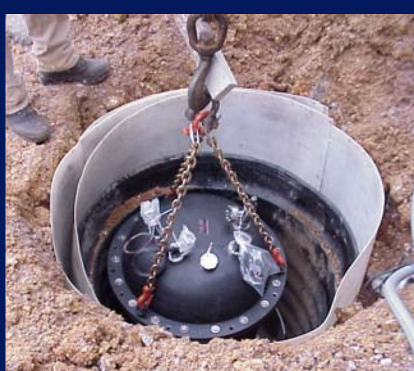


Energy Storage Technologies for Distributed Energy Resources and Other Electric Power Systems

Short Course Sponsored by:
NETL and NRCCE
Morgantown, WV
August 14-15,2003

Presented by:
EPRI PEAC Corporation and
Sandia National Laboratory

Course Outline

I. End-use and Utility-grid Applications
   – Basic concepts, comparison of near-term applications
II. Energy Storage Technology Overview
   – Advantage and disadvantages of technologies use for both short and long-term energy support
III. R&D Activities, Technology, and Cost Considerations
   – Update on current research in DOE, CEC and other programs
IV. Example Cases and Future Technology Applications
   – Performance comparisons, hybrid, and future applications

I. End-use and Utility-grid Applications

Instructor Thomas Key, EPRI PEAC

- Basic Concepts, Power and Energy, Discharge and Recharge Times, Ragone Charts
- Energy Storage Applications for End-use Quality and Reliability, including DER
- Energy Storage Applications for Utility Grid from Generation to Premium Power
- Application Performance Measures

What technical features are most important for electric energy storage?

- <u>**Energy Density or Specific Energy**</u>
- <u>**Power Density**</u>
- <u>**Discharge and Recharge Characteristics**</u>
- <u>**Roundtrip Efficiency**</u>
- Environmental Friendliness
- Self-Discharge Rate
- Maintenance
- Temperature Range
- Design Complexity
- Useful Voltage Range
- Equalization
- Power Electronics
- Life Cycle Cost
- Reliability
- Cycle Life
- State-of-Charge

Energy Density or Specific Energy

Energy density is the amount of energy, on the basis of volume, that can be taken from an energy source, e.g. BTU/cuft or kW-H/liter.

Specific energy also describes available energy but on the basis of weight, e.g. BTU/lb, joules/kg or kW-H/kg.

Example	Range
Electric Car with 500 kg of lead-acid batteries	**150 miles**
Internal Combustion Car with 50 kg of gasoline	**300 miles**

Assuming the vehicles have equal weights, follow the same course, and ignoring conversion efficiencies…. The gasoline driven car has 20 times higher specific energy than the electric car.

Power Density or Specific Power

Power density is the rate that energy, on the basis of volume, that can be taken from an energy source, e.g. watts/liter. ***Specific power*** also describes the rate of available energy but on the basis of weight, e.g. watts/kg, HP/lb

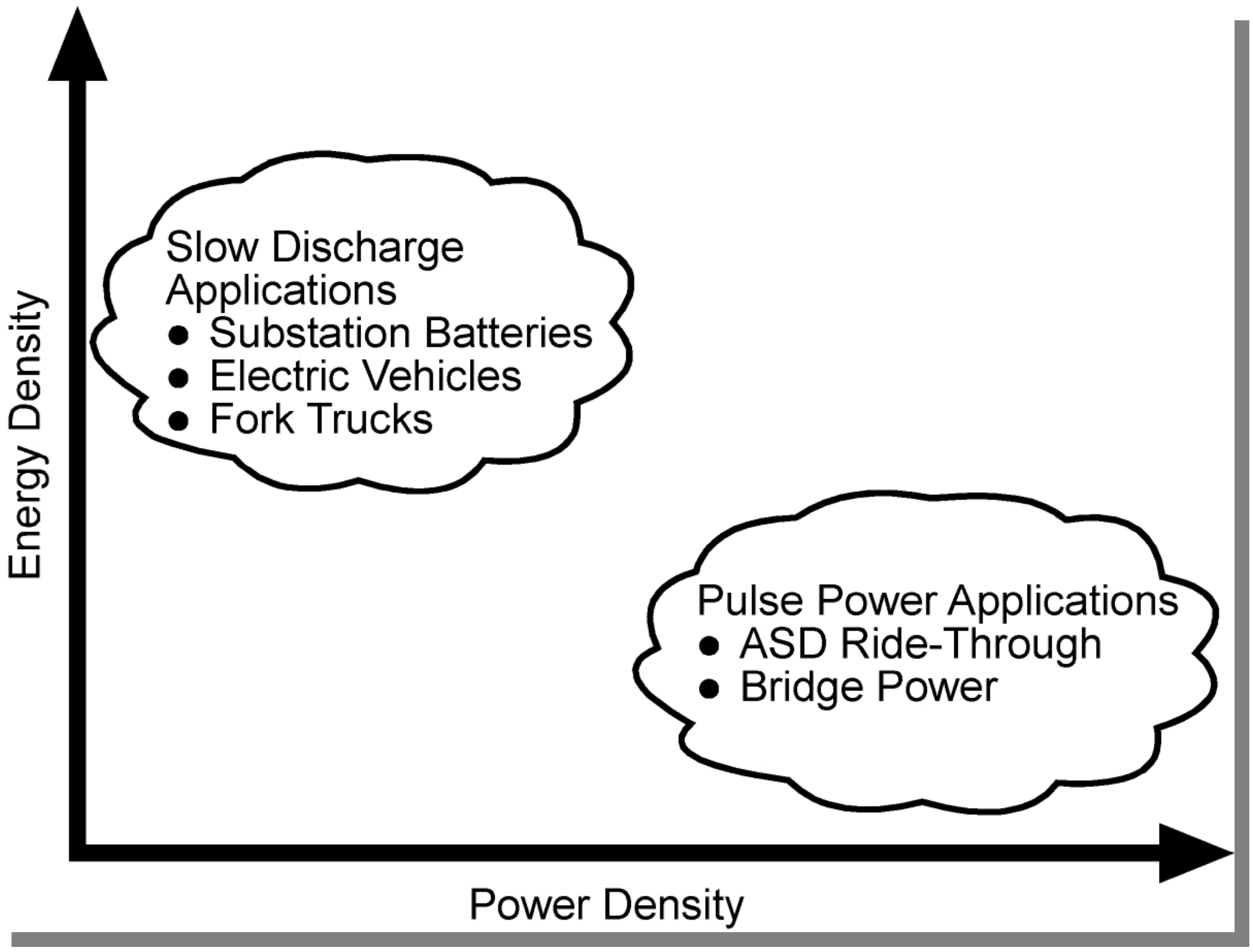
Example	Top Speed (mph)
Race Car with 4.3 L V6 engine	**180 @ 230 HP**
Passenger Car 4.3 L V6 engine	**90 @ 100 HP**

Assuming both engines weigh the same, the race car engine can deliver more horse power and thus has higher power density without regard to fuel type or efficiency.

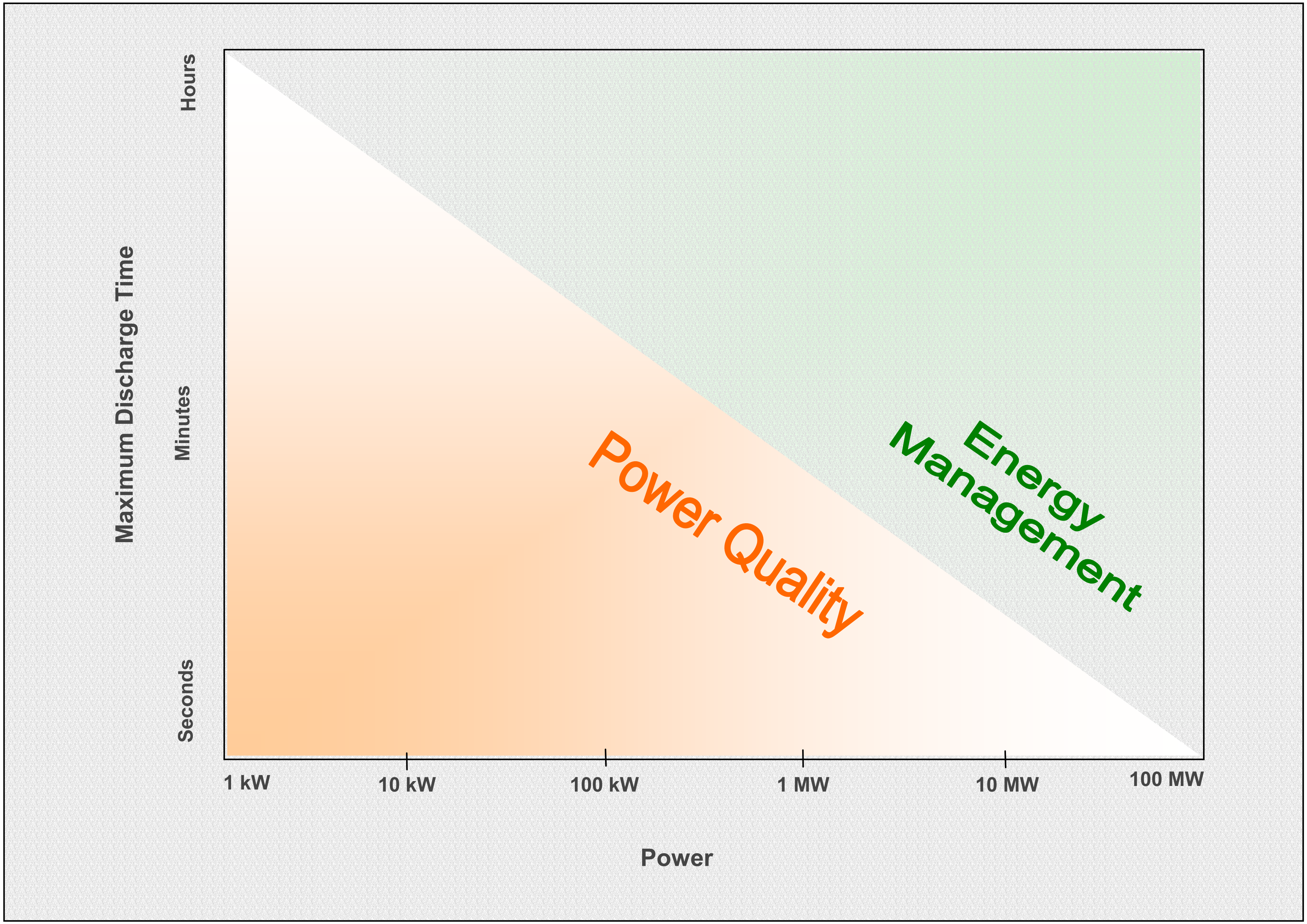
Power and Energy Attributes of Storage Technologies

Energy-Storage Technologies	*Energy Density (Whr/kg)*	*Power Density (W/kg)*	*Commercial Availability*
Battery Technology			
Lead Acid	35	300	Very mature/readily available
Nickel Cadmium	35	200	Mature and available
Lithium-Ion	75	180	Available
Nickel Hydride	50	200	Available
Sodium Chloride	90	150	Available
Sodium Sulfur	110	260	Available
Zinc Bromine	70	75	Available
Zinc-Air	375	175	Emerging
Ultracapacitors			
Asymmetrical	1-12	10-15,000	Available
Symmetrical	1	10-2,000	Available
Advanced Flywheels	10-100	1,000-10,000	Available
SMES	50	300-1,000	Available

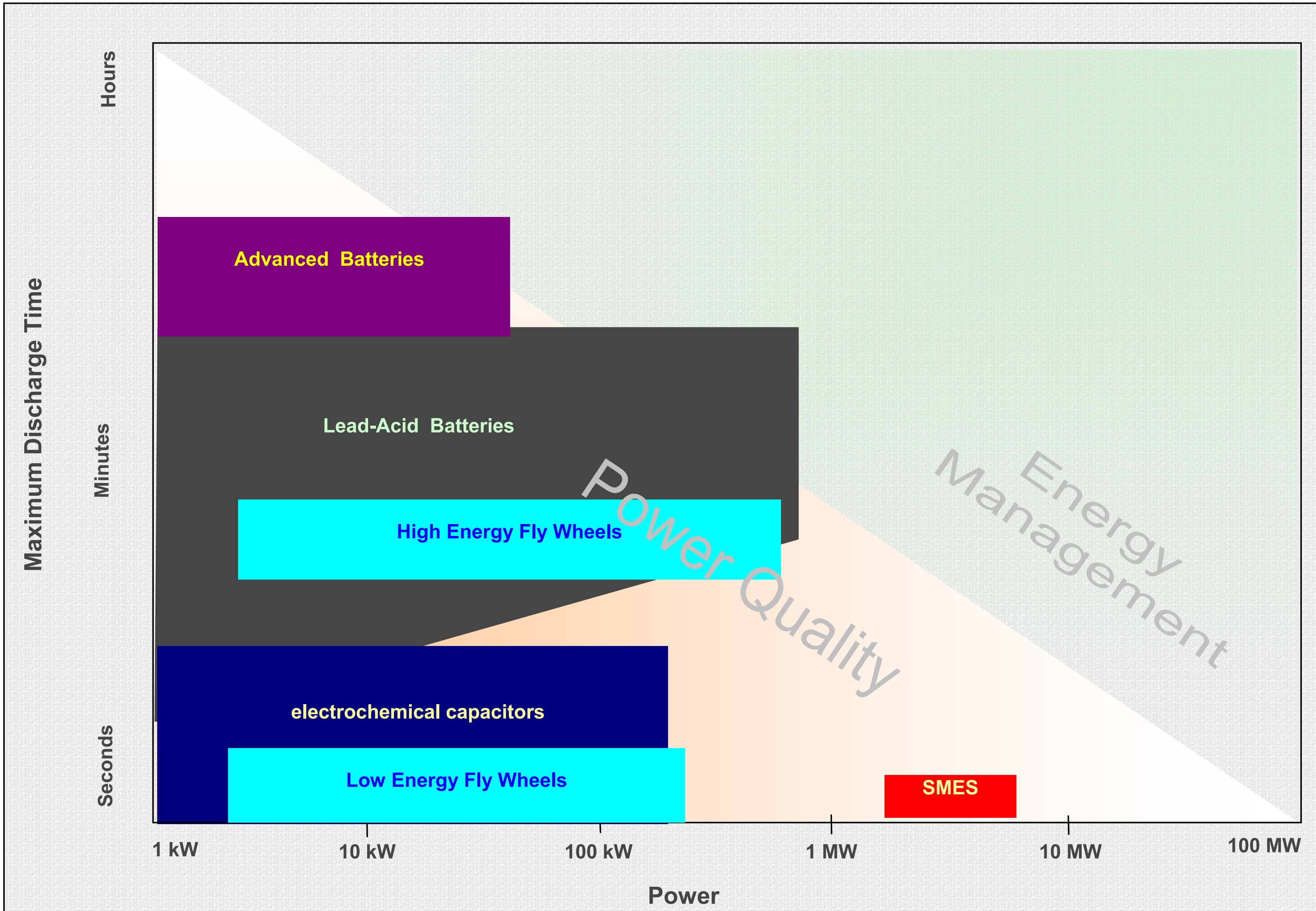
Need for Energy and Power Varies Significantly Among Storage Applications



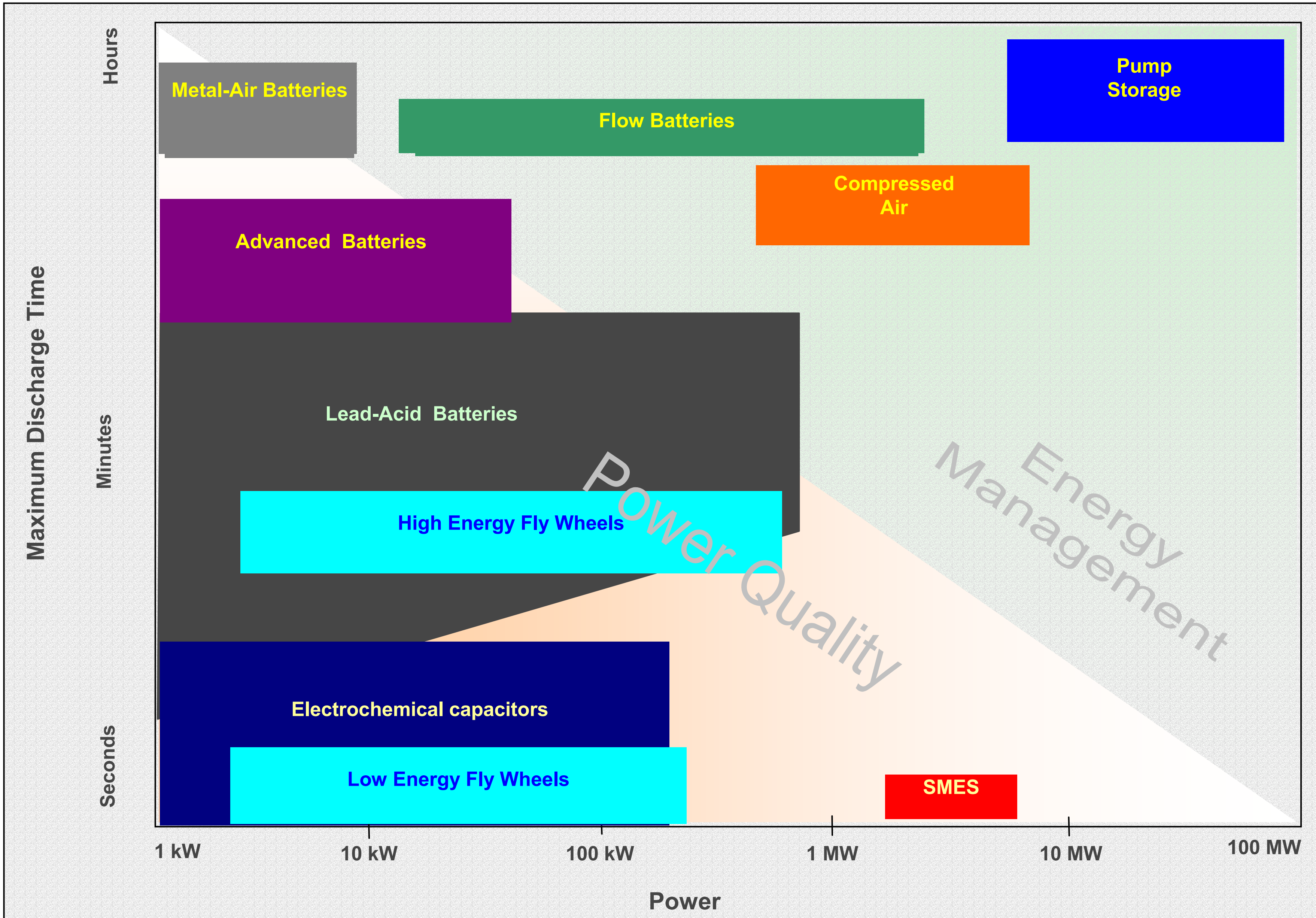
Discharge Time and Power Rating



Technologies for Power Quality Applications



Technologies for Longer Term Applications



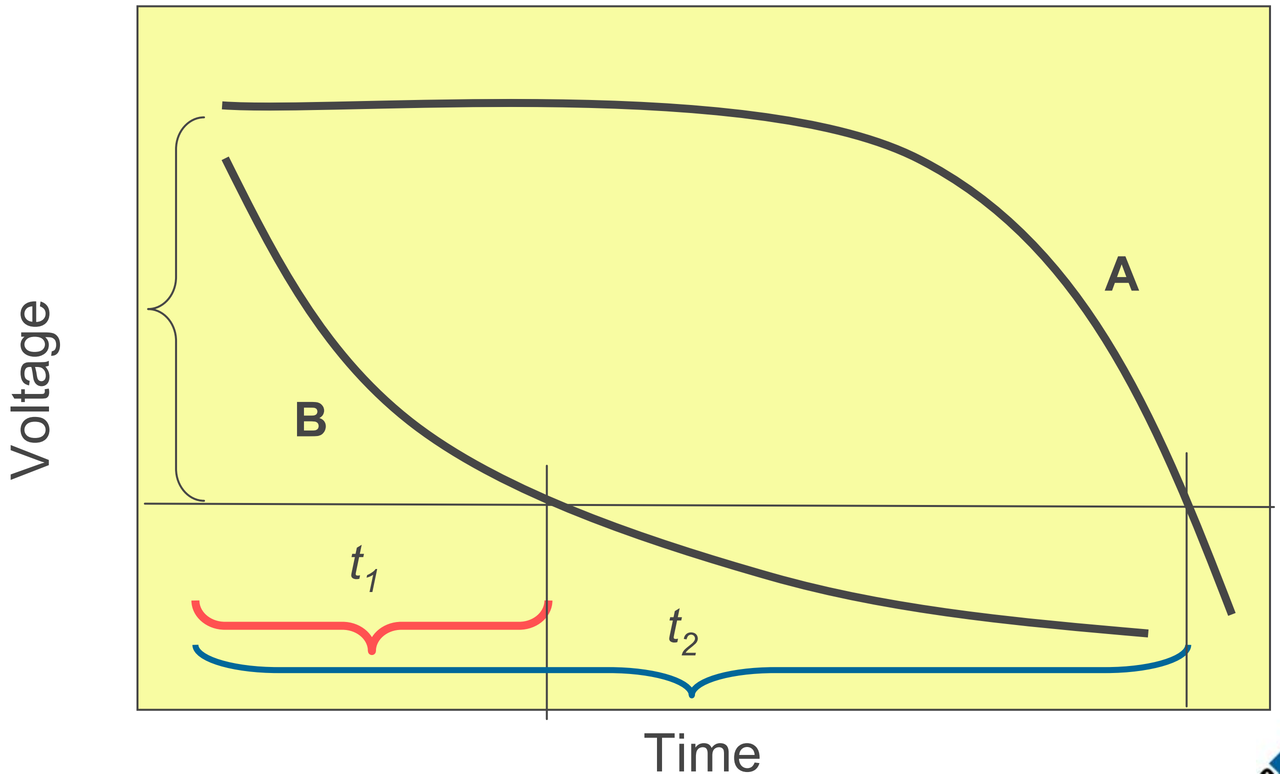
Discharge Characteristics

Discharge time depends on the power or load level and is the amount of time energy can be delivered within an allowable voltage operating window.

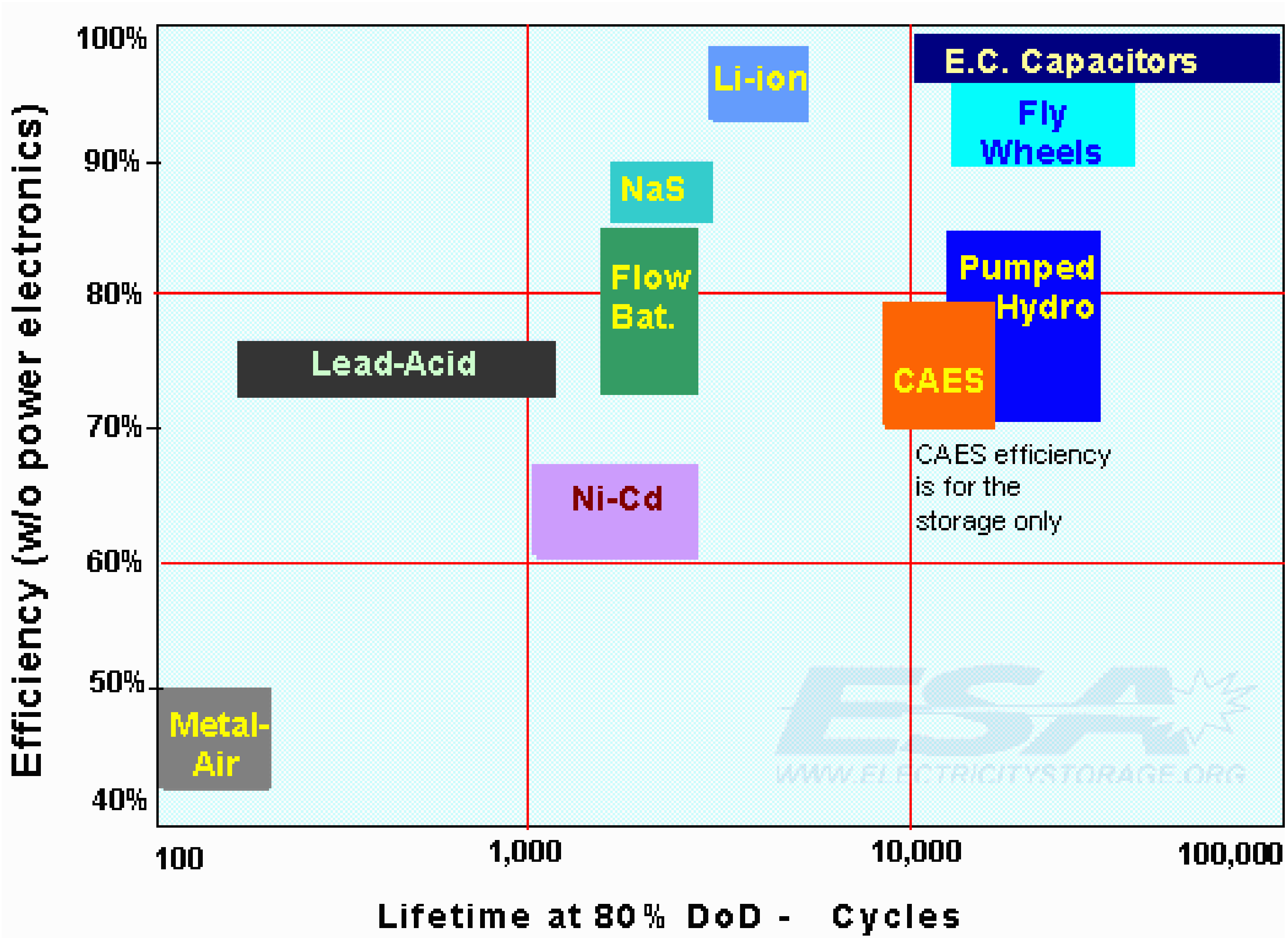
Characteristic depends on technology and loading, e.g.

A – relatively light constant power load on a battery

B – relatively heavy resistive load on a capacitor



Storage Technology RT Efficiency and Cycle Life Comparison (from ESA)

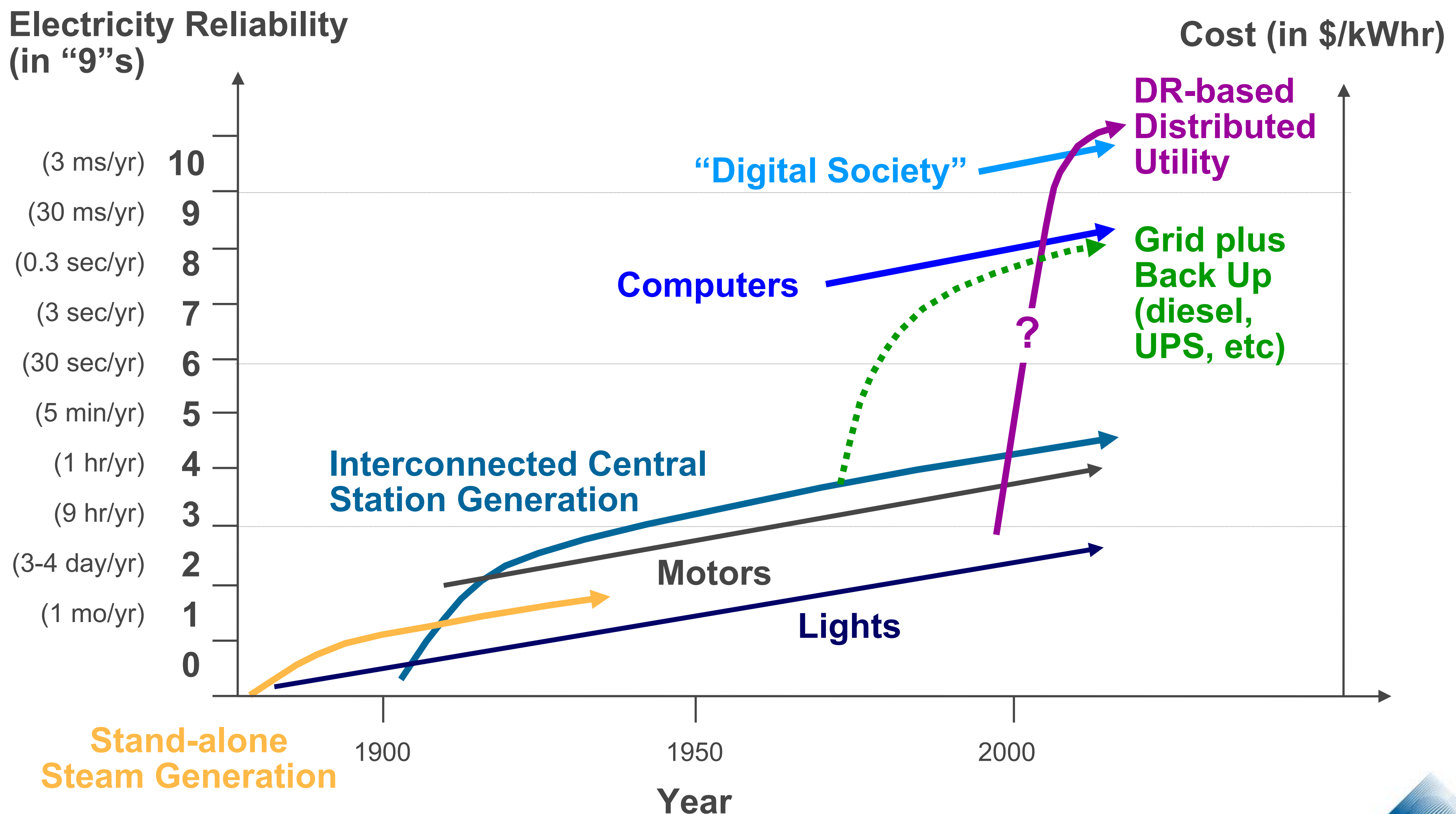


Energy Storage Application:
for Electrical Reliability and Quality

Today a vital part of many industries:

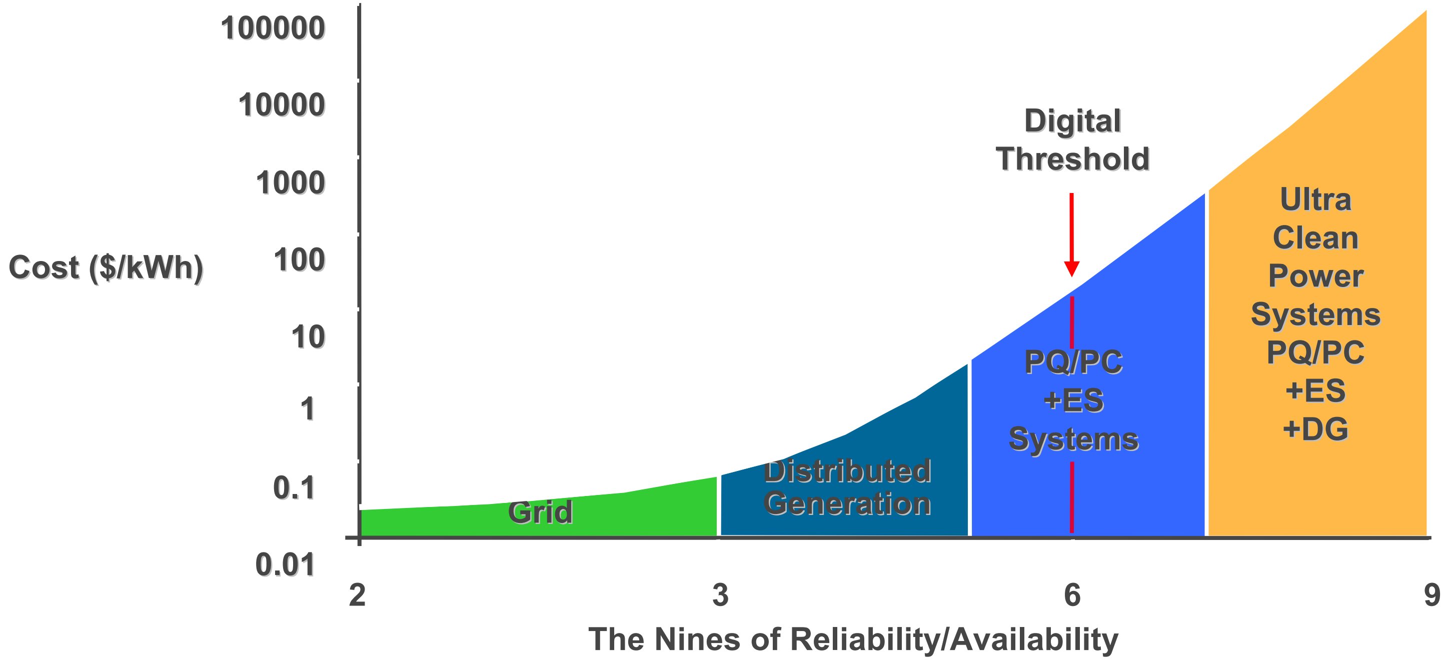
- Transportation
- Communications
- Healthcare
- Commercial
- Industrial
- Home office

Need for Electricity Reliability and Evolution of Technology

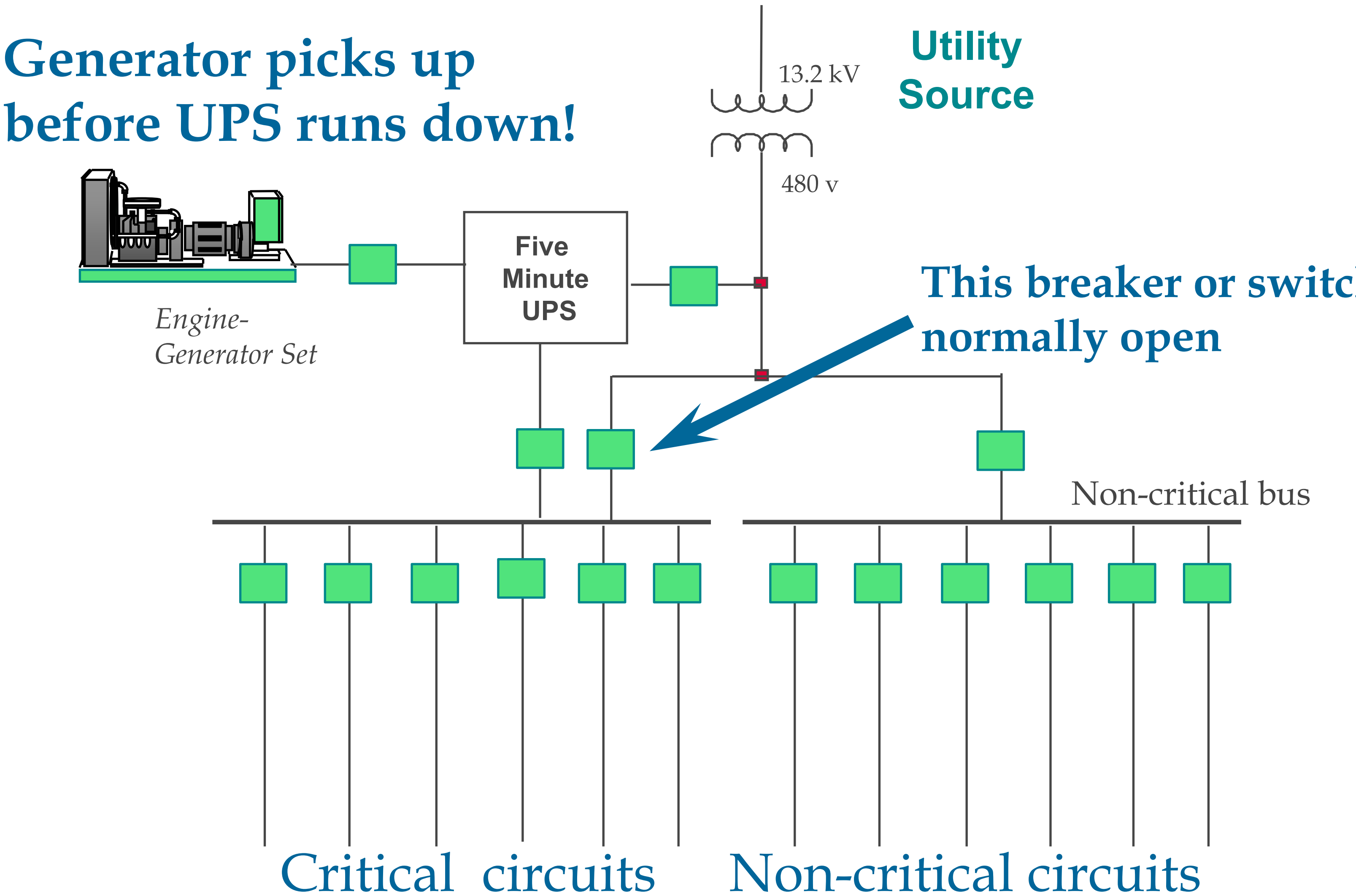


Increased Availability Measured by Number of "Nines" and Associated Cost

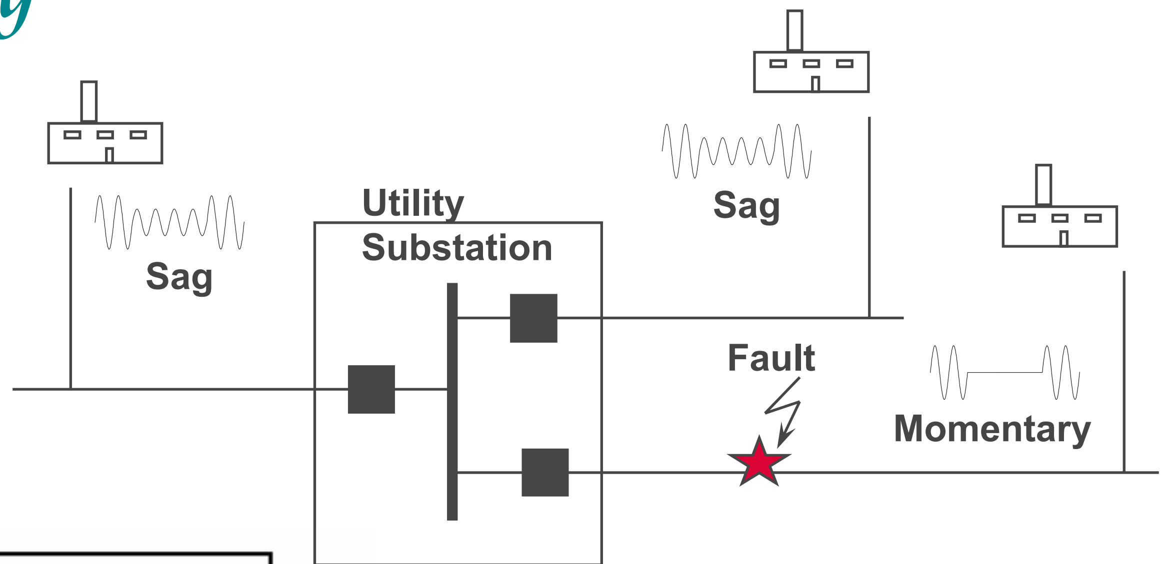
% of Time Power Available	99.9%	99.99%	99.9999%
No. of 9's Available:	3	4 to 5	6 to 9
Power Disruptions per Year (time)	8.8 hours	53 – 5.3 min	31 – 0.03 sec.
Generally Acceptable for:	Homes	Hospitals, Airports	E-Businesses, ISEs

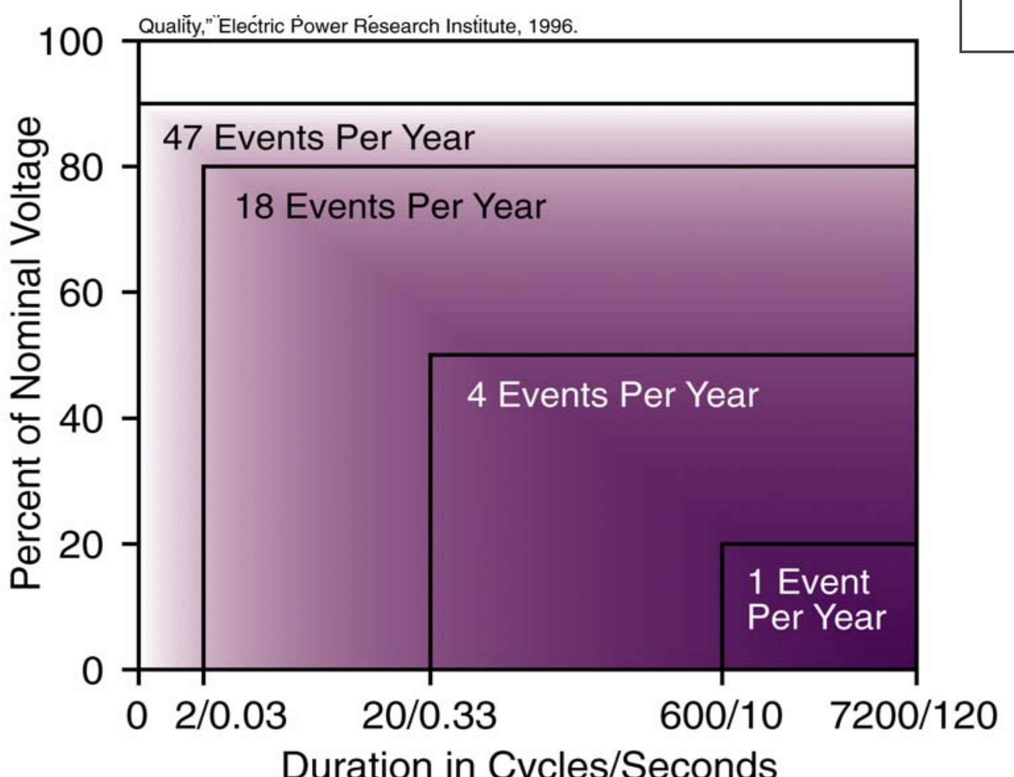


Conventional Solution: Back-Up Generator / UPS



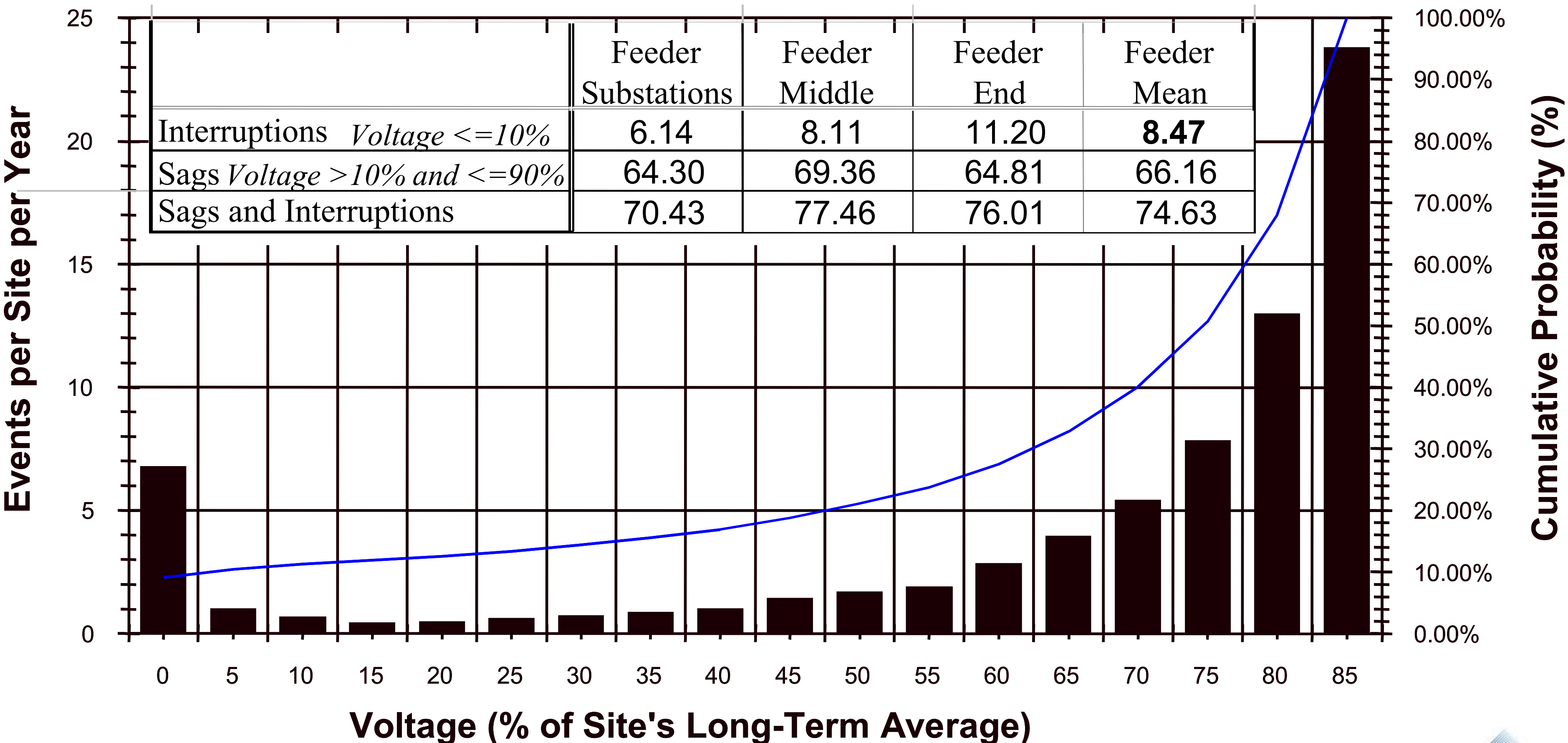
Know Thy Enemy ... it is "Momentary Events"





EPRI distribution power quality study and many other monitoring campaigns around the world have been consistent about ubiquitous sags and dips.

Voltage Monitoring Data shows Typical Interruption and Sag Rates

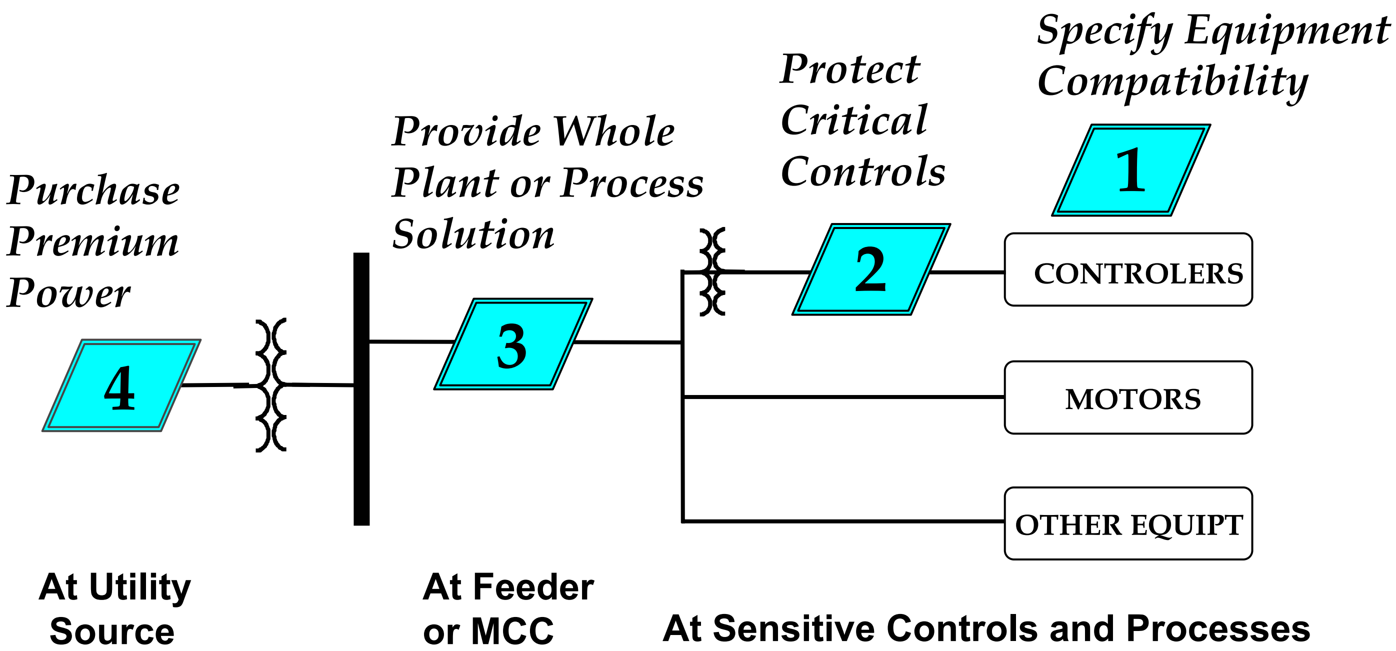


	Feeder Substations	Feeder Middle	Feeder End	Feeder Mean
Interruptions *Voltage <=10%*	6.14	8.11	11.20	**8.47**
Sags *Voltage >10% and <=90%*	64.30	69.36	64.81	66.16
Sags and Interruptions	70.43	77.46	76.01	74.63

Different Quality and Reliability Solution Strategies

Increasing knowledge about specific equipment protection requirements →

← Increasing cost to condition and less variability in conditioning needs



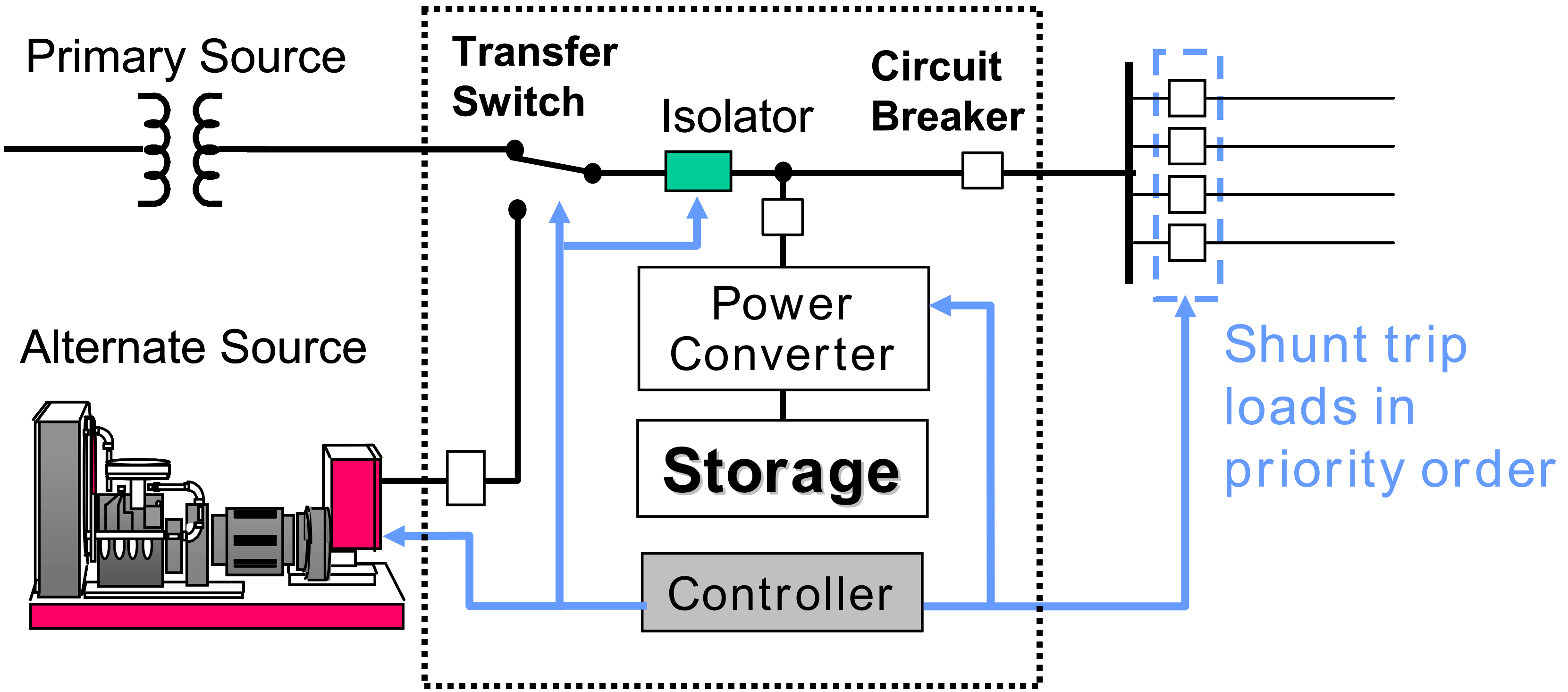
Energy Storage Applications Related to Power System Quality or Reliability

1. **Bridging Power/UPS – 10 to 30 seconds**
   - Provides continuous real and reactive, regulated, and conditioned power support during a switching transition from one power source to another.
   - Commercial products: S&C, Cat UPS, Piller, Hitec, Urenco, others
2. **Stabilizing Voltage – Cycles to seconds**
   - Provides real and reactive, and conditioned, power support are provided to supplement a primary or distributed power system.
   - Commercial products: Active Power, ASC, others
3. **Replace Missing Voltage (& Inrush) – Cycles**
   - Solves the problem where power system overloads or fault conditions cause the delivered voltage to be momentarily low, sometimes reduced to zero, during clearing and power delivery system restoration.
   - Commercial products: S&C DVR, Soft Switching Dysc, ASC, others.

Short-term Storage Technology Options

- Batteries
- Flywheel
- EC Capacitors
- SMES

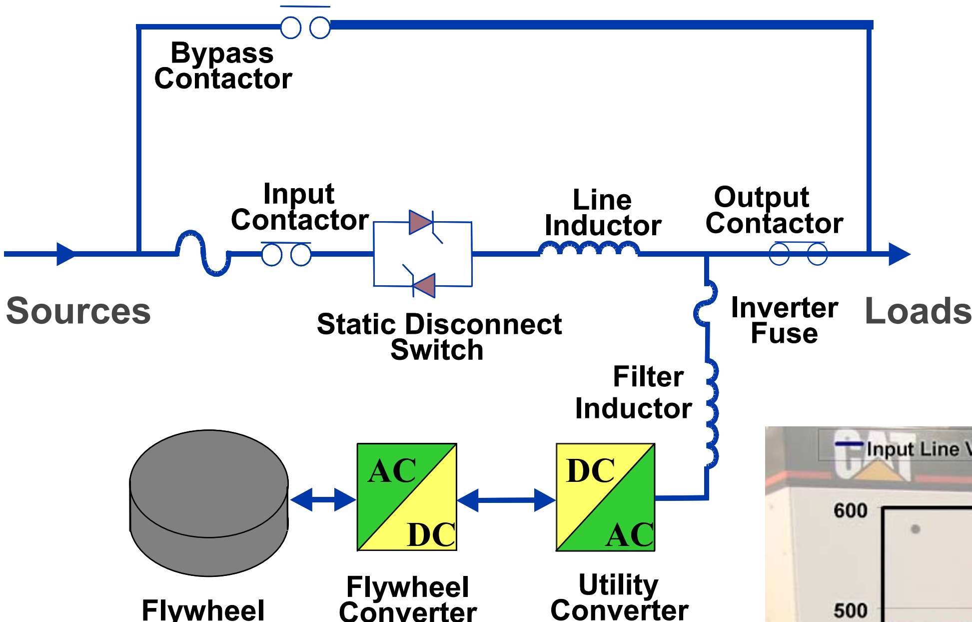
Energy Storage Application # 1: AC Bridge Power/UPS



Basic Functions

- rapid isolation, energy recovery from on-board storage
- conversion of stored energy, synchronization, paralleling, and soft transfer to alternate

Commercial Bridging Power Product with medium speed flywheel



- •Bridging Power System
- •Cat UPS High-speed Flywheel
- •12 sec at 250 kW
- •150 sec recharge)

Full load test for 10 seconds

Commercial Bridging Power Product with Plug-in Lead-Acid Battery

- 313 kVA, 480 V, 3-phase
- Grid- Interactive
- Standby UPS (very low loss)

- **30-second lead-acid cranking battery**

Cranking Battery for Bridging Power

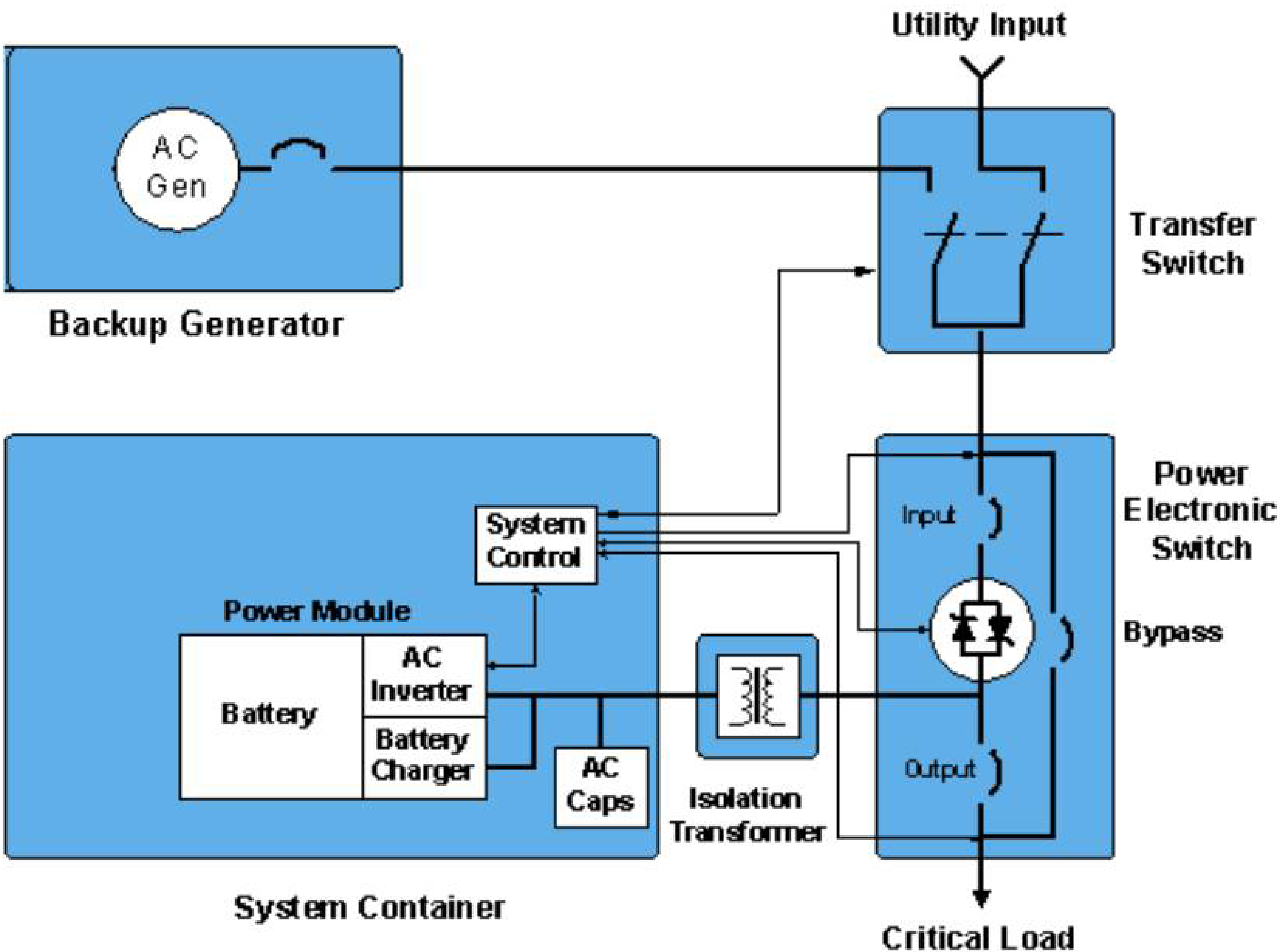
- **Standard truck battery**
- **CCA 625 (min 7.2Vdc)**
- **Reserve Capacity 180 minutes at 26° C**
- **Energy Rating 75 Amp-Hours (min 10.5Vdc)**
- **Cost around $115**
- **$136.90/kW-H @ 180 min**

Specific Energy

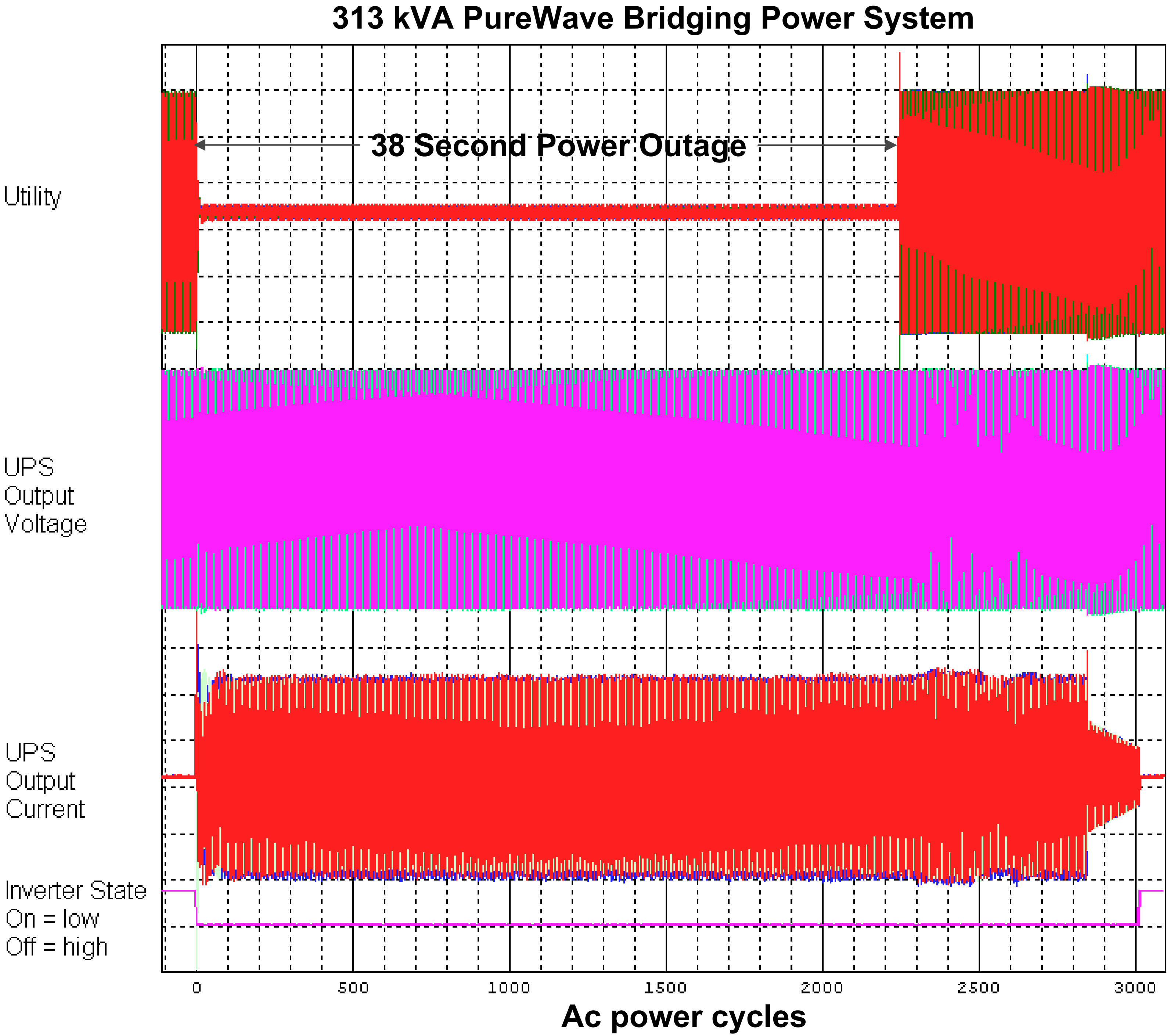
W = 11.2Vave x 25A
= 280W
W-H = 280 x 3 = 840
W-H/kg = 840/27 = 31

Specification	Delco 1150 Battery
Voltage	12.0 Vdc nominal
Size	13" L x 6.8" W x 9.5" H (0.33 m x 0.17 m x 0.24 m)
Weight	60 lbs. (est.) (27 kg)

Operating one-line in UPS Configuration



Ride-Thru Test Results



100-kVA AC Bridge Power/UPS Application

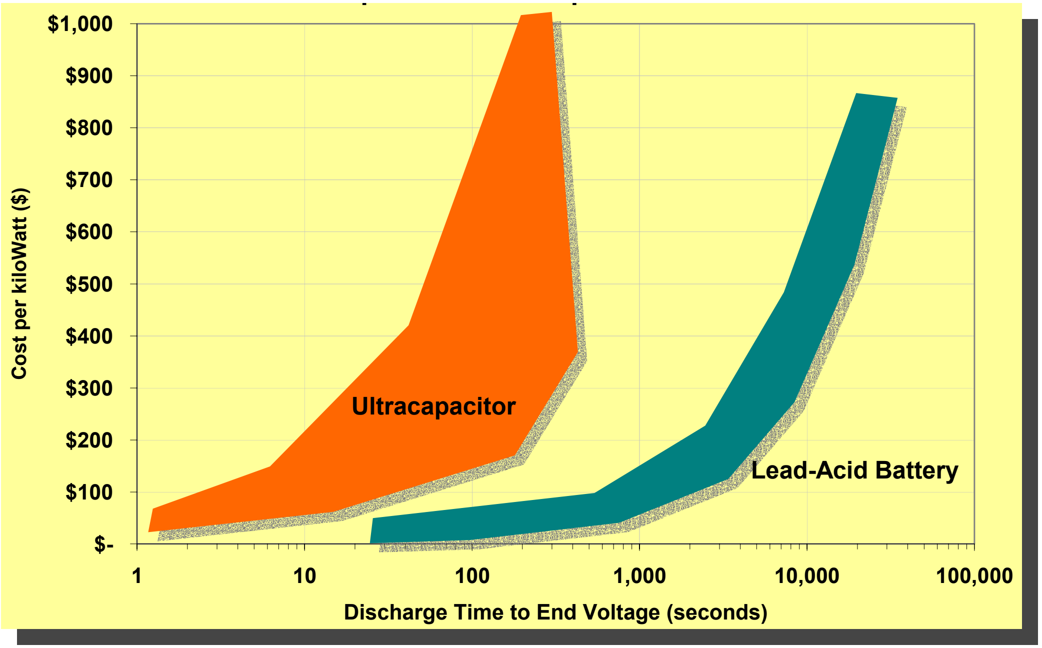
Battery-less UPS

- **Modified commercial UPS designed with capacitors in place of batteries to allow fast charging and longer life.**
- **9, 42V ESMA 30EC402 pulse-type electrochemical capacitor with dc to dc converter, 15-sec discharge at 100 kW, .42 kW-H**
- **In addition to backup power, the system provides voltage support on the output line through active power line conditioning.**

Comparison between Delco Battery and ESMA Electrochemical Capacitor

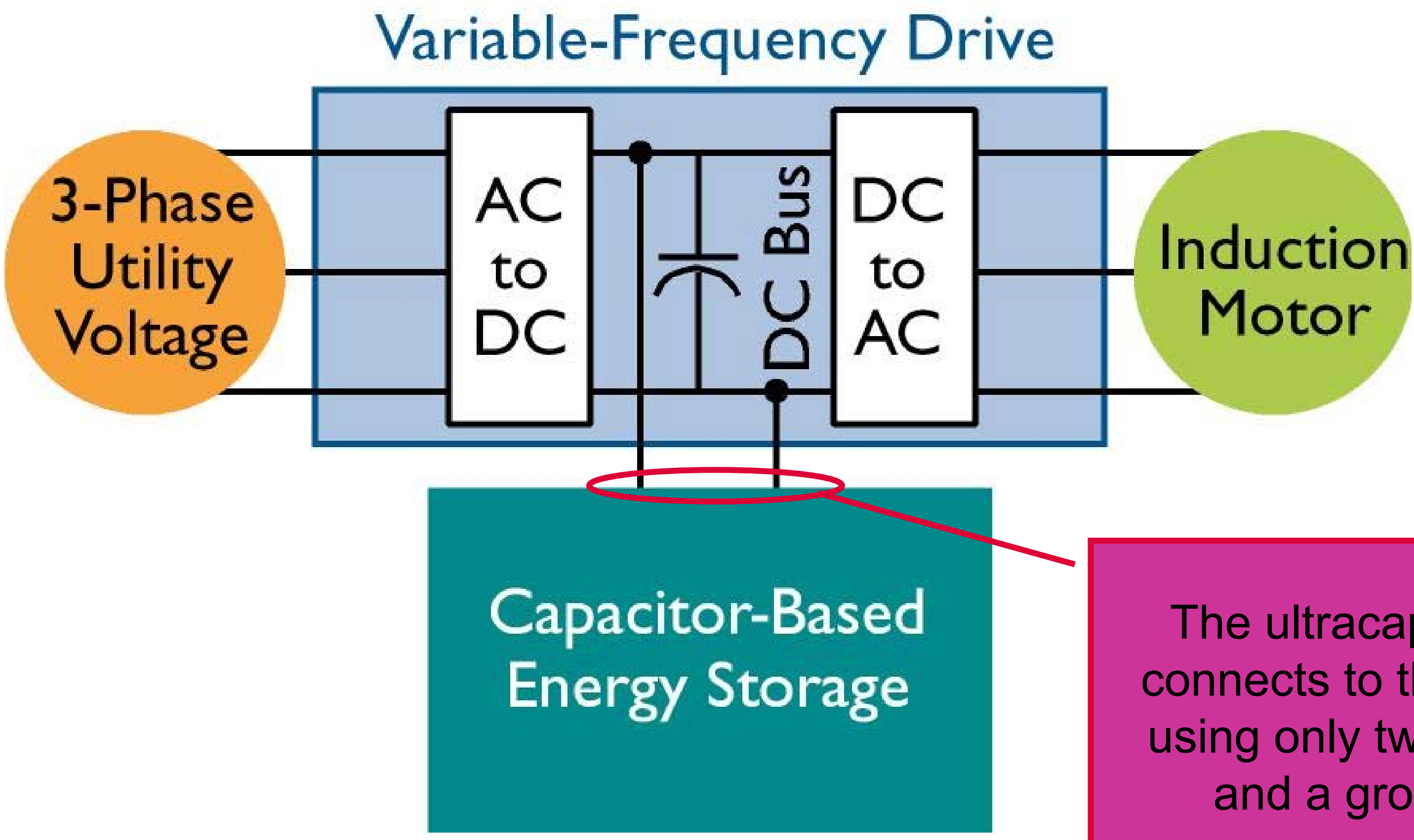
- 48, 12V Delco 1150 cranking type lead acid batteries at 576 V 30-sec at 250kW, 2.08 kW-H
- 14, 42V ESMA 30EC402 pulse type electrochemical capacitor at 588V, 3-sec discharge at 250 kW, .2 kW-H
- Energy needed .1 to 1 kW-H

- Size Comparison



- Cost Comparison

Energy Storage Application # 2:
DC Bridge Power for Variable Frequency Drive



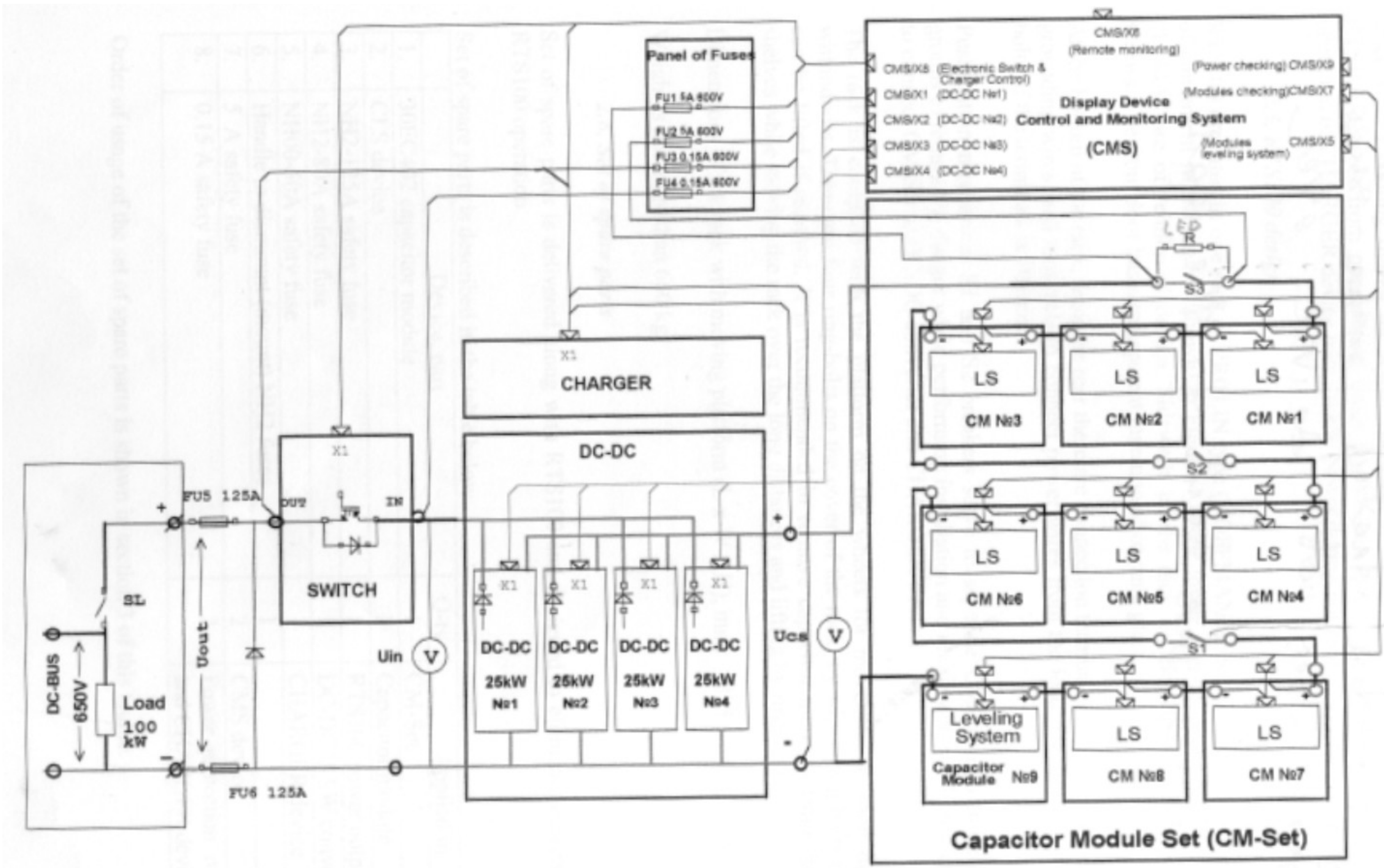
The ultracapacitor connects to the drive using only two wires and a ground.

Battery-Less DC Backup Source for 100-HP Process Control Drive

- Used for industrial process applications with adjustable speed control (ASD or VFD)
- Capacitor System, 9-42Vdc, 220 F Modules operate from 42-21 Vdc
- Energy delivered ~2MJ, 133kW for 15-seconds, from dc to dc converters at 600 Vdc

RTS 100 System

Detailed Schematic RTS 100 Ride thru System



Pre-installation Photo at Semi Plant VFD Location

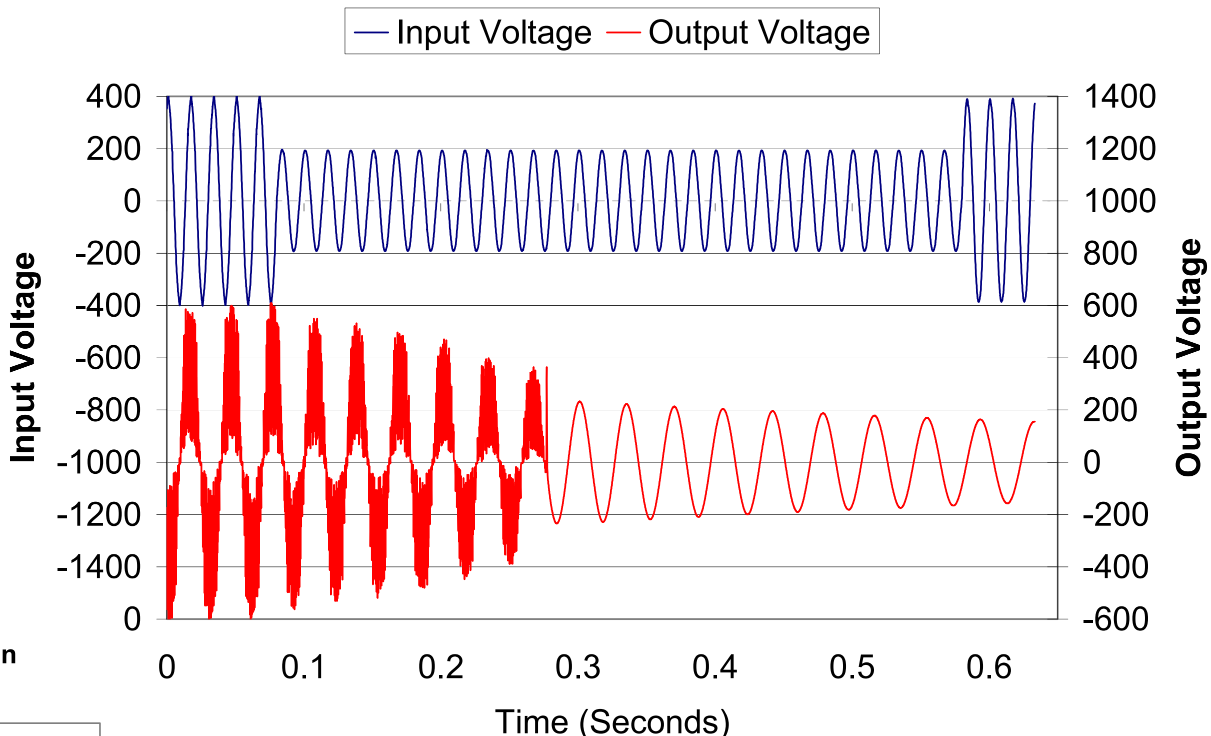
Chilled water pump

VFD for process chilled water pump

RTS 100 Capacitor Cabinet to be installed here

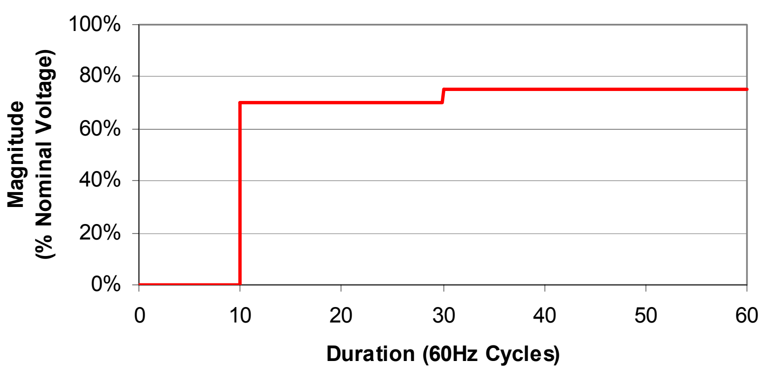
Test Results – Voltage Sag affect on VFD and Pump Without Energy Storage

Without RTS

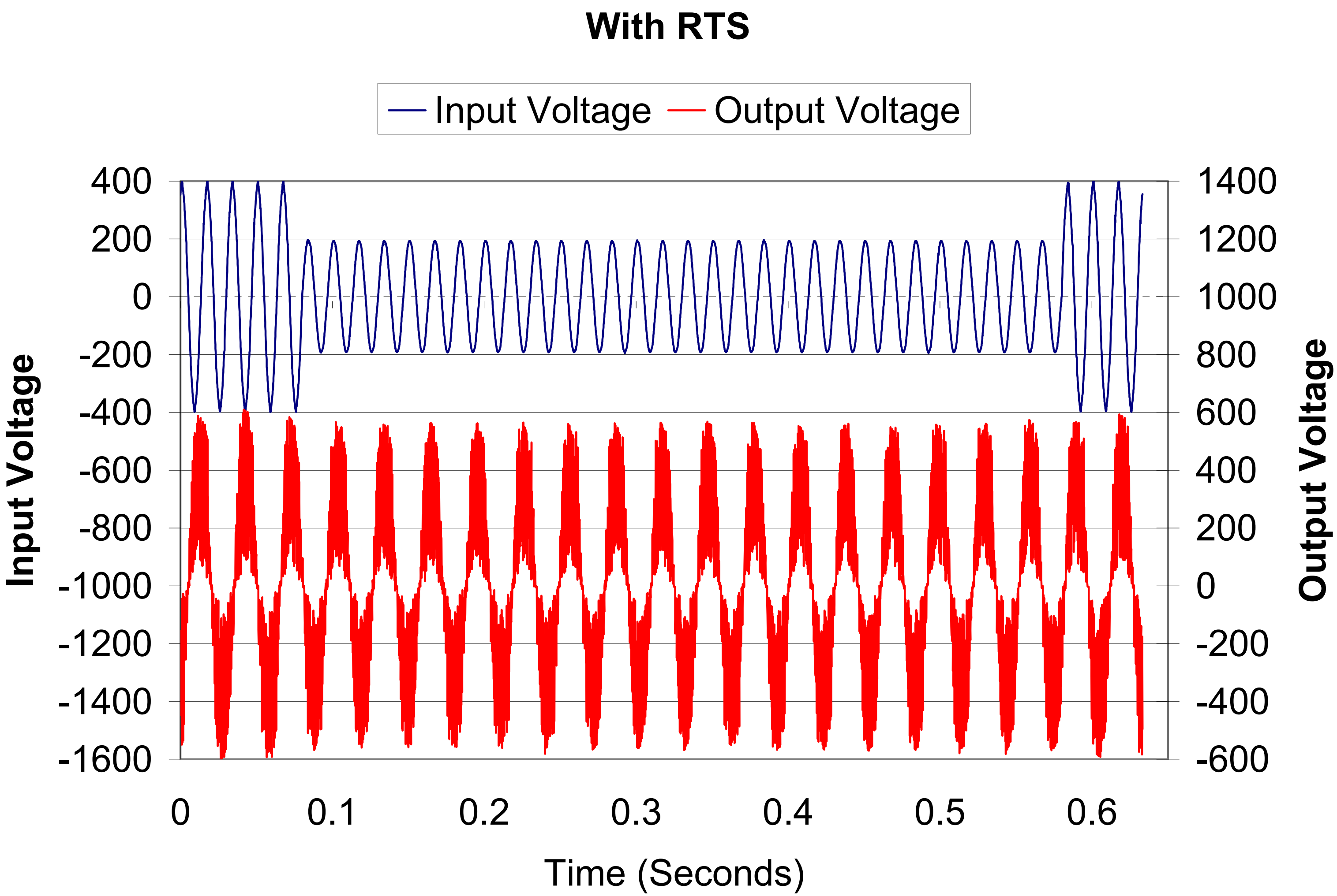


Voltage vs Time "Trip Curve" VFD trips if voltage is below the line

Ride-Through Curve for the Intel VFD at Approximately 20% Load - without Protection

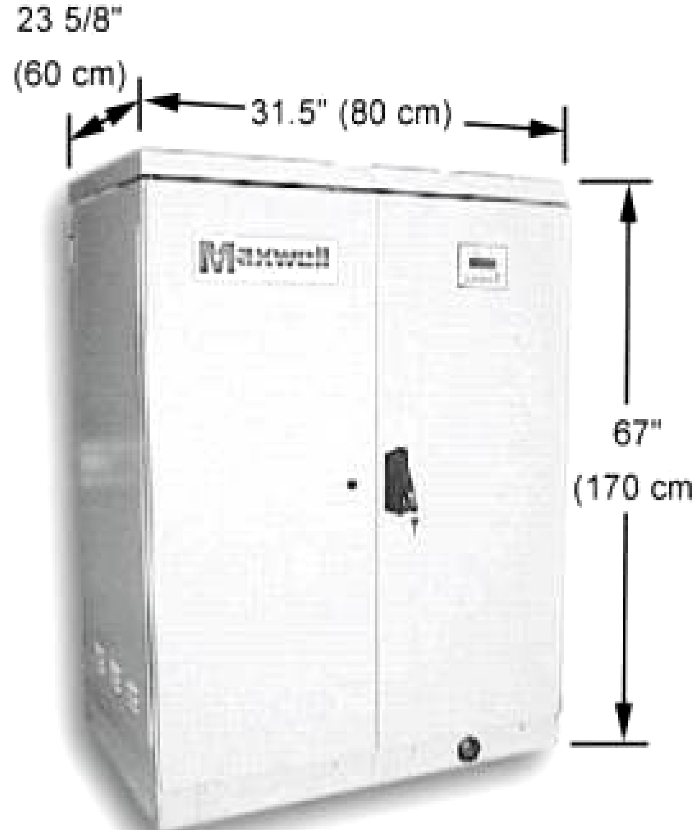


Test Results – Voltage Sag affect on VFD and Pump With Energy Storage Protection



Another Battery-less DC Backup Using Electro-Chemical Capacitors

- **100-kW energy storage system using Maxwell Technologies capacitors was installed at a water treatment facility in Ft. Wayne, Indiana**
- **Objection was to prevent 100-HP pump shutdowns for events up to 10 seconds duration at full load**

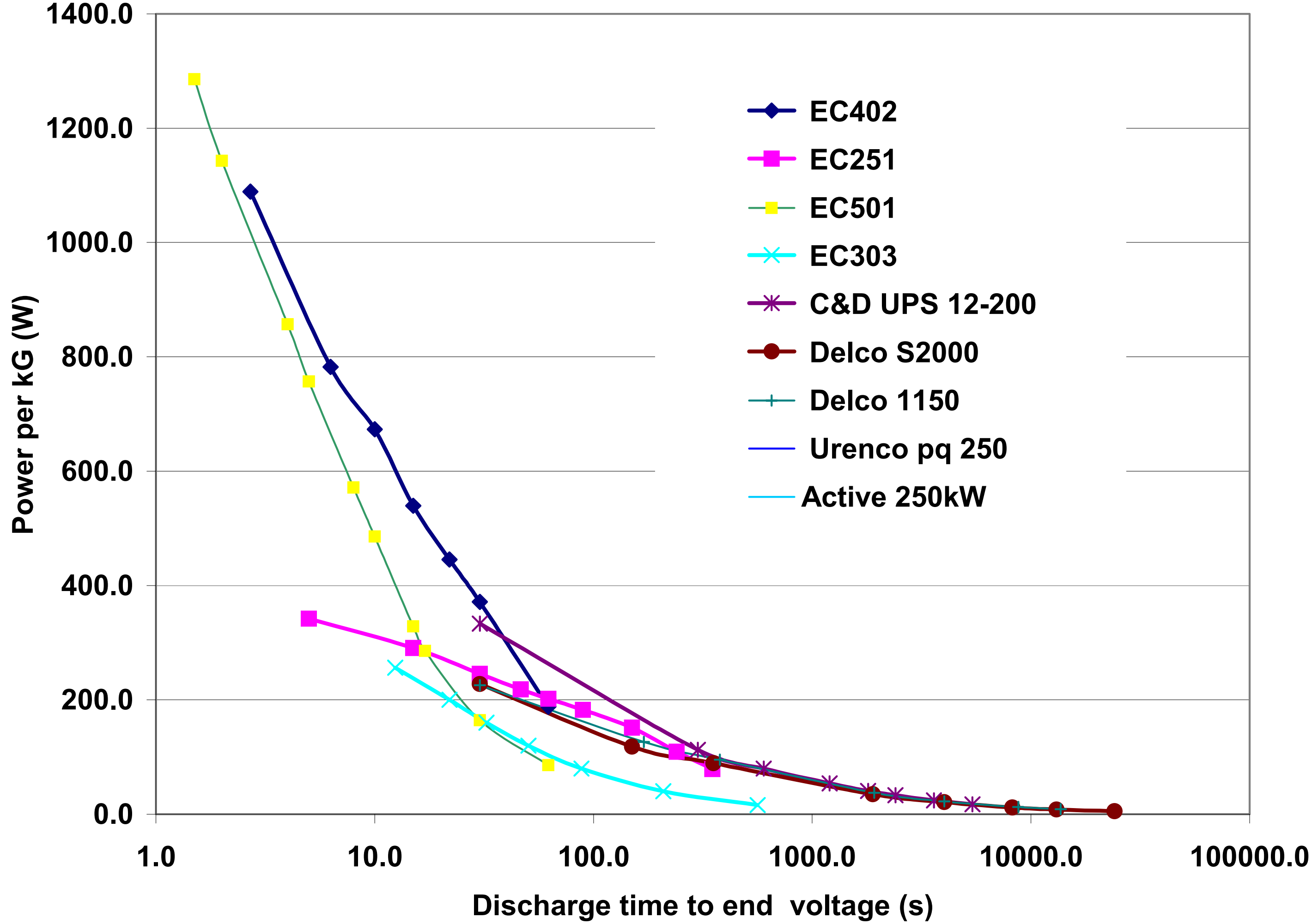


Output Power: 0 - 100 kW
(0 - 135 HP)
Weight: 1200 lb (550 kg)
Output Voltage: 455 to 615 VDC

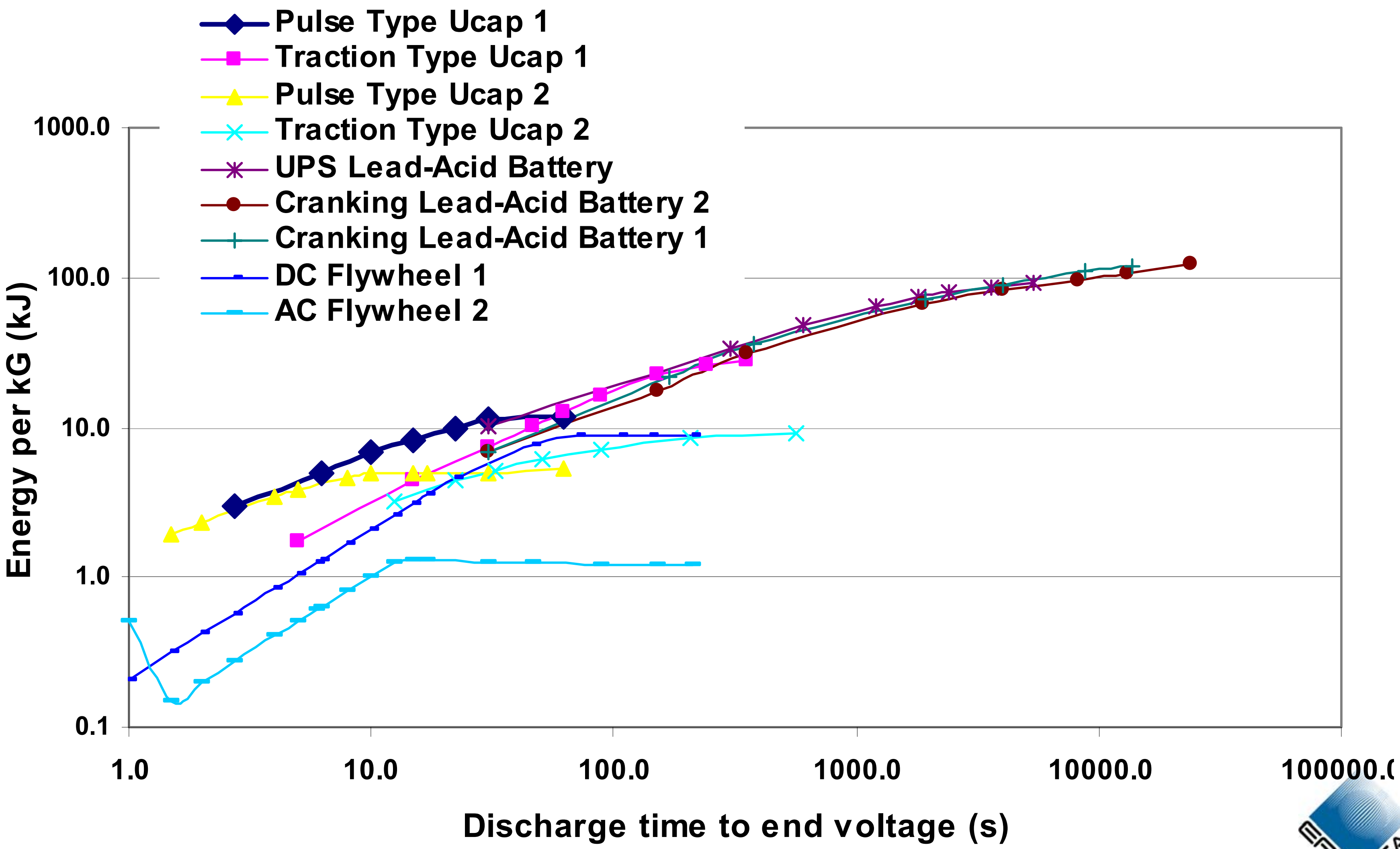
Another Battery-less DC Backup Using High-speed Flywheel

- Urenco 100-kW flywheel energy storage system
  - Composite rotor spinning at up to 30,000 RPM
  - Delivers 100kW for up to 30 seconds
- System was tested with a 3-phase 460V, 200hp AC drive to assess the capability of the flywheel to protect the drive from momentary interruptions in power.

Comparison of Watts per kG for Lead acid, U-caps, and Flywheel



Comparison of Energy per kG in Short- term Storage options

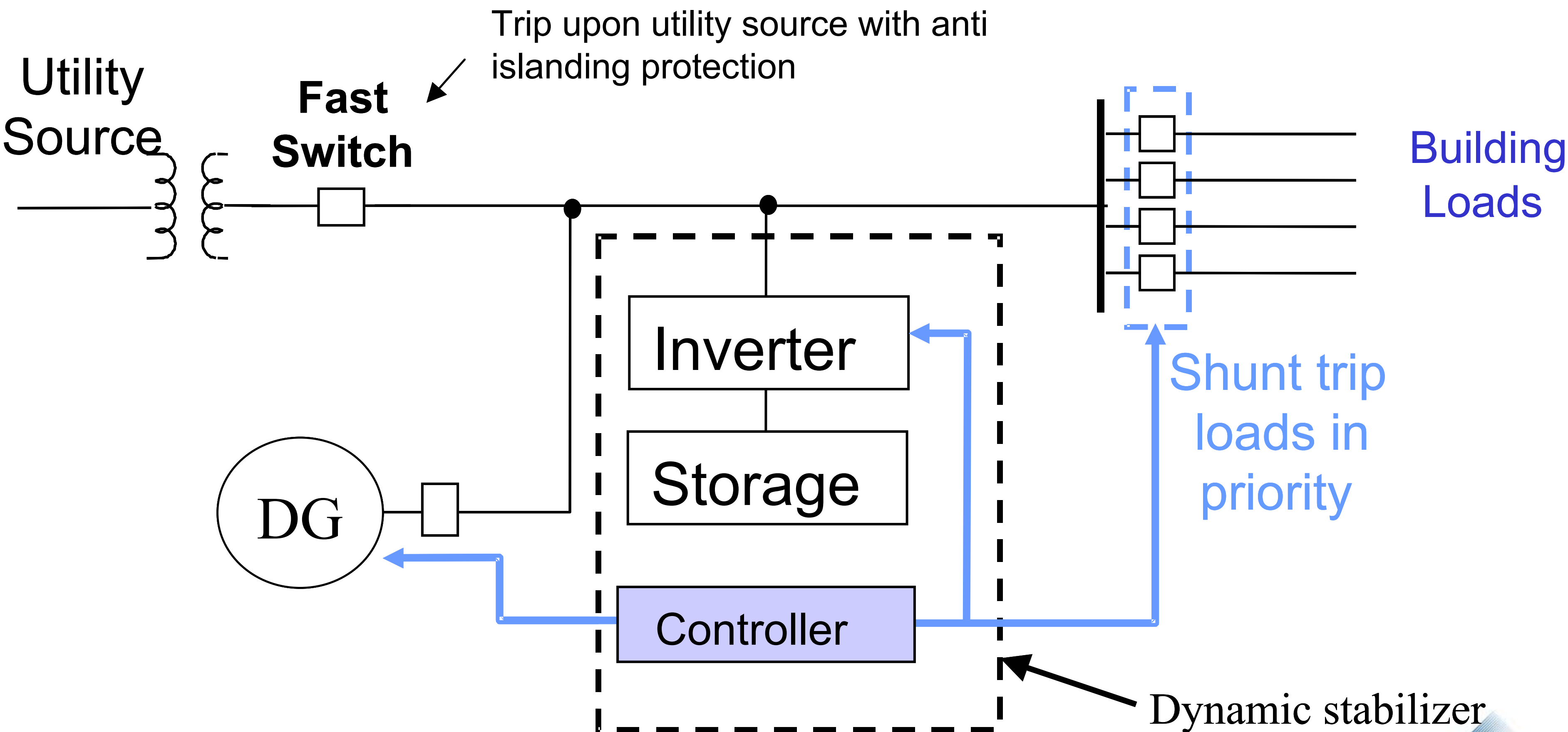


Comparison of Short-Duration Energy Storage Options

Parameter	Flywheels[1]	Electrochemical-Capacitors	Lead-Acid Batteries
Power Rating kWp (at 1 sec)	N/A	300 – 1000 (per kg)	400 - 600 (per kg)
Power @ 15s W/kg	10 – 130	200 – 600	200 – 350
Energy @ 15s kJ/kg (Wh/kg)	6 – 10 (1.7 – 2.8)	4 – 8 (1.1 – 2.2)	4 – 6 (1.1 – 1.7)
Energy Range kJ/kg (Wh/kg)	2 – 10 (.5 – 2.8)	1 – 26 (.28 – 7.2)	6 – 93 (1.7 – 26)
Discharge Time Range	2 – 200 seconds	.1 – 60 seconds	.25 – 480 minutes
Recharge Time Range	Seconds to minutes	Seconds to minutes	Minutes to hours
Response Time	10s of mSec	.10s of mSec	100s of mSec
Roundtrip Efficiency[2]	92-97%	90-97%	80%
Typical Cycle Life	10,000 cycles	100,000 cycles	2,000 cycles
Operating temp. range, °C	N/A	-50 / +50 (90 – 100%)	0 to 26 (65 –100%)
Cost $/kJ Range[3]	$1 – 4	$5 – 40	$.1 - 1
Technology Status	Available	Emerging	Mature

1. Flywheel performance, cost, and weight includes the rotor, generator and containment
2. Higher efficiencies occur for longer discharge/recharge cycles
3. First cost over rated discharge time range from longest (lowest cost) to shortest time (highest cost)

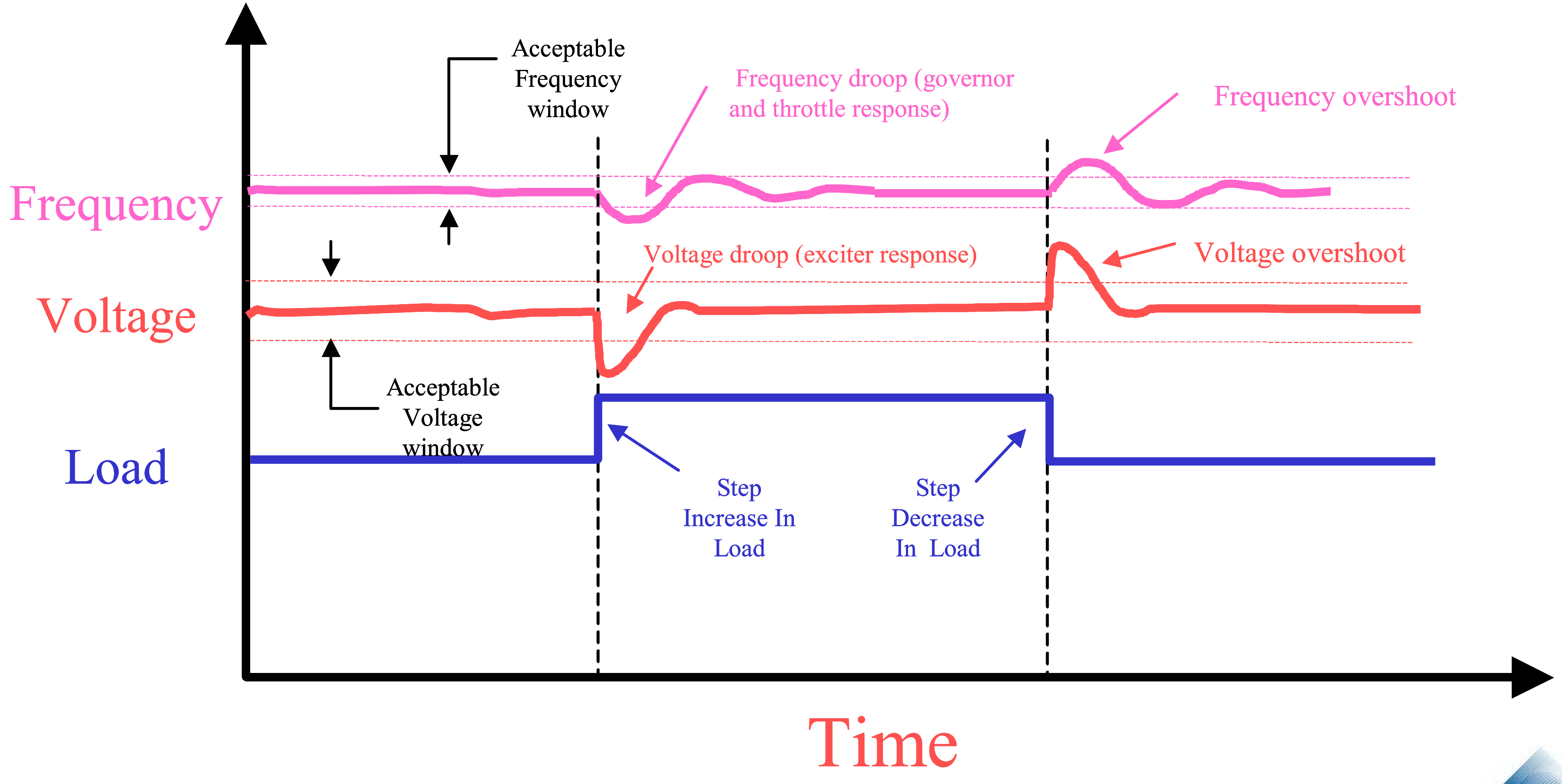
Energy Storage Application # 3: Voltage Stabilization for Small Isolated Power System with DG



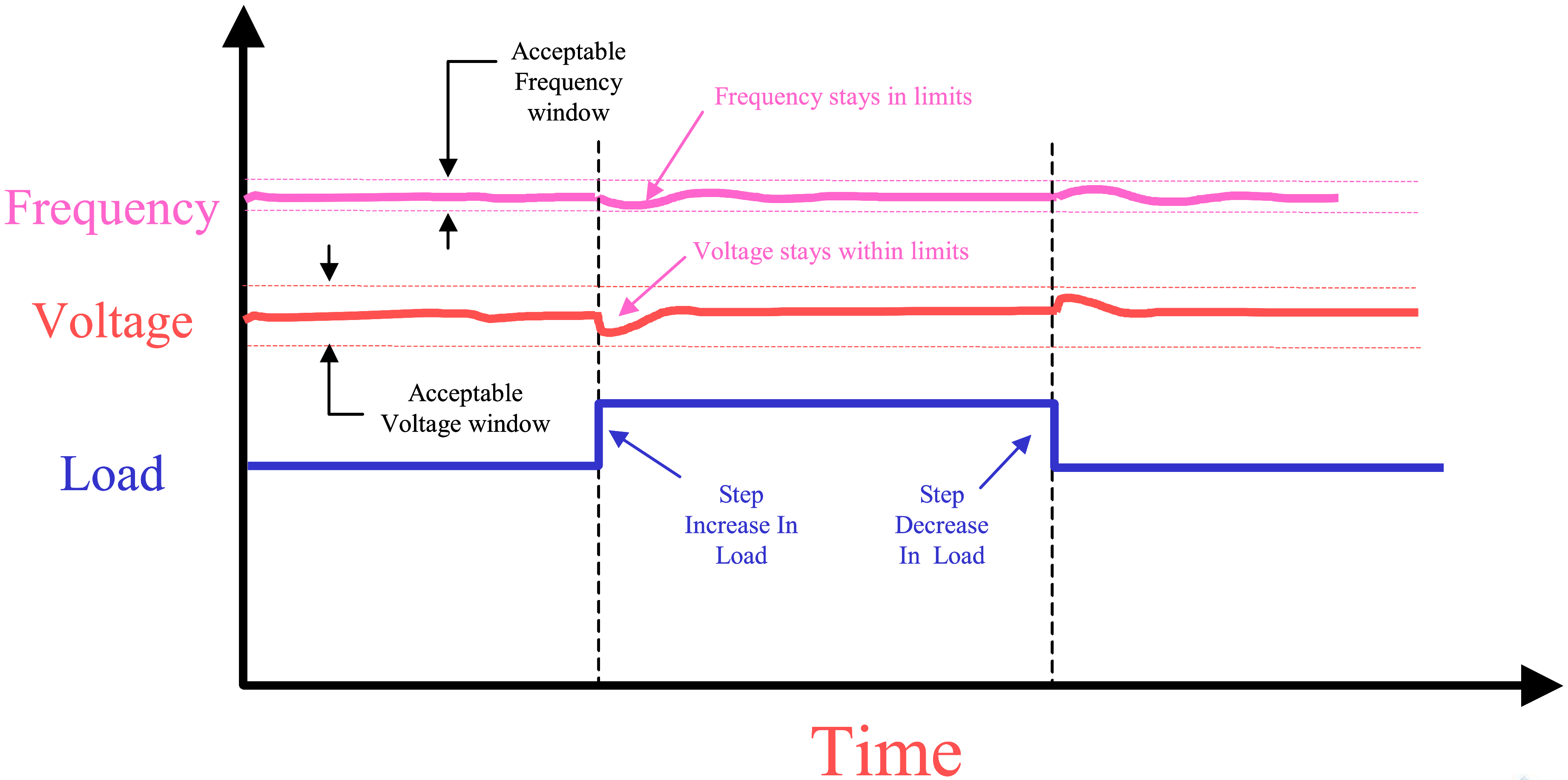
Typical load events seen by a distributed generator

Load Event	Typical Duration	Comment
Motor start	10 cycles	In addition to energy, the addition of a motor load will typically require the generator to supply additional reactive power.
Load increase Or decrease	Instantaneous	While the change in load is instantaneous, the response time of the generator is not and will vary as a function of the percent of load change.
Overload	Instantaneous	While the application of the overload is instantaneous, the duration of the overload is a function of the amount of overload and the response time of circuit protection.
Transfer to standby generator	10-15 seconds	Assumes an automatic transfer switch
Transfer to microturbines	0.5 - 2 minutes	Assumes an automatic transfer switch. The time to get the microturbine up to speed and ready to handle the load, varies by size and design

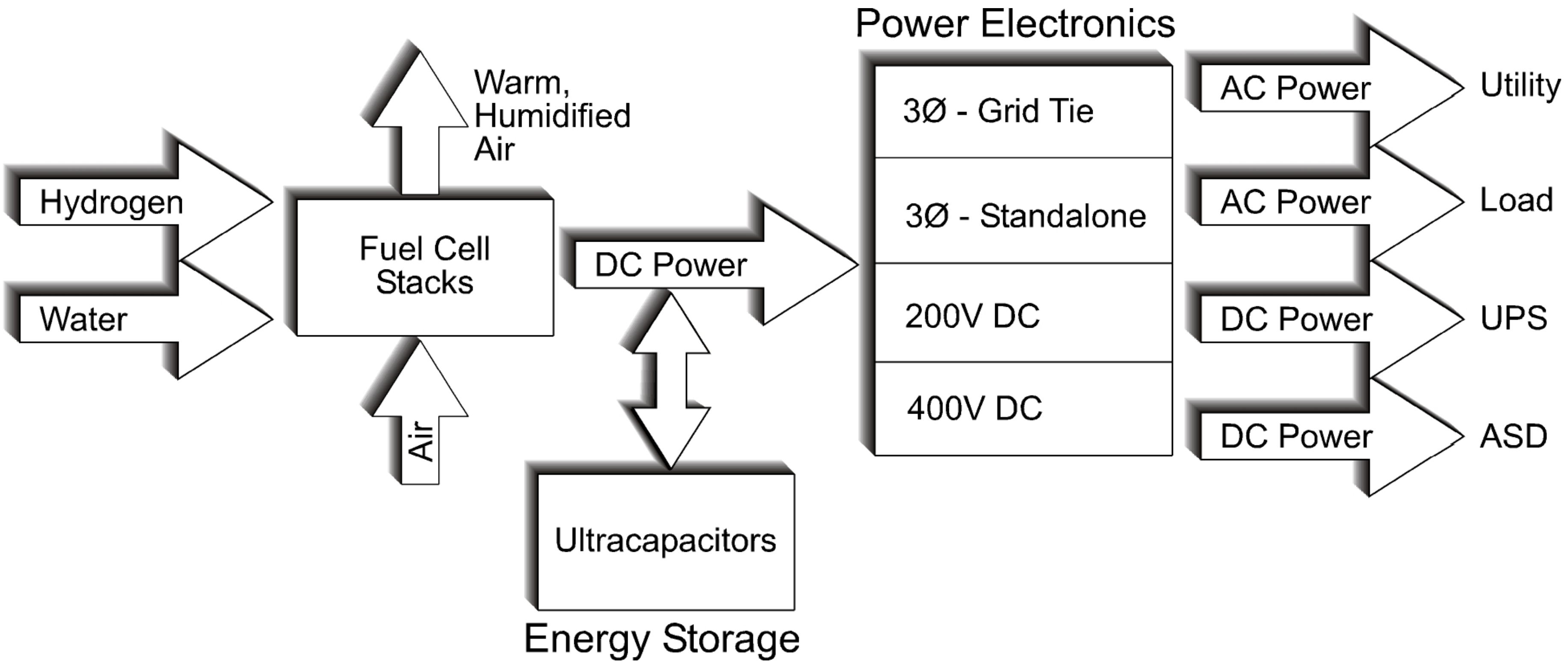
Need for Grid Stabilizer….relatively large load change on power system



Value of energy storage in stabilizing the power system



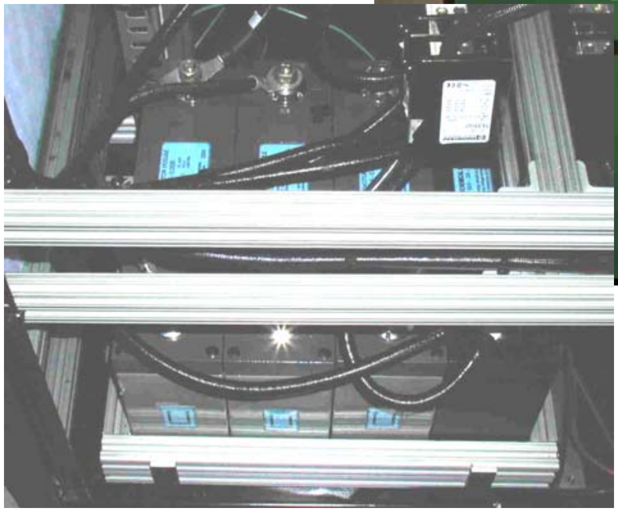
Energy Storage Application # 4: Inrush Support Application in Hybrid Capacitor/Fuel Cell System



- **Fuel cell system designed for robust grid connection and response with potential improve load and grid support via Electrochemical capacitors**

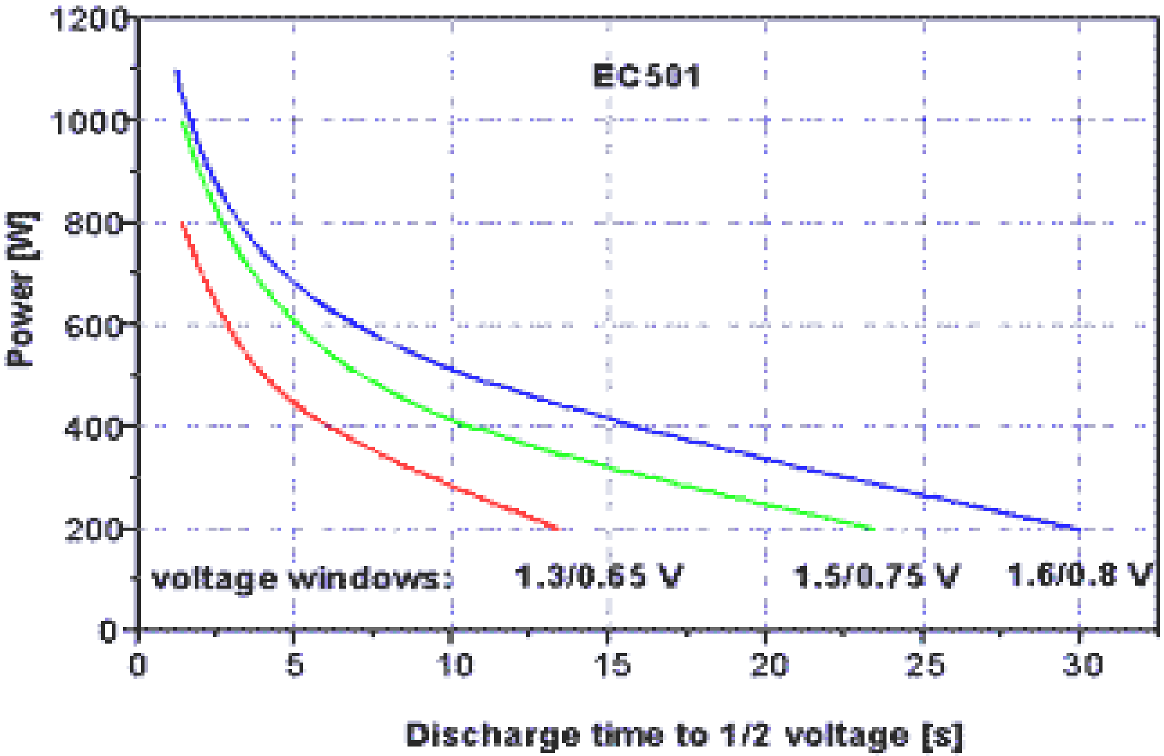
3-kW PEM Fuel Cell and EC Hybrid System

- 4-14Vdc Electrochemical Capacitors, 56Vdc in base of fuel cell cabinet
- 40 cells at 4.41 kJ/cell ~ 176 kJ
- Cost is ~ $50/cell, $2000 total

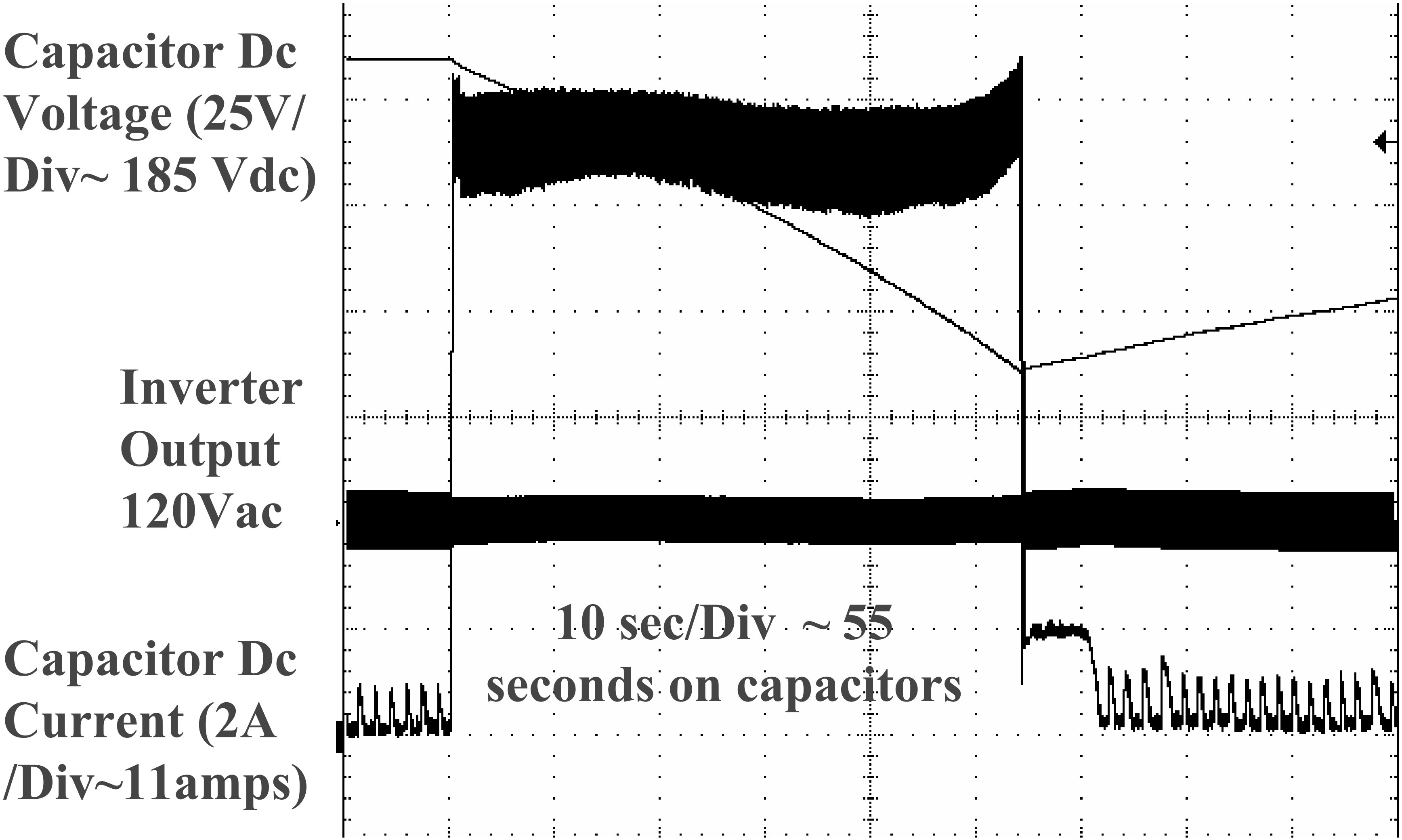


Electrochemical Capacitor Module Selection

Capacitor module type	Rated operating voltage window, V	Capacitance F, not less than	Energy stored in rated operating voltage window, kJ, not less than	Internal resistance at +20 °C (-30 °C), mOhm, not more than
10EC501.2-35-13/6.5-0.0035	13 - 6.5	600	35	3.5(4.5)



System Response for Momentary Loss of Fuel Cell Stack Voltage



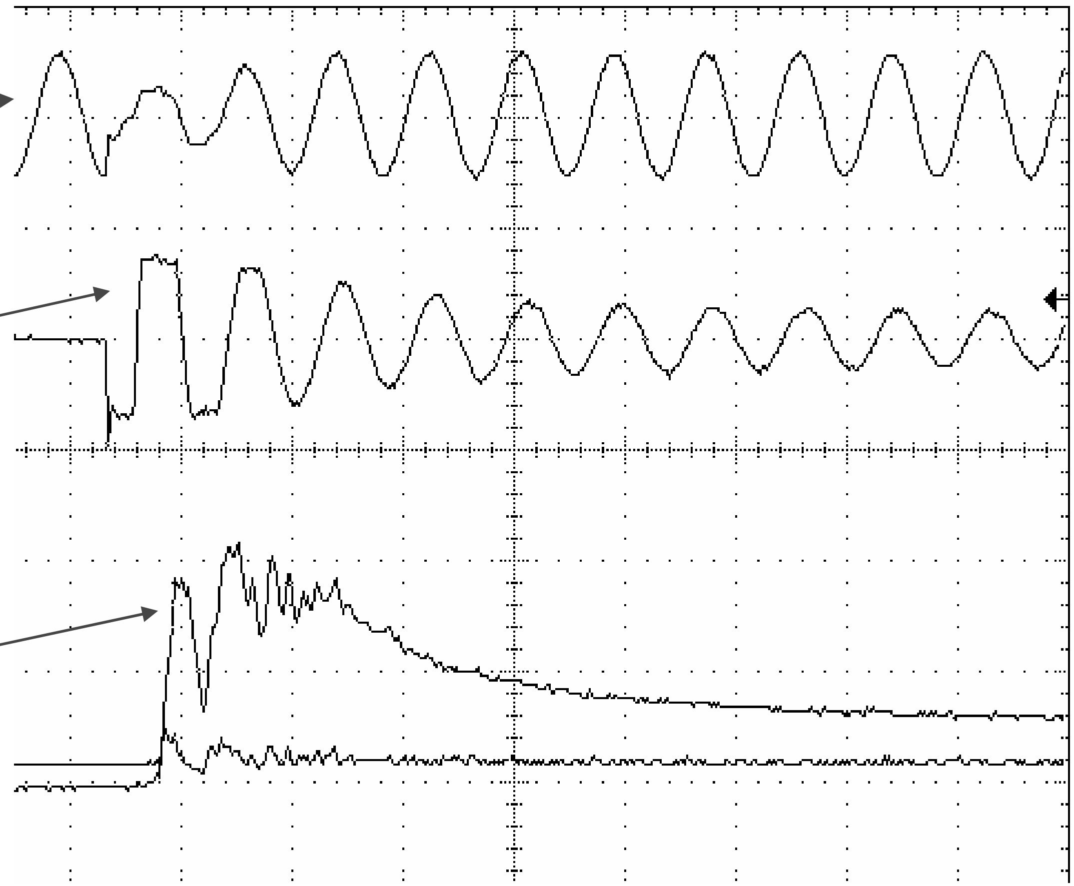
Note: No measurable change after 2000 ride-thru cycles

System Step Response – Start from 0 to 100% Loading

AC Voltage Output
500 Volts / Division

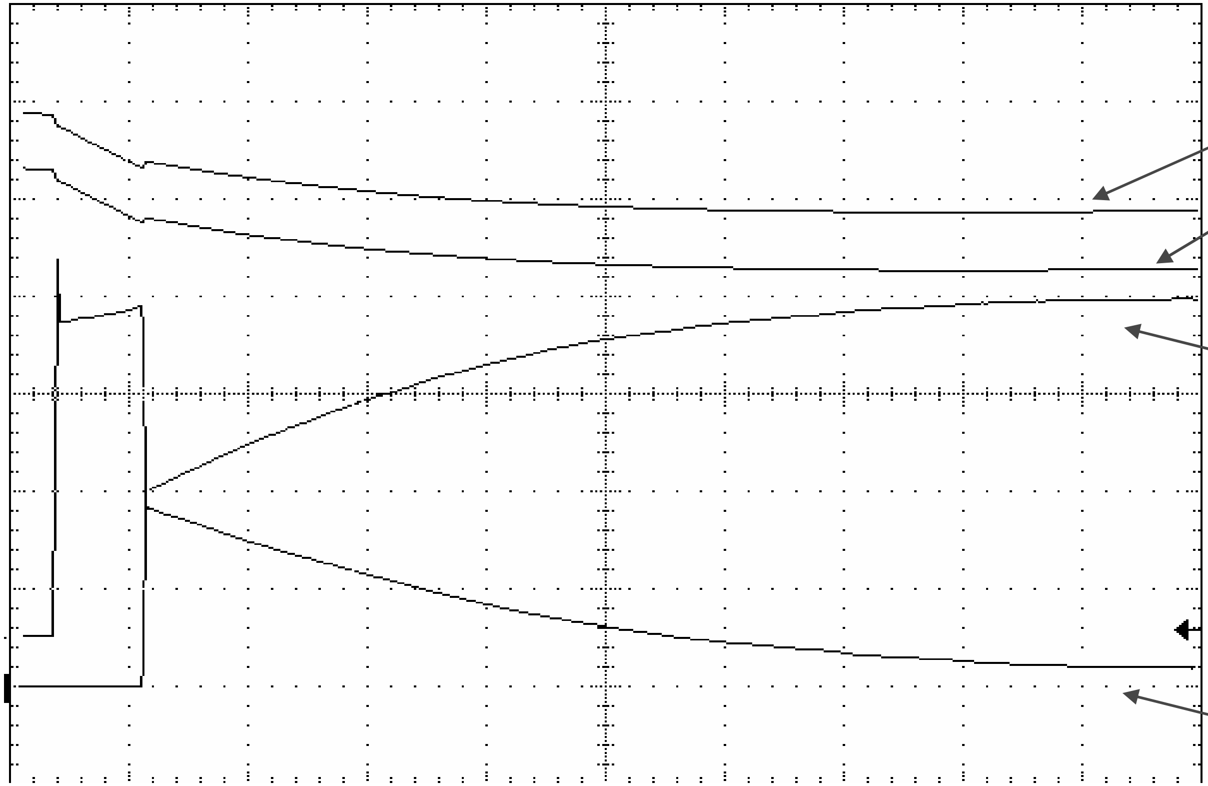
Phase A Current
25 Amps / Division

electrochemical capacitor Current 100 Amps / Division and Stack Current 100 Amps / Division



Step Loading to Full Load When electrochemical capacitor is Charging. Timebase is 20 Msec per Division

System Step Response – 1.5 HP Motor Start



Stack voltage and Capacitor voltages

10 Volts / Div

Stack Current

20 Amps / Division

Capacitor Current

20 Amps / Division

Startup of a 1 ½ HP Motor, Three-Phase, 208 V (Timebase is 10 Seconds/Division)

Practical Energy Storage Applications in Today's Distributed Energy Resources

	DE Fuel	Rating kW	Battery ES Vdc	ES kW-H	Start-up Control	Grid-Tie Functions	Standalone Functions
Fuel Cells							
1-ϕ Grid Only	NG/H2	2-12	28-48	3-6	C, D, J	F, G	N/A
1-ϕ Dual mode	NG/H2	2-12	28-48	3-6	C, D, J	F, G	E, F, G, I
3-ϕ Dual mode	NG	100-300	12-240	1-4	C, J	F, G	E, F, G, I
Micro turbines							
3-ϕ Grid Only	NG+	30-250	12-24	.5-1	B, D, J	None	N/A
3-ϕ Dual mode	NG+	60	200-300	2-8	A, B, D, J	E, H	E, F, H, I
IC Engines							
3-ϕ Standalone	NG/D	50-1500	12-24	1-2	A, D, J	N/A	None
3-ϕ Dual mode	NG/D	250-up	12-24	1-2	A, D, J	None	None
Bridging Systems							
3-ϕ Flywheel	NG/D	100-300	N/A	15-20	None	E, F, K	E, F, K, J
3-ϕ Battery	NG/D	250-up	600	40-50	J	E, F, K	E, F, K, J

A – cranking dc motor start
B – inverter drive motor start
C – FC cold start-up
D – back-up oil/fuel/cooling pumps
E – provides current for overloads
F – output voltage stabilization

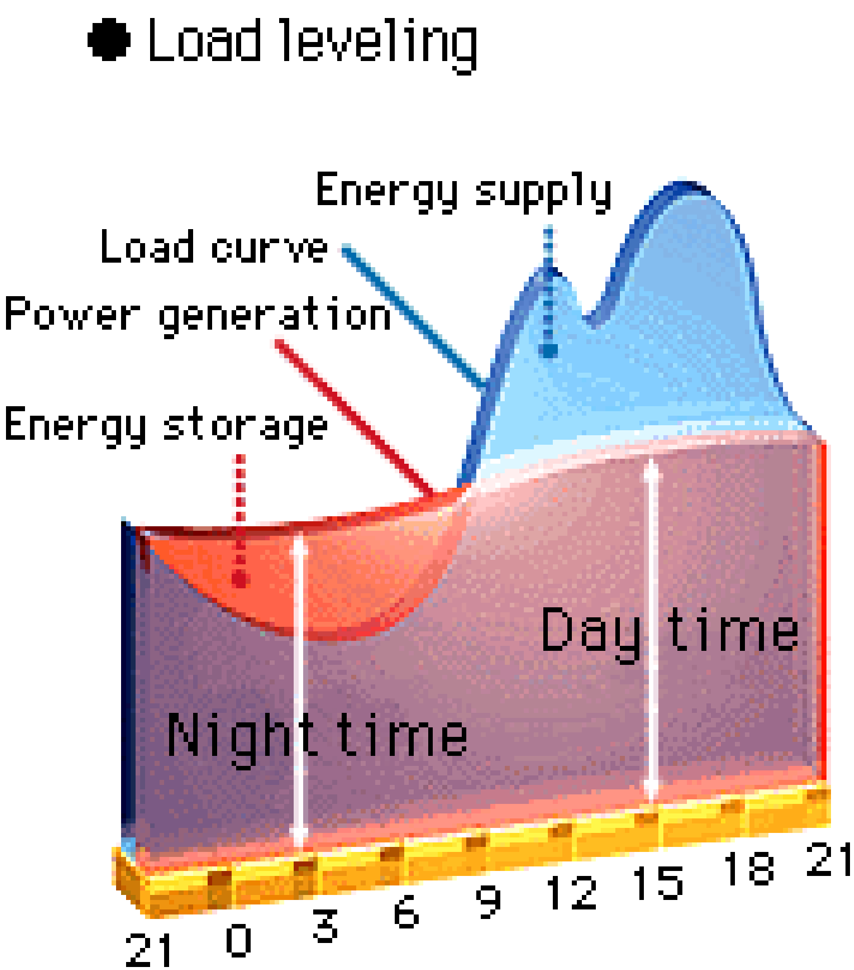
G – FC cleaning cycle H2 purge
H – load leveling/management
I – ramp-up reformer or turbine
J – control power backup/regulation
K – bridging power
L – arbitrage, time of day

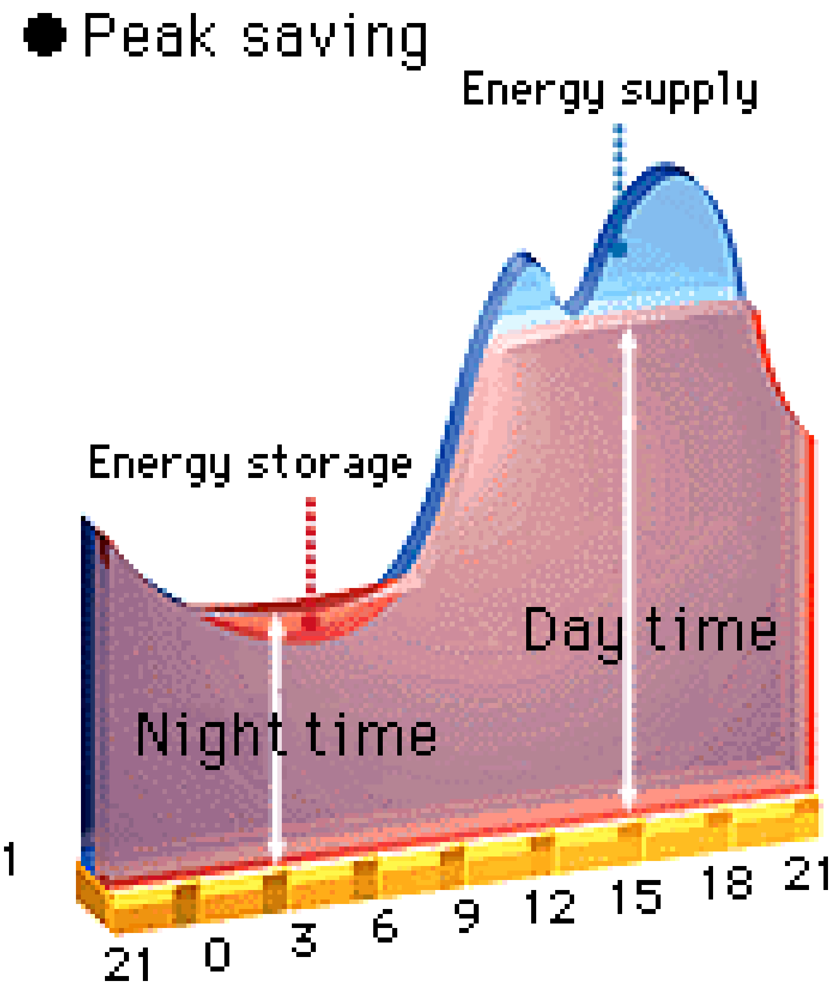
Future *Value-Added* Applications of Energy Storage for Distributed Energy Systems

Energy Storage Application	Energy Storage Benefits for Distributed Energy	Duration of Discharge	Storage Technologies Typically Used
Voltage Stabilization and Flicker Control	*Enables independent operation and may improve grid-voltage control in a remote connection.*	A few seconds, may be reoccurring	*Batteries, Flywheels, or Ultracapacitors*
Energy for black start ramp up and Engine Cranking	*Enables independent operation for various DE technologies such as IC engines and MTGs.*	2 seconds to 2 minutes depends on DE	*Lead Acid Battery or Ultracapacitors*
Supplemental Current for Motor Starts/Overloads	*Enables independent operation for various DE technologies that are not robust generators*	Seconds for inrush or motor starts	*Batteries, Flywheels, or Ultracapacitors*
Momentary Voltage Support or Replacement	*Provides momentary load protection when temporary grid disturbances are detected.*	<.25 seconds for sags & 1-15s for reclosures	*Batteries, Flywheels, or Ultracapacitors*
Energy for Bridging Events or Between Power Sources	*Provides momentary load protection from line voltage and DE cycling events, or transfer to an alternate source.*	10 to 30 seconds for bridge and less time to return	*Batteries or Flywheels*

Power Quality, Distributed Generation and Storage System Test Facility Knoxville, TN

Energy Storage Applications for Utility Scale Power Systems





Courtesy: *Energy Storage Association (ESA)*

Summary of Utility Energy Storage Applications (adapted from Sand97-0443)

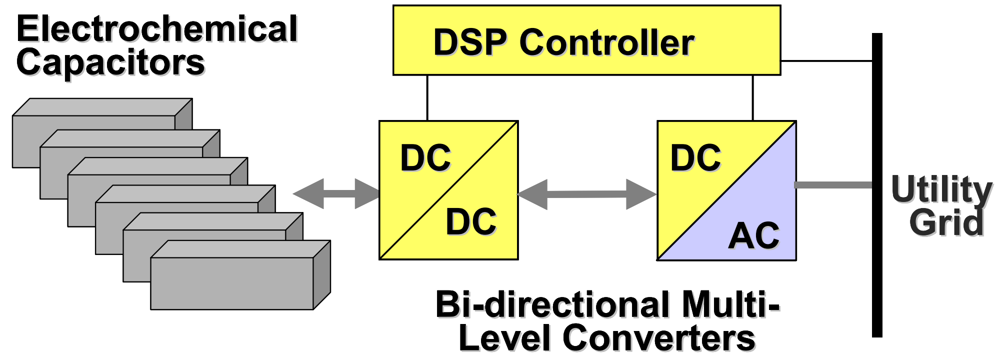
Application	Power Range (MW)	Duration (Hours)	Voltage (kVac)	Cycles/year
GENERATION				
Spinning Reserve	10 – 100	0.5	12 – 138	20 – 50
Capacity Deferral	10 – 100	2 – 4	12 – 138	5 – 100
Area/Frequency Regulation	10	<1	12 – 138	250
Load Leveling	100	>4	69 – 765	250
Power Plant UPS	<.1	4 – 8	480	<5
TRANSMISSION & DISTRIBUTION				
Transmission Line Stability	100	<0.01	69 – 765	100
Voltage Regulation	1 MVAR	<0.25	12 – 34.5	250
Transmission Facility Deferral	10	2 – 4	12 – 138	5 – 20
Distribution Facility Deferral	1	1 – 3	4 – 34.5	30
Substation UPS	<.1	8	48 – 120 Vdc	<5
CUSTOMER SERVICE				
Demand Peak Reduction	1	1 -2	0.48 – 12	50 – 500
Transit System Peak Reduction	1	1 -2	0.48 – 2.4	250 – 500
Reliability & Power Quality (<1 MW)	0.1	<0.25	0.48	<10

Definitions for Utility Applications of Energy Storage

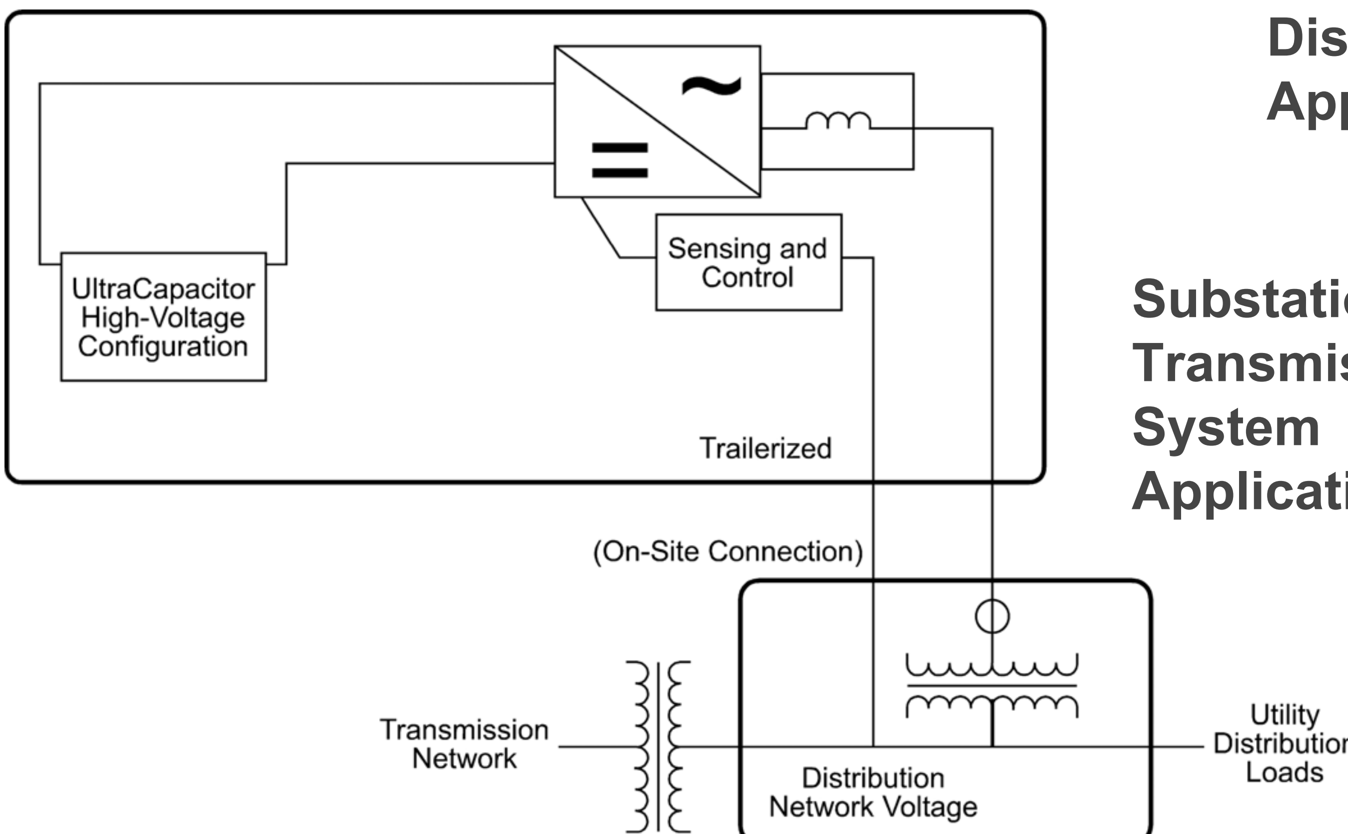
Category	Application Name and Definition
Generation	**Rapid Reserve** Generation capacity that a utility holds in reserve to meet North American Electric Reliability Council (NERC) Policy 10* requirements to prevent interruption of service to customers in the event of a failure of an operating generating station.
Generation	**Area Control and Frequency Responsive Reserve** The ability for grid-connected utilities to prevent unplanned transfer of power between themselves and neighboring utilities (Area Control) and the ability of isolated utilities to instantaneously respond to frequency deviations (Frequency Responsive Reserve). Both applications stem from NERC Policy 10 requirements.
Generation	**Commodity Storage** Storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours. In this report, Commodity Storage refers to applications that require less than four hours of storage.
Transmission & Distribution	**Transmission System Stability** Ability to keep all components on a transmission line in sync with each other and prevent system collapse.
Transmission & Distribution	**Transmission Voltage Regulation** Ability to maintain the voltages at the generation and load ends of a transmission line within five percent of each other.
Transmission & Distribution	**Transmission Facility Deferral** Ability of a utility to postpone installation of new transmission lines and transformers by supplementing the existing facilities with another resource.
Transmission & Distribution	**Distribution Facility Deferral** Ability of a utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resource.
Customer Service	**Customer Energy Management** Dispatching energy stored during off-peak or low cost times to manage demand on utility-sourced power.
Customer Service	**Renewable Energy Management** Applications through which renewable power is available during peak utility demand (coincident peak) and available at a consistent level.
Customer Service	**Power Quality and Reliability** Ability to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (less than one second) to minutes from causing data and production loss for customers.

From: Sand02-1314

Energy Storage Application # 5: Voltage Stabilization for Utility Scale T&D



Distribution Feeder Application



Substation and Transmission System Application

Application Example for Grid Stabilizer

- **Power Rating** – 2-40 MVA (power may be real, reactive, or both)
- **Energy Capacity –** .5-10 kWh **at** MVA rating
- **Duration** – Corrective action for cycles up to a few seconds
- **Response Time** – 5 to 100 Milliseconds
- **Duty Cycle** – Variable depending on conditions, may be a continuous problem
- **Roundtrip Efficiency** – 80-90% (assumes less than 10% duty cycle)
- **No load Losses** – less than 3%
- **Plant Footprint** – .05 MW/m^2 (assumes siting in low-density area)
- **Environmental Issues** – EMI

Candidate Energy Storage Technologies by Application

See Note 1 (Re: "X", "M") / Applications / Technologies	Grid Stabilization (GS)			Grid Operational Support (GOS)		Distribution Power Quality (PQ)		Load-Shifting (LS)	
	Angular Instability (GAI)	Voltage Instability (GVI)	Frequency Excursions (GFE)	Regulation Control (RC)	Cnvntnl Spinning Reserve (SR)	Short Duration PQ (SPQ)	Long Duration PQ (LPQ)	10 hr (LS10)	3 hr (LS3)
PbA	M (Note 4)		X	M	M	X	X		M
NiCad	M (Note 4)		X	M	M	X	X		M
NAS	M (Note 4)		X	M	M	X	X	X	M
ZnBr				M	M		X	X	M
VRB				M	M		X	X	M
Regenesys				M	M		X	X	M
SMES	X	X				X			
Flywheels	X	X				X			
Ultracaps	X	X				X			
CAES (above grade)				M	M				M
CAES (below grade) (Note 5)				M	M			X	

Note 1: "X" indicates an expected economic application of a technology, "M" indicates applications thought at this time to be economically marginal
Note 2: GS applications pertain to transmission ("T") utility ownership, PQ applications to distribution "D" utility ownership, and LS to either "T" or "D" ownership
Note 3: Priority applications are indicated in the upper part of the caption (GFI, GAI, SPQ, LPQ). One or more secondary applications (lower part of caption) are combined to achieve economic optimum (e.g., part year).
Note 4: If the technology cannot charge at the same rate as discharge, energy to be absorbed may be dissipated via resistive load banks. In this case, the energy to be injected must come from storage capacity sufficient for the duration of the event, e.g., 20 seconds
Note 5: CAES (below grade) based on 100 MW rating