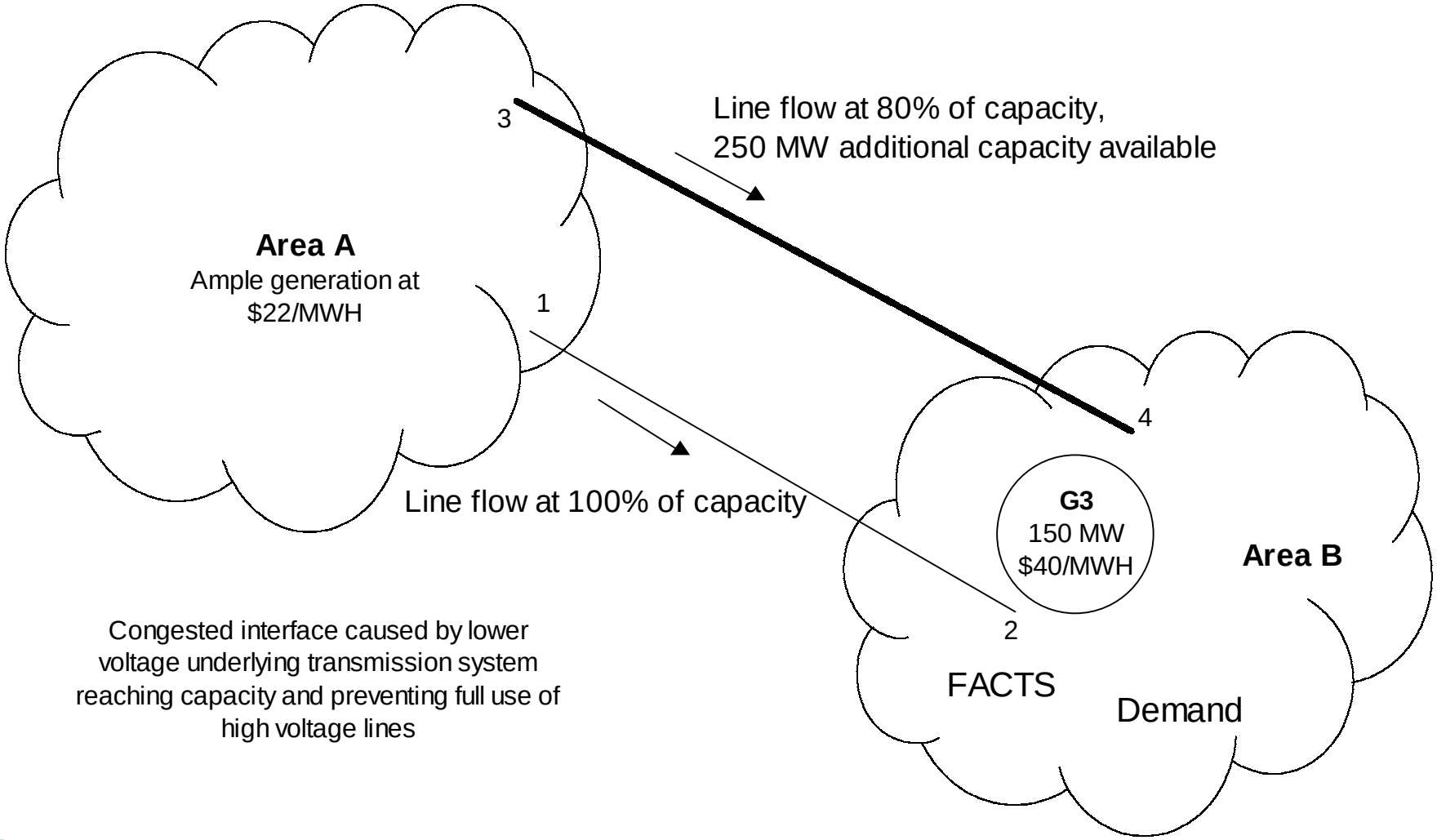
The Future vs the Present

- A distributed generator connecting today is stuck with the power system of today
  - Too small to provide benefit to the power system
  - Trying to minimize the impact on and expense to the power system
- In the future the power system may recognize distributed generators as a valuable resource
  - Aggregated size can positively impact the system
  - The system will encourage deployment

Real-Time Metering Has An Unexpected Regulated Aspect

- The most economic technology appears to be fixed network radio
- To be economic it required high deployment density
- It may be to everyone's advantage to standardize on advanced metering technology within an area

FACTs Can Increase Transfer Capacity



Congested interface caused by lower voltage underlying transmission system reaching capacity and preventing full use of high voltage lines

Power Quality Concerns and Solutions

The Best Place to Correct Power Quality is Locally With Local Storage and Generation

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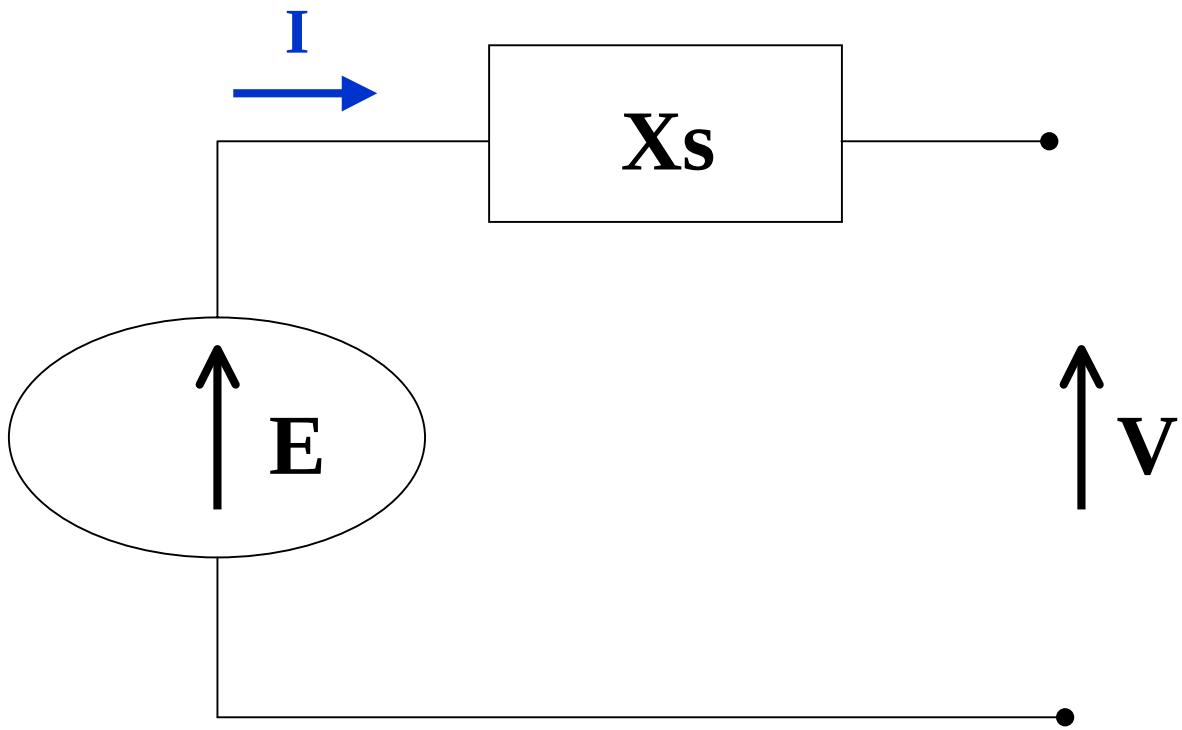
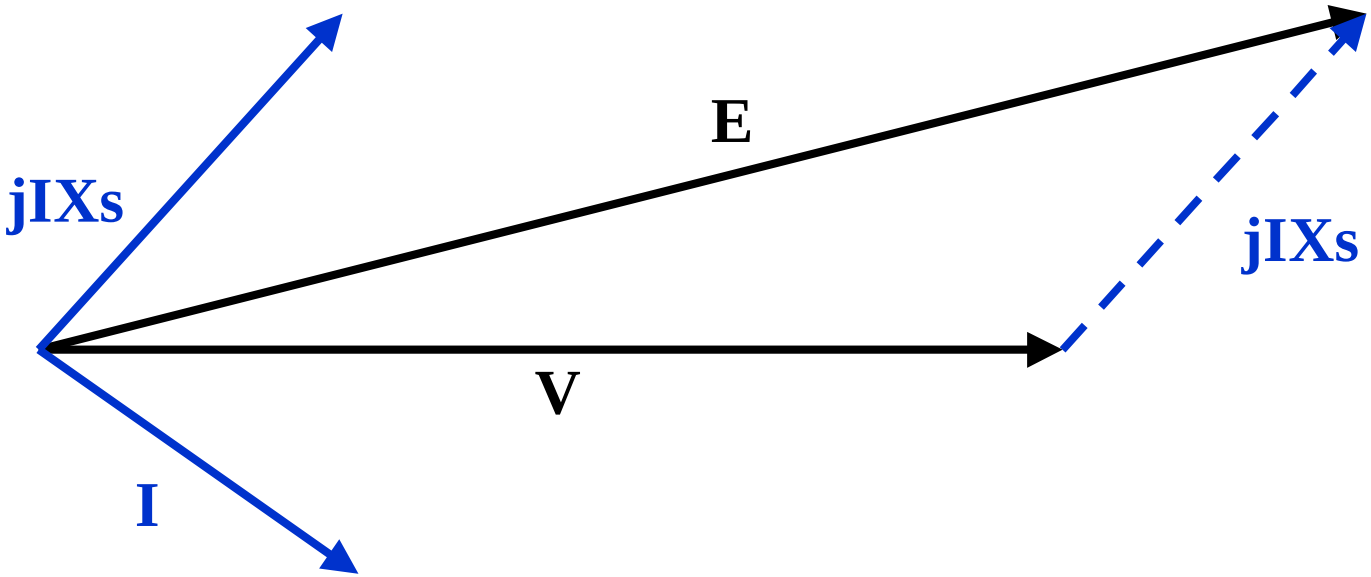
Lagging Power Factor

- Remember that lagging power factor is caused by inductive loads.
- It results in extra current flow, but the extra current does not do any work, it just causes extra losses.
- One way to solve the problem is to supply capacitance at the load. (Utility Lingo - Supply Reactive Power, or VARS)
- Another way is to supply VARS from the local generator.



Generator Simplified Model



Over Excited Generator Supplying VARS: Supplying Reactive Power Locally is Highly Effective, It Reduces Current Flow and Voltage Drop on the Transmission and Distribution Lines and Will Enable Local Voltage Regulation

Power Quality

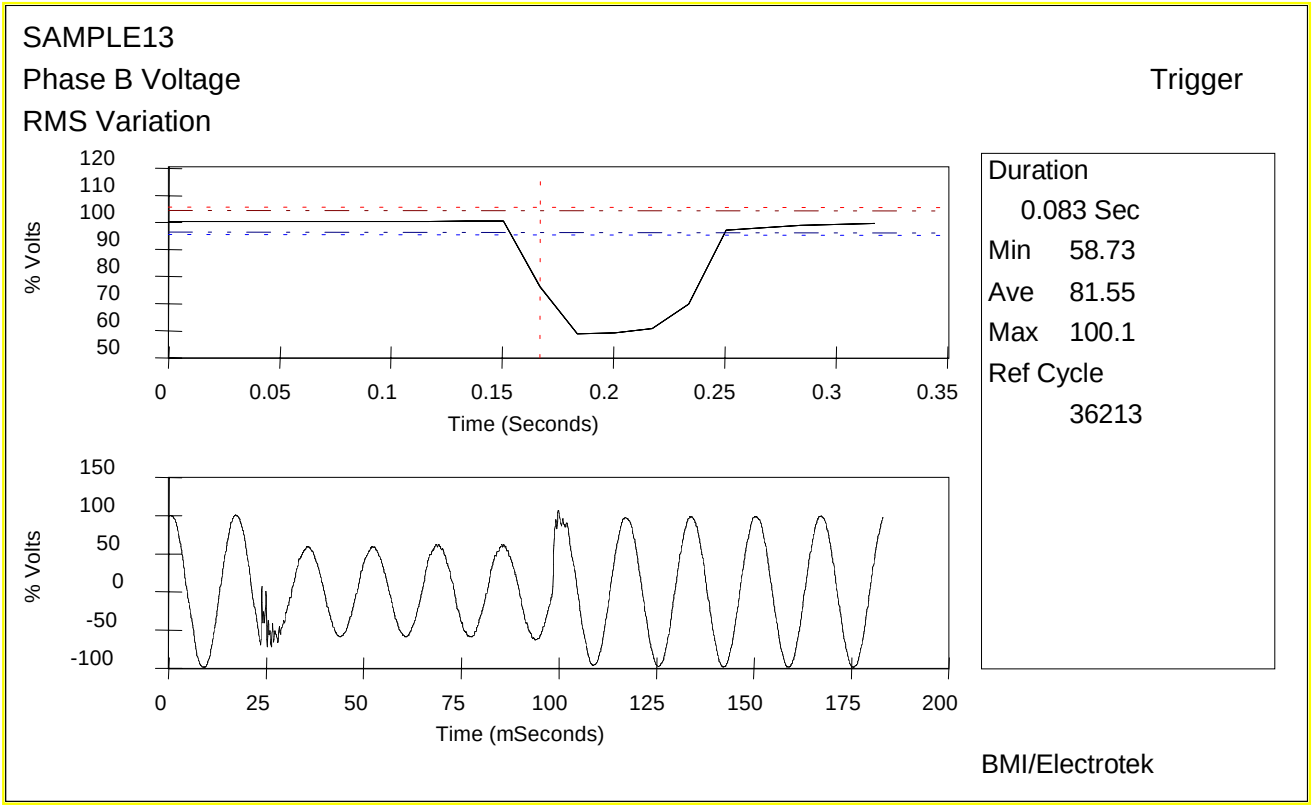
- Power Quality can be compared to air quality; there are a host of problems with both.
  - Worst problem is no air, when this happens for very long, damages result.
  - Loss of air for a short time may be ok, but the length of time depends on the specific application.
  - Contaminated air, there are many types of contamination, and new ones are constantly being identified or created.
  - Too much air is rarely a problem, but too much voltage can be.

Typical Power Quality Problems

- Harmonic Distortion - Multiples of the fundamental frequency that cause distortion of the voltage or current waveform. (the fifth harmonic is 300 Hz)
- Voltage sags - Momentary reductions in the voltage amplitude, caused by faults, heavy loads, switching operations.
- Voltage surges - Cause by switching, capacitor connection, lightning, fuse blowing, etc.
- Notching, DC Offset, Electromagnetic Interference, Unbalance and many others.

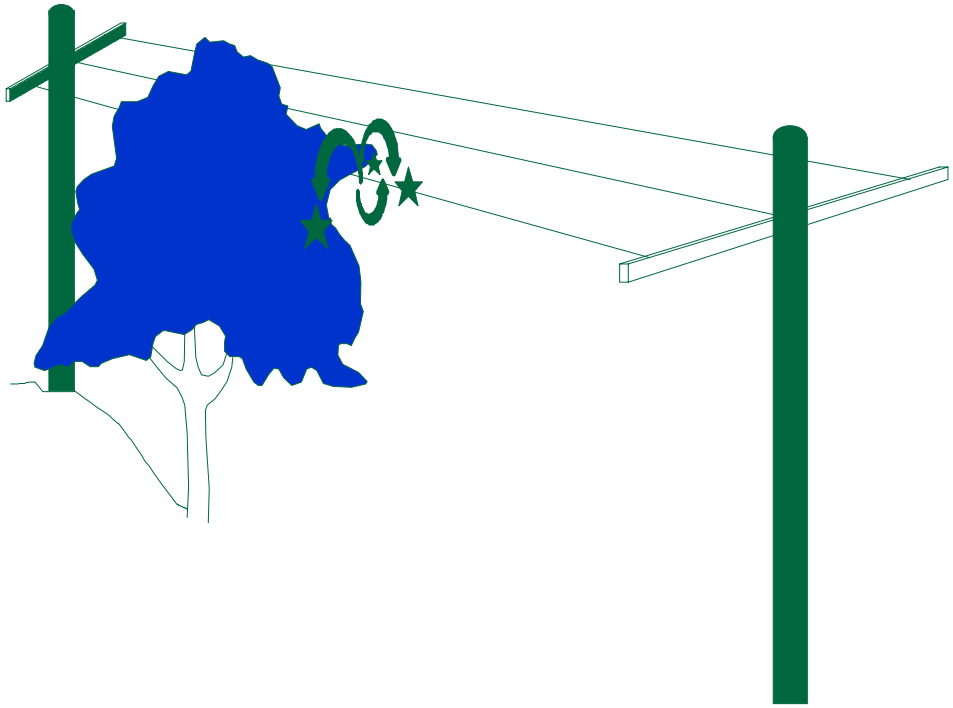
Voltage Sags

- Known as Glitch/Bump/Brownout/Power Surge
- Characterized by Duration and Depth, but don't forget point on wave and phase shift



Cause of Voltage Sags

Faults



Cause of Voltage Sags

Cause of Voltage Sags

Cause of Voltage Sags

Voltage Unbalance

- A common problem (.25% Nuclear Navy – Good, to 5% Bad)
- Voltage is unbalanced because each phase is not loaded equally.
- During fault conditions, voltage is unbalanced because each phase usually does not see the same fault impedance.
- Voltage unbalance causes motor overheating, vibration and current flow in the neutral.

Voltage Unbalance Causes Complications in Calculation

- The three phases are divided into three sets of vectors.
- Positive, negative and zero sequence.
- Positive are like the normal phases, negative rotate backwards, and zero correspond to neutral current.
- The calculation becomes more time consuming.
- The positive, negative and zero sequence also relate to the harmonics.

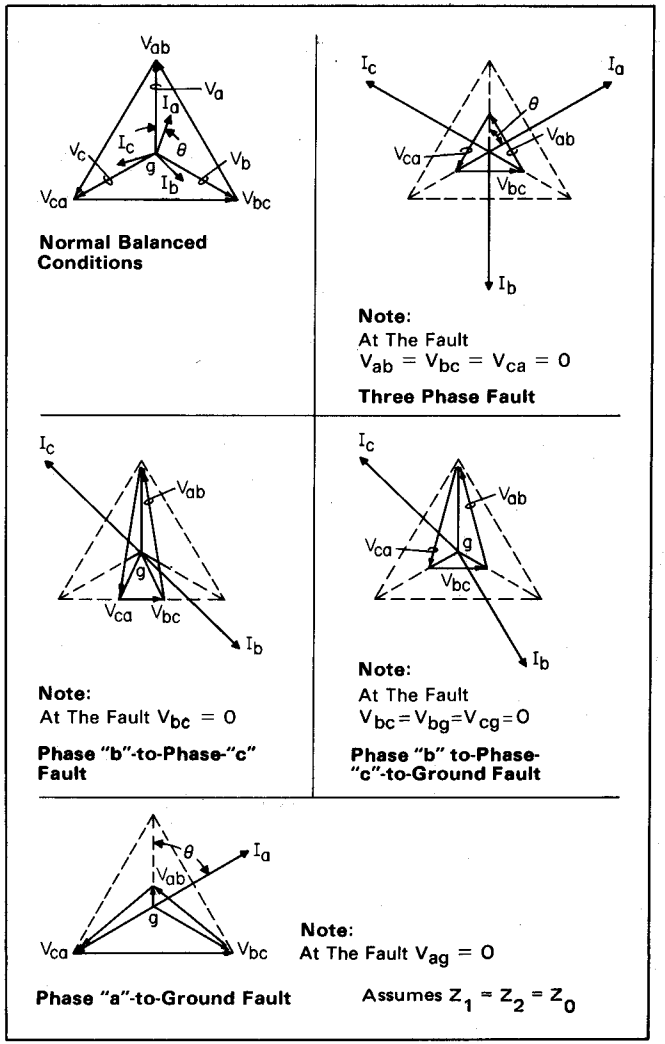
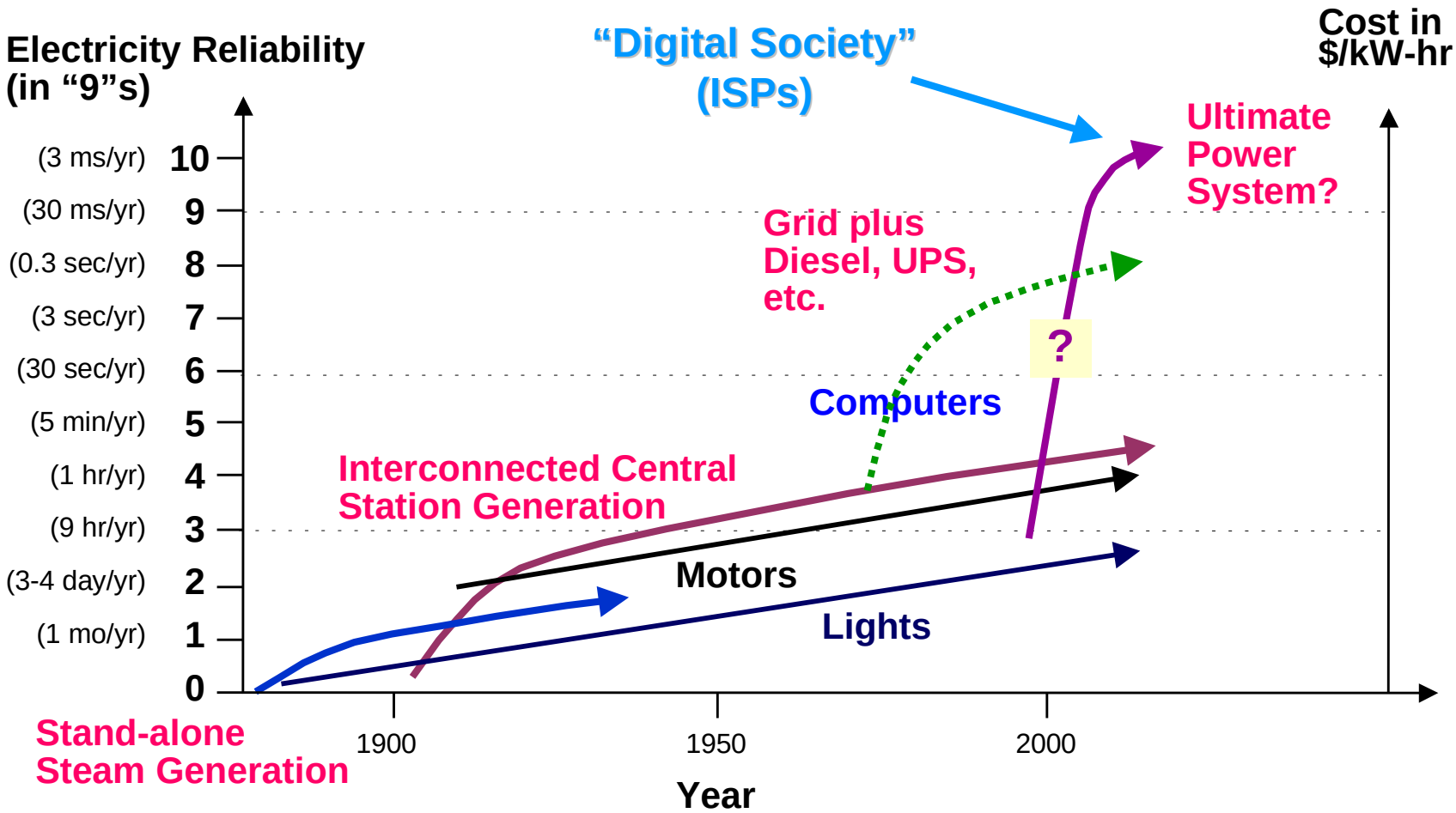


Figure 2-20: Phasor Diagrams for The Various Types of Solid Faults Occurring on a Typical Power System as Shown in Figure 2-7.

Power Quality Standards and Guides

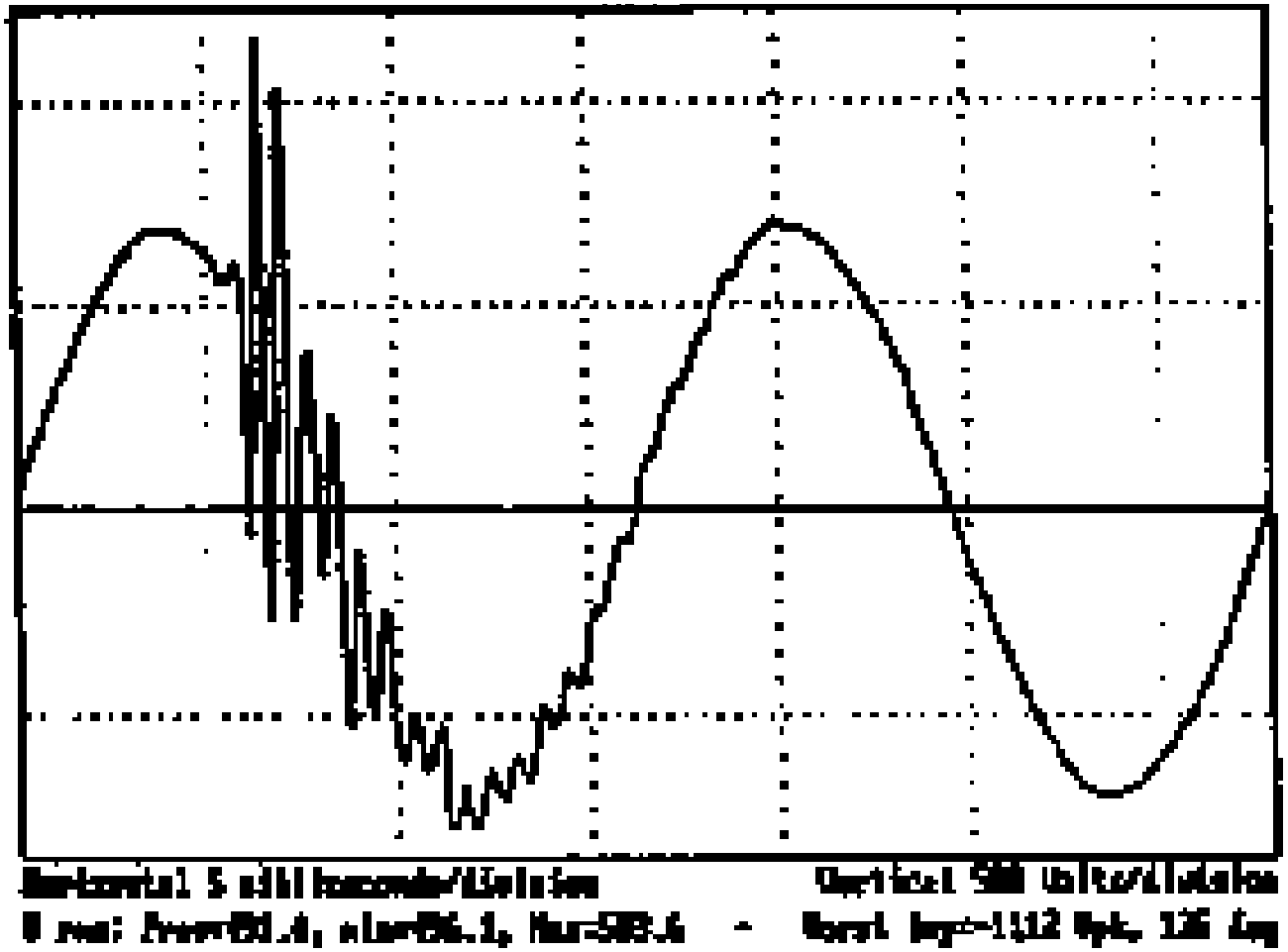
- IEEE Std 1159-1995 Recommended Practice for Monitoring Electric Power Quality (Rev. 2001)
- IEEE P1366 Trial Use Guide for Electric Power Distribution Reliability (SAIFI, CAIDI, ASAI, …)
- IEEE P1564 Recommended Practice for the Establishment of Voltage Sag Indices (In Prep.)
- IEEE 859-1987 (R1993) Standard Terms for Reporting and Analyzing Outage Occurrences and Outage States of Electrical Transmission Facilities
- IEEE Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems (Also a Guide)

Electricity Reliability vs. Technology

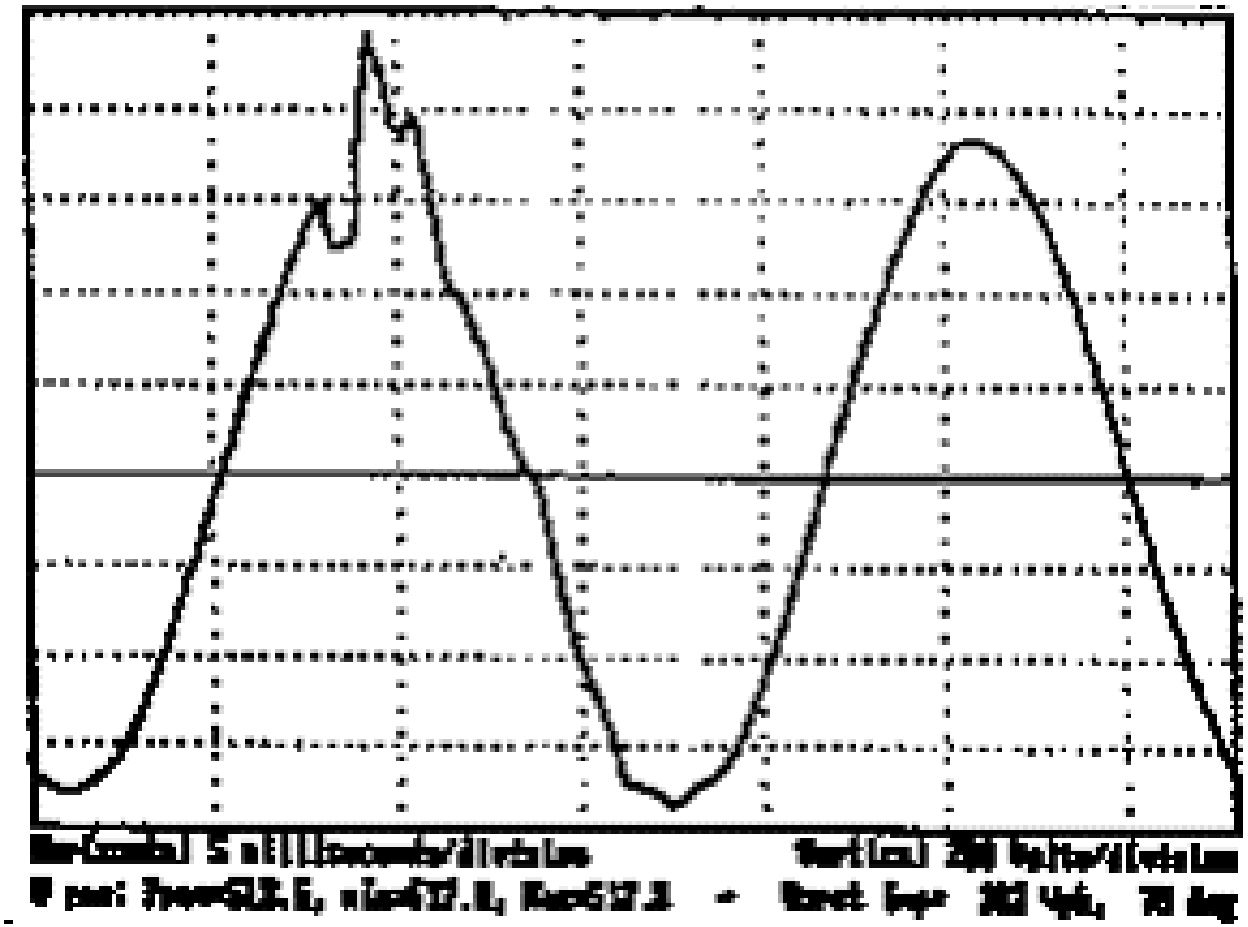


Power Quality Solutions

- Distributed Energy Resources
- Storage devices.
- Filters (Passive and Active)
- Larger cable gauges (Stiffer System)
- Surge Suppressors (Metal Oxide Varistors)
- Shielding
- Distribution System Configuration
- Many others depending on the problem
- Let us look at a few case histories and plots



Ringing Caused by Capacitor Connection in Nearby Substation

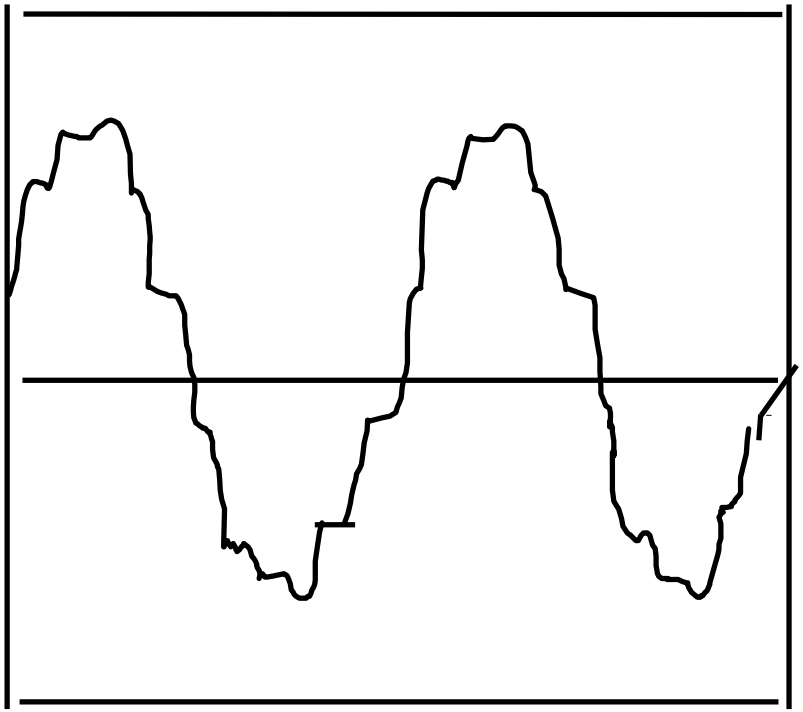


Filtered Ringing (Active Filter, 1 kHz)

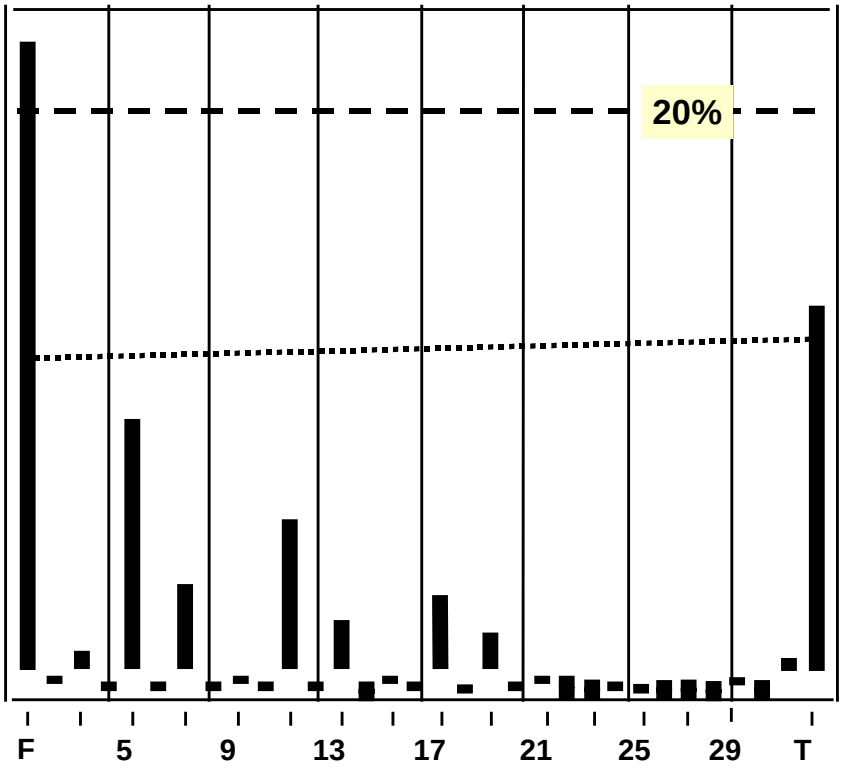
What Is a Filter ?

- There are basically two types, active and passive.
- The passive filter can be as simple as an inductor, or it can be an RLC circuit that is tuned to provide a high impedance to a certain frequency.
- The active filter contains power electronics switching elements, energy storage, and cancels out the unwanted frequencies.

Harmonic Currents



Current Waveform

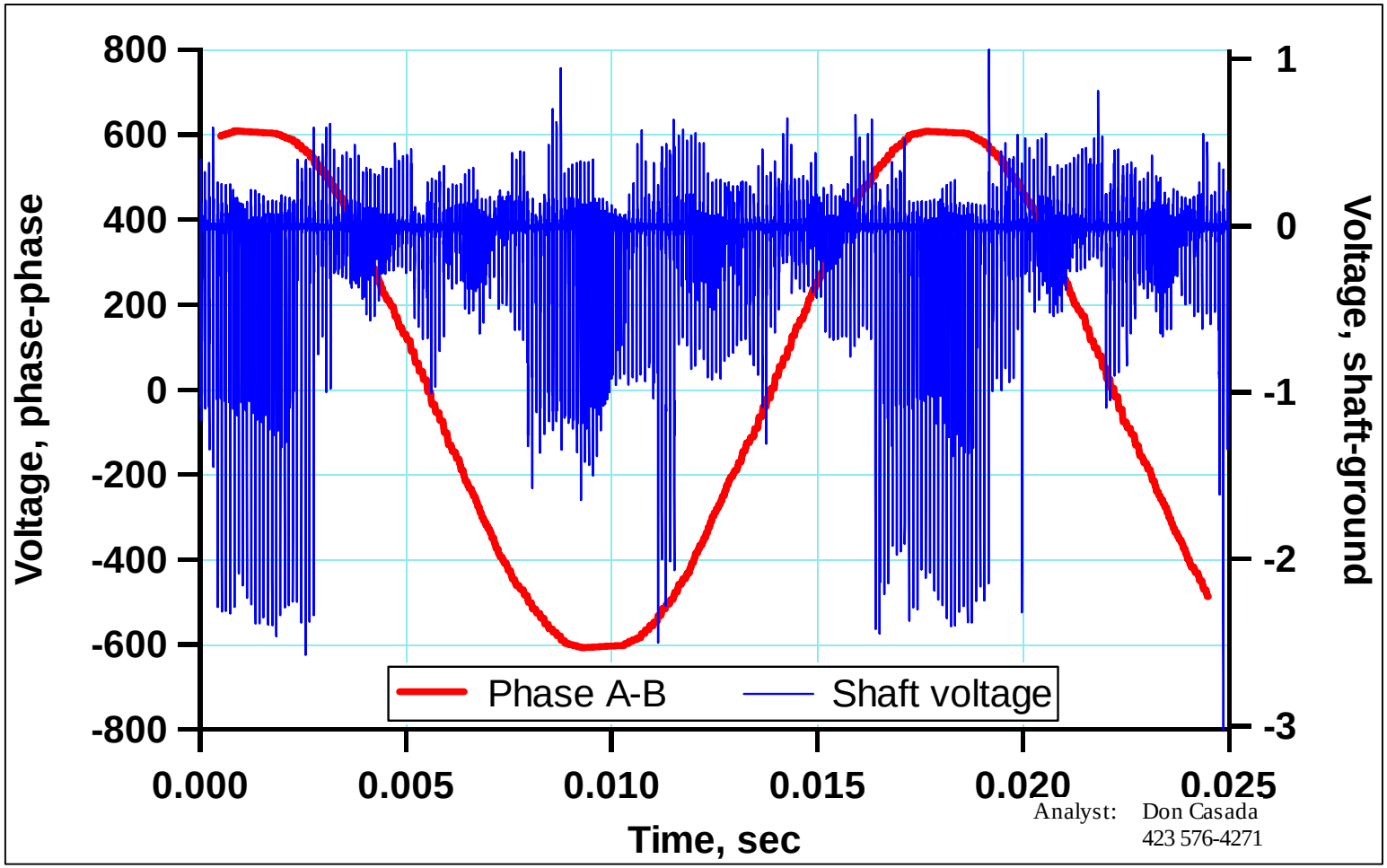


Harmonic Analysis

Harmonic Distortion

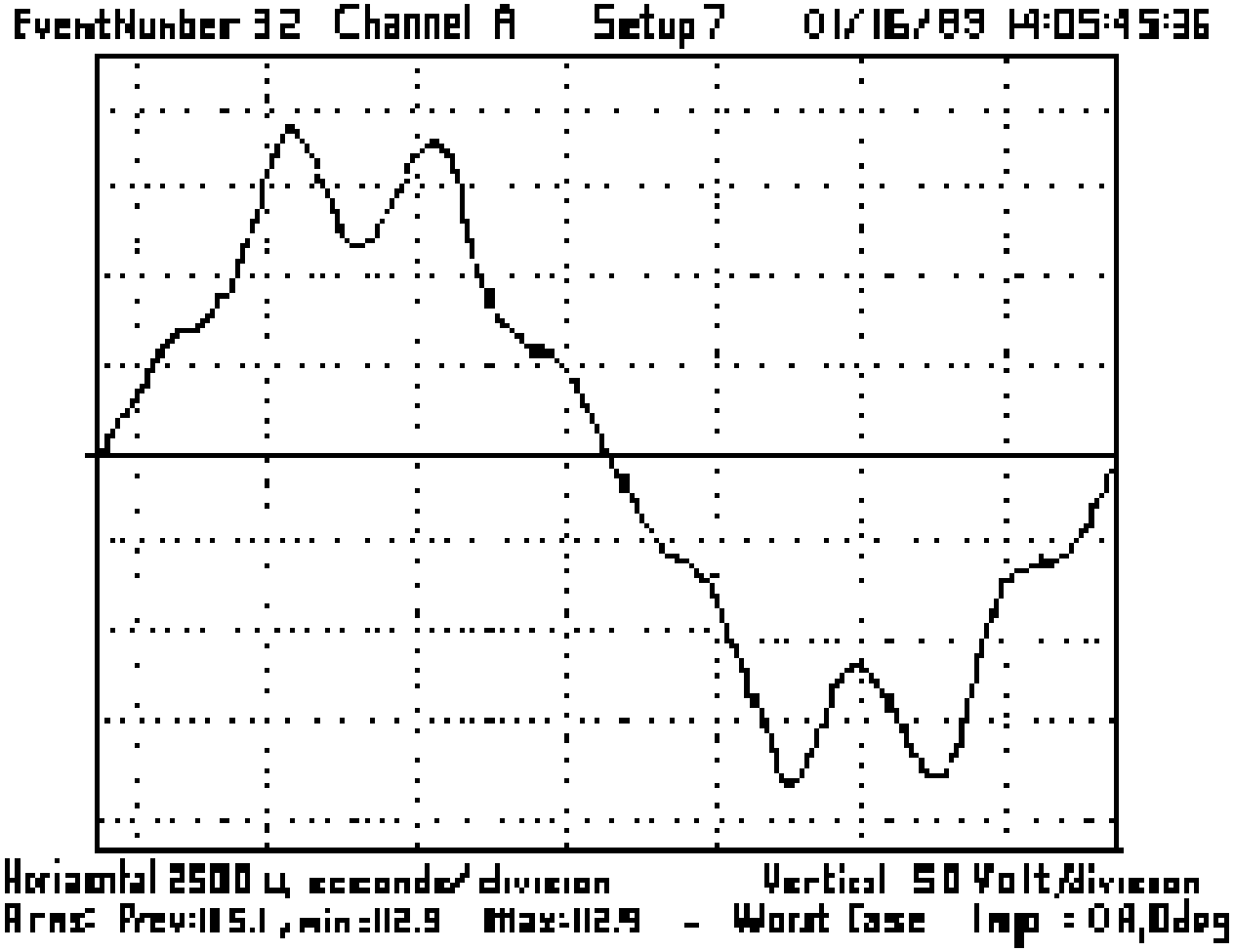
- IEEE 519 Defines Total Harmonic Distortion (THD) - General Criteria
- NEMA MG1 Defines Harmonic Voltage Factor for Motors
- Typically, when the motors are having problems, the phones and computers will have stopped working long ago, unless the problem is just in the motor feeder.
- Be more concerned with voltage than current.
- A "Stiff" system can be compared to a stiff fishing pole, it will have less flex when there is a fish on the line (non-linear load)

Generation of Bearing Currents



Variable Frequency Drives

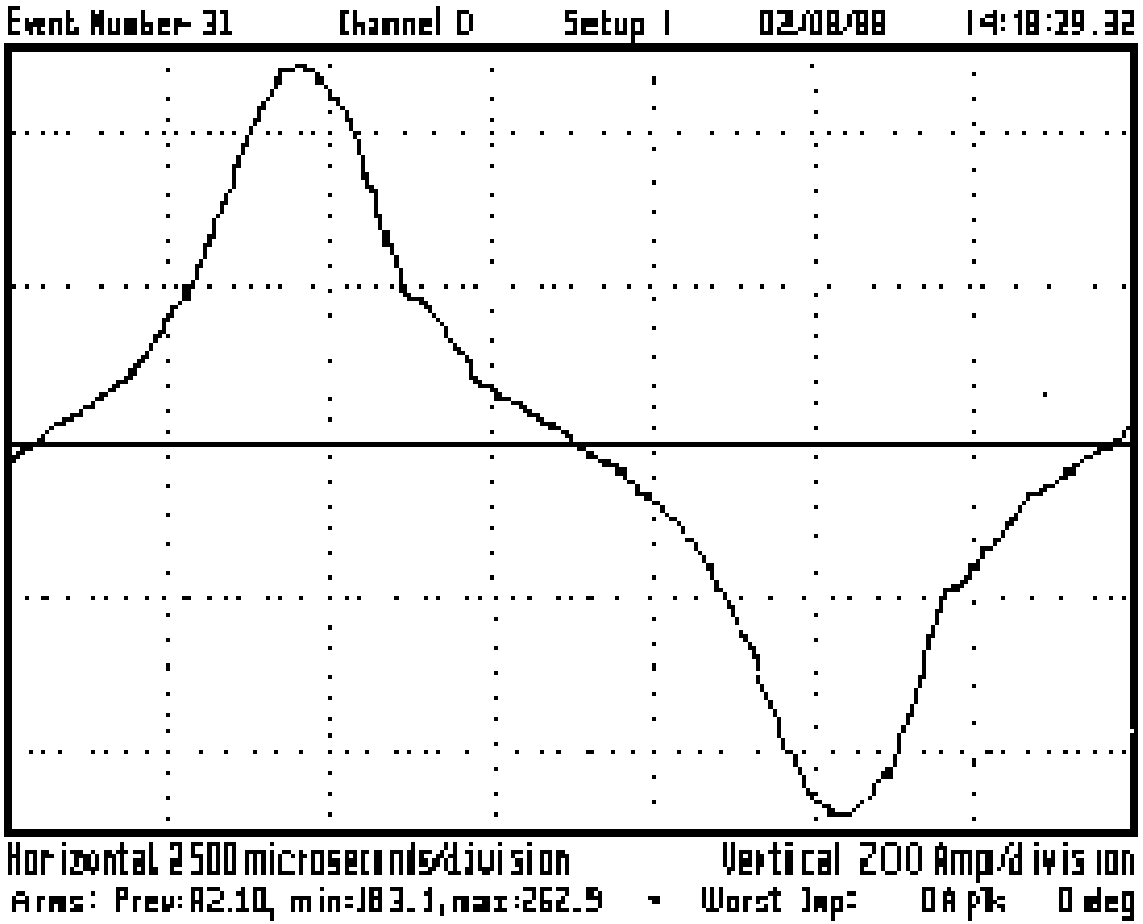
- <u>Improperly applied</u> drives have created a host of problems.
- The newer Pulse Width Modulated Drives can have switching frequencies up to 20 kHz.
- EMI, reflected voltage waves and bearing damage are common problems.
- The solutions are simple, using filters, installing cable in conduit, better grounding, insulating bearings, etc.



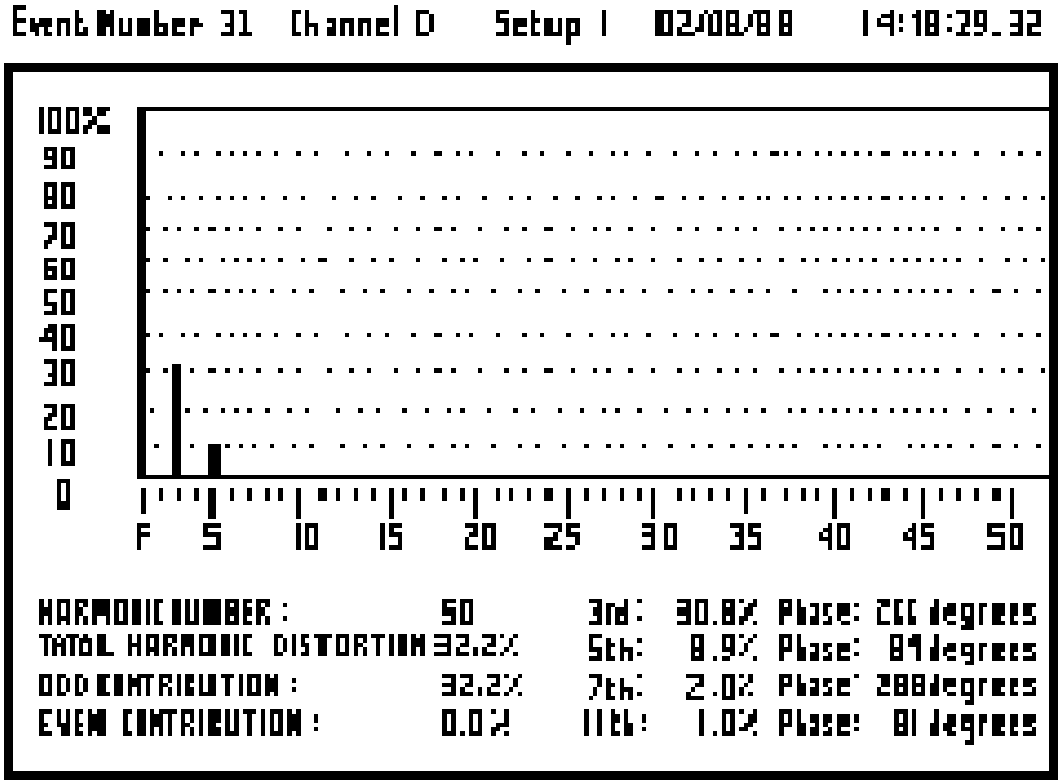
Total	19.2%
7th	15.8%
5th	9.8%
8th	2.5%
2nd	2.3%

This distortion was caused by the reactance of the generator windings, and non linear load.

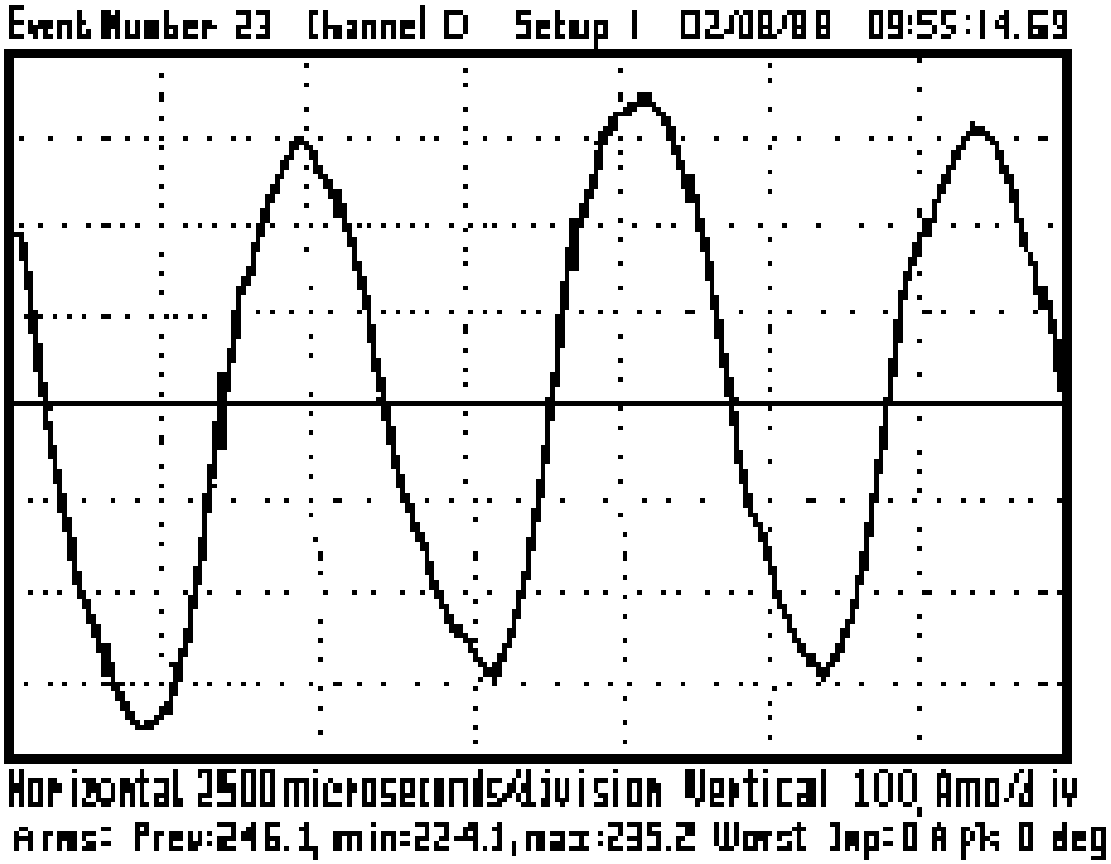
Voltage Distortion at Elevator Motor When Powered from Emergency Engine Generator



Unbalanced current due to switching mode power supply used in personal computers, copiers, etc. Current starts to flow in the neutral.



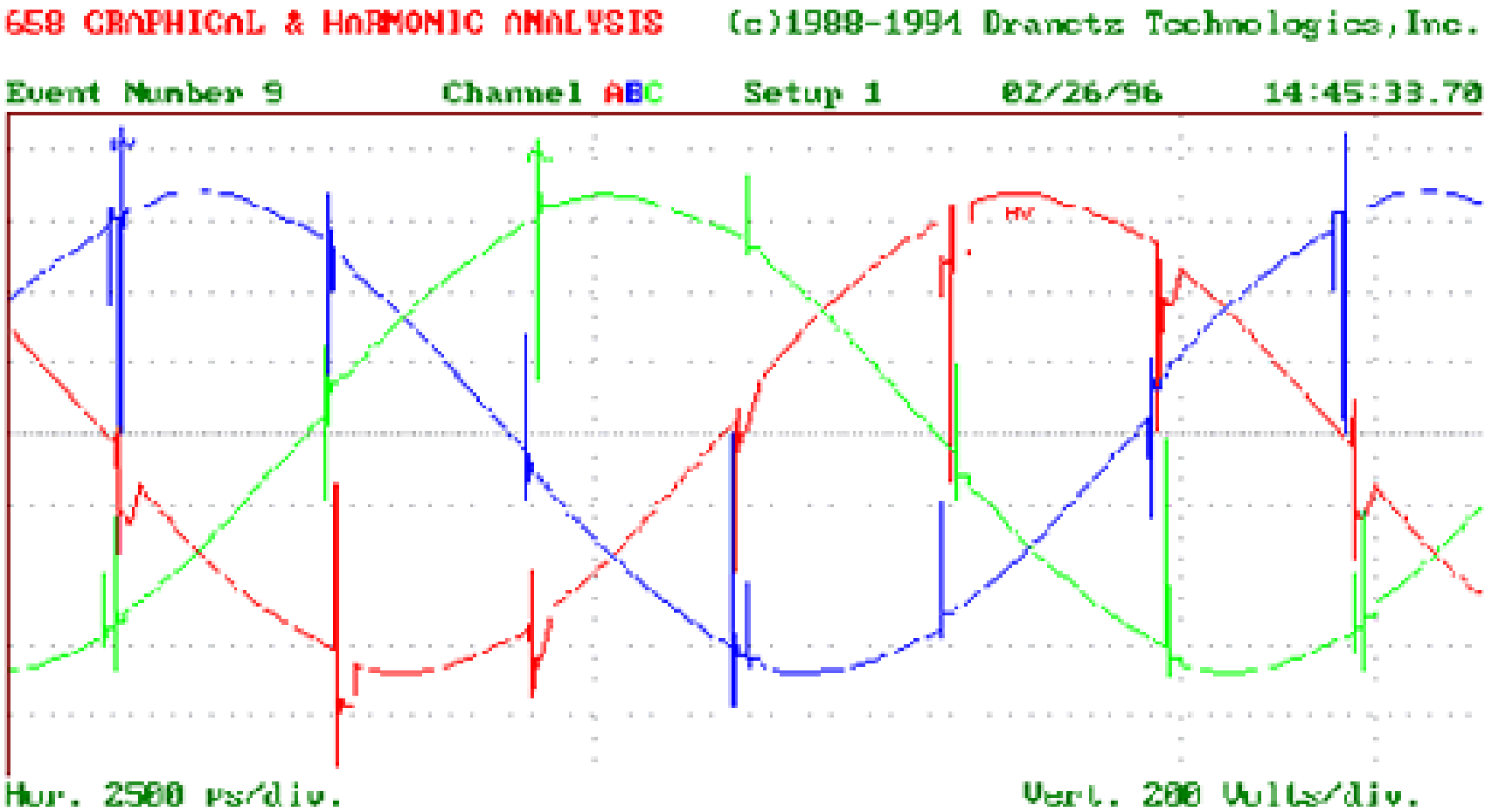
Unbalanced current always shows high triplen harmonic. The 3rd harmonic here is 31 %. The THD is 32%.



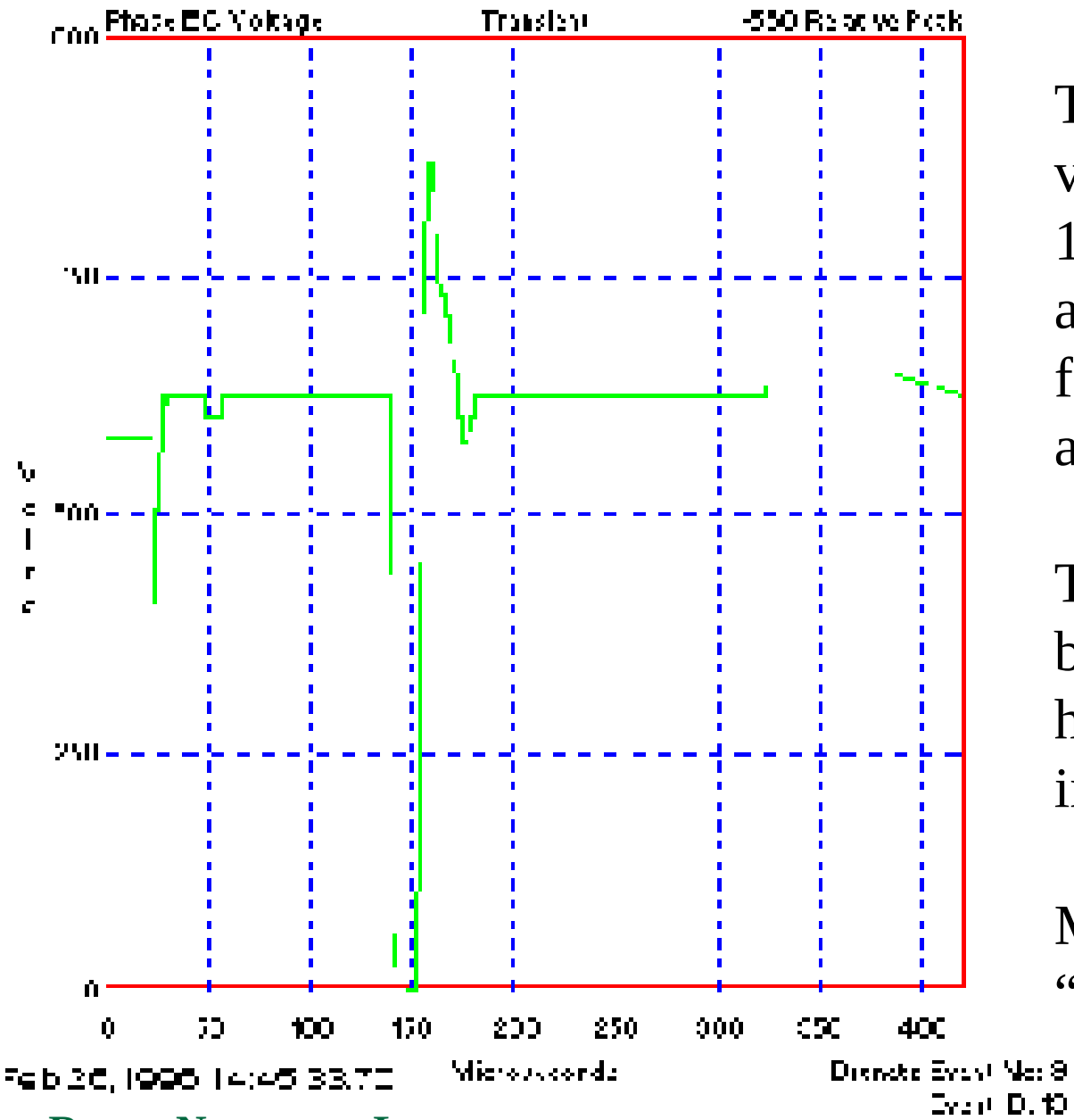
Unbalanced current also shows up in the neutral.

Here the component is 180 Hz.

The neutral and the transformers have to be re-sized.



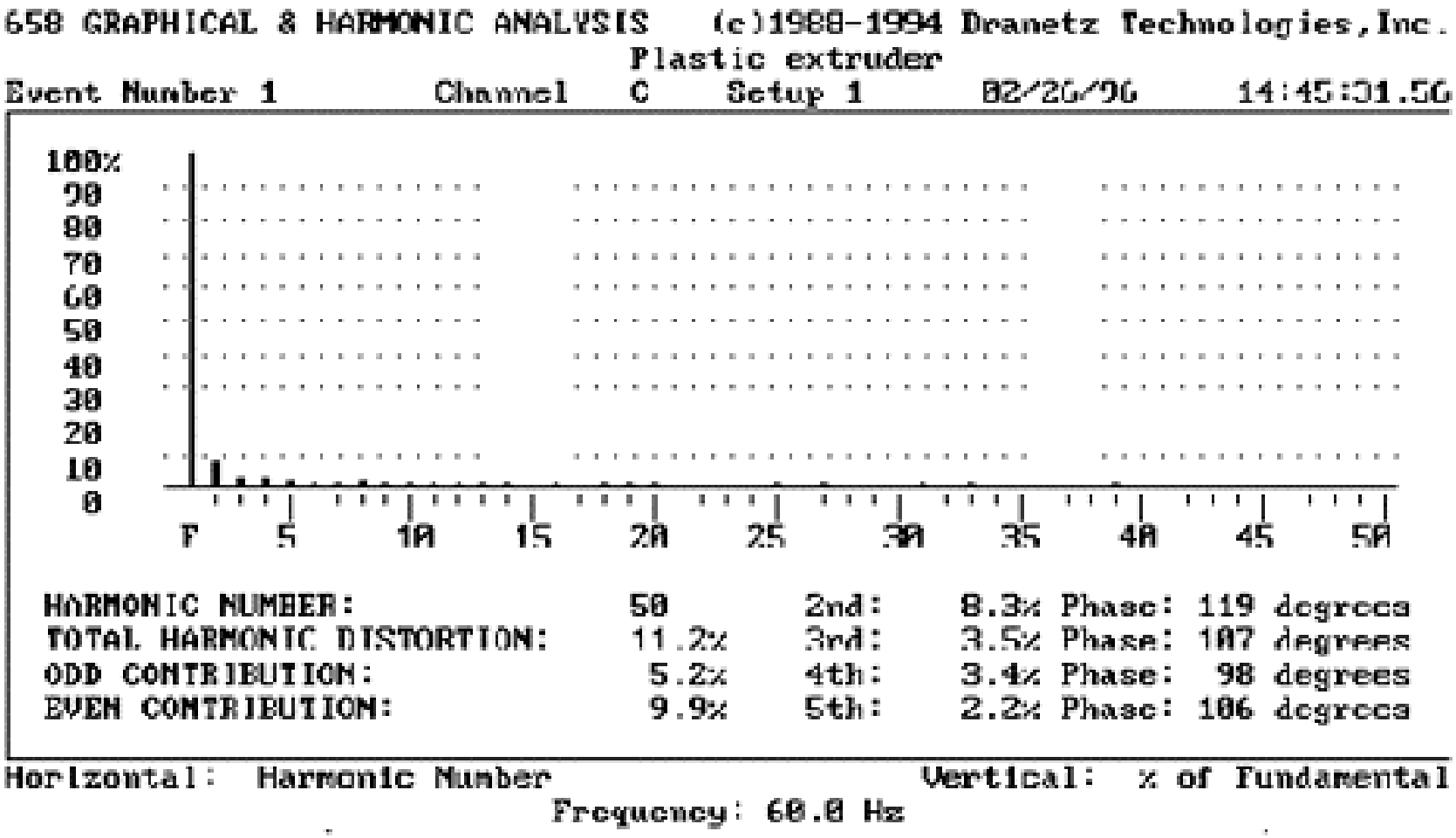
Voltage Transient Occurring Six Times per Cycle



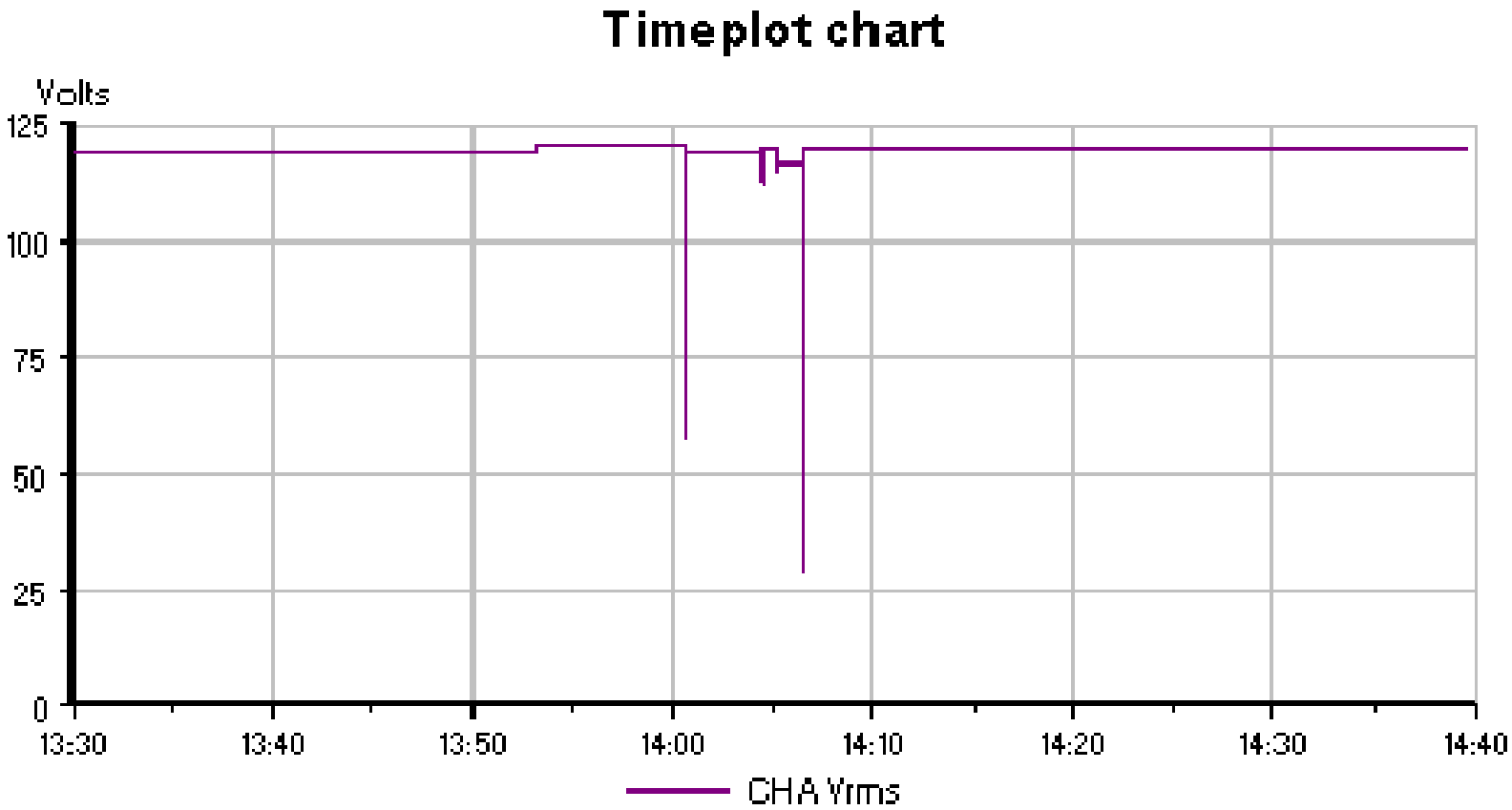
The transient has a very fast rise time 1.08 microseconds and equivalent frequency of 230khz, amplitude of 864V.

The notches were being caused by a half bridge rectifier in a motor drive.

MOVs were used to “clamp” the voltage.

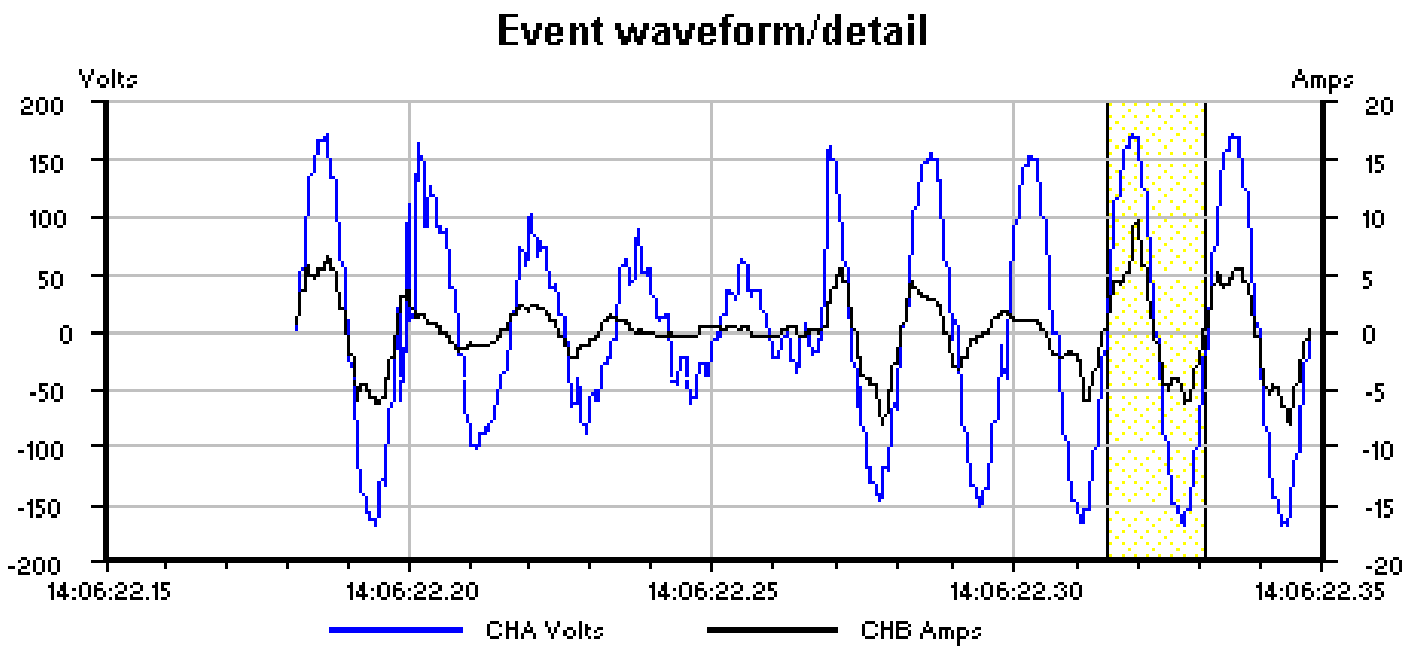


The 2nd harmonic was caused by the half wave rectifier.



Unit	A	B	C	D	ABC
V	119.6	119.5	119.8	0.5	119.6
I	6.2	4.6	5.8	0.0	6.2

Voltage sag time plot. Symptoms were computer misoperation and light flicker.



AV RMS Lo to Norm at 14:06:22.314
Threshold Crossed: 116.0 V
Category: INSTANTANEOUS SAG
Out Of Limit Max/Min: 29.15 V
Duration Out Of Limits: 0.116 Sec.

Unit	A	B	C	D	ABC
V	119.1	118.8	119.0	0.6	119.1
I	6.3	4.7	5.9	0.0	6.3
Vtrans	6.1	9.1	9.1	6.1	6.1
Itrans	-1.0	-1.0	-0.9	0.0	-1.0
HZ	60.0				

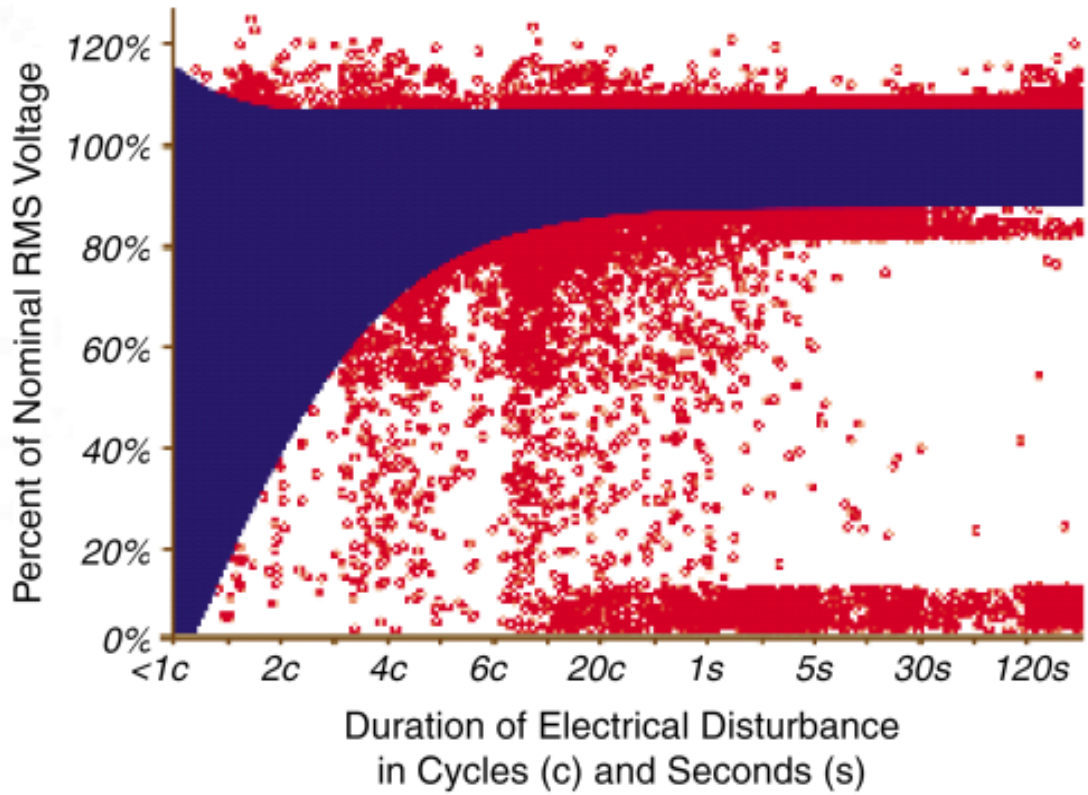
Because there was no increase in current when the sag began, we know the source was towards the utility, it turned out to be loose bus bar bolts.

Power Quality per IEEE 1159

Categories	Spectral Content	Typical Duration	Typical Magnitudes
1.0 Transients			
1.1 Impulsive			
1.1.1 Voltage	> 5 kHz	< 200 µs	
1.1.2 Current	> 5 kHz	< 200 µs	
1.2 Oscillatory			
1.2.1 Low Frequency	< 500 kHz	< 30 cycles	
1.2.2 Medium Frequency	300–2 kHz	< 3 cycles	
1.2.3 High Frequency	> 2 kHz	< 0.5 cycle	
2.0 Short-Duration Variations			
2.1 Sags			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.0 pu
2.1.2 Momentary		30–120 cycles	0.1–1.0 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.0 pu
2.2 Swells			
2.1.1 Instantaneous		0.5–30 cycles	0.1–1.8 pu
2.1.2 Momentary		30–120 cycles	0.1–1.8 pu
2.1.3 Temporary		2 sec–2 min	0.1–1.8 pu
3.0 Long-Duration Variations			
3.1 Overvoltages		> 2 min	0.1–1.2 pu
3.2 Undervoltages		> 2 min	0.8–1.0 pu
4.0 Interruptions			
4.1 Momentary		< 2 sec	0
4.2 Temporary		2 sec–2 min	0
4.3 Long-Term		> 2 min	0
5.0 Waveform Distortion			
5.2 Voltage	0–100th Harmonic	steady-state	0–20%
5.3 Current	0–100th Harmonic	steady-state	0–100%
6.0 Waveform Notching	0–200 kHz	steady-state	
7.0 Flicker	< 30 Hz	intermittent	0.1–7%
8.0 Noise	0–200 kHz	intermittent	

Compatibility Challenges— CBEMA Curve Applications and Shortfalls

- Reality of the environment
- Limitations and Missing dimensions
  - the back door, communication ports
  - interference and harmonics
  - 3-phase, unbalance, phase shift, etc.
- Application Success Stories
  - Semi
  - General industries



The Power of Power Electronics

- Power electronics allows us to limit fault current very quickly and to have no impact on conventional relaying and protection.
- Power electronics allows us to control voltage magnitude, frequency and phase angle.
- Power electronics allows us to control the voltage at both ends of a feeder.
- Power electronics allows us to incorporate energy storage devices.

Fault Current

- Conventional relaying and fusing typically respond in times of half a cycle or longer.
- Power electronics can detect a fault and limit fault current so quickly that conventional protection has not yet started to actuate.
- This will enable DER equipped with a power electronic interface to be connected to a distribution system without impacting the existing infrastructure.

Control of Voltage, Frequency and Phase Angle

- Power electronics allows us to synthesize the voltage waveform. We can create whatever shape, frequency or angle we need.
- Thus we can control the amount of real and reactive power delivered. We can then provide a full range of reliability services, such as reactive power supply and voltage and frequency regulation.
- We could even provide new services that are not yet being provided, such as damping subsynchronous oscillations.

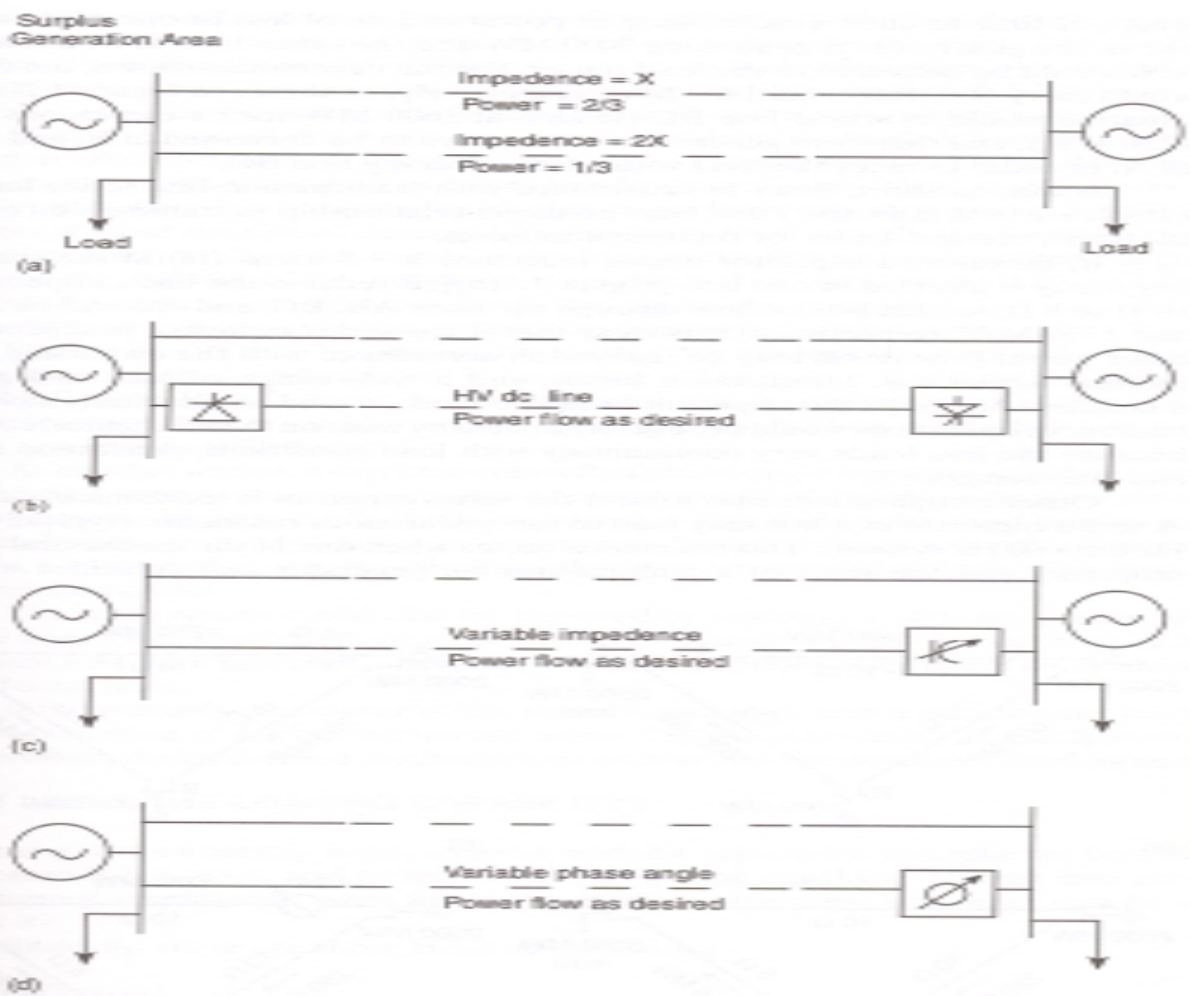
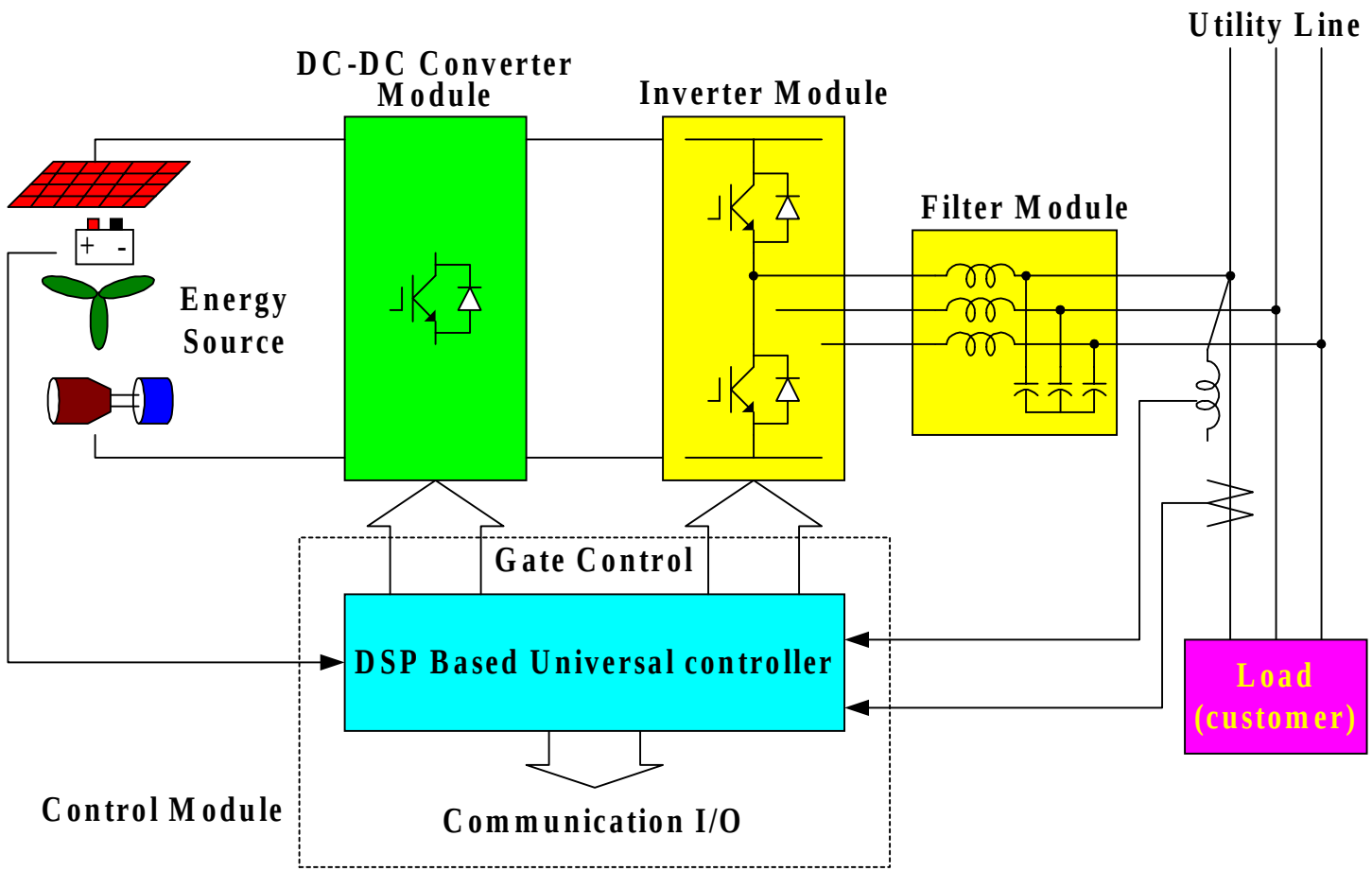


Figure 1.1 Power flow in parallel paths: (a) ac power flow with parallel paths; (b) power flow control with HVDC; (c) power flow control with variable impedance; (d) power flow control with variable phase angle.

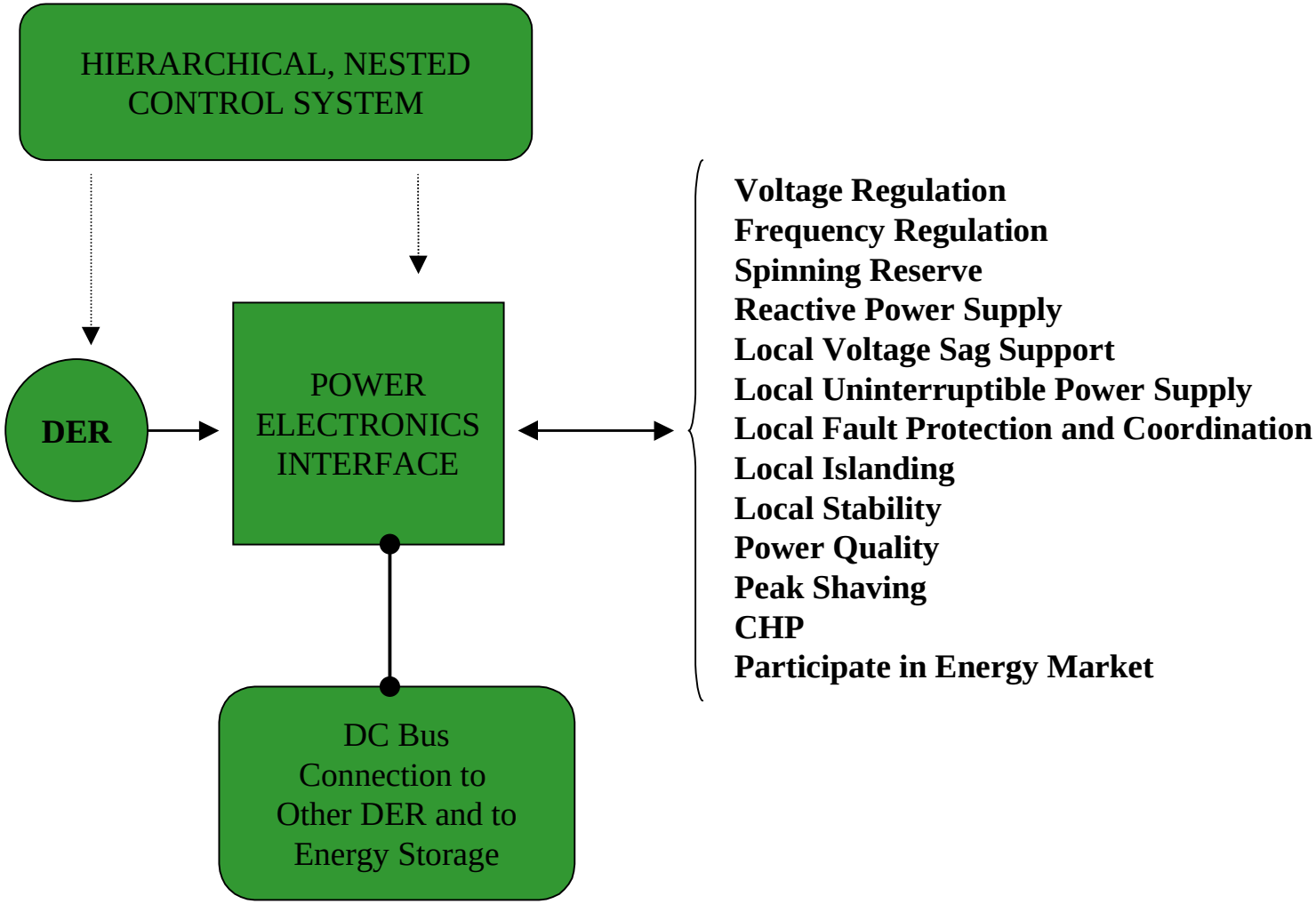
Energy Storage

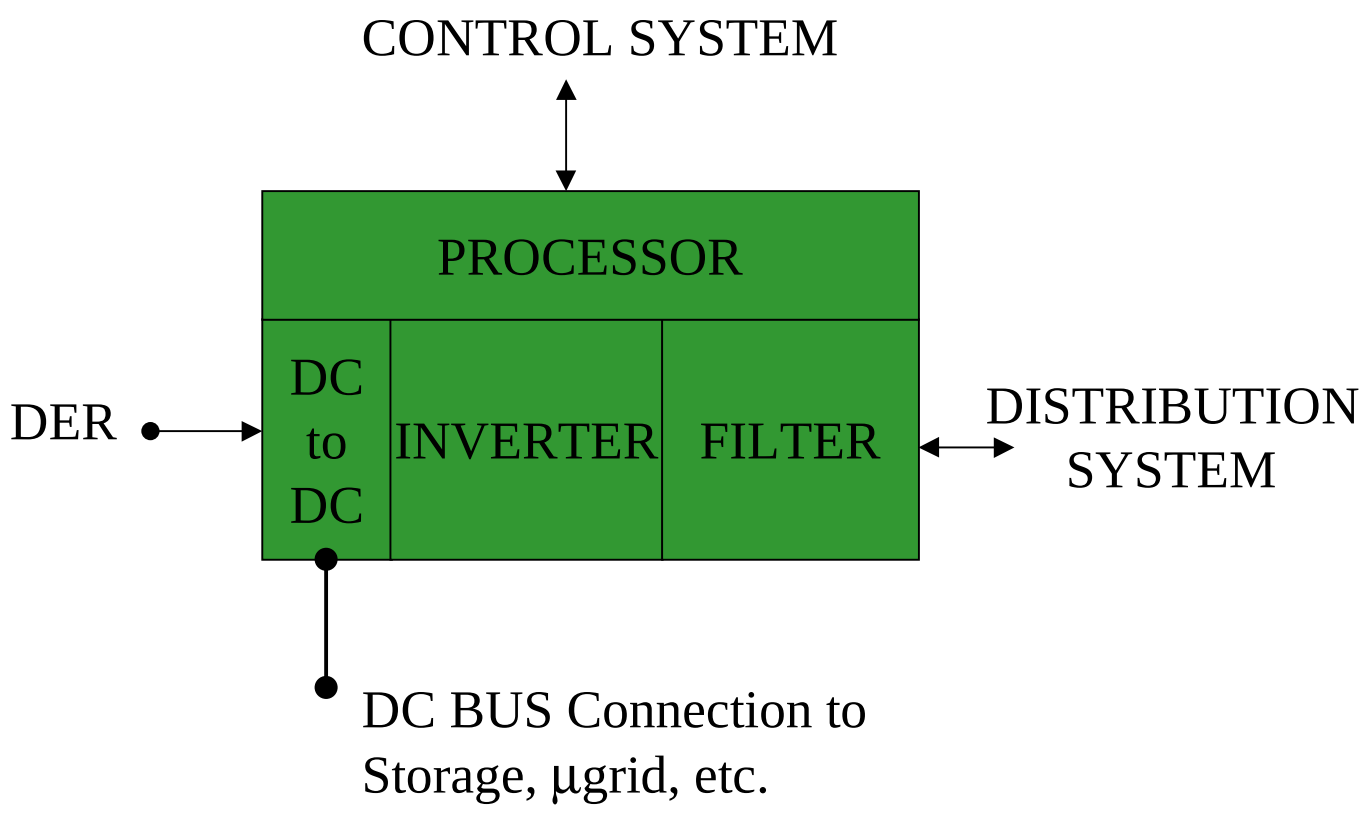
- Typically, power electronics converters contain a dc bus which is connected to an energy storage device, such as a capacitor.
- When the energy storage device is made larger, such as a battery or ultra capacitor, the converter can then ride through voltage sags.
- The power electronics converter can also provide a method for connecting several DERs together with a DC link.

Project Approach - PEBB



PEBB Concept to Provide a Universal Interface


HIERARCHICAL, NESTED CONTROL SYSTEM
DER
POWER ELECTRONICS INTERFACE
DC Bus Connection to Other DER and to Energy Storage
Voltage Regulation
Frequency Regulation
Spinning Reserve
Reactive Power Supply
Local Voltage Sag Support
Local Uninterruptible Power Supply
Local Fault Protection and Coordination
Local Islanding
Local Stability
Power Quality
Peak Shaving
CHP
Participate in Energy Market

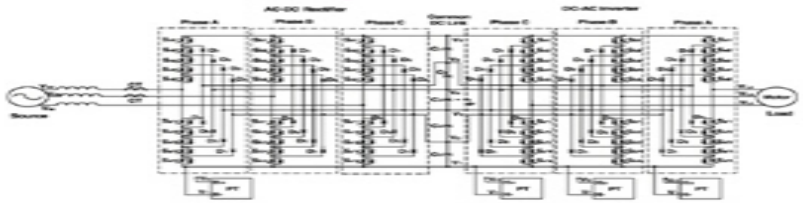

CONTROL SYSTEM
PROCESSOR
DER
DC to DC
INVERTER
FILTER
DISTRIBUTION SYSTEM
DC BUS Connection to Storage, µgrid, etc.

Compact Diode-Clamped Multilevel Converter

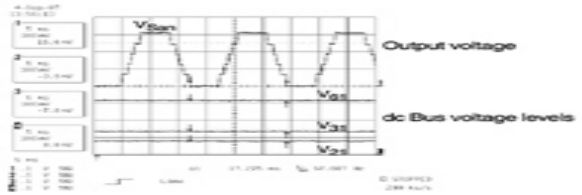
Objective: *To provide a transformerless converter for medium-voltage motor drives and high-voltage power system intertie*

Test Results from the 10-kW Prototype of a Back-to-Back Diode-Clamped Six-Level Converter

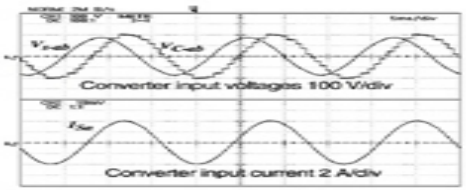
Six-Level Diode-Clamped Back-to-Back Converter



Experimental Converter dc Bus Voltage Levels

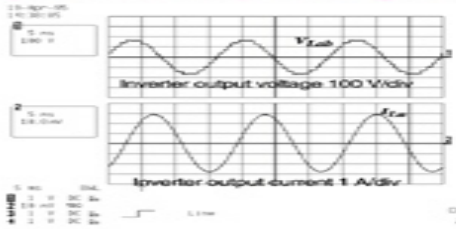


Experimental Input Voltage and Current Waveforms



- Multilevel Rectifer
  - Unity input power factor
  - Distortionless input
- Conventional Rectifier
  - Power factor 0.8
  - Input current THD from 25% to 50%

Experimental Output Voltage and Current Waveforms



- Output voltage has THD of 5%
- dv/dt is 11 times lower than high-frequency PWM drive
- Load current drawn by motor has THD of 1%

Leon Tolbert (front) and Fang Peng (back) apply power to a multilevel-converter-based bidirectional adjustable speed drive for a 50-kW axial gap permanent magnet motor

- ***Technology Importance:***
  - The diode-clamped multilevel converter provides a high-efficiency (99%) and low EMI inverter for motor drives
  - The large reduction in dv/dt significantly hardens motors against bearing failures and insulation breakdown
- ***Technology Use:***
  - Industry
    - High-voltage, high-power motor drive manufacturers
  - Military
    - High-voltage, high-power electric drive for tanks and other land vehicles

Oak Ridge National Laboratory

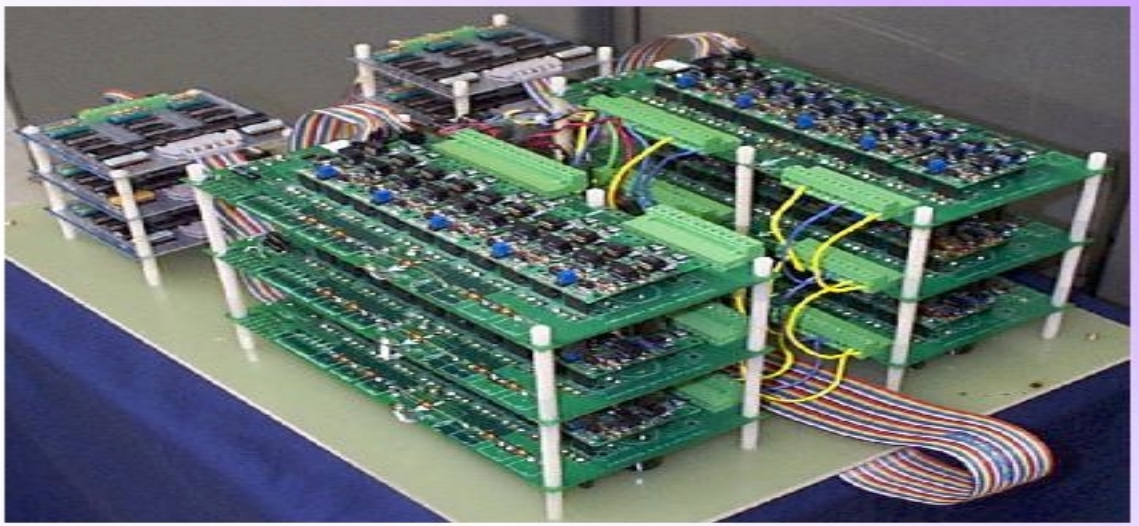
Multilevel Universal Power Conditioner

Objective: Improve the power quality of both the utilities and their customers at the point of common coupling (PCC).

Goal: Develop multilevel PWM strategies for active filtering by a back-to-back diode-clamped multilevel inverter connected in a series-parallel arrangement to the utility.

Technology Uses:

- A multilevel universal power conditioner can improve the quality of the voltage delivered by a utility to the customer and reduce the harmonic and reactive current demanded by customers from the utility.



A prototype 10 kW, back-to-back, six-level, diode-clamped inverter

Project Accomplishments:

- Novel multilevel PWM techniques have been developed to minimizethe number of switchings in multilevel inverters.
- Methods have been identified to balance device usage and increase the effective switching frequency of multilevel inverters operated at low amplitude modulation indices.

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Oak Ridge National Laboratory
Power Electronics &
PEEMRC
Electric Machinery
Research Center
United States Department of Energy

Distributed Energy Resources - Challenges

Integration of DER into the Distribution System

GOAL: Integrate high penetrations of DER into the electric distribution system so that they are a functional part of the system.

2005

2010

2020

Benefits

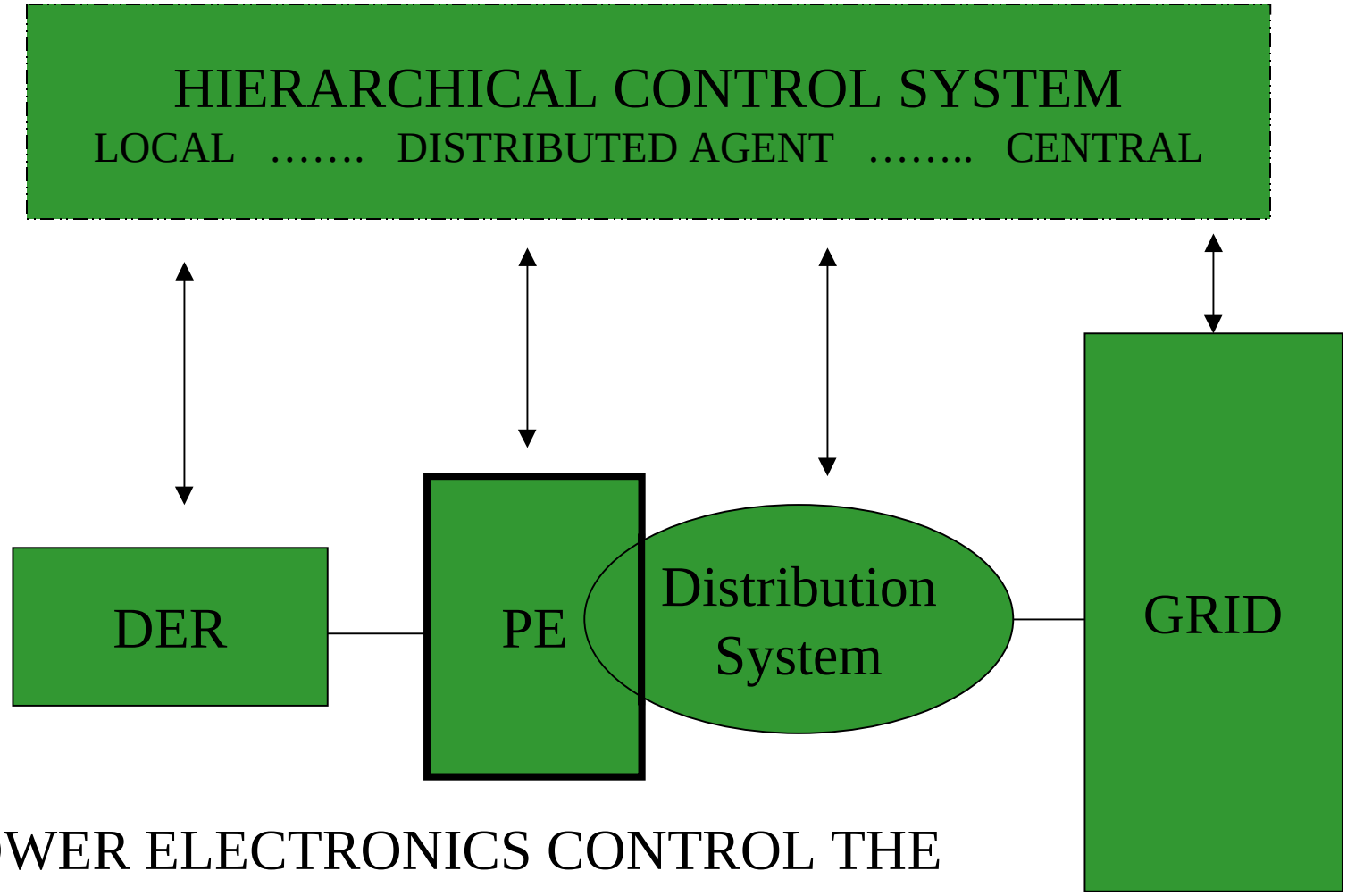
- Economy
- Market Relief
- Power Quality
- Reliability
- Gen. Capacity

Barriers

- Communication
- Sensors
- Power Conditioning
- Architecture
- Interconnection

Advances in Control and Power Electronics Technology Can Enable DER Integration

- Rapid decision making and control will be performed at the distribution level; DER will provide services such as voltage control.
- Distributed control agents will receive "upper level" instructions from the central control authority (ISO) and will advise this authority on local conditions.
- Power electronics will control the power flow from DER to provide exactly what is needed for the distribution system.



POWER ELECTRONICS CONTROL THE POWER FLOW, VOLTAGE REGULATION AND PROVIDE OTHER SERVICES TO THE DISTRIBUTION SYSTEM AND GRID

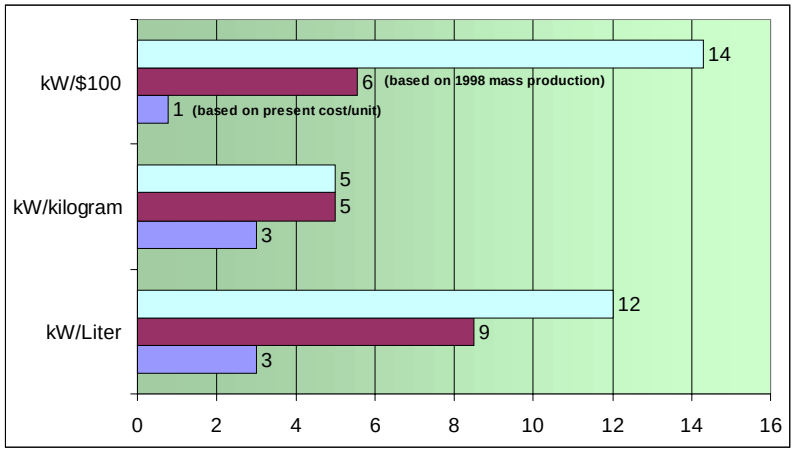
Leveraging Transportation Technology

Similarities

- Modularity, Integration
- High Efficiency
- Low Cost
- Reliability
- Control
- Bi-directional Power Flow
- Electric Machine Interaction
- Energy Storage
- Minimize EMI

Differences

- Voltage/Power Scale
- Utility/System Interaction
- Multifunctional
- Communications



PNGV Size, Cost, Weight Goals

Summary

Electricity Has Two Genuinely Unique Characteristics…

- Consumption and Production must be balanced continuously and instantaneously
  - there is no practical/economic storage
- There is no flow control within the transmission system
  - exceptions are DC lines, phase angle regulators, and back-to-back AC-DC-AC converters, and some FACTS devices

...With Four Natural Consequences

- **Costs (prices) are inherently volatile**
- **System operations and transmission are communal and must be regulated**
- **Current operations are often restricted by preparations for the next unlikely event**
- **Response has value**

It is important to separate inherent characteristics from historical choices & *technology from policy*

It is also important to recognize when technology changes the inherent characteristics

Response Has Value

- In energy markets and in ancillary service (reliability) markets - faster is better, real-time is best
- Decisions must be the customers
  - true for large industrials
  - true for residential customers
- Distributed energy offers great opportunities
  - coupled load and distributed generation are better than either alone
- Aggregation and communications are obstacles
  - the future will be different than the present

Mobile Generators and FACTS Devices May Be More Common In The Future

What Is Technically Required?

- Balance generation & load
  - normal operations
  - contingencies
- Maintain voltages
  - normal operations
  - contingencies
- Don't burn down lines
- Restart the system after you screw up