https://littleboxchallenge.com/

Red Devils

Schneider

VT – Future Energy

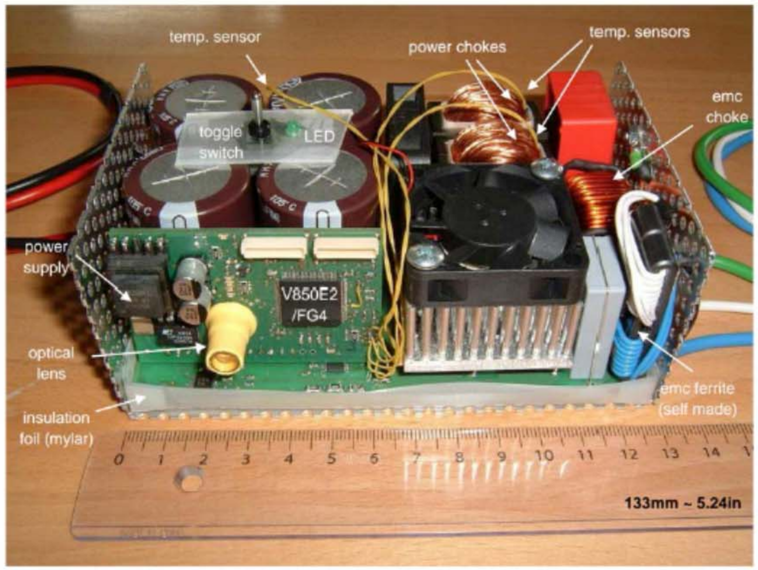
LITTLE BOX CHALLENGE

Google

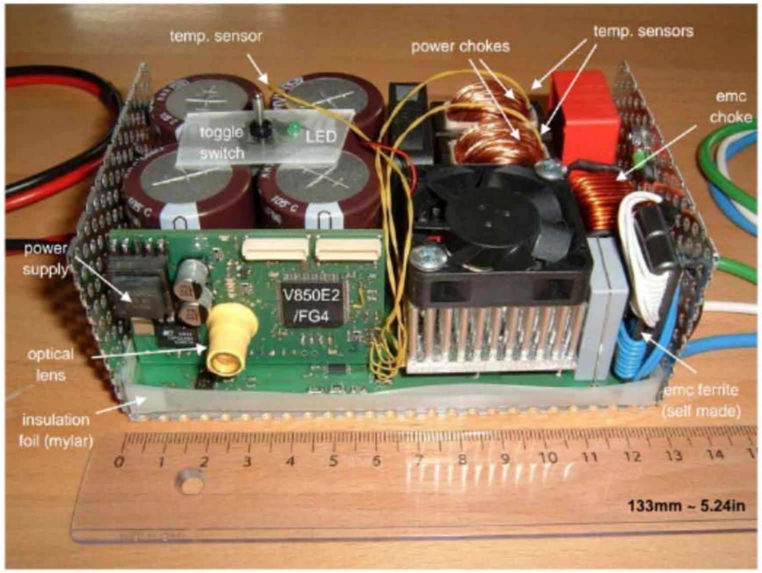
IEEE

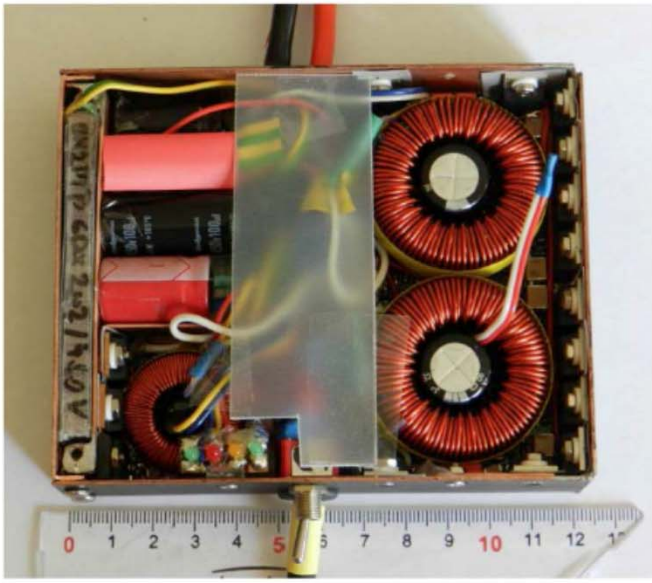
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

In mid July, we got our first inverter entry

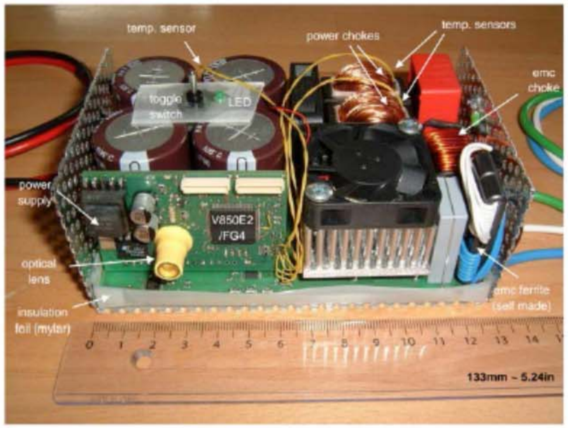


then we had 2


temp. sensor
power chokes
temp. sensors
emc
choke
toggle
switch
LED
power
supply
V850E2
/FG4
optical
lens
insulation
foil (mylar)
emc ferrite
(self made)
133mm ~ 5.24in



then 4


temp. sensor
power chokes
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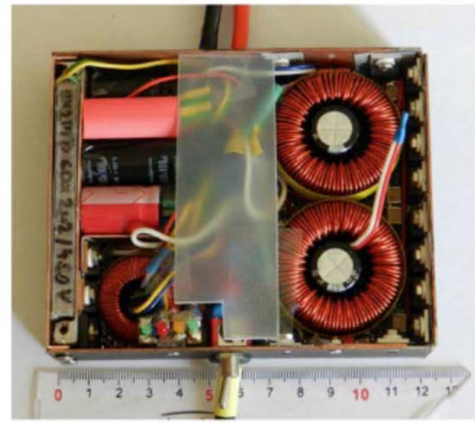
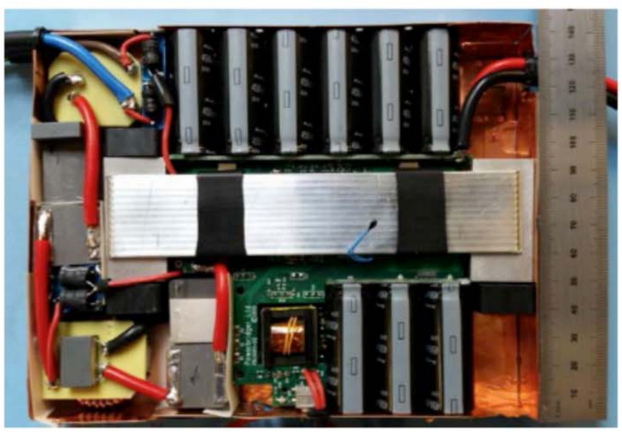
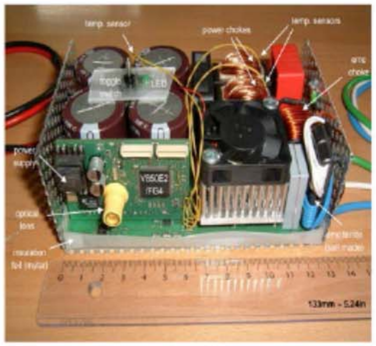





FISKARS

then 8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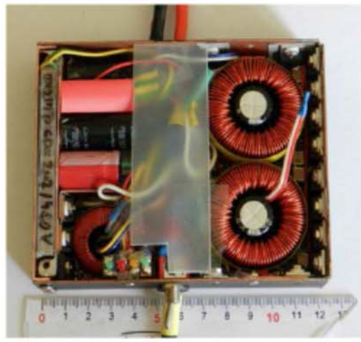

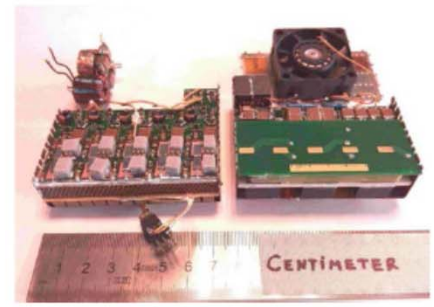
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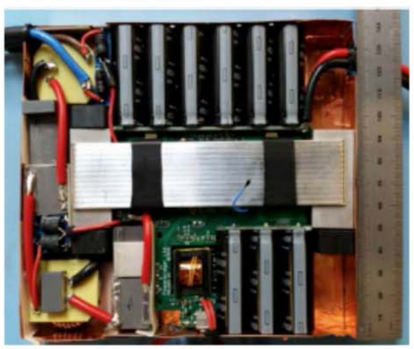


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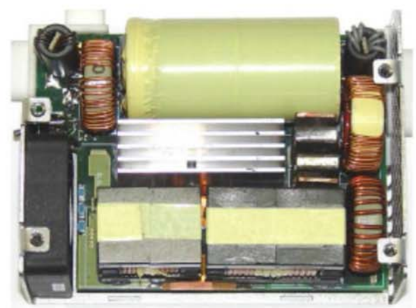

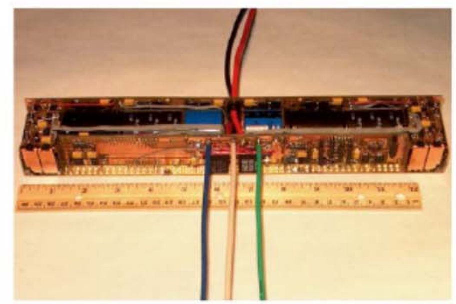

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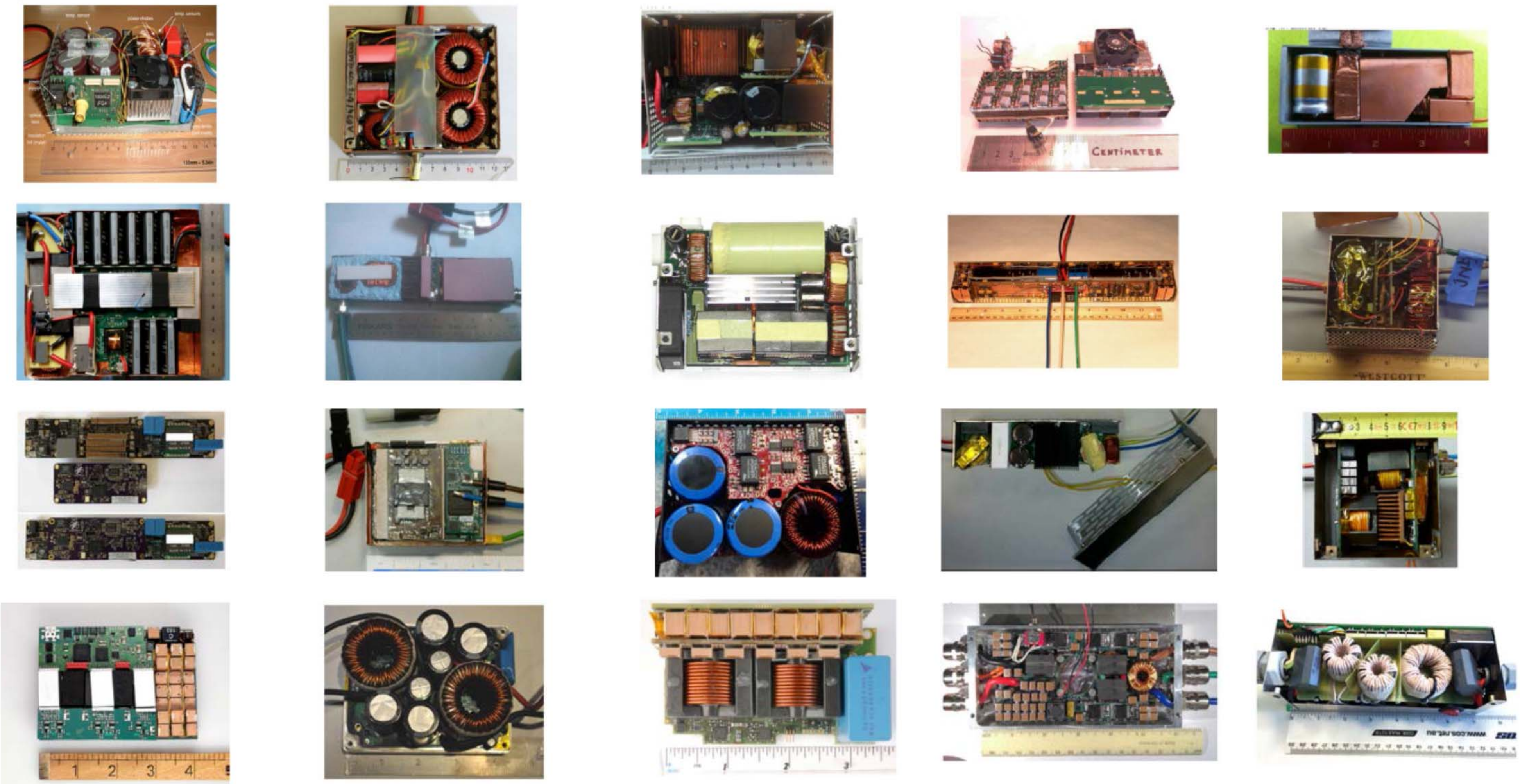

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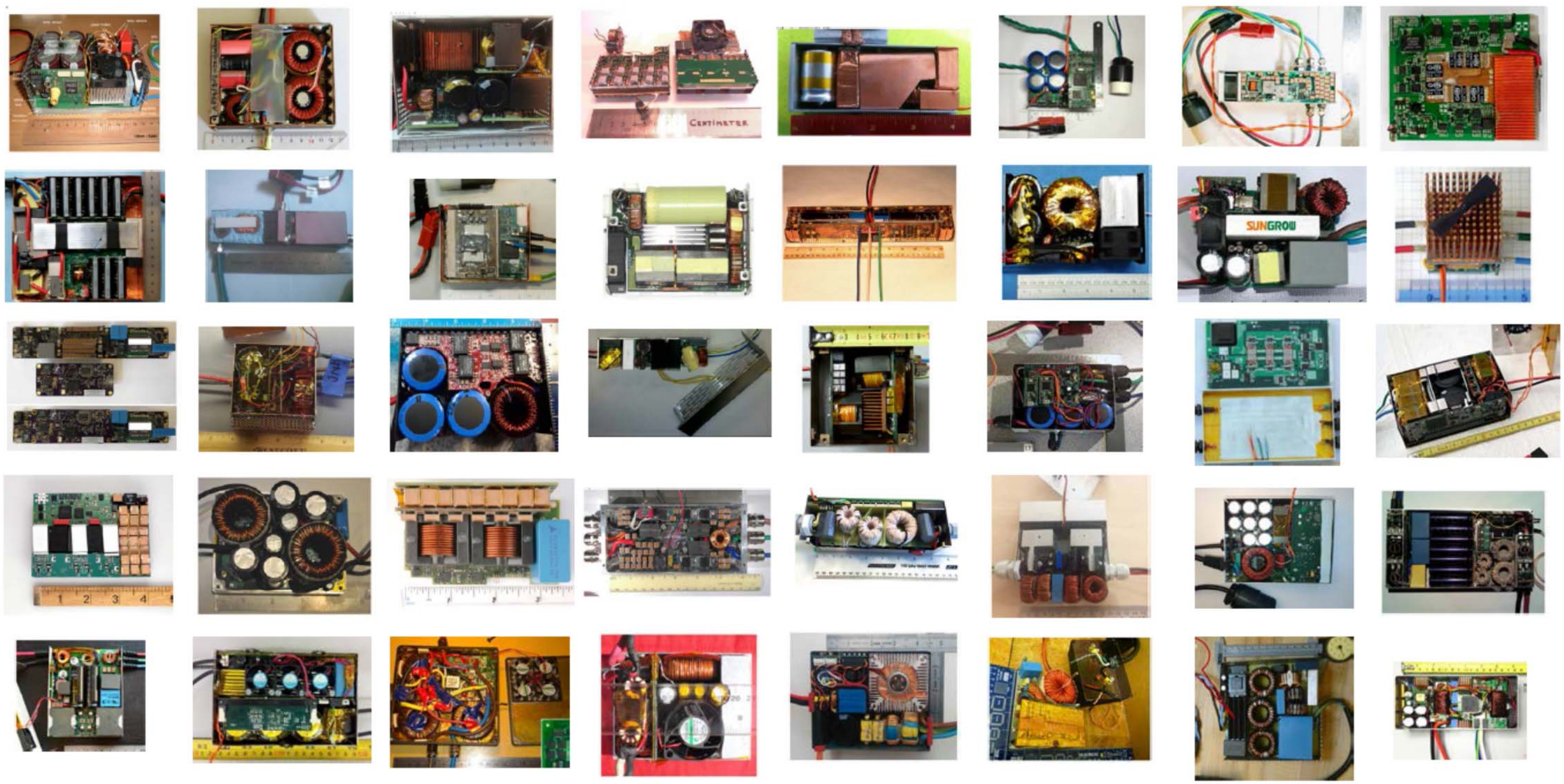


then 82

LiTTLE BOX CHALLENGE

> 2000 teams registered

> 100 applications for grants

> 100 testing applications

> 30 reviewers

Lowest Power Density Claimed: 50 W/in^3

Highest Power Density Claimed: 5220 W/in^3

Other Organizations Attending Today

LiTTLE BOX CHALLENGE

8 - 9 AM:	Breakfast and preliminary drop off of inverters
9 - 9:30 AM:	Opening comments by Google, IEEE and NREL
9:30 - 10:15 AM:	Presentations from teams 1-6 and Q&A
10:15 - 10:45 AM:	Break
10:45 - Noon:	Presentations from teams 7-12 and Q&A
Noon - 1:30 PM:	Lunch and tour of ESIF
1:30 PM - 2:15:	Presentations from teams 13-18 and Q&A
2:15 - 2:30 PM:	Break
2:30 PM - 5 PM:	Reception (free time to socialize in the meeting room) and formal drop off of inverters

Group 1

1	Helios
2	LBC1
3	Future Energy Electronics
4	OKE-Services
5	Fraunhofer IISB
6	Red Electrical Devils

Group 2

7	Energylayer
8	Rompower
9	Cambridge Active Magnetics
10	Schneider Electric Team
11	AMR
12	The University of Tennessee

Group 3

13	AHED
14	Tommasi - Bailly
15	Adiabatic Logic
16	UIUC Pilawa Group
17	!verter
18	Venderbosch

Enabling High-Penetration Solar PV through Next-Generation Power Electronic Technologies

- Workshop -

10/12/2016

Leo F. Casey, ScD
leocasey@google.com

DG(PV), Storage, Grids & Power Electronics





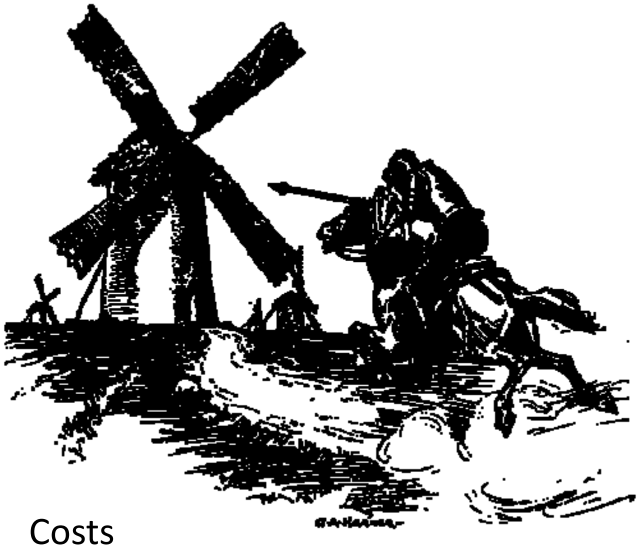




The Narrative we present -- Overview

- Grid(s), are changing, it was metamorphosis, now transformation? Physical layer? Grid Modernization? Instability on many fronts.
- Costs, standards, prices, complexity
- Role for Grid Electronics, power electronics can be transformative, examples
- Limitations, Devices, thermals, developments/trends
- Tipping point? Killer applications?

- Grid electronics typically at the edge (interfaces/parallel, vs series devices … challenging)
- Grid Connected PE vs Grid Controlling PE
- Discuss these points/issues using examples: Inverters for Renewables, μGrid switches, Solid State Transformers, voltage controllers



Electricity:
-How we make it
-How we move it
-How we use it

-role of electronics
-rugged, reliable, outdoor
-modularity
-density? Easier when small

Systems:
-storage integration (dc coupled), sw. bd rating, choices
-uGrids
-BOS

Costs
Efficiency
~density
Reliability/Resiliency
Power Quality

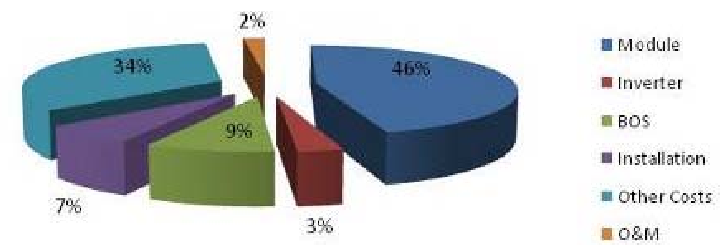
Barriers
AHJ ?
Renewables/DG IEEE1547, NFPA70 (NEC) Article 690
Bulk -- FERC 661

Ride-thru, islanding, reverse power flow, voltage control, reliability, transient suppression, voltage range on dc side (active clamps?)

Barriers to High Penetration of Renewables

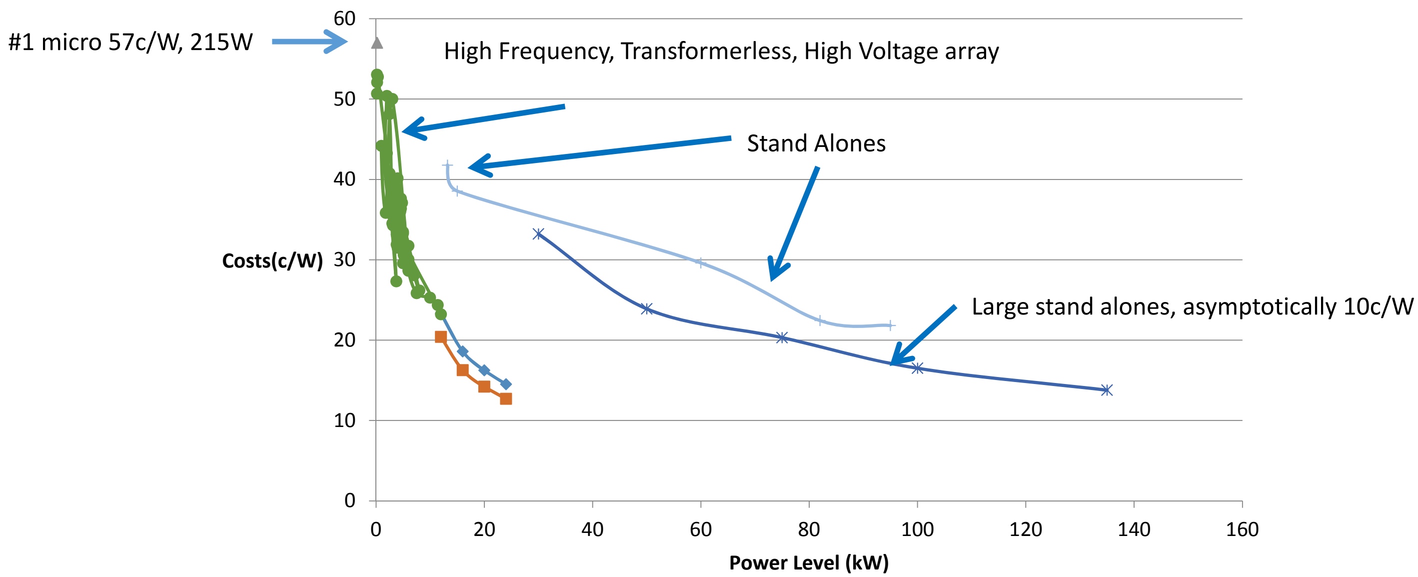
~2004 DOE/NREL

1. **Cost**
   - Panels
   - Inverters, BOS
   - O&M



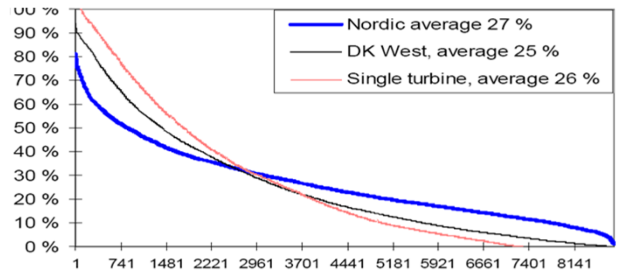
2. Controllability
3. **Intermittency** (Variability/Capacity Factor/Capacity Value)
4. Utility Industry Acceptance/Adoption
   - Scale
   - Performance
   - Standards
   - Familiarity (interconnection, protection)

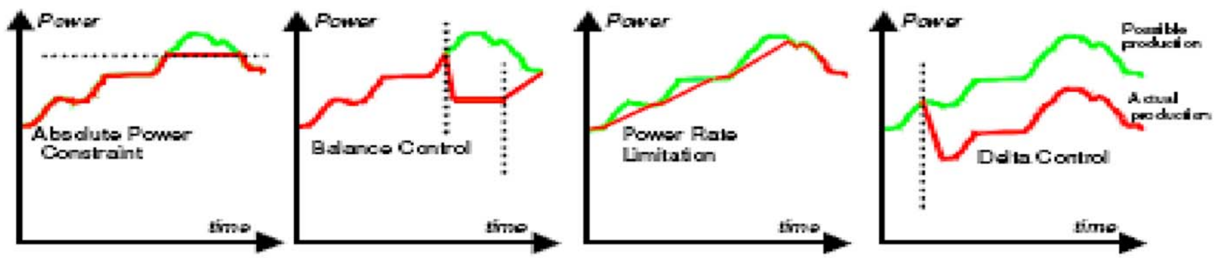
Inverter Cost Comparisons



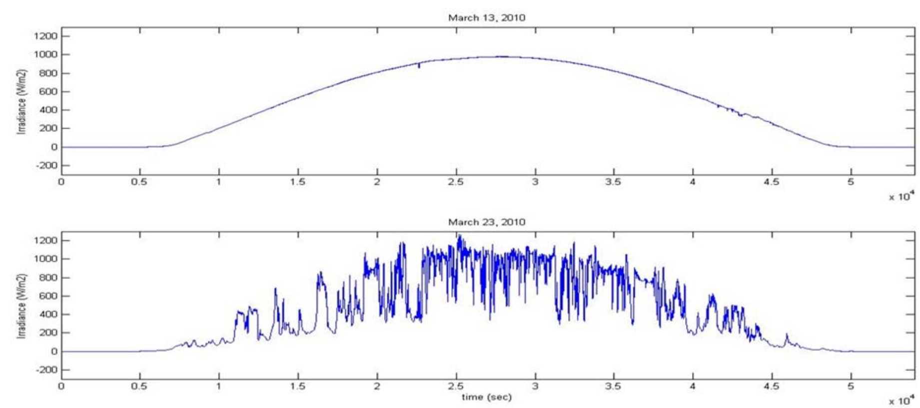
Controllability allows Increasing Penetration of Renewables, BUT, still Intermittency concerns (bulk and distributed)

Denmark
•42% of Electrical Energy, lots of spatial averaging -->
•New Control Regs.
•European Grid
•Curtailment and dynamic range





Dynamic Range thru Curtailment



New Zealand
•80% + renewables
•Hydro, geothermal, wind
•Curtailment

Lanai
•20% PV in diesel grid
•no storage but heavily curtailed
•35% of peak with storage
•Ramp rates, curtailment, remote control, site controller, VARs, ride-thru (CPUC SIWG features)

SCE
- 40-60% on individual feeders (but where on the feeder?)
- c.f. Hawaii 20% on individual feeders **(backfeed concerns)**

Studies, NREL east and west, 10-30%, no storage, ramp Coal
EU15, DisPower Study, 15-35%

Multi-MW Platform

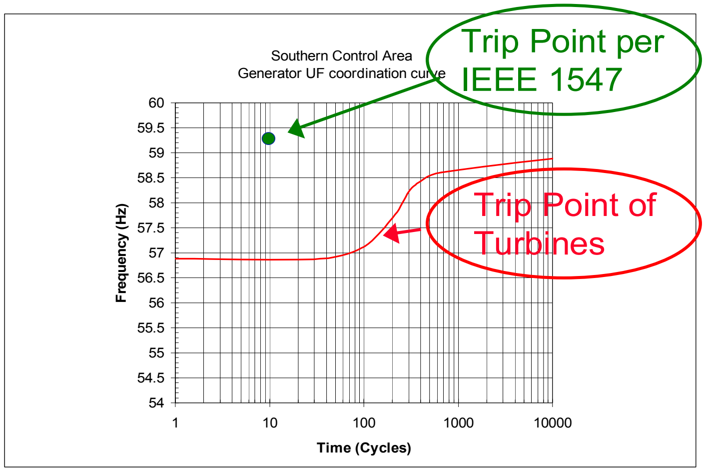
- 1 to 2 MW integrated medium voltage PV solution (4.2kV – 69kV)
- Single skid combines and integrates inverter, MV transformer, MV fuse and disconnect, AC breaker, EMI filter, AC switch, DC switch, and DC fused combiner
- Ships as single skid, fully tested
- System mass (including MV transformer) ~ 30,000 lbs.

1) The current EQX250KW (CSA certification) with transformer selling to Makani is US$39K.
2) EQX500KW (CSA certification) without transformer is selling at US$45K
3) EQX1000KW (CSA certification) without Transformer is selling at US$58K
4) EQX1000KW (CQC certification) without Transformer is selling at US$44K.
5) EQMX1000KW (CQC certification) without transformer is selling at US$39K with LS Breaker and Contactor.

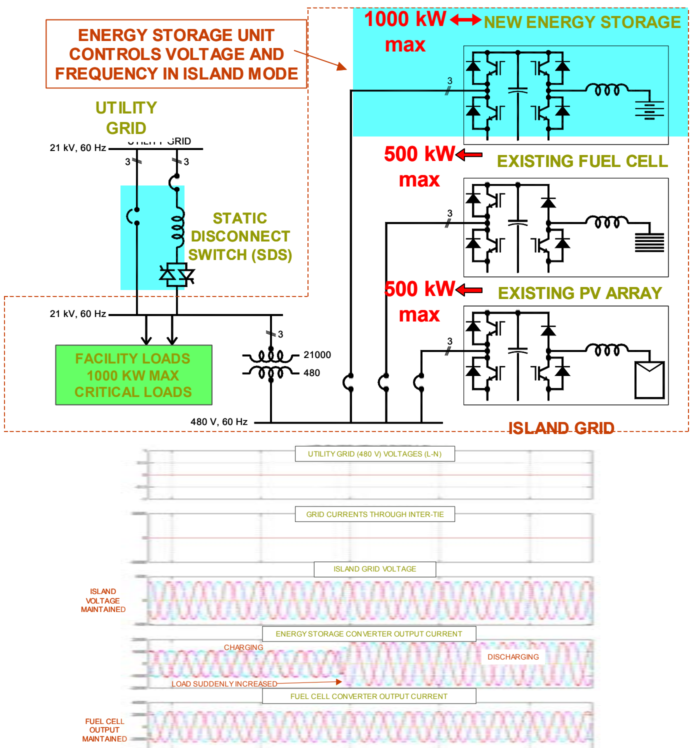
Item 2 to 5 all come with 5 years warranty.

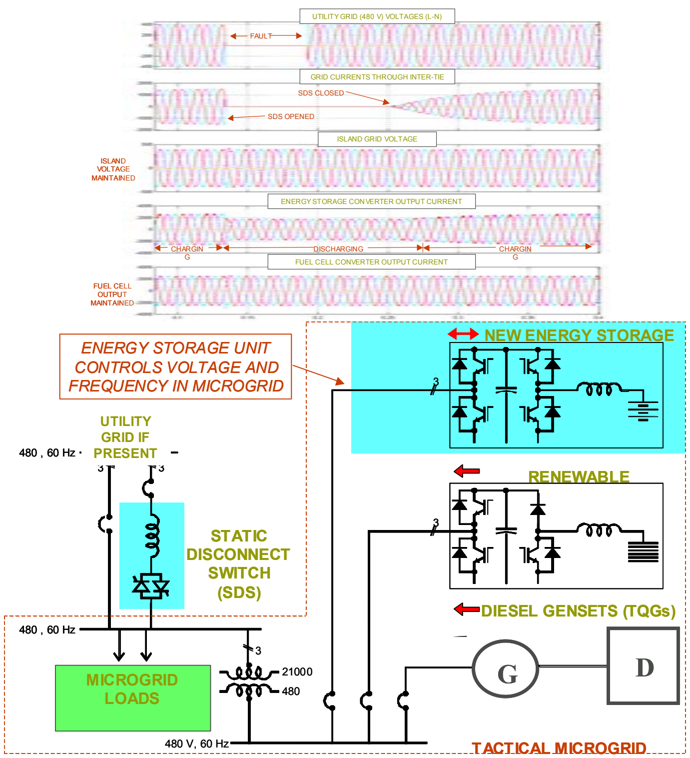
Electronics can be Transformative – BUT different Paradigm – and System

- Readily Controllable (remotely)
- Supply Real Power, P, Dynamically
- Reactive power, Q, ($|P + jQ| < S_{INV}$), Dynamically
- Active Damping (stabilizing)
- Controllable or Synthetic Inertia
- Fault Clearing
- Rapid Dynamics
- Unbalanced
- Non-linear sourcing
- Active Filtering
- Harmonic cancellation
- Also, high speed series devices would limit faults and enable robust interactive microgrids



Micro-Grids for Digital Quality Power

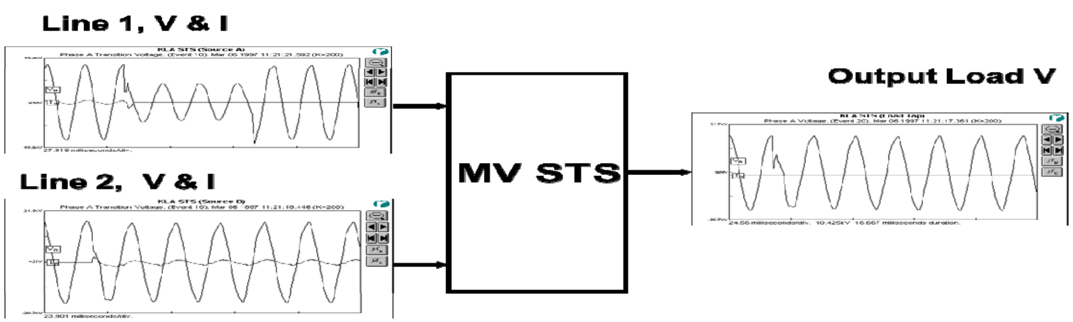




- Renewables plus back-up generation plus storage plus SDS
- → UPS quality power

Thyristor based MV Switch

Max Voltage (MSV)	15 kV Class
Lightning Impulse (BIL)	95 kV
Power Frequency	60Hz
Withstand Voltage, Pole-Ground	36kV, 1min.
Nominal L-L System Voltage	13.8 kV, 60 Hz
Rated Continuous Current (RC)	300 A
Overload, 120 seconds	375A(125% RC)
Short-circuit-current, 10 cycles	12kA(rms,sym)
Short-circuit-current,1 cycle	25.0 kA(peak)



“NEW” **Transfer Switch**

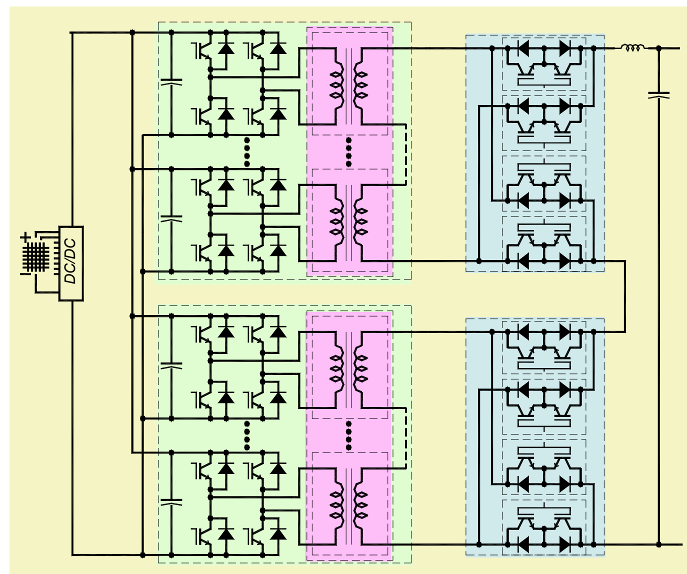
MV Direct Connect Inverter (ARPA-E)

Metric	Typical Present Day	Target
Cost	$0.22/W[1]	$0.10/W
Weight	~30,000 lbs (incl MV tranformer)	<2,000 lbs
Efficiency	97%[3] (incl. MV transformer)	98% (direct to MV)
Rating (MVA)	1.25 MVA[2]	2 MVA
Native Voltage	320VAC[2]	13.8 kVAC
Reliability	20 year lifetime	30 year lifetime
"Agility"	Parallel connection to the grid, limited ability to respond to system events	High frequency, series connected to grid: rapidly respond/clear faults, tune power quality

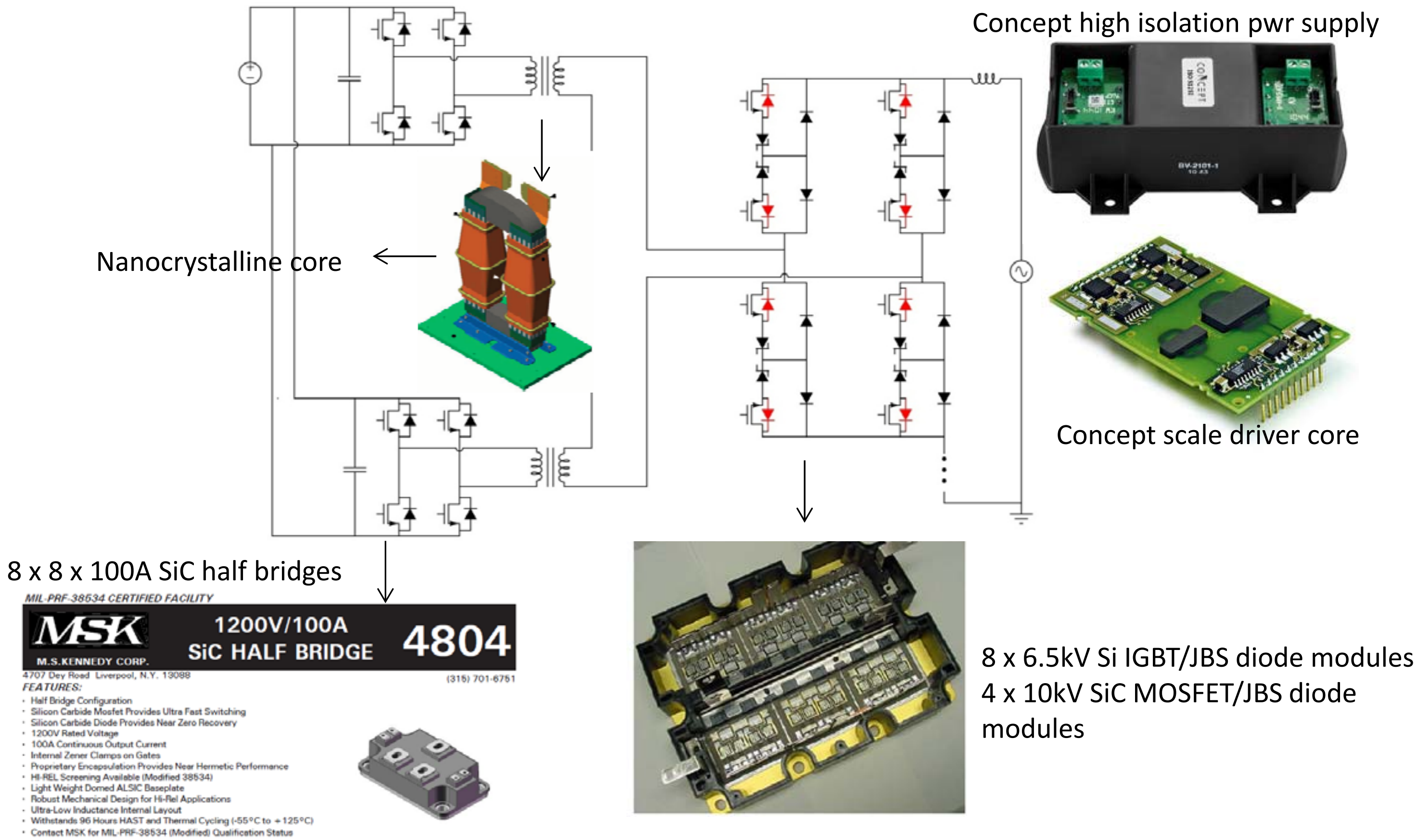
[1]DOE 2011. SEGIS-AC FOA
[2]Based on Satcon Prism 1.25MW inverter
[3]CEC weighted, module-to-grid, including MV transformer losses

System Overview: Multilevel Inverter

- 2 MW module (1- or 3-phase)
- Solid-State AC Output Switch
- Two-Stage Conversion
- 20 kHz 600VDC → 6 kV AC Front End 60 Hz Modulator
- 6kV → 10kV Matrix Demodulator
- 4-Q, PF Operation

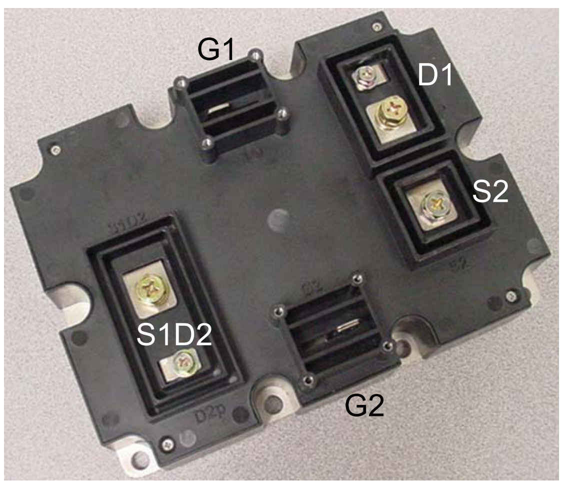


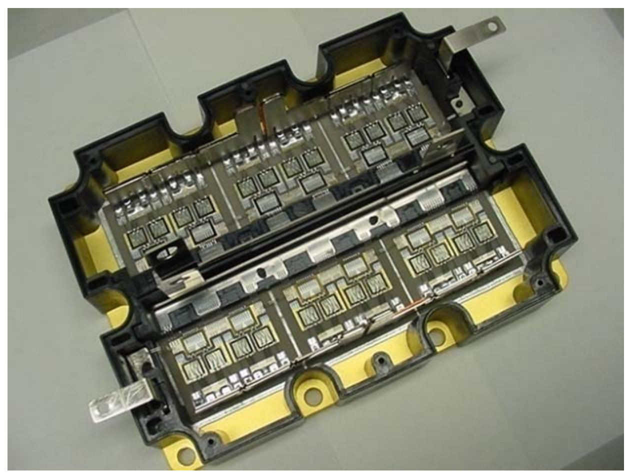
System Building Blocks

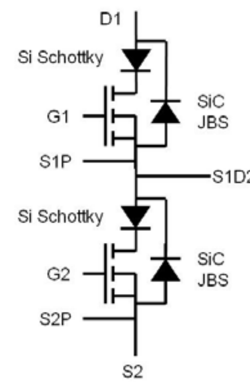


10kV, 120A Half H-Bridge SiC Mosfet Module

- Utilize 10kV SiC Mosfet Module Design Developed for ONR/DARPA WBG HPE Program
- Module Footprint is Standard 140 x 190mm – Fully Populated Module Has 24x 10A SiC Mosfet and 12x 10A SiC JBS Diode Die
- Module Demonstrated to Operate at 20kHz in 13.8kV to 480V SSPS System and up to 40kHz in Subsequent Tests
- 42 Modules Have Been Delivered Over The Past 3 Years





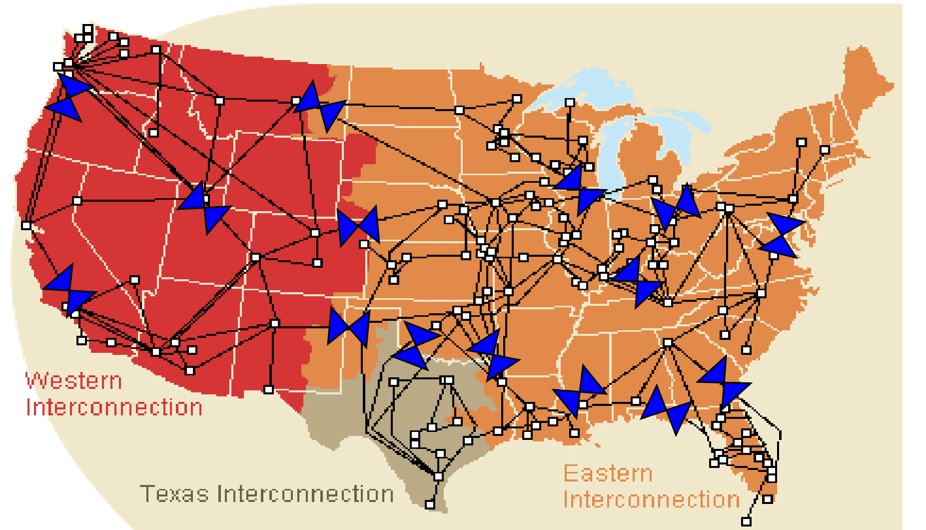


Technology Comparison

Characteristic	Typical Present Day	MV Direct-Connect Inverter	η	Mass	Reliability	Cost
Semiconductor Technology	Silicon	Silicon Carbide (SiC)	↑	↑	↓, ↑	↓
Switching Frequency	2-8 kHz	Tens of kHz	↓, ↑	↑	↔	↔
Topology	DC-AC-XFRMR	DC-AC(HF)-AC(LF)	↑	↑	↔	↔
Transformer Core	Si Steel	Nanocrystalline	↑	↑	↔	↑
Semiconductor Output Voltage	320VAC	13.8 kVAC	↑	↑	↓	↑
Junction Temp.	100-125 deg C	>200 deg C (SiC chip)	↔	↑	↓, ↑	↔
Thermal Management	Actively Cooled (fans), aluminum heat sink	Passive cooling, carbon foam heat pipe	↔	↑	↑	↔
Modularity	Parallel-Input, Parallel-Output 2-level building blocks	Parallel-Input, Series-Output multilevel building blocks	↔	↔	↑	↔
Prognostics	Based on historic reliability data	Based on predictive algorithms	↔	↔	↓,↑	↔

Some Possible Game Changers

•Back to Back DC links with short term (mandatory) area balance (μTile the Country)



•Distributed Inverters (many provided through renewable integration)

•Local Voltage Regulation

- fast! Even sub cycle, can mitigate existing flicker, increase quality and reliability, achieve voltage regulation with no tap-changers, line regulators, or capacitors

•Fault Limiting

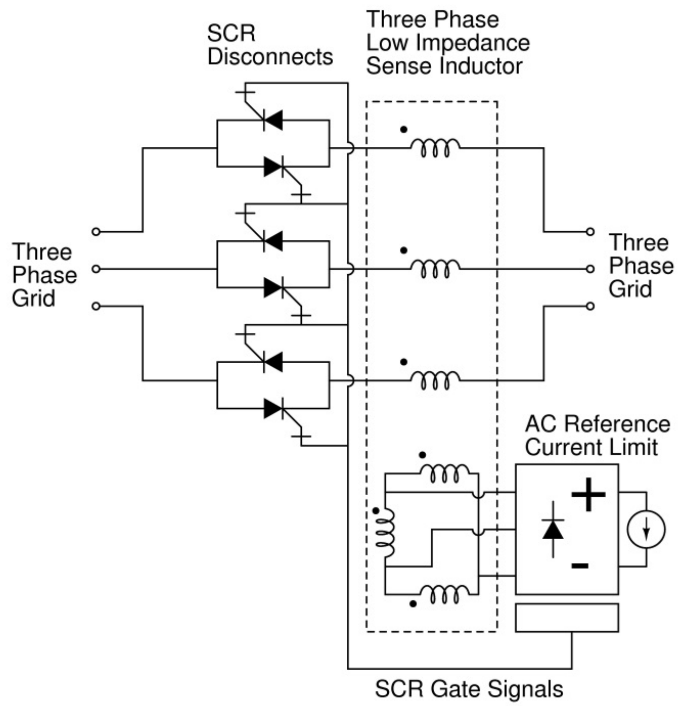
•Storage Integration (very cost effective as element of renewable power plant)

•Feeder Decoupling, possibly with shared storage, s

•Hybrid AC/DC Converters, dc for building etc … , plus AC, hybrid transformers

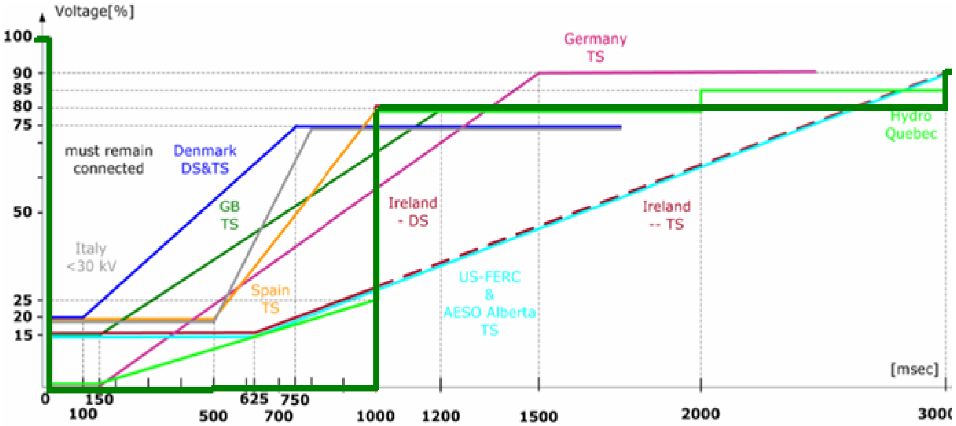
Faults, Protection, Switching and Current Limiting, Series Device very challenging (ac easier)

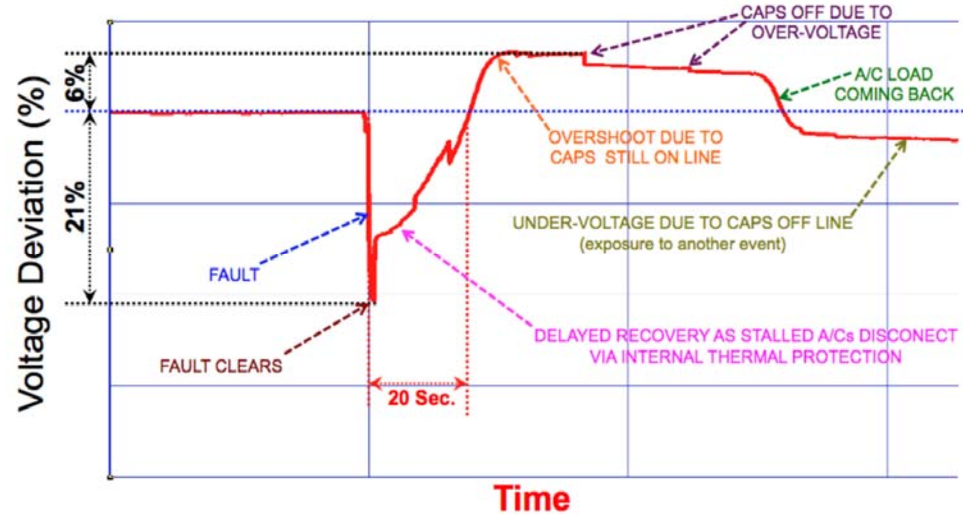
- Faults have debilitating effect on Grid, why? 20x rated current for seconds to 10's of seconds
- Ideal Application for Power Semiconductors (Loss? Hybrid devices?

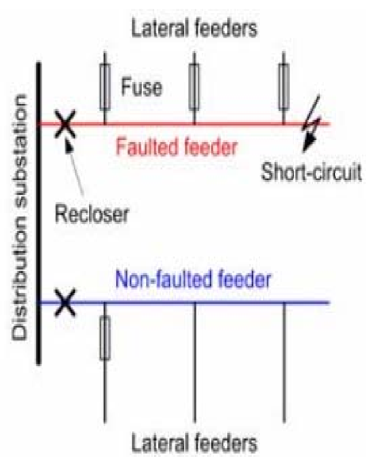


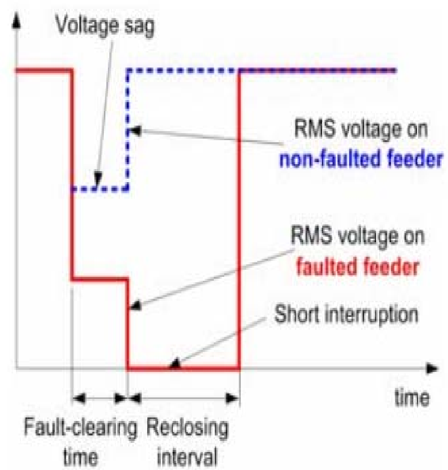
Advance Inverter Fault Capabilities

- LVRT (and OVRT and FRT and ROCOF)









- FIDVR
- Not compatible rotating machine based DG
- Inverter can provide real and reactive power

- **Fault studies limit DG penetration due to Recloser overload in substation with shared MV bus (common).**
- **Very big deal in some places today (Ontario)**
- **BUT, fault current is reactive as is traditional DG fault current.**
- **Inverter fault current?** **Overload Capability**
- **Much like inertia, what do you want it to be?**
- **Naturally the current is real, so orthogonal to fault current, but it could even be capacitive if needed**

- **Inertia, frequency, voltage ?**
- **Decouple? Freedom to vary inertia**

- **Devices**
- **Applications – Solutions**
- **Adoption ?**

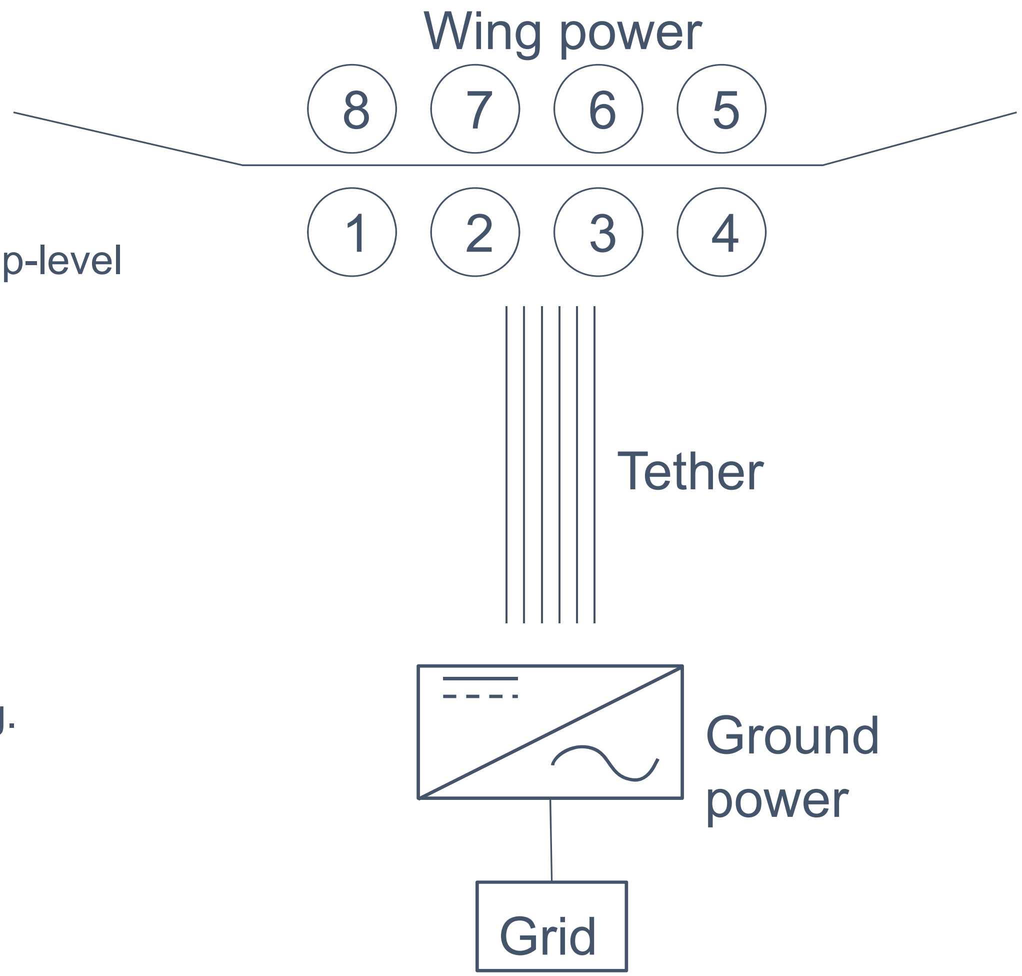
MAKANI – airborne wind turbine

SUBSYSTEM OVERVIEW

Wing-side
Eight two-quadrant motor/generators (M/G) (top-level spec)

Tether
4 - 16 separately insulated conductors
V ~ 4kV
I ~ 200A
DC (see justification later)

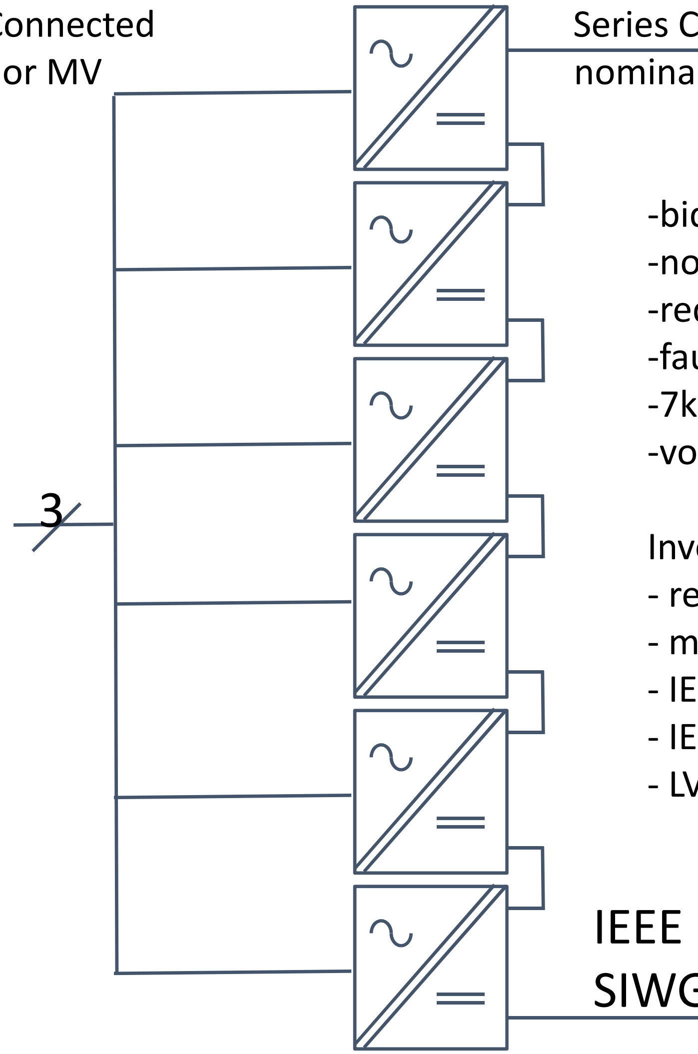
Grid-side
Standard service-level interconnect to grid (e.g. 480VAC 3ph 4w)



MV DC – Another Type of Multi-Level

Parallel Connected
480V ac, or MV

Series Connected
nominally 3400V (3200V -- 3600V)

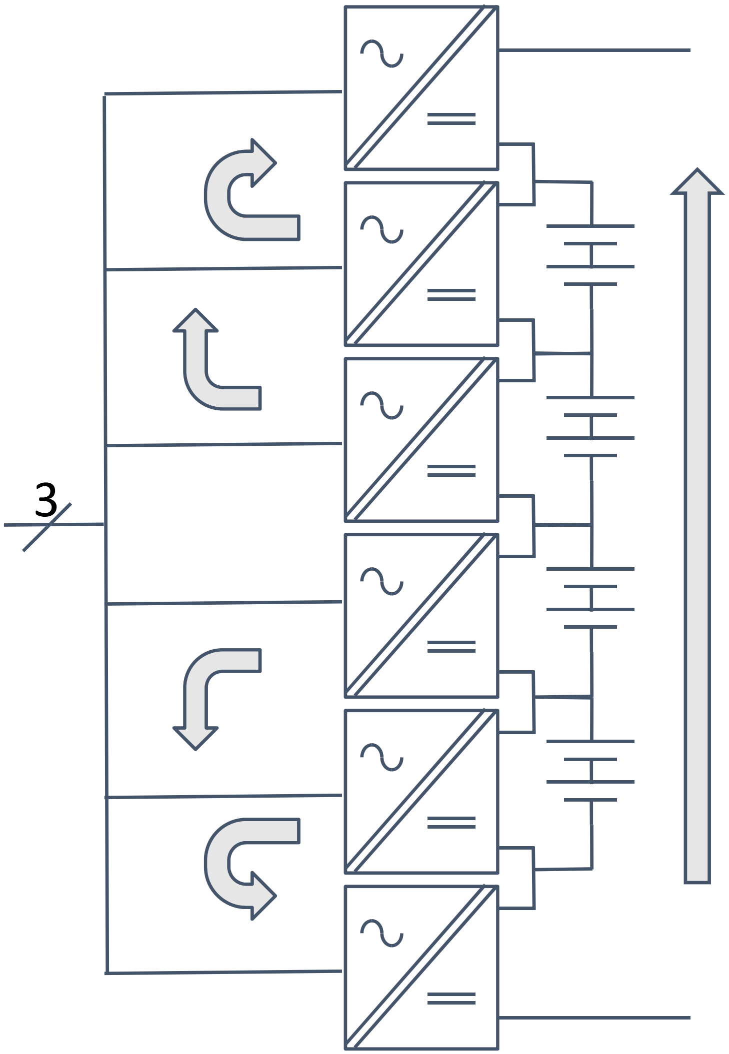


-bidirectional MV Inverter
-nominally 98% efficient
-redundant (6 x 125kW Inverters)
-fault limiting (wing faults, and inverter faults using current steering)
-7kHz switching, 6x interleaved, effective 40kHz switching rate
-voltages stack to 3200--3600V but can be independent

Inverter and Advanced Inverter Features
- remotely controllable
- metering/monitoring (remote)
- IEEE519 harmonics
- IEEE1547 and UL1741 anti-islanding
- LVRT, ZVRT, Ramp rates,

IEEE 1547 certified inverters + UL1741, CE, CEC-rule-21, CEC-SIWG, Hawaii, PREPA, ...

Simple Storage Integration (single wing)



Ideal Power Dispatch

-ramp up smoothly

-maintain constant dispatched power

-ramp down smoothly

-Partial Power (rating) Scheme

-direct connection of battery

-as battery voltages fall under loading and discharge, outer inverters compensate for the droop

-OR - one battery per inverter, but use contactor/switch to control stack level voltage