Solid State Transformer and FREEDM System Power Management Strategies

Prof. Alex Q. Huang, Progress Energy Distinguished Professor
NSF FREEDM Systems Center
NC State University

FREEDM SYSTEMS CENTER

NC STATE UNIVERSITY

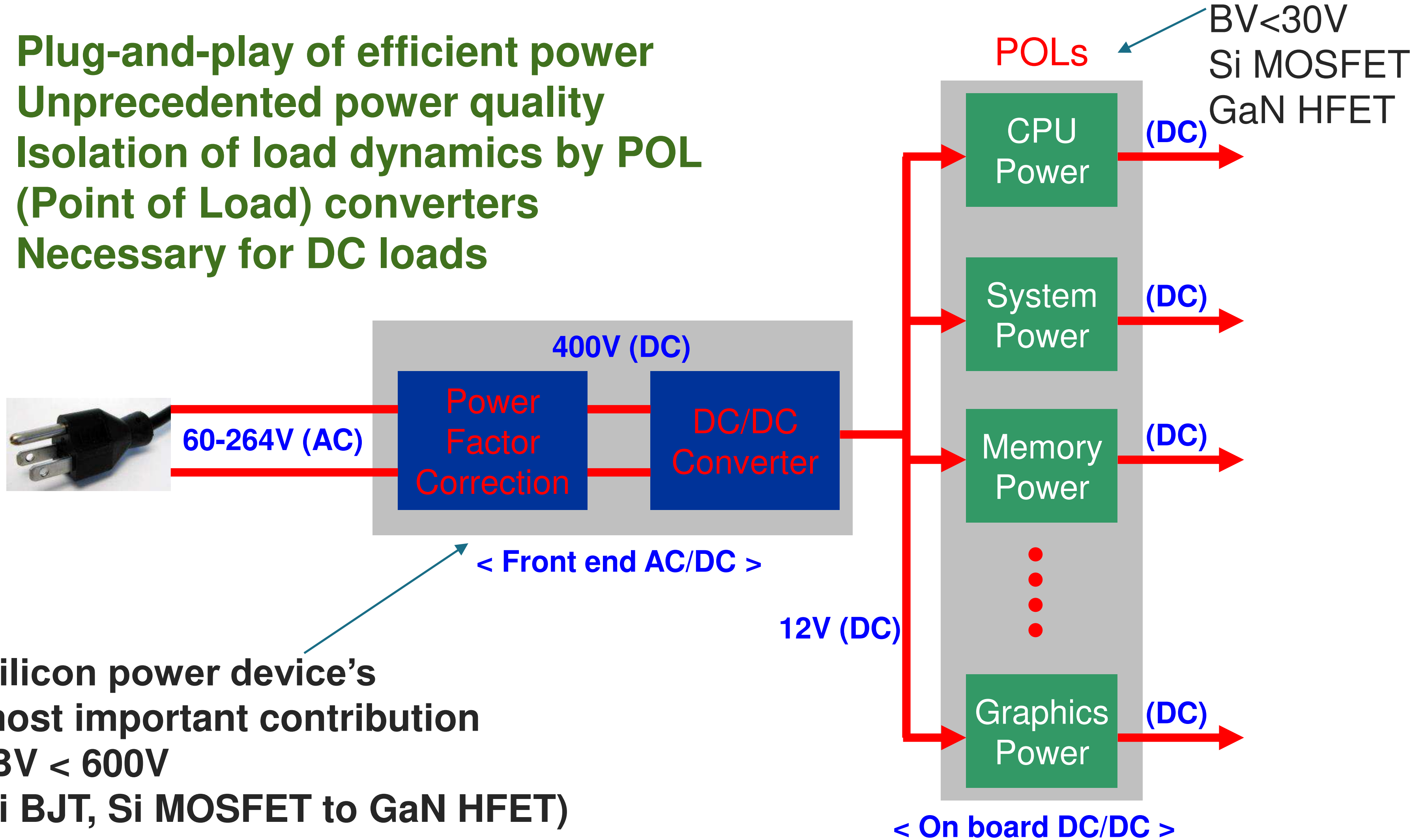
NSF

Presentation Outline

1. FREEDM System: A Resilient and Smart Distribution System
2. Solid State Transformer
    - Three Generations of FREEDM Developed SST Technology
3. Advanced Power Management Functions of the SST
4. FREEDM System Intelligent Power Management (IPM) Control
5. Towards Energy Internet

Low Voltage Power Delivery System at the Edge of ICT: Power Electronics Impact in the last 50 Years

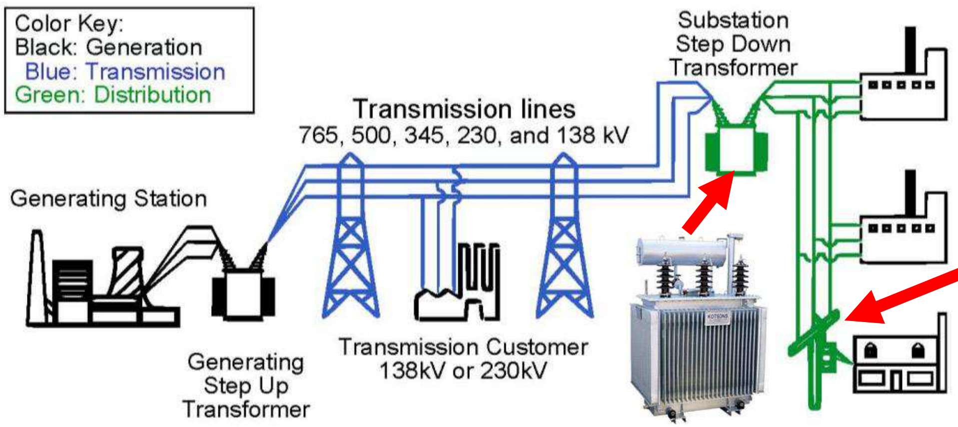
- Plug-and-play of efficient power
- Unprecedented power quality
- Isolation of load dynamics by POL
- (Point of Load) converters
- Necessary for DC loads



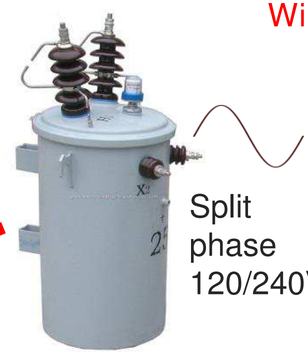
Silicon power device's most important contribution (BV < 600V Si BJT, Si MOSFET to GaN HFET)

BJT: 1947 — 1970: SMPS — 1980: power MOSFET — 2010: GaN HFET

High Voltage and Medium Voltage Power Delivery System: Grid Edge Control Challenge



Electricity grid in North America. Source: [1]



Distribution grid transformer (pole mounted)

Transformer History: invented in 1886 by William Stanley

- Designed for unidirectional power flow and century-old transformer technology with little controllability beyond substation
- Requires a wide spectrum of products for power quality improvement (SVC, active filter, voltage compensator, DVR, etc.)
- Strong coupling and won’t isolate harmonics/other disturbances
- Not friendly for integration of renewable energy source (DC-typed sources need more conversion stages, synchronization), EV, electronic load

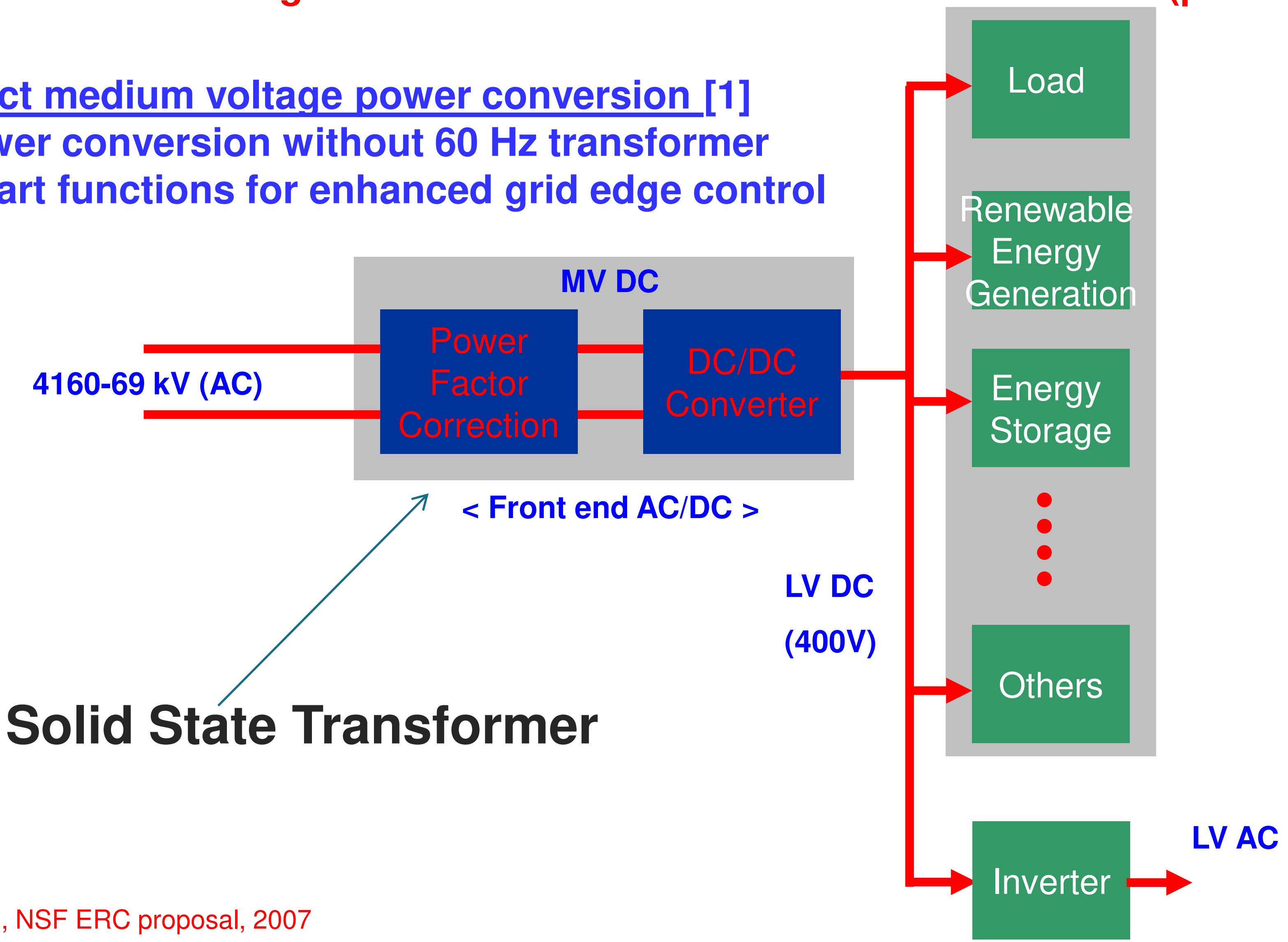
[1] Electricity grid simple- North America" by United States Department of Energy, SVG version by User:J Jmesserly - http://www.ferc.gov/industries/electric/indus-act/reliability/blackout/ch1-3.pdf Page 13 Title:"Final Report on the August 14, 2003 Blackout in the United States and Canada" Dated April 2004. Accessed on 2010-12-25. Licensed under Public domain via Wikimedia Commons http://commons.wikimedia.org/wiki/File:Electricity_grid_simple-_North_America.svg#mediaviewer/File:Electricity_grid_simple-_North_America.svg

Direct medium voltage power conversion

Addressing climate change grand challenge: higher penetration of distributed generation/storage/renewable hence the need for better control (μs~hour)

Direct medium voltage power conversion [1]

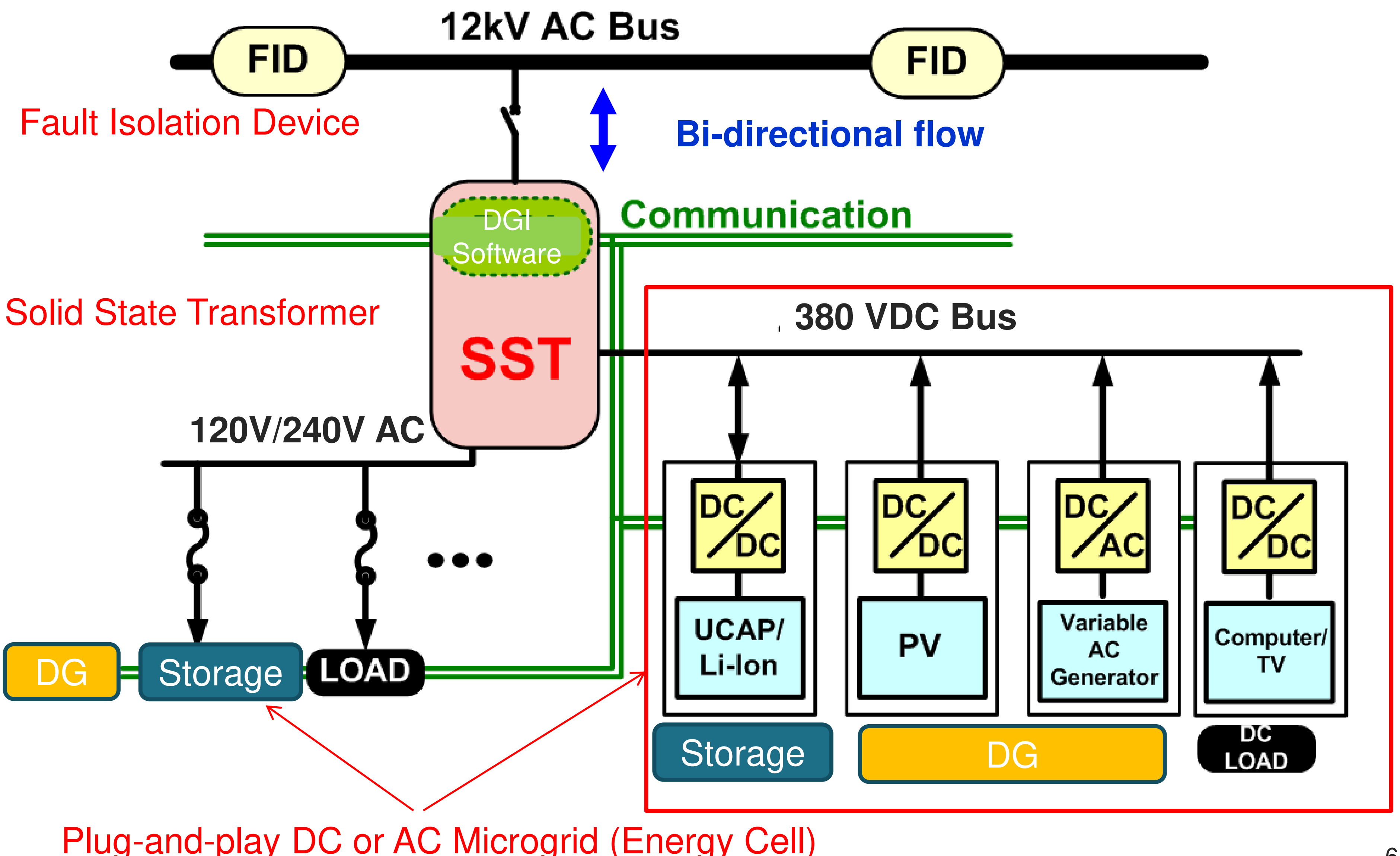
- **power conversion without 60 Hz transformer**
- **Smart functions for enhanced grid edge control**



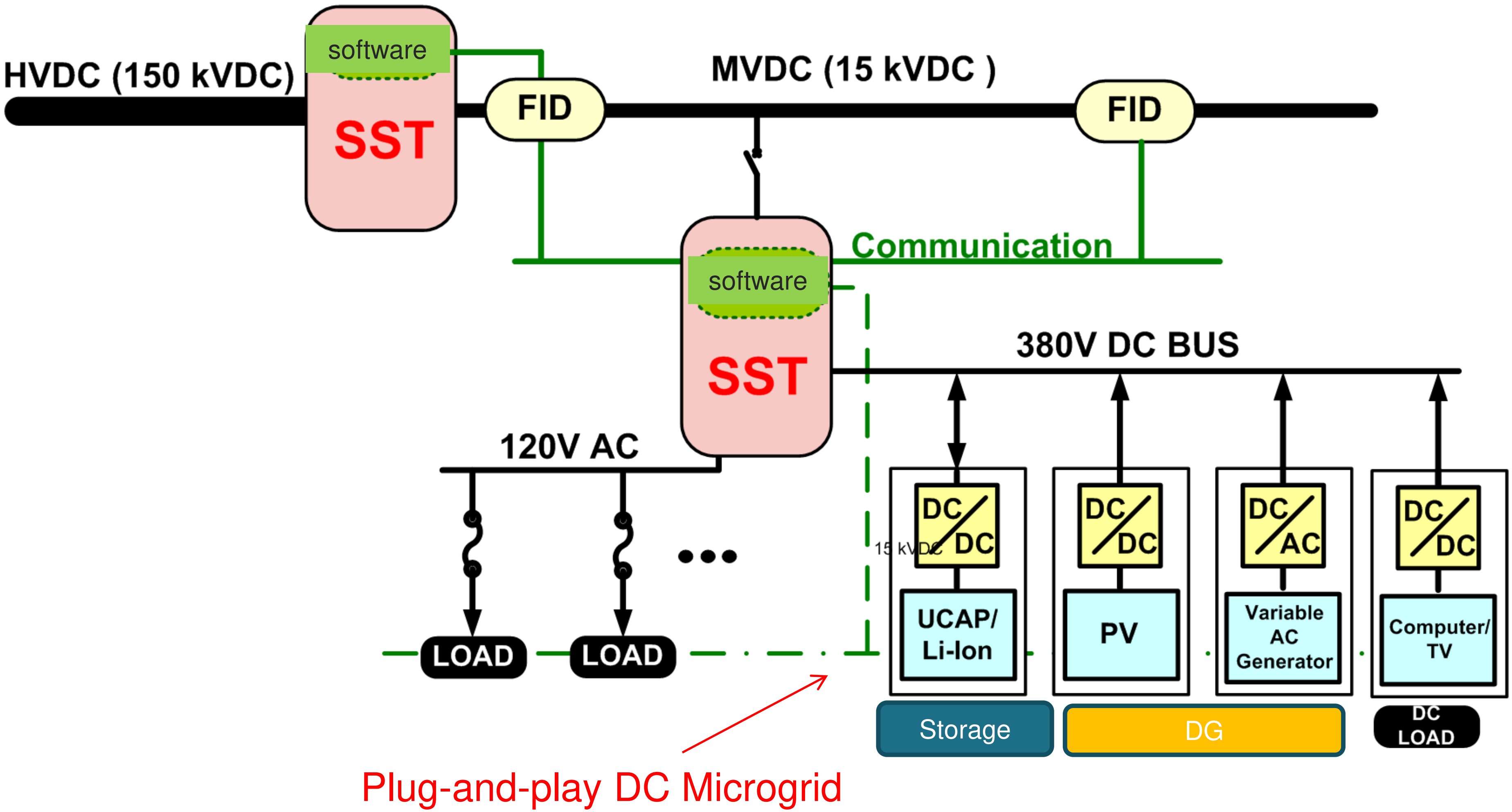
[1] Huang, NSF ERC proposal, 2007

FREEDM System Physical Architecture

A resilient grid and an ubiquitous IT node are needed for future grid



SST for A Complete DC Grid

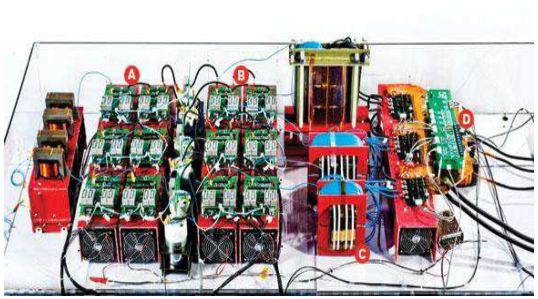


In this case SST is absolutely needed since there is no 60Hz DC Transformer

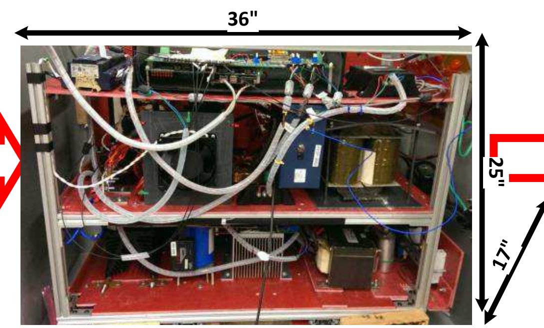
Medium Voltage (MV) SST Technical Approach & Research Areas

Vision:
(plug-and-play and resilient grid for high DER penetration)

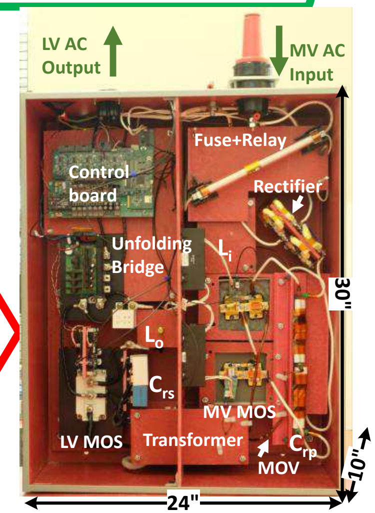
60Hz Transformer



Gen- 1 SST: Si-based (6.5 kV IGBT 3kHz)



Gen- 2 SST: SiC-based (15 kV SiC MOSFET 10 kHz)



Gen- 3 SST: SiC @ 40 kHz

Controls

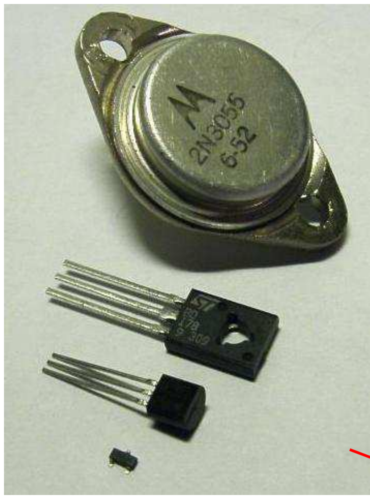
Topology /magnetics

Wide Bandgap Devices

SiC & GaN power devices, other wide bandgap

WBG power device packaging

SST Grand Challenge: High Input Voltage



????

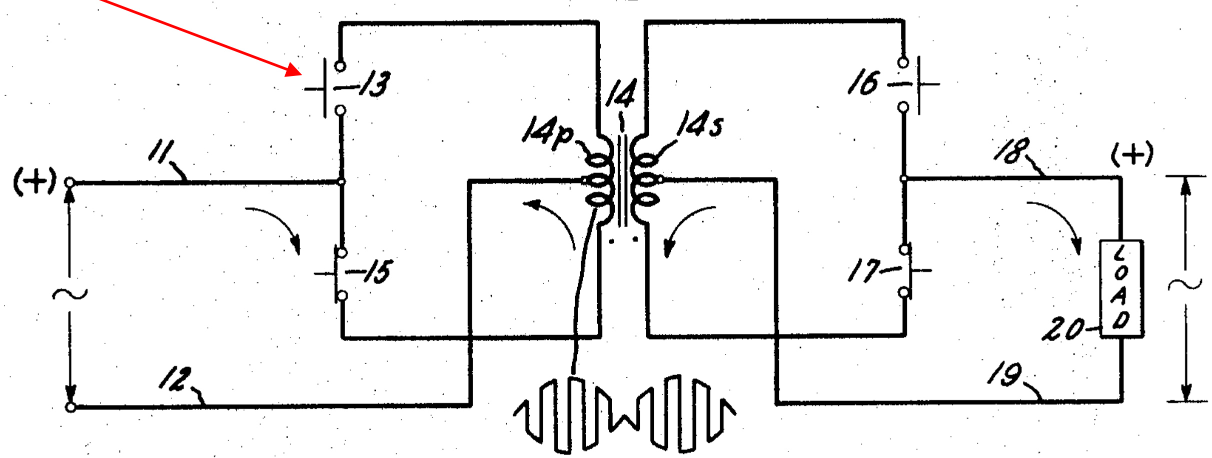
United States Patent Office

1

3,517,300
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK
William McMurray, Schenectady, N.Y., assignor to General Electric Company, a corporation of New York
Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims

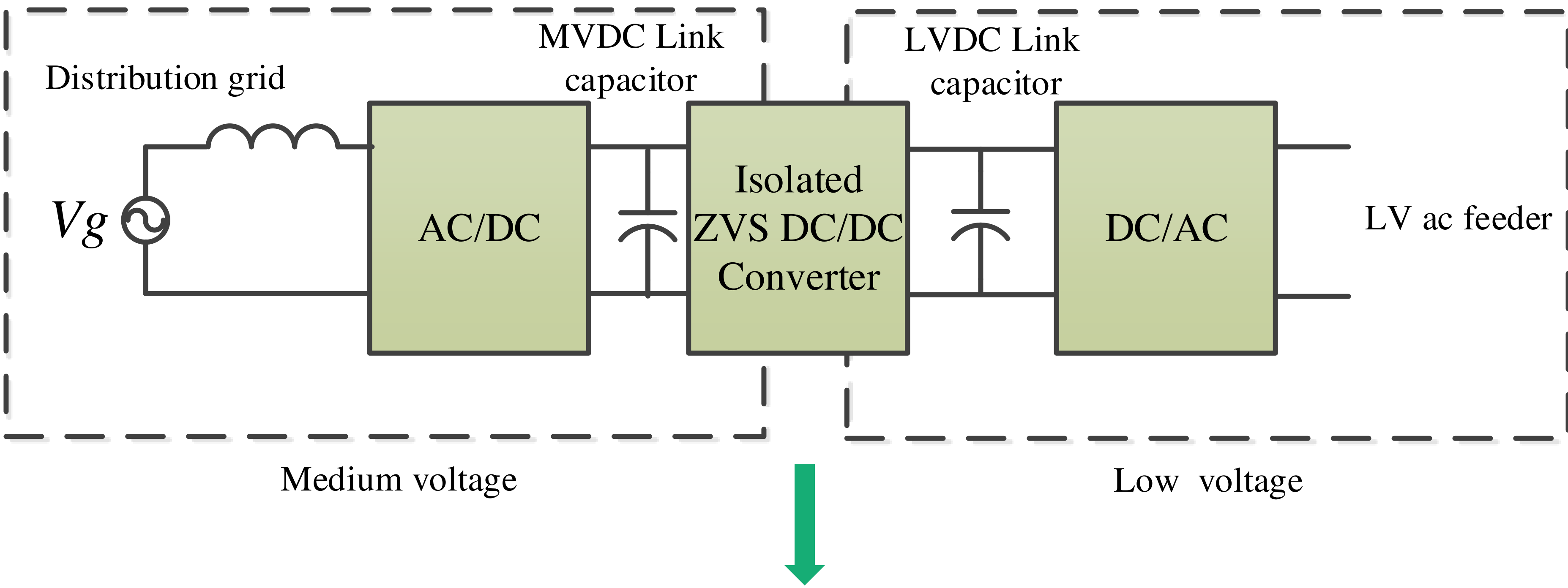
To be economica verter circuit shou such as current li regulation, and cu now provided by example circuit t changers, but the p the circuit suggests

Fig. 1a



- 1968: Si bipolar transistor breakdown voltage is only ~100V
- Also the topology is not directly usable due to voltage overshoot etc

Three Stage Medium Voltage SST

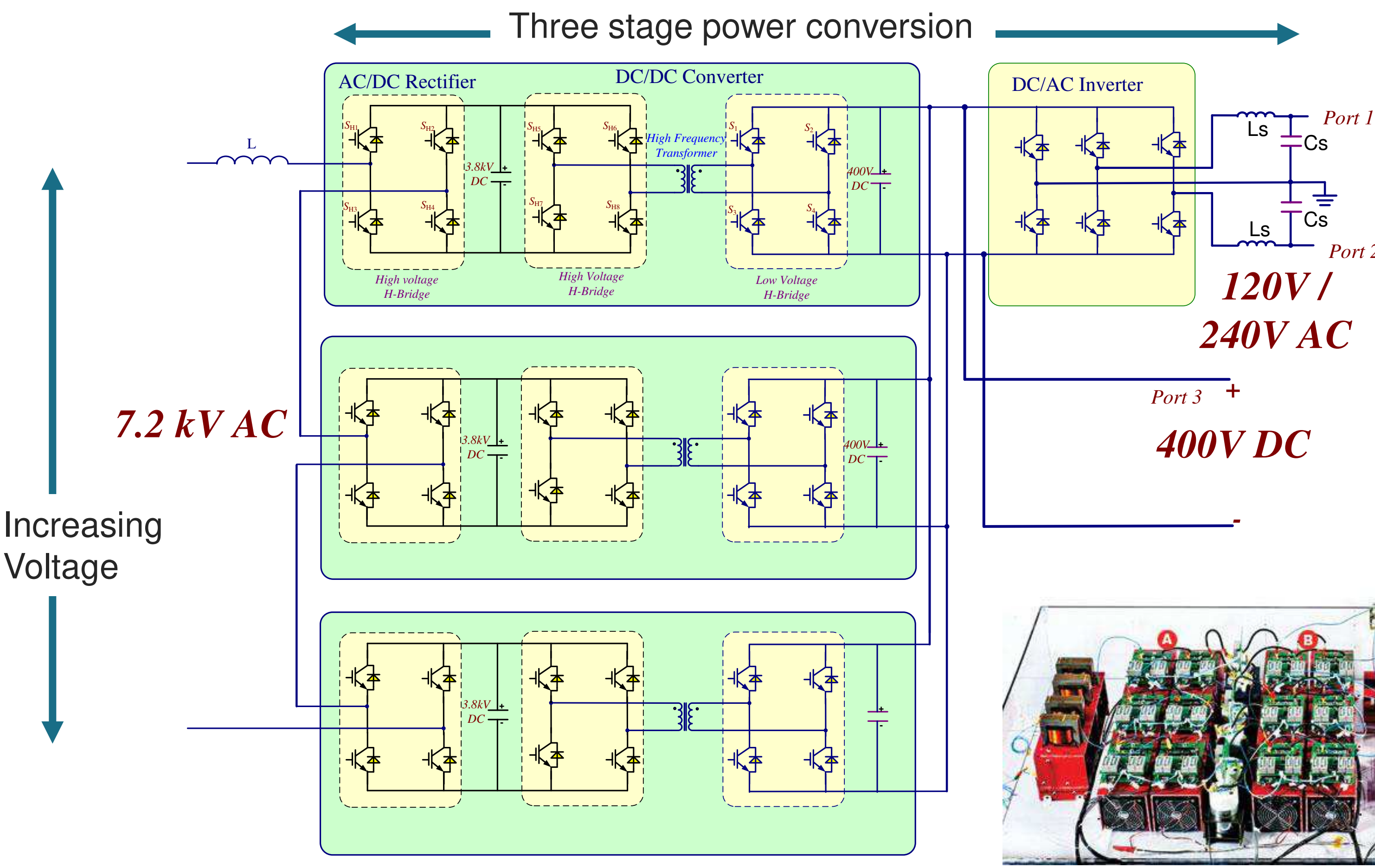


Medium Frequency Transformer for galvanic isolation

SST Grand Challenge: High Input Voltage

Gen-I SST 6.5kV Si IGBT based

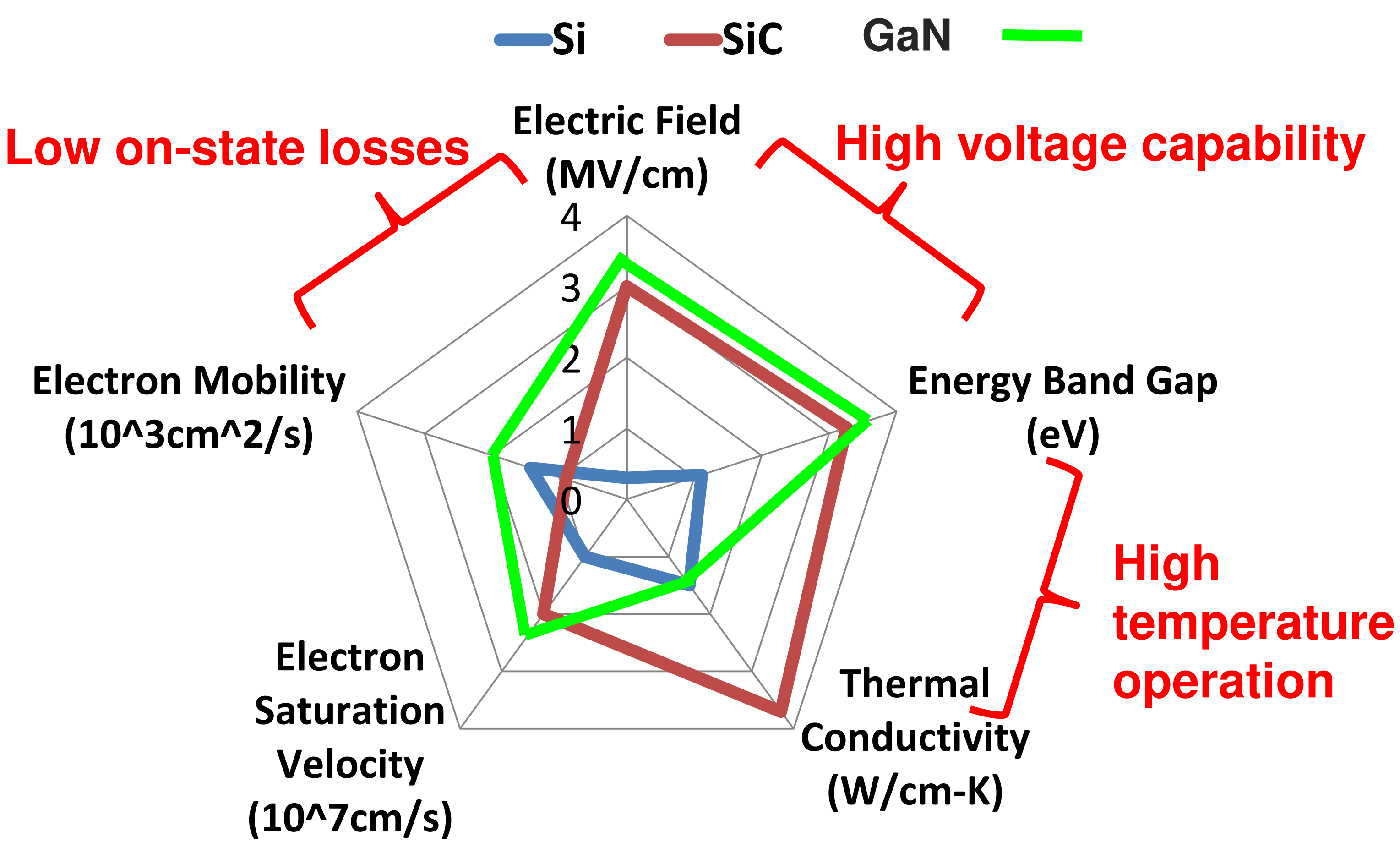
Input: 7.2kVac Output: 240Vac/120Vac; 400Vdc Power rating: 20kVA



6.5-kV / 25-A Si IGBT

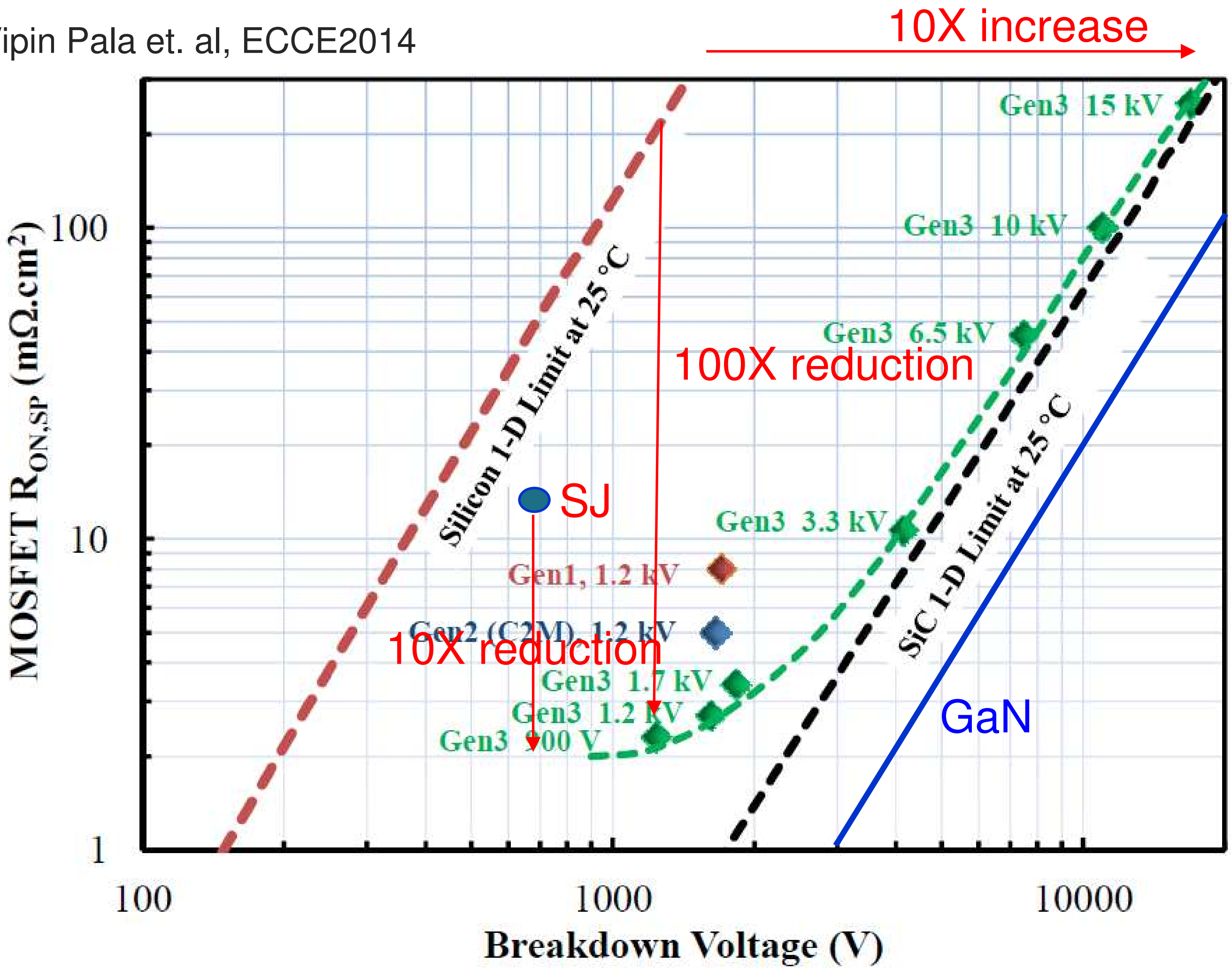
Wang et. al, "Design and hardware implementation of Gen-1 silicon based solid state transformer," APEC 2011

WBG Material Advantages



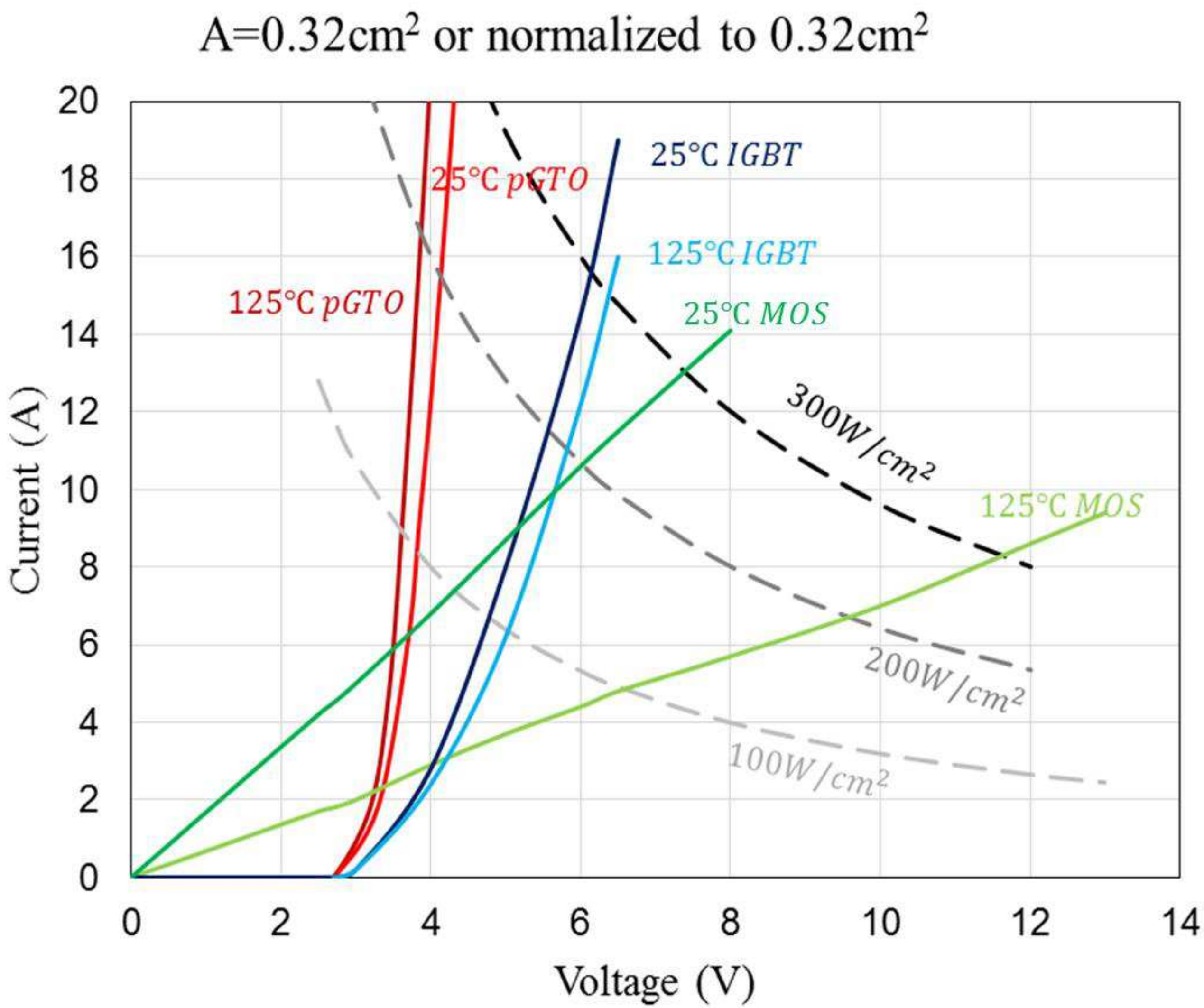
SiC Capability

Source: Vipin Pala et. al, ECCE2014



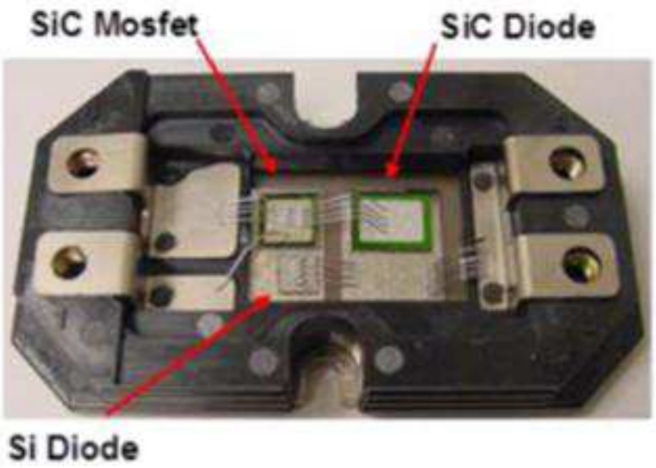
Theoretically about 1000X reduction over Si MOS
Currently about 100X reduction achieved for >600V range
The improvement is only about 10X over SJ devices!

15kV SiC GTO, n-IGBT and MOSFET

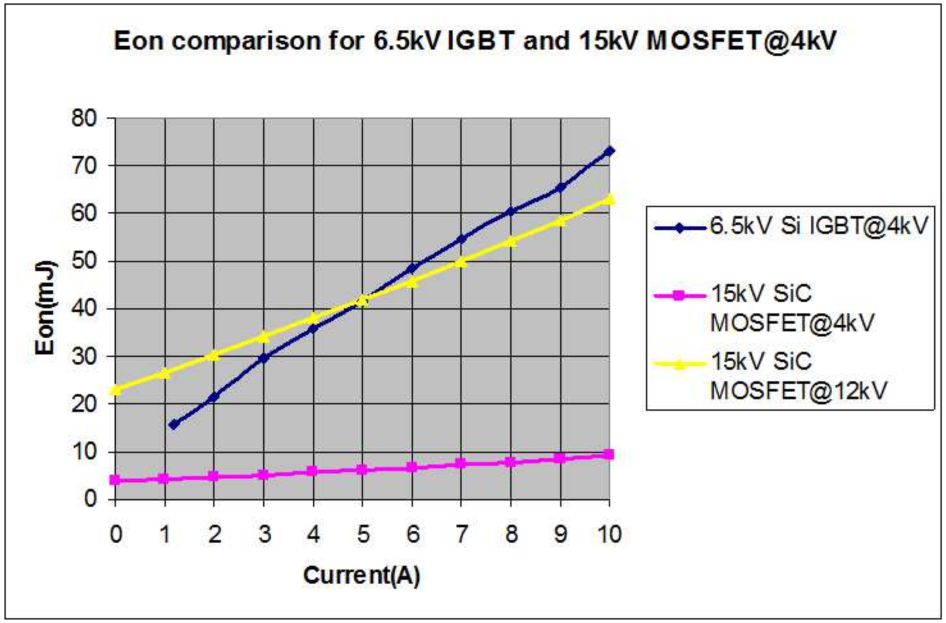


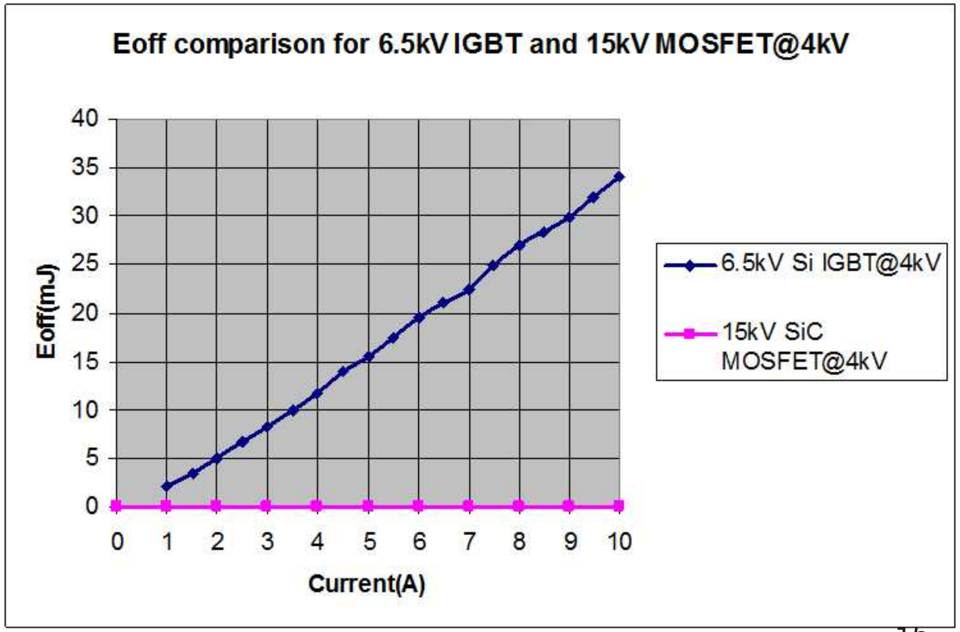
SiC bipolar devices are more suitable for high temperature operation

15 kV SiC MOSFET Switching Losses

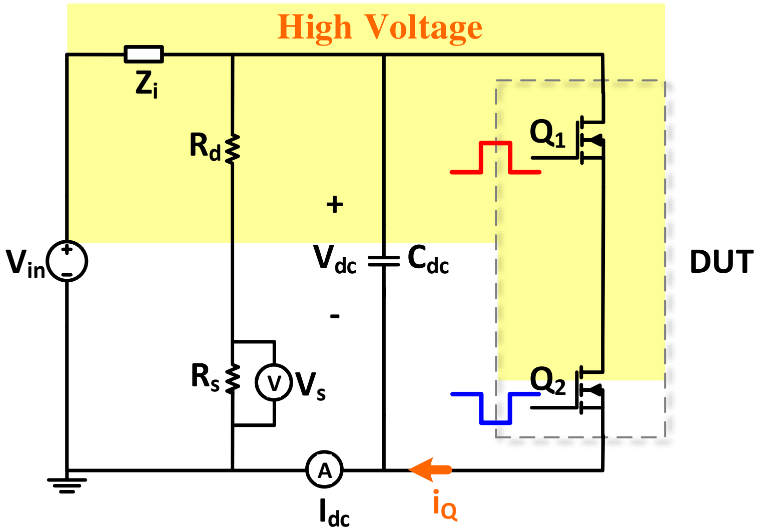


- Much lower switching loss compared with 6.5 kV IGBT;
- Up to 8 kHz even in hard switching condition.
- Turn-on loss can be eliminated in ZVS operation





15 kV SiC MOSFET Output Charge Measurement and Modeling

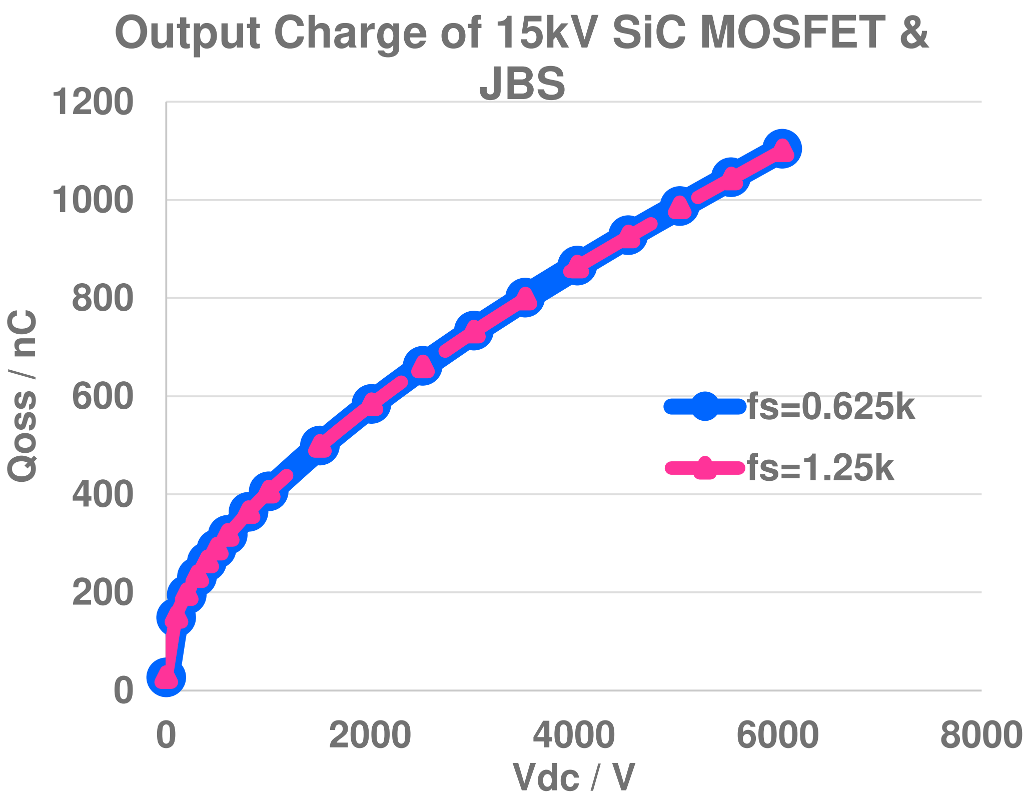


Half-Bridge Output Charge Measurement System

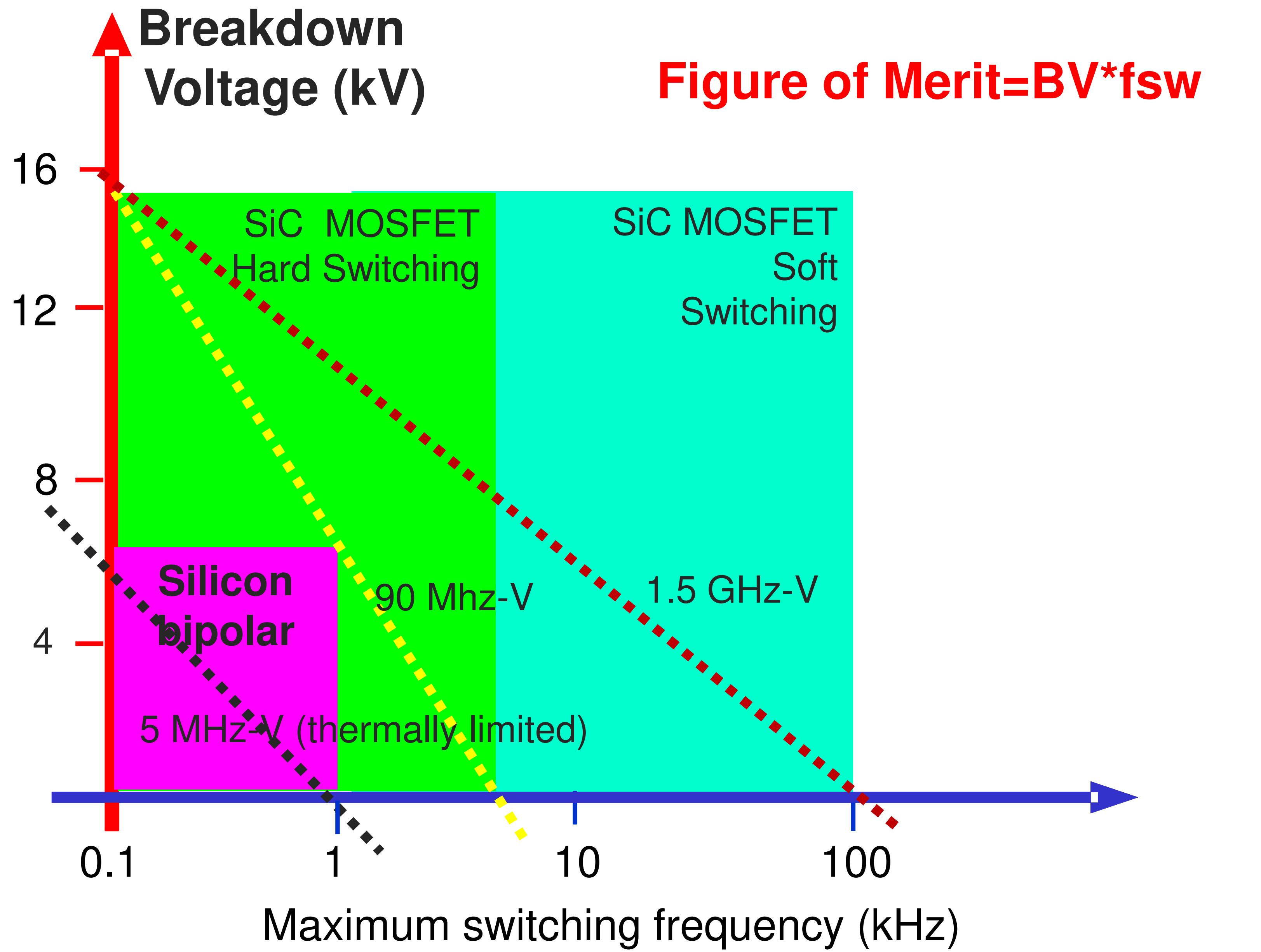
- Δ **Simple configuration**
- Δ **<u>High voltage (up to kV)</u>**
- Δ **<u>High accuracy (<1% error)</u>**
- Δ **No special equipment needed**

Output charge model :

$$Q_{oss}(V_{ds}) \approx 11.43\sqrt{V_{ds}} + 0.0406\ (nC)$$



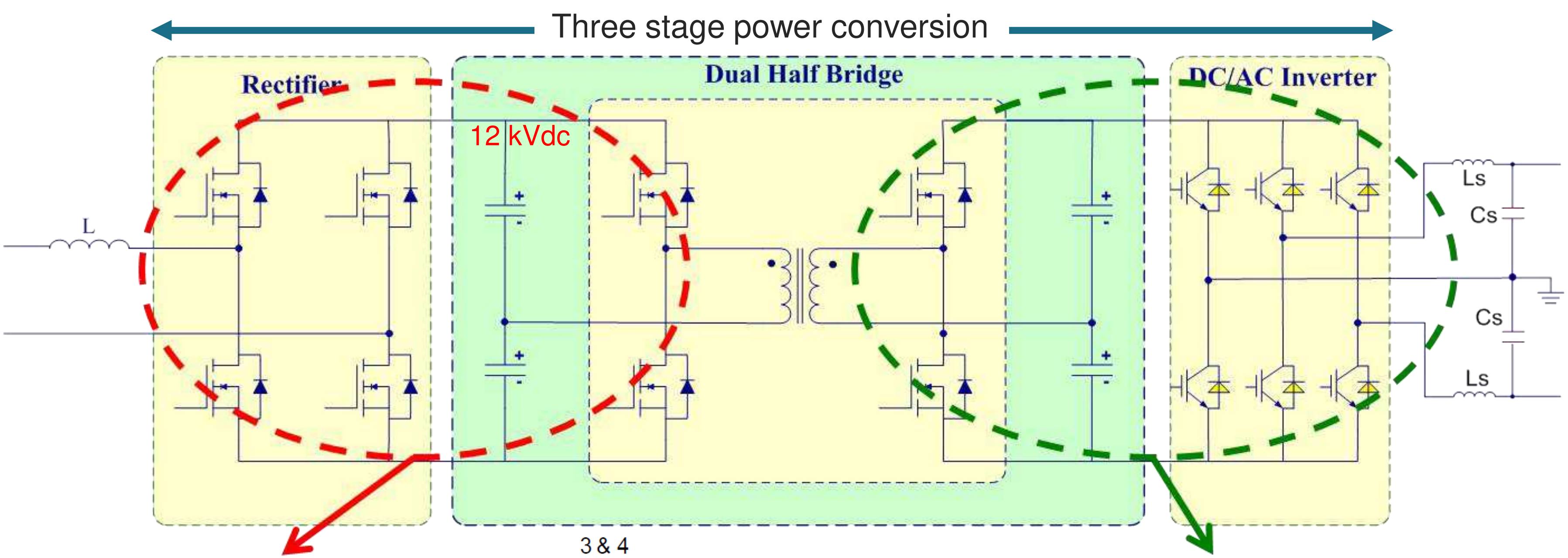
With SiC MOSFET: 15 to 300 X improvements



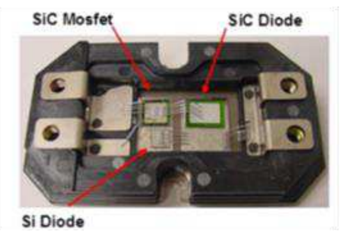
Three Stage SST with DAB Isolated DC-DC Converter

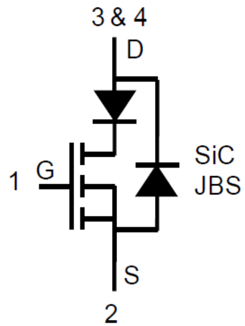
Gen-II SST Specifications:
- **Input: 7.2kVac**
- **Output: 240Vac/120Vac; 400Vdc**
- **Power rating: 20kVA**

Tested Condition:
- **Input: 3.6kVac**
- **Output: 240Vac; 400Vdc**
- **Power rating: 10kVA**

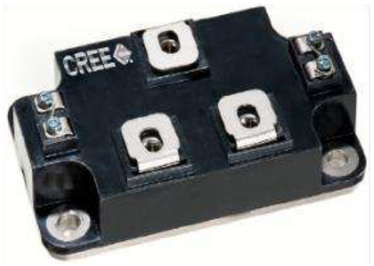


15kV 10A SiC MOSFET

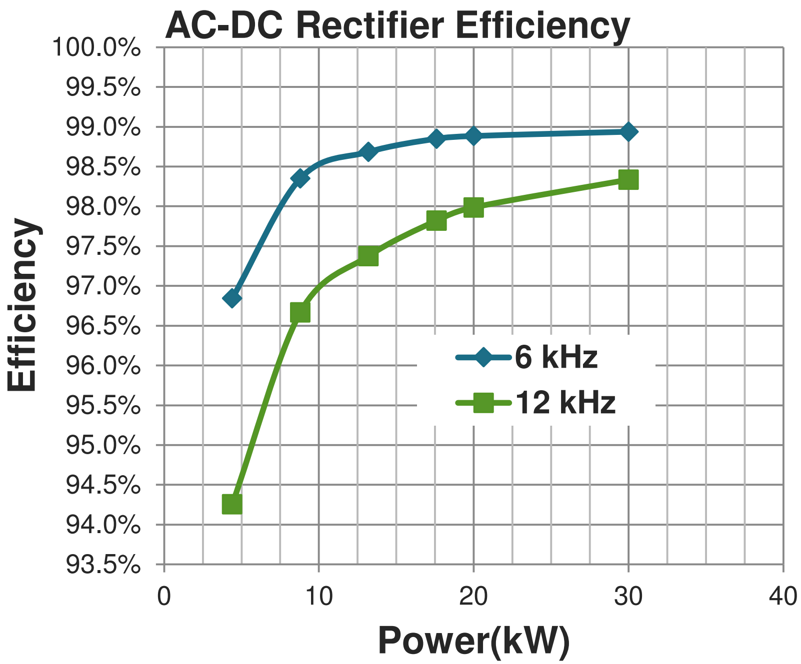


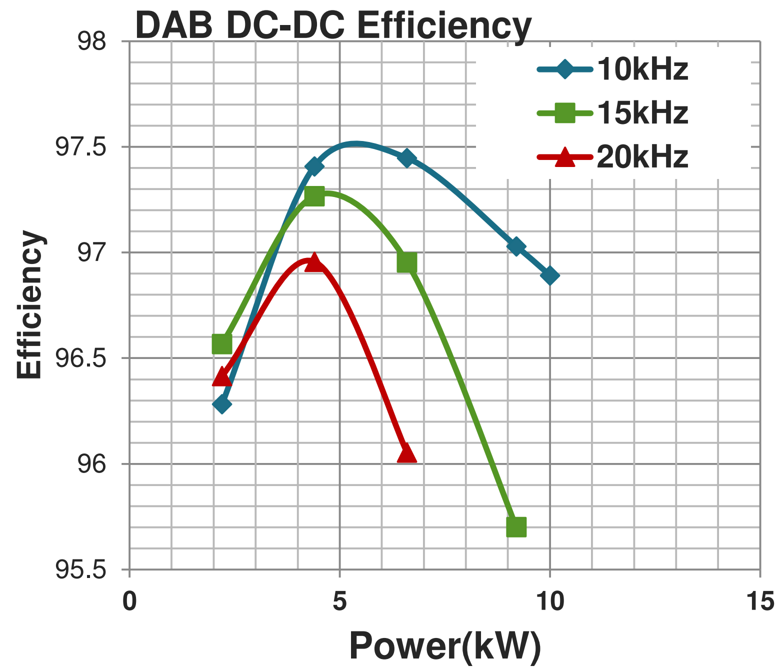


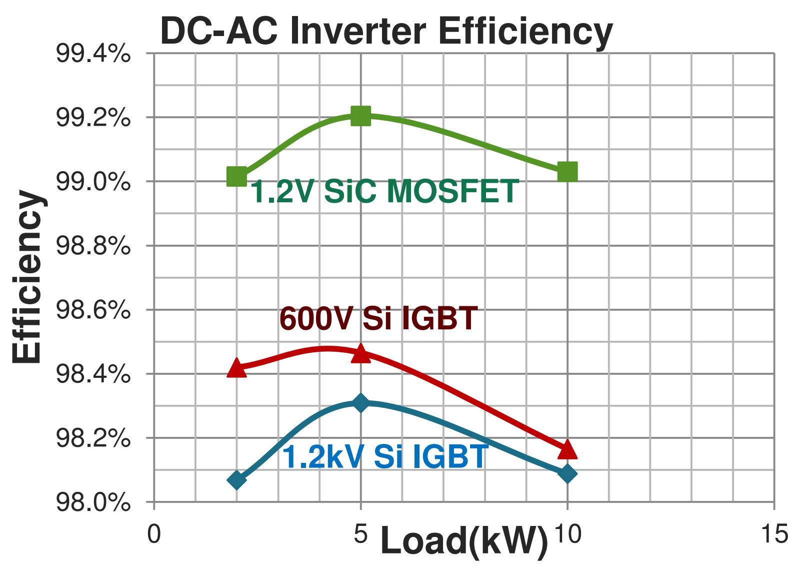
1200V 100A SiC MOSFET

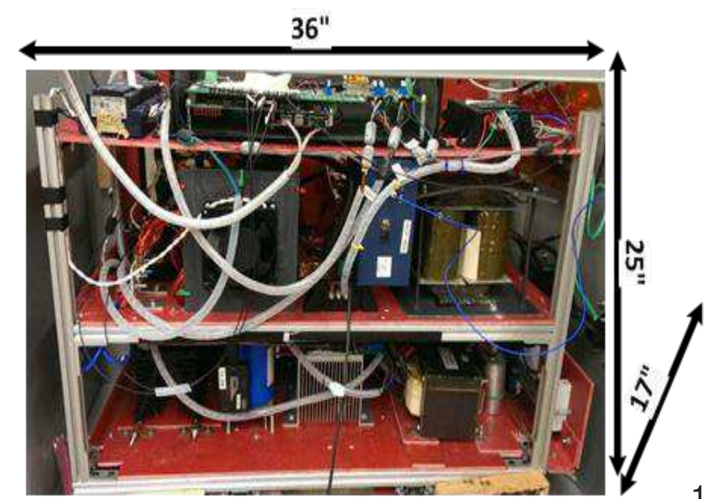


Measured Efficiency of Three Stage SST with DAB Isolated DC-DC Converter









Improved Three Stage SST with SRC Isolated DC-DC Converter

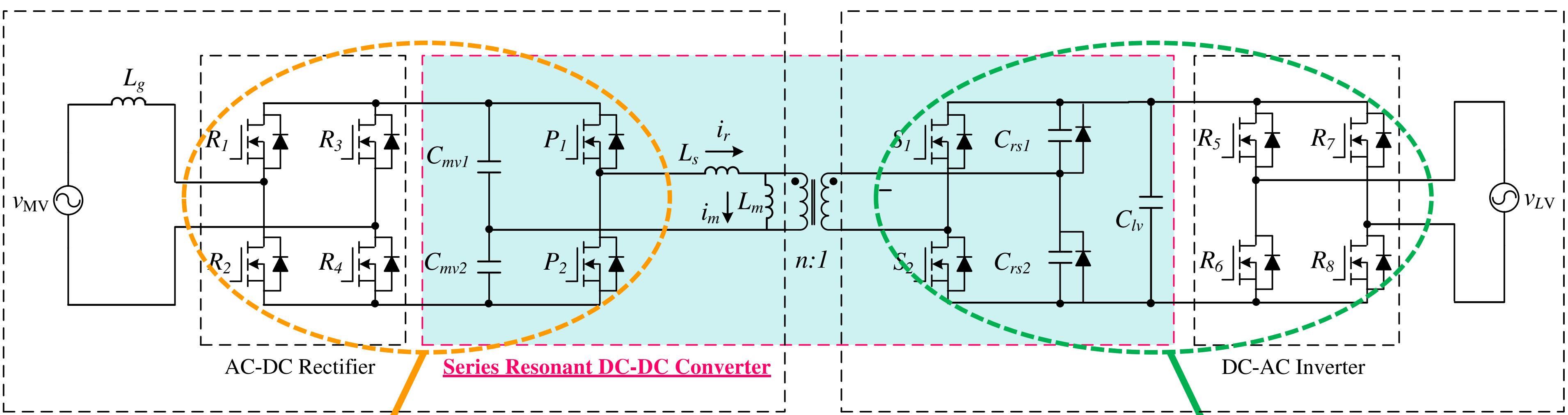
Gen-II SST Specifications:

- Input: 7.2kVac
- Output: 240Vac/120Vac; 400Vdc
- Power rating: 20kVA

Tested Condition:

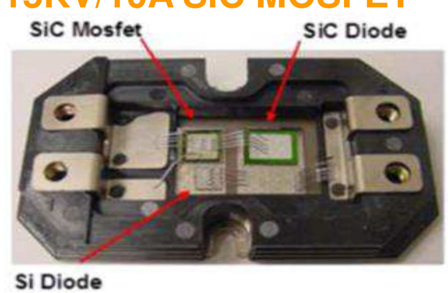
- Input: 3.6kVac
- Output: 240Vac; 400Vdc
- Power rating: 10kVA

Three stage power conversion



Medium Voltage

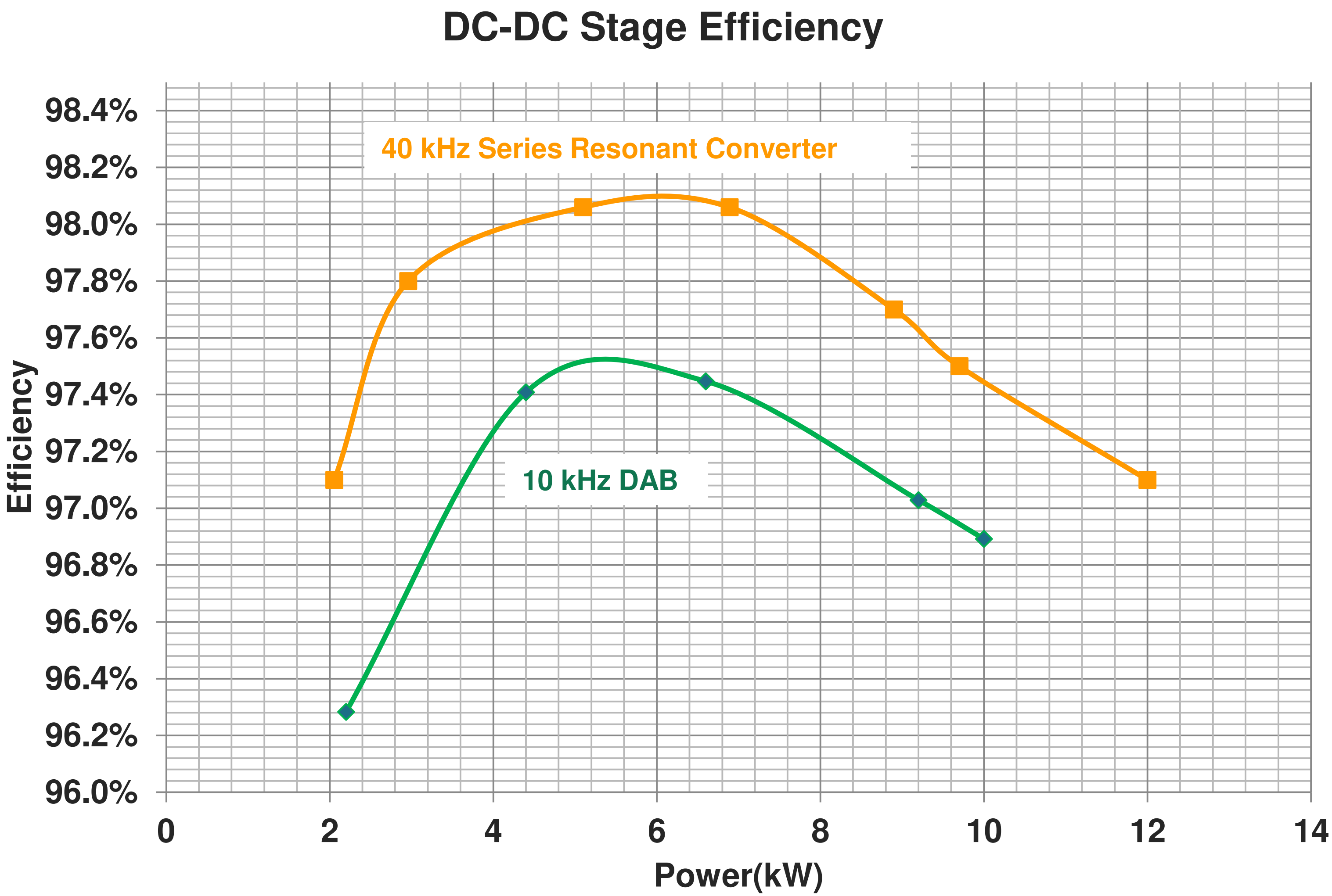
15KV/10A SiC MOSFET



Low Voltage

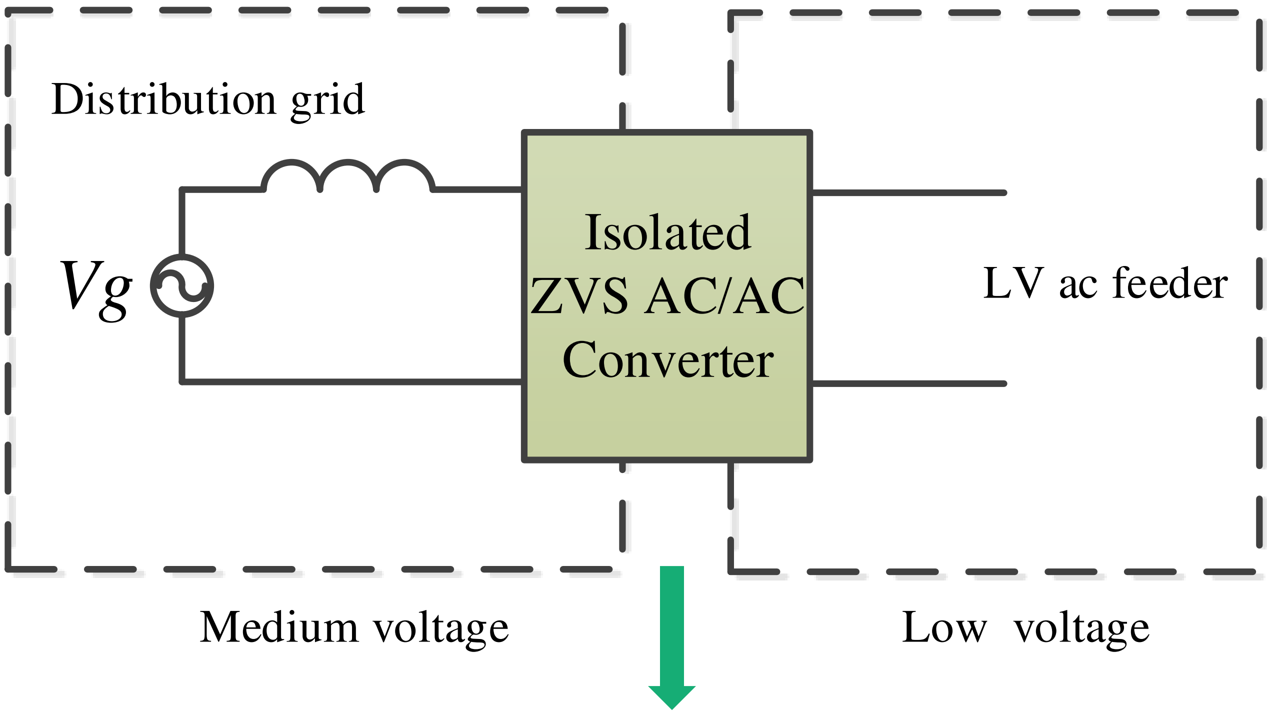
1.2KV/100A SiC MOSFET

Medium Voltage Isolated DAB vs SRC



- Soft Switching Over Full Load range
- Improved medium frequency transformer design

Single Stage Medium Voltage SST



Medium Frequency Transformer for galvanic isolation

Single Stage Medium Voltage SST

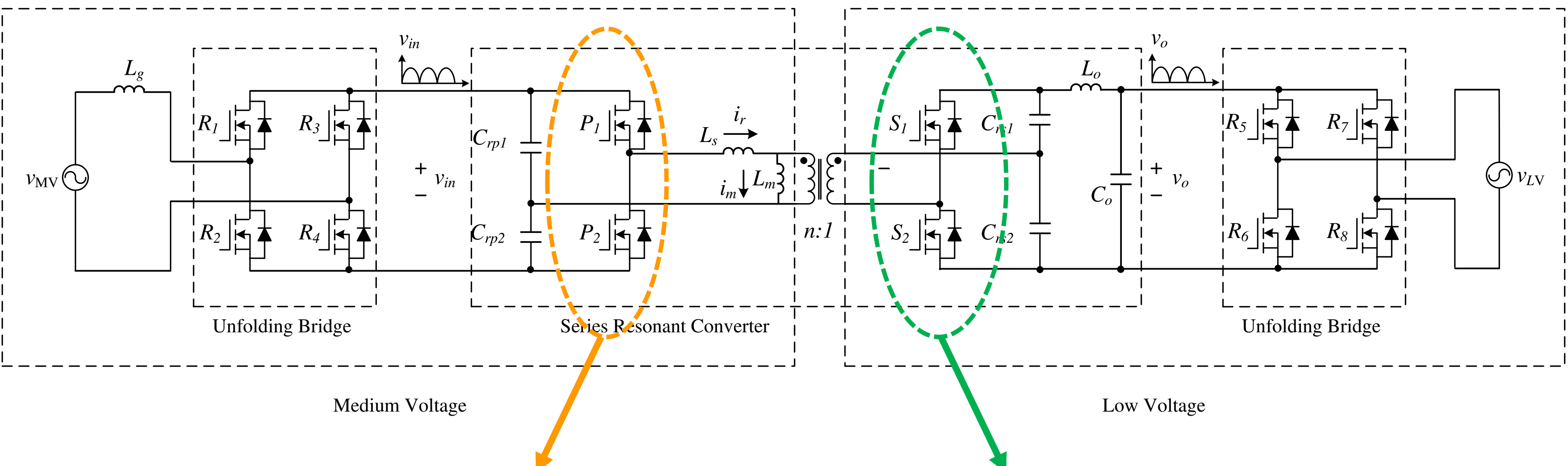
Gen-III SST Specifications:

- **Input: 7.2kVac**
- **Output: 280Vac**
- **Power rating: 20kVA**

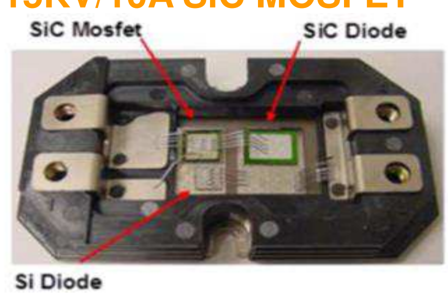
Tested Conditions:

- **Input: 3.6kVac**
- **Output: 280Vac**
- **Power rating: 10kVA**

Single stage power conversion

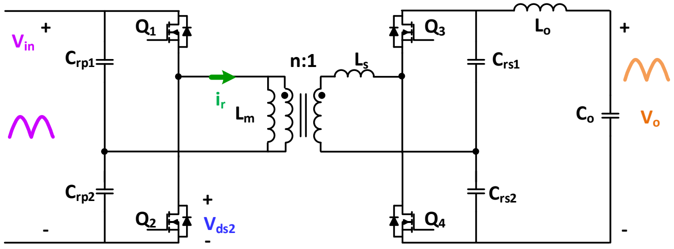


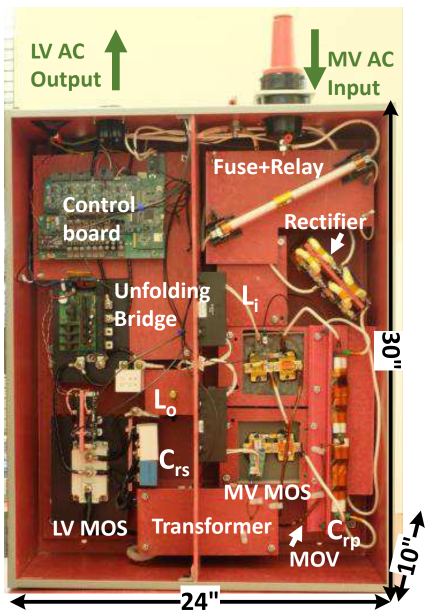
15KV/10A SiC MOSFET

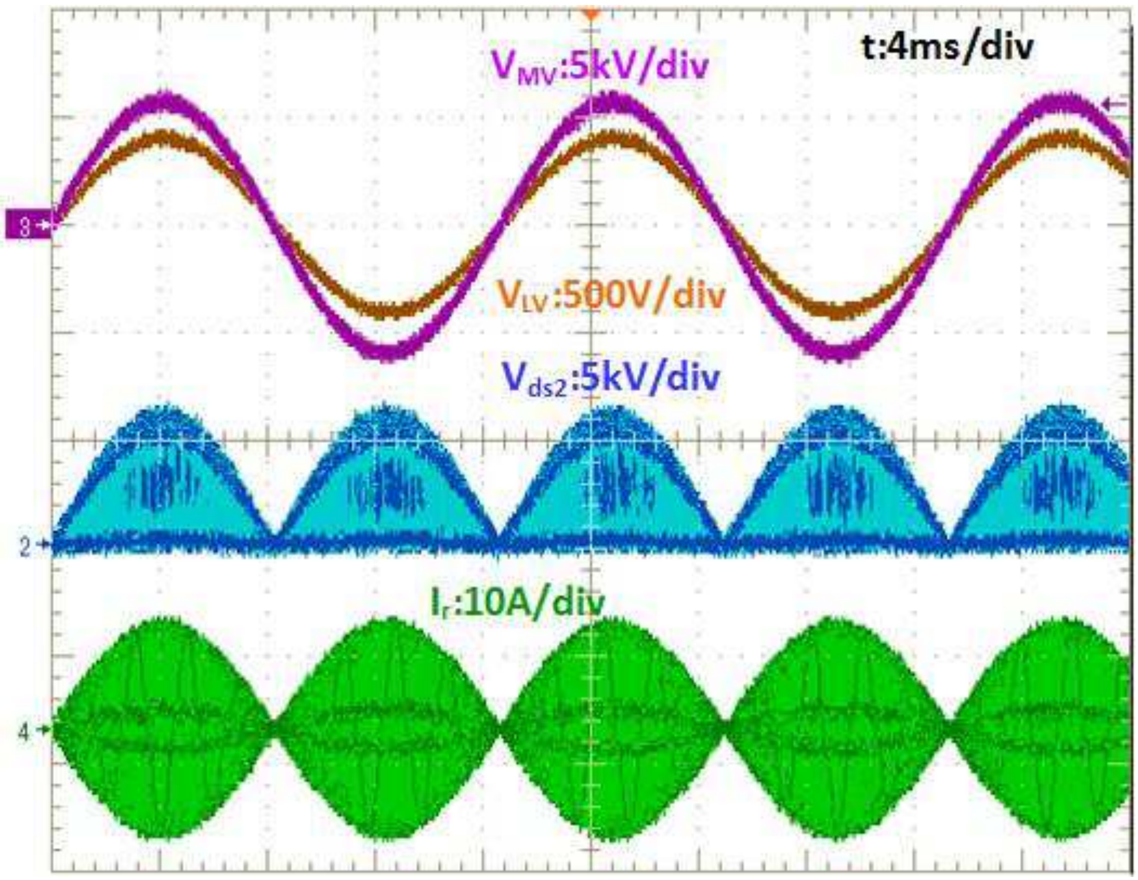


1.2KV/100A SiC MOSFET

Gen-III SST Major Achievement:
Vin=4.2 kV AC, Po = 8kW







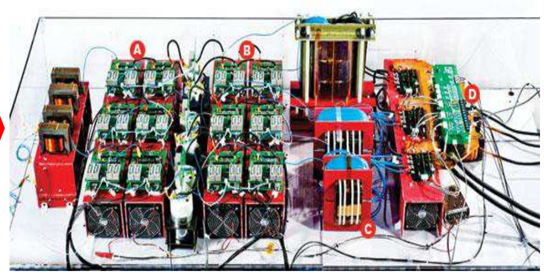
Gen-III SST Prototype
(24inch*30inch*10inch)

4.2kV AC – 280V AC Experimental Waveforms @ 8kW

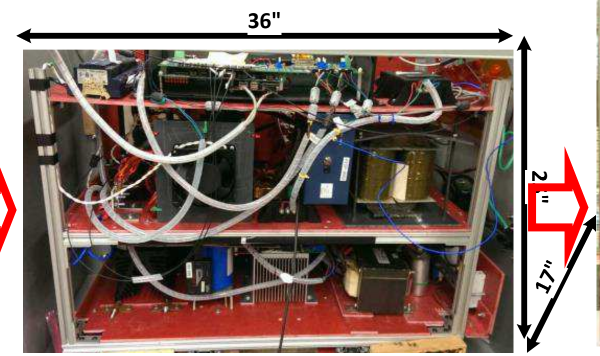
Three Generations of SSTs

Transformation of the distribution power grid with smart Solid State Transformers

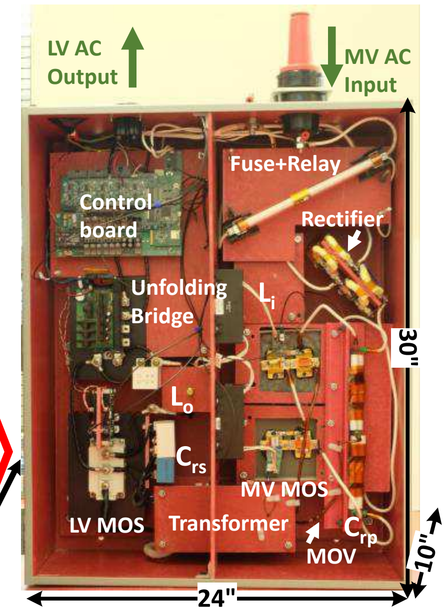
60Hz Transformer



Gen- 1 SST:
6.5 kV IGBT
@ 3 kHz



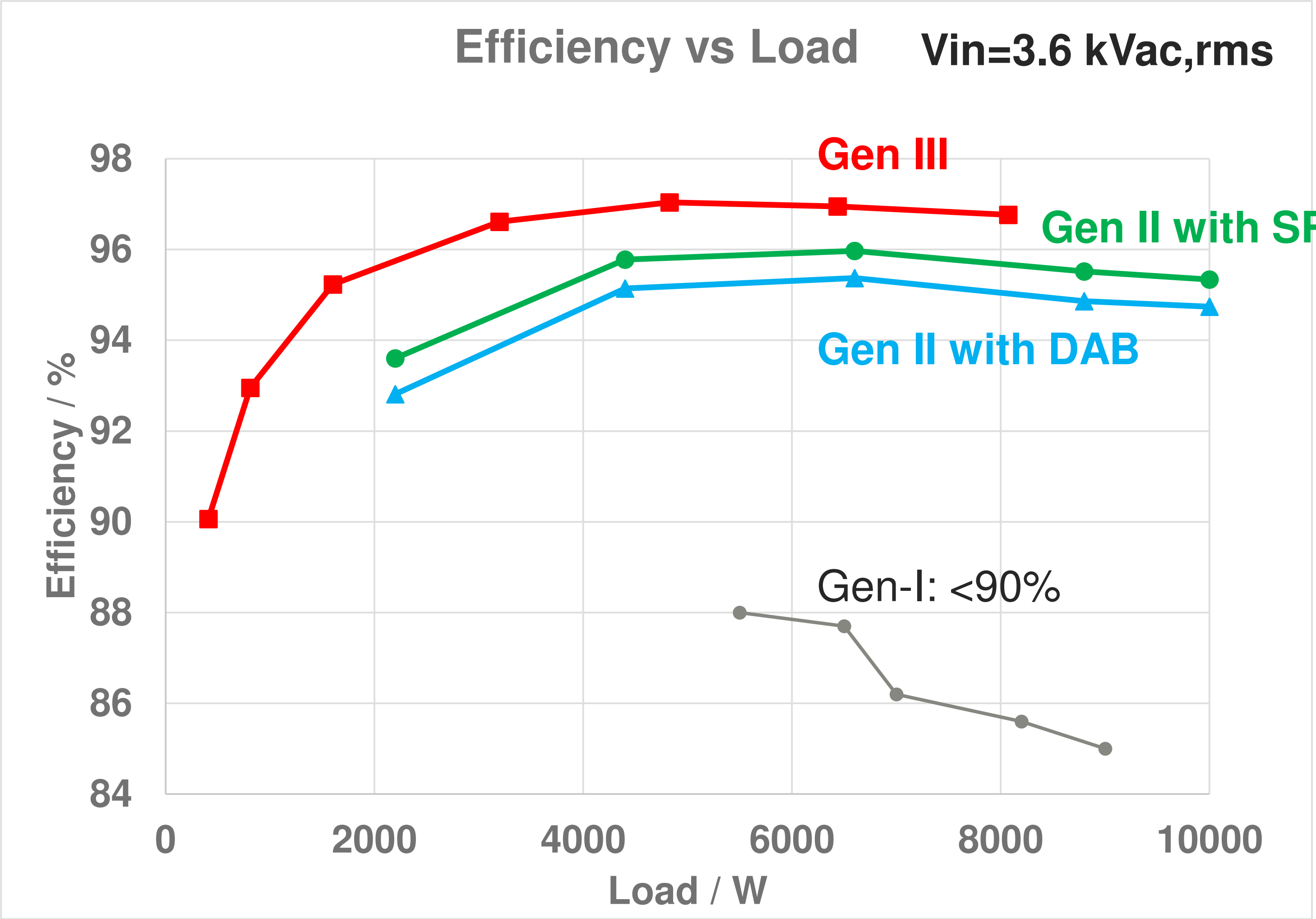
Gen- 2 SST:
15 kV SiC
@ 6 kHz & 40 kHz



Gen- 3 SST:
15 kV SiC
@37 kHz

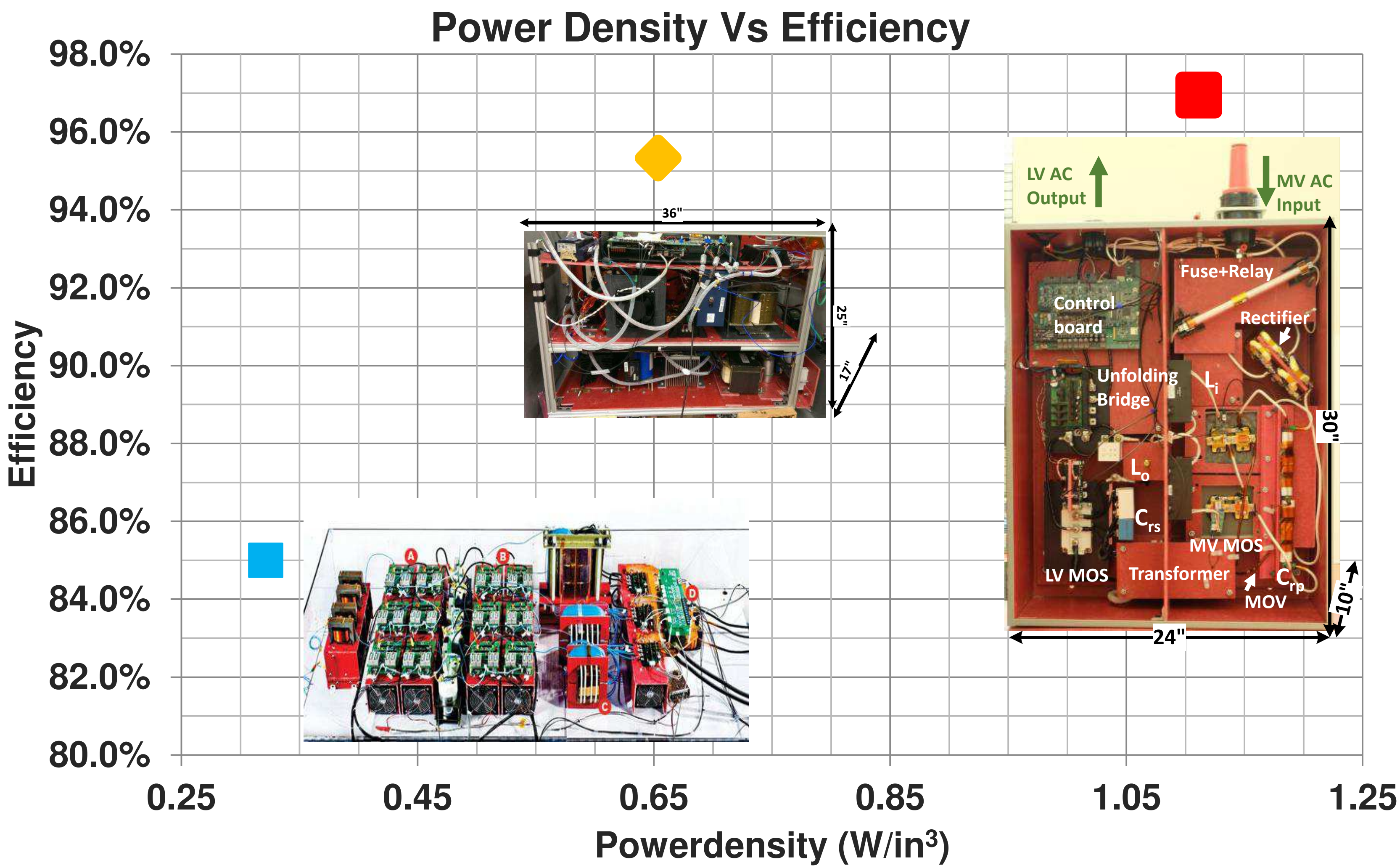
- **Gen-1 and Gen-2 features three stage solutions, and have all the desired smart functions**
- **Gen-3 is a single stage solution, the focus is on cost and efficiency**

Three Generations of SST Measured Efficiency (MV AC- LV AC)

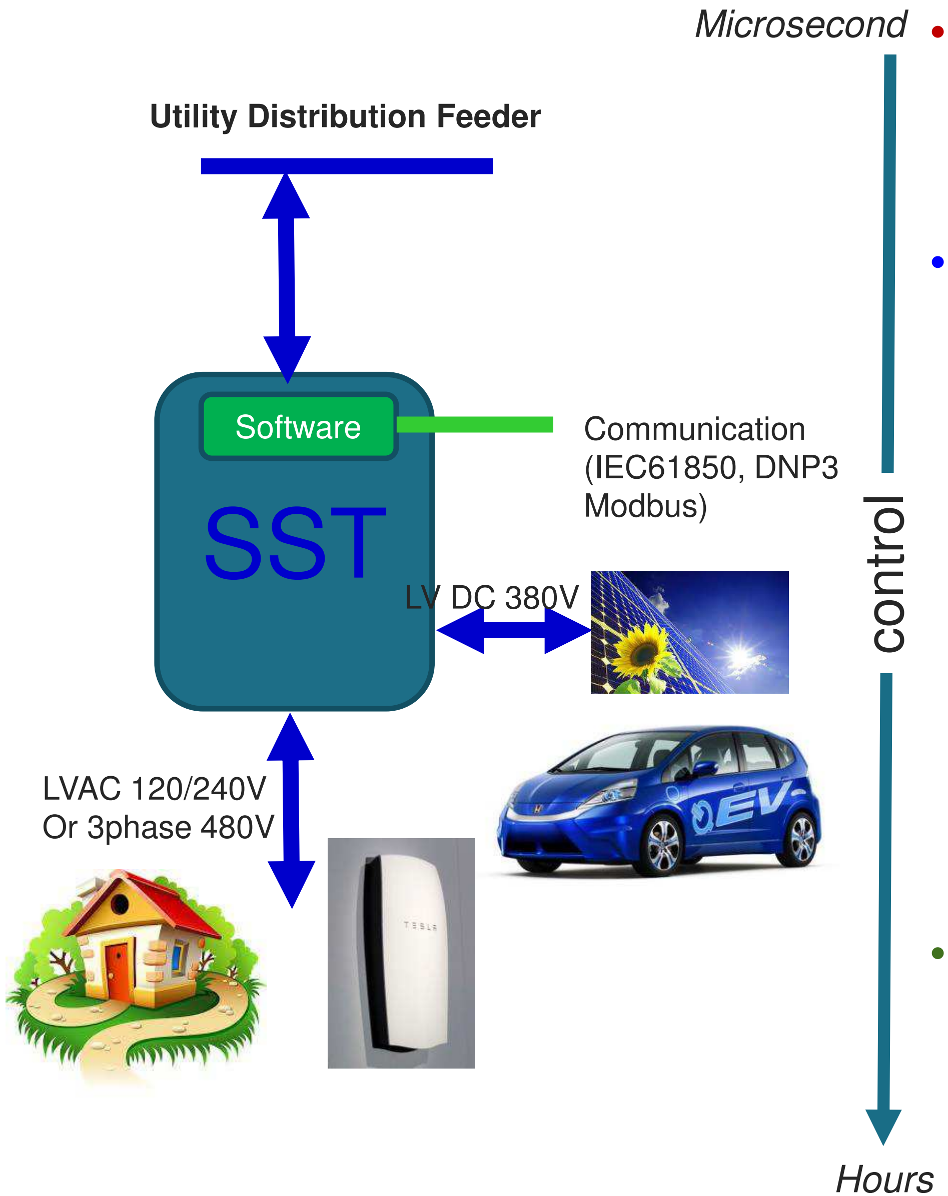


- **Much higher efficiency through single stage, improved magnetics and soft switching**
- **2% improvement compared to Gen-II SST, 7% over Gen-I**
- **Reached >97% for the MV AC-AC SST**

Three Generations of SST Power Density Vs Efficiency



SST Winning Strategy for Smart Grid

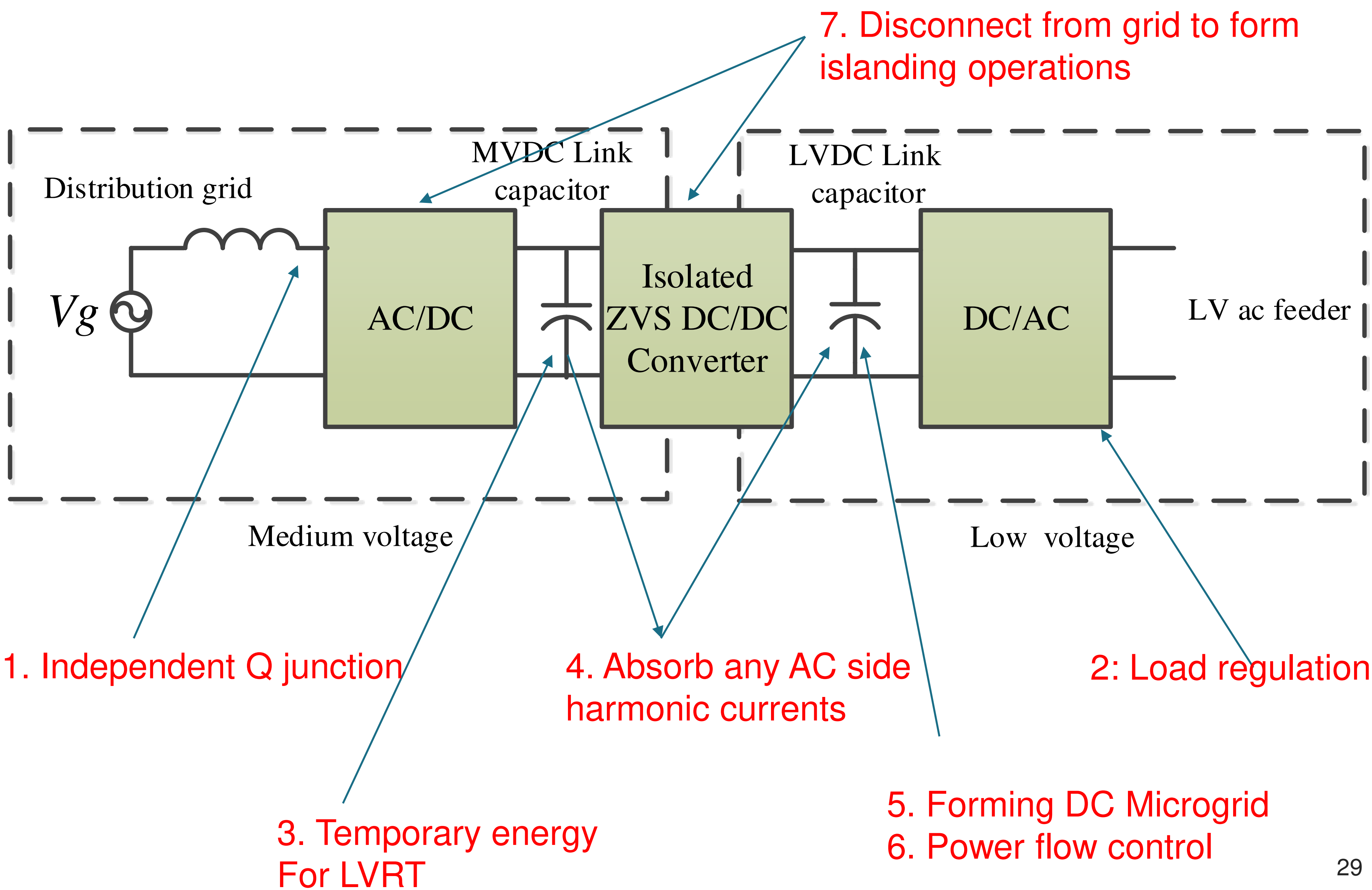


- **Fault management**
  - **Current limiting**
  - **Disconnect/reconnect**

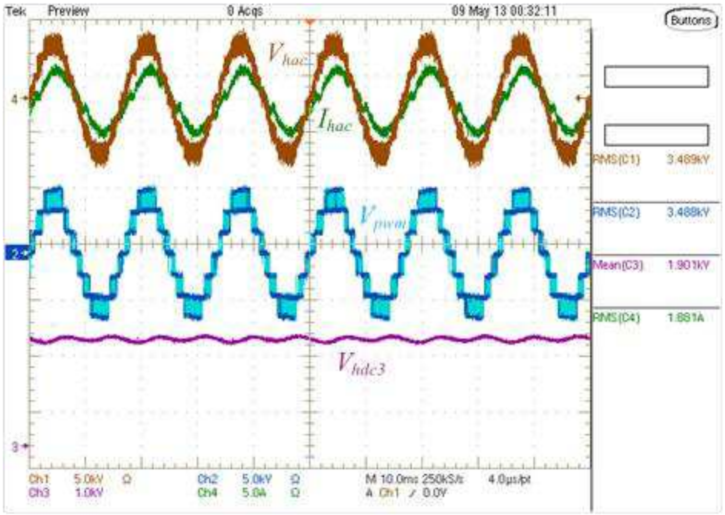
- **Power Management:**
  1. **Control power factor/Var Injection**
  2. **Change/Control customer voltage**
  3. **Low voltage ride through**
  4. **Eliminate customer side harmonics**
  5. **Provide DC power/Forming DC Microgrid**
  6. **Bidirectional Power flow control via Energy Cell aggregation**
  7. **Supports advanced power managements and islanding modes**

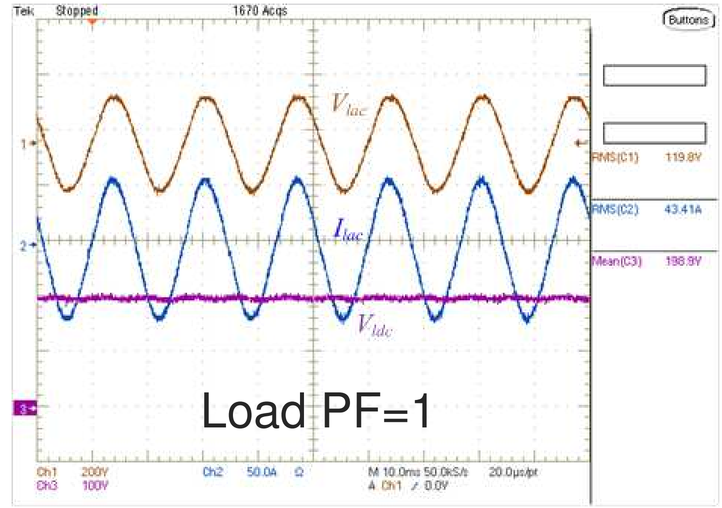
- **Energy Management**
  - **Monitor energy usage (AMI)**
  - **Can control/dispatch power *via microgrids (Energy Cell)***
  - **Demand side management**

Three Stage Medium Voltage SST: Supports Many Power Management Smart Features

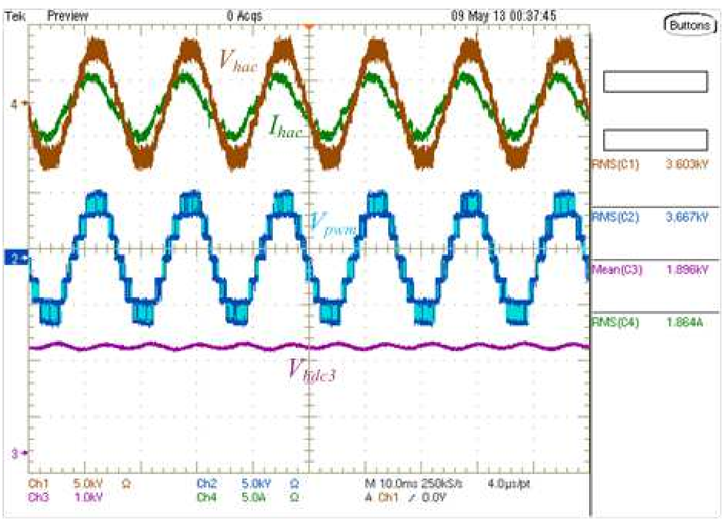


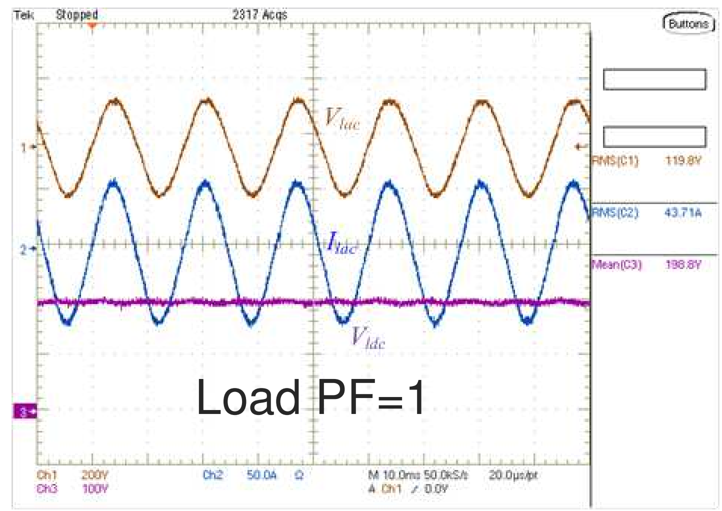
1. Reactive power compensation: 3.6KV-120V, 5KW, 2KVar (Gen-I SST Result)





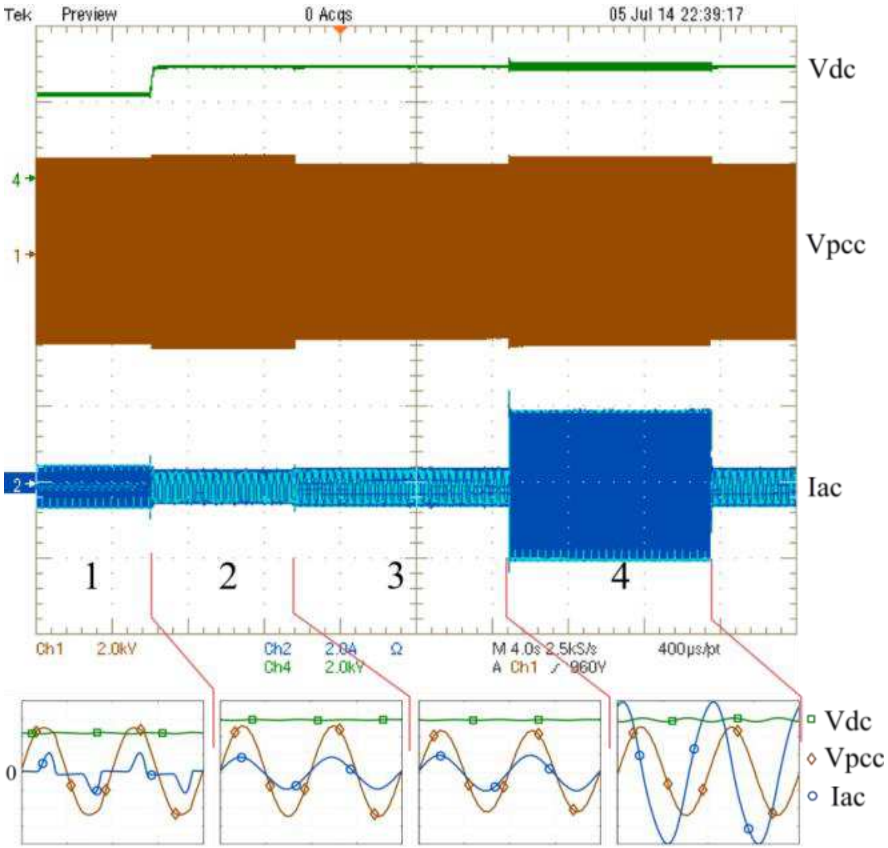
Inductive mode operation

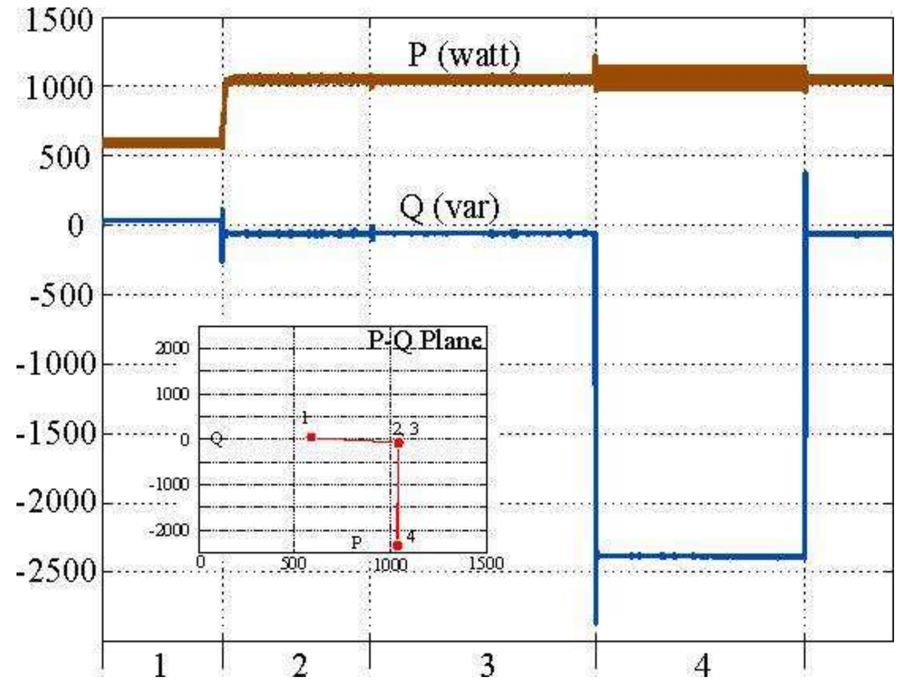




Capacitive mode operation

1. Grid Voltage Support Via Q injection





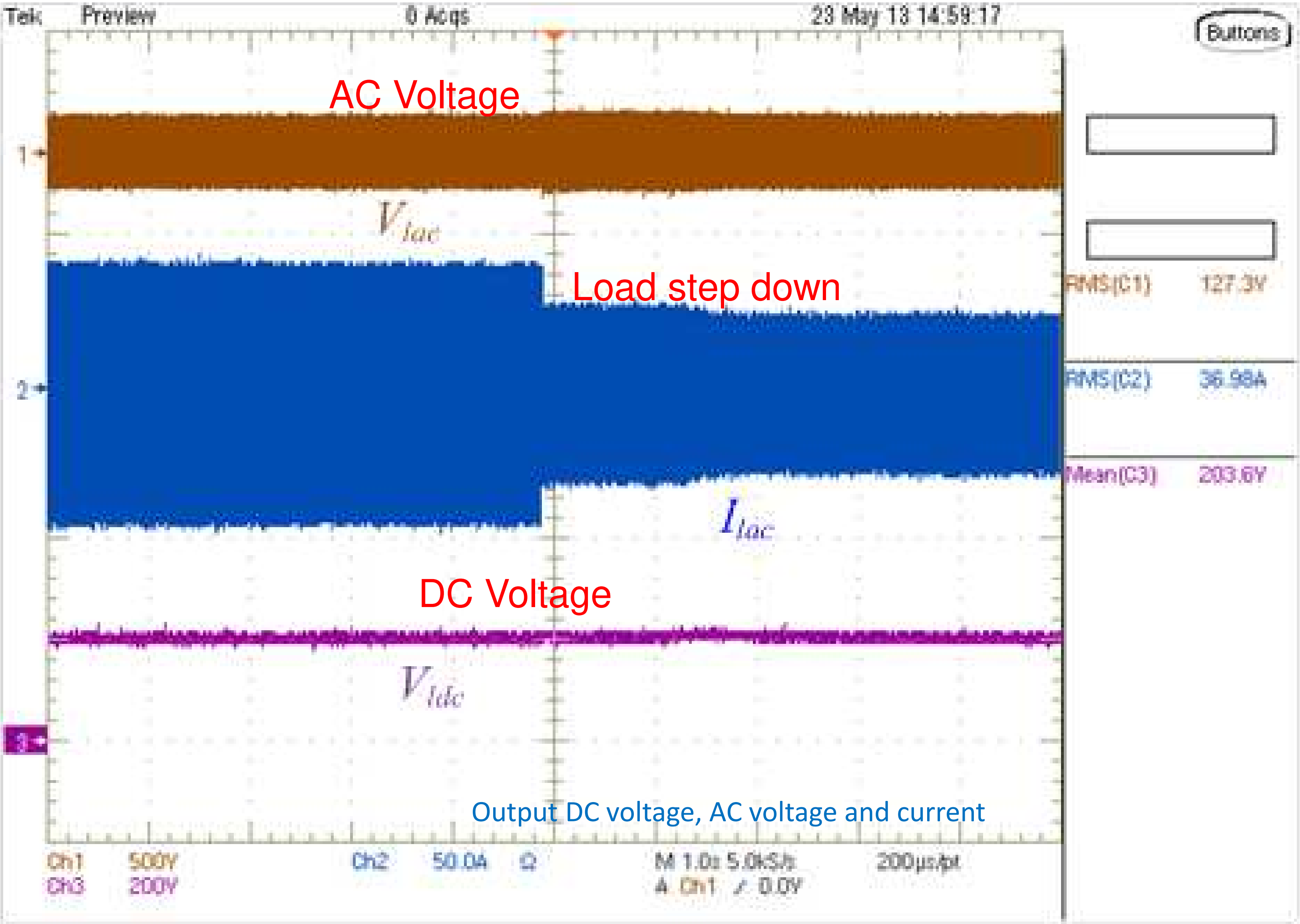
1: SST rectifier in diode mode (1.8kV distribution grid voltage)

– 2: SST starts with 1kW load

– 3: Grid voltage drops 10%

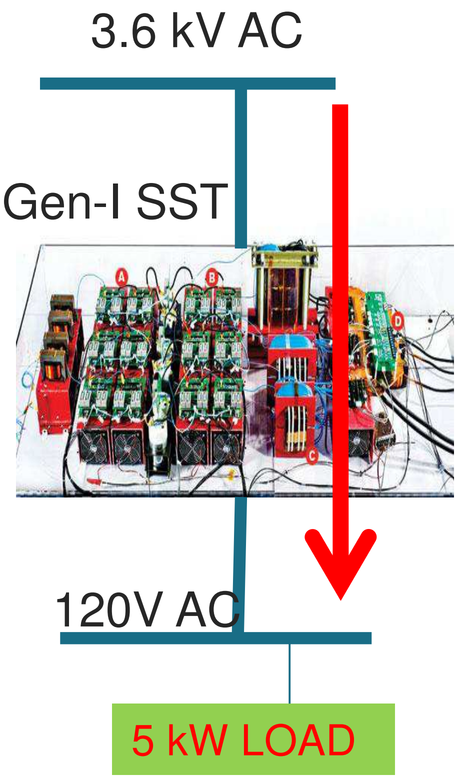
– 4: SST generates reactive power to restore Vpcc

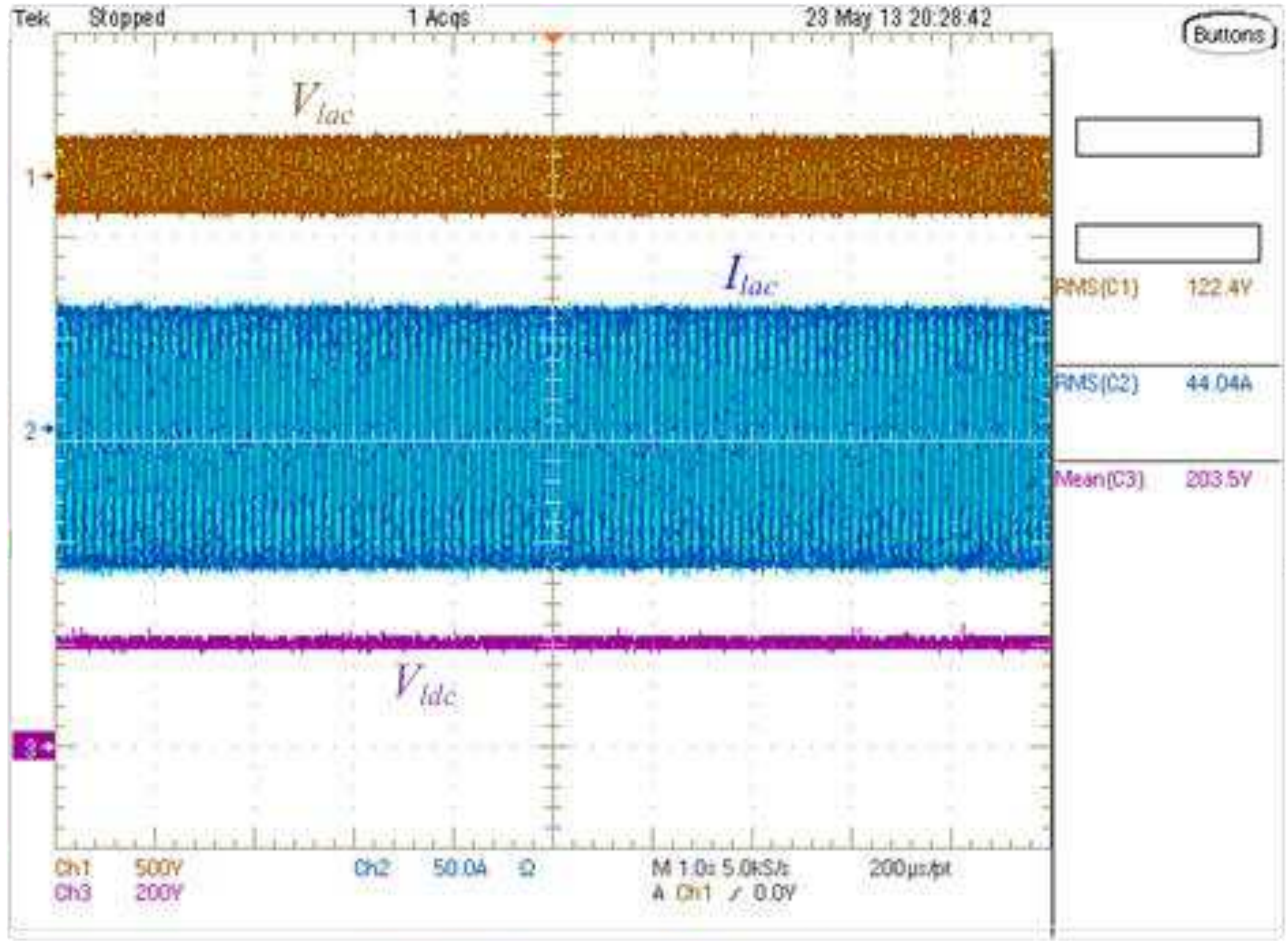
2. Load regulation: : 3.6KV-120V, 5KW-3KW (Gen-I)



Output DC voltage, AC voltage and current

3. Smart Feature: Low Voltage Ride Through (LVRT)



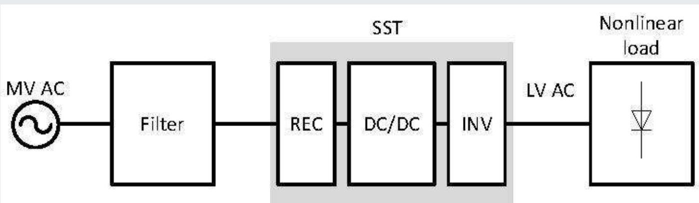


Output DC voltage, AC voltage and current

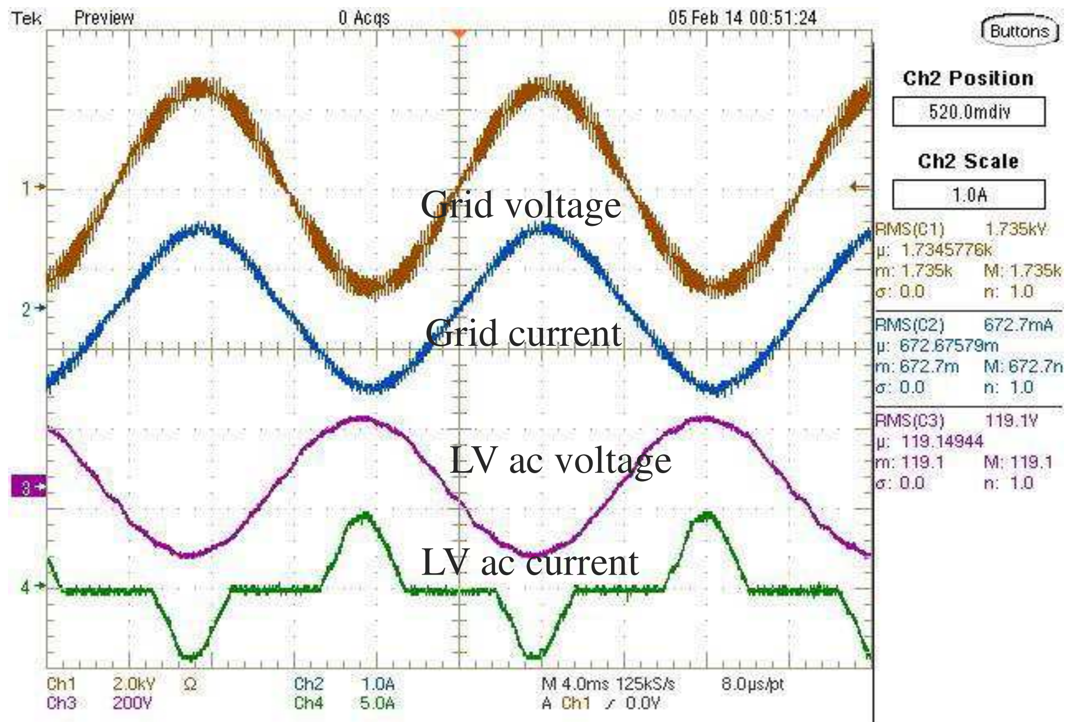
Input voltage, current, PWM voltage, high voltage DC link 3

4. Smart Feature: Load Harmonic Mitigation

Test setup and condition

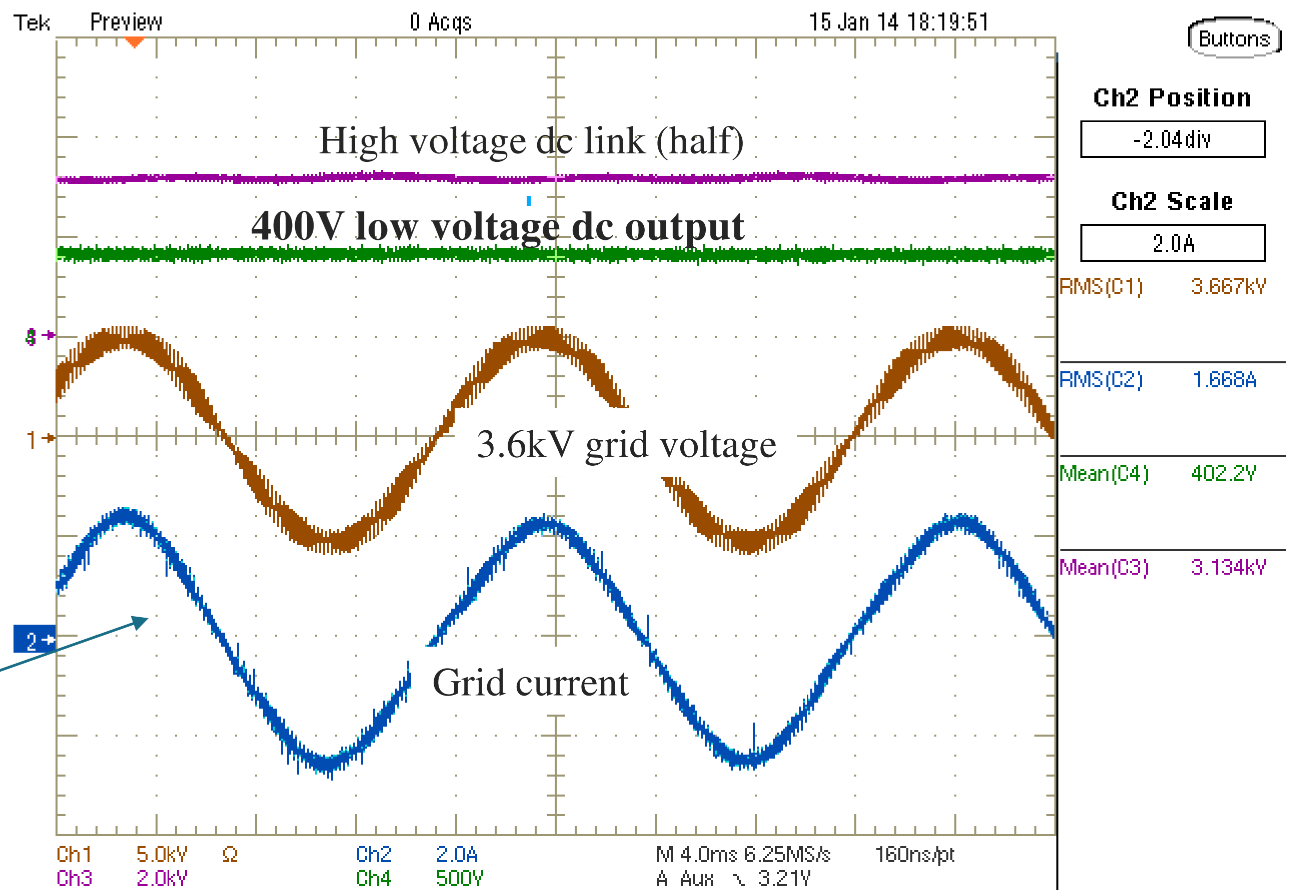


Grid voltage:	1.8kV
HV dc link voltage:	3kV
Low voltage dc output:	200V
Low voltage ac output	120V



5. Grid-Connected Operation: 3.6kV steady state/DC Microgrid

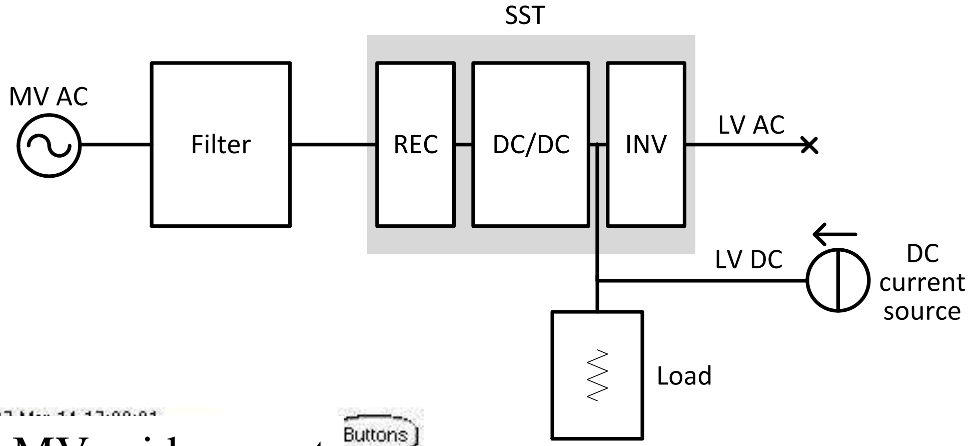
- Grid voltage: 3.6kV
- MVDC link voltage: 6kV
- Low voltage dc output: regulated at 400V

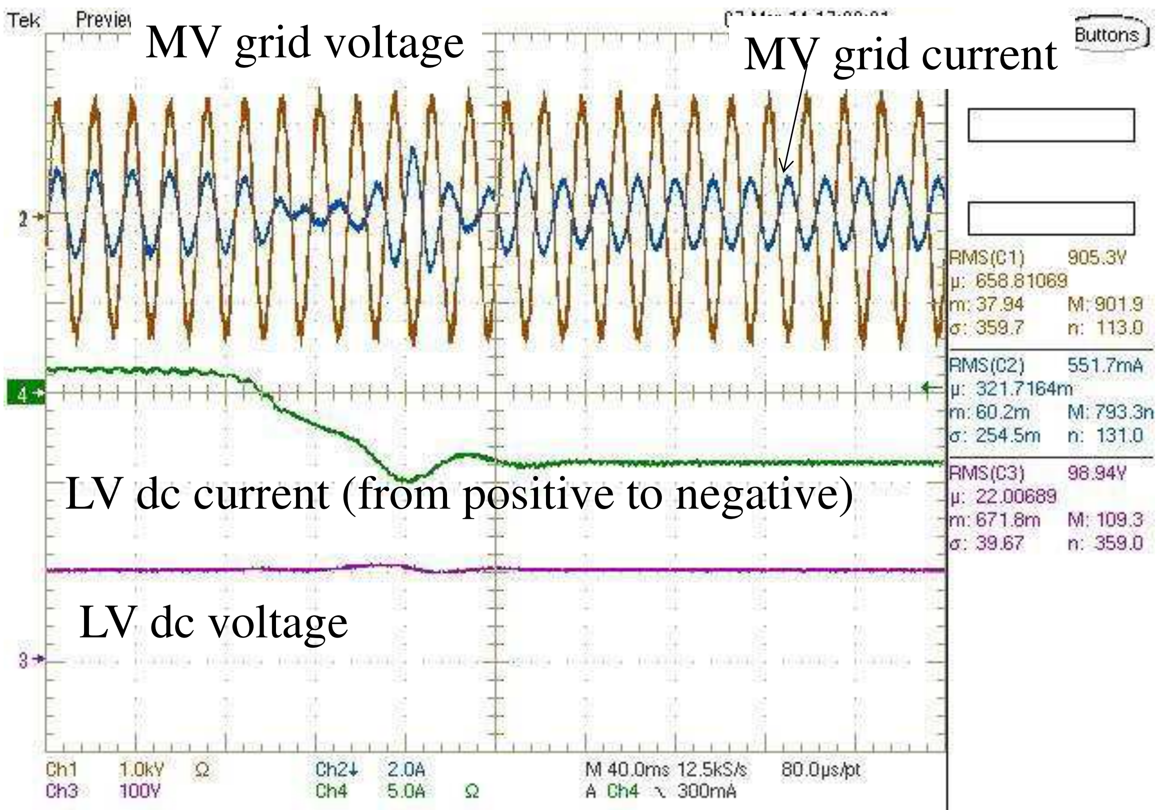


PF=1

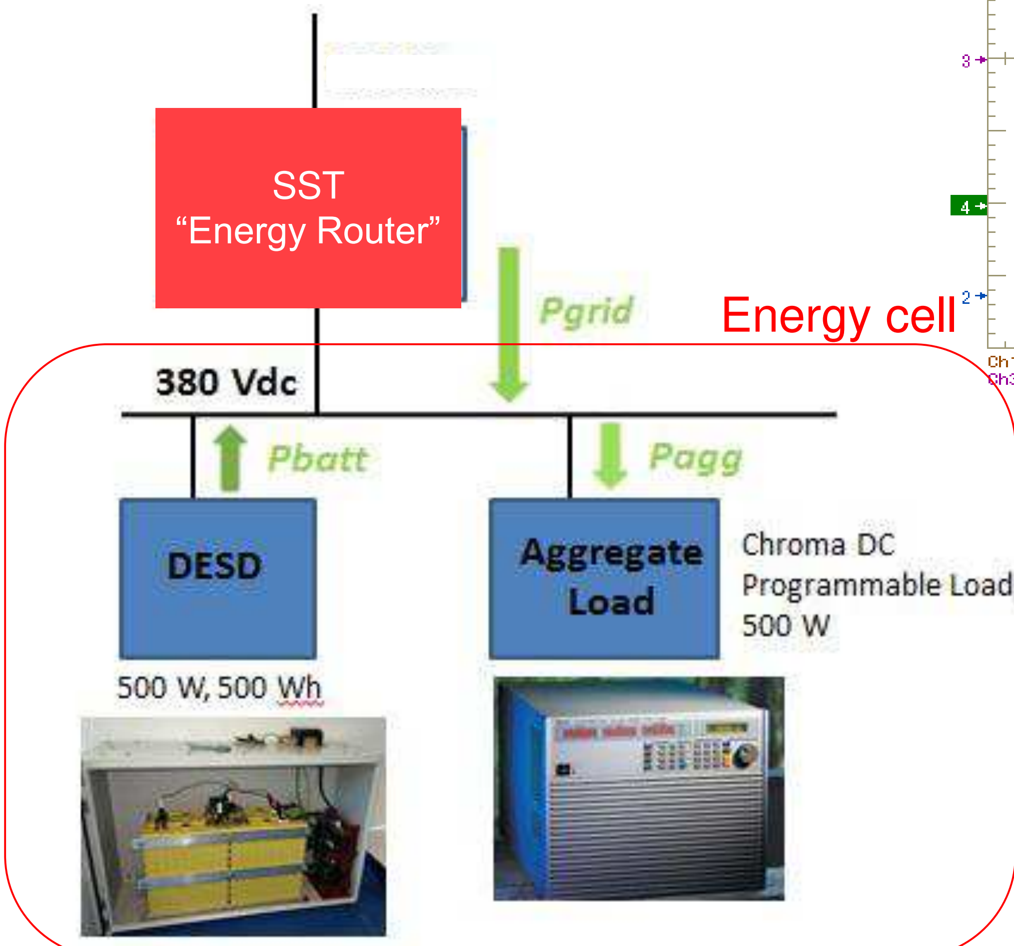
6. **Grid-Connected Operation:** Regenerative mode/bidirectional power flow

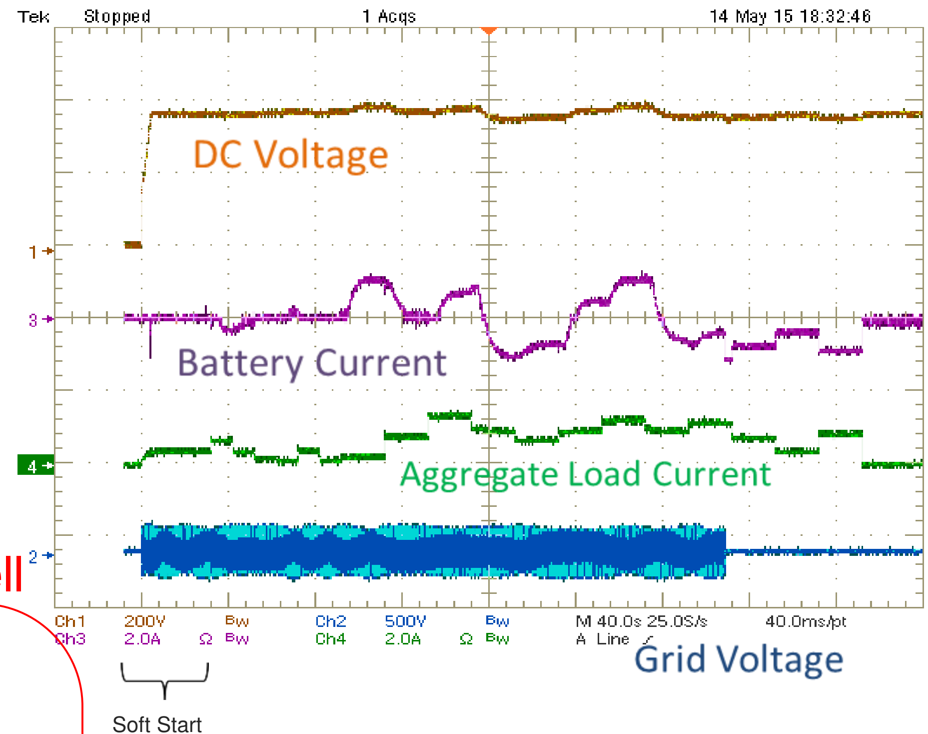
- Grid voltage: 900V
- MVDC link voltage: 1.5kV
- Low voltage dc: 100V





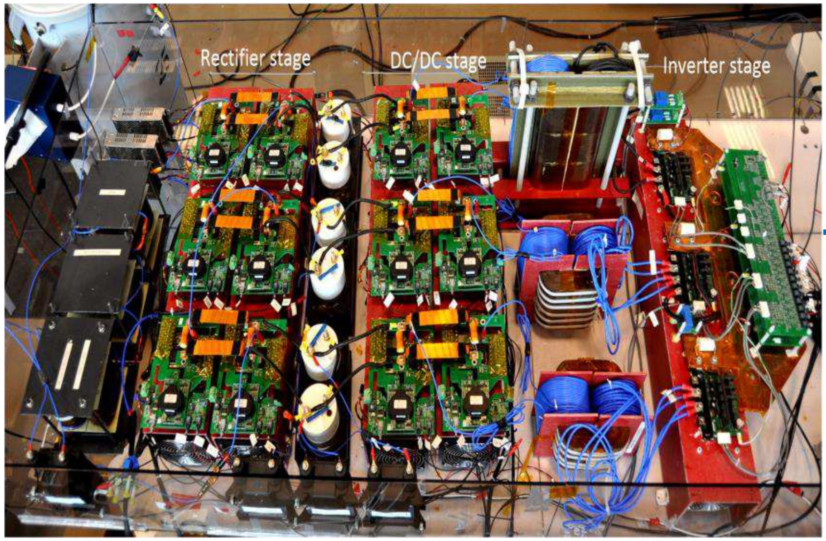
6. SST Power Flow Control: Control DC Bus Voltage As a Aggregation Signal





Power Balance: $P_{grid} = \underbrace{P_{load} - P_{pv}}_{P_{agg}} - P_{batt}$

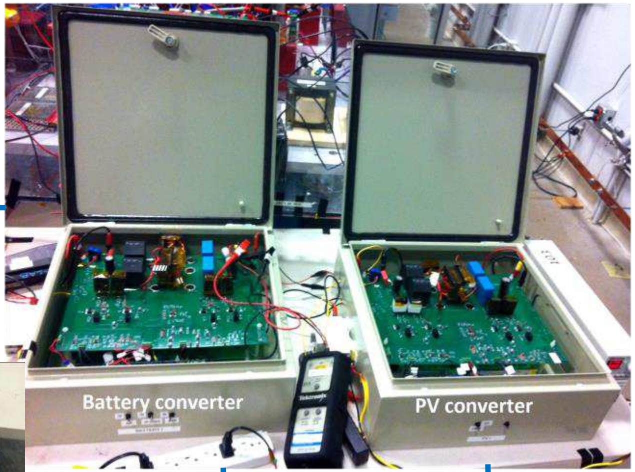
SST and DC Microgrid Testbed



Gen-I SST

switch

Load bank



20Ah battery

120 W PV panel

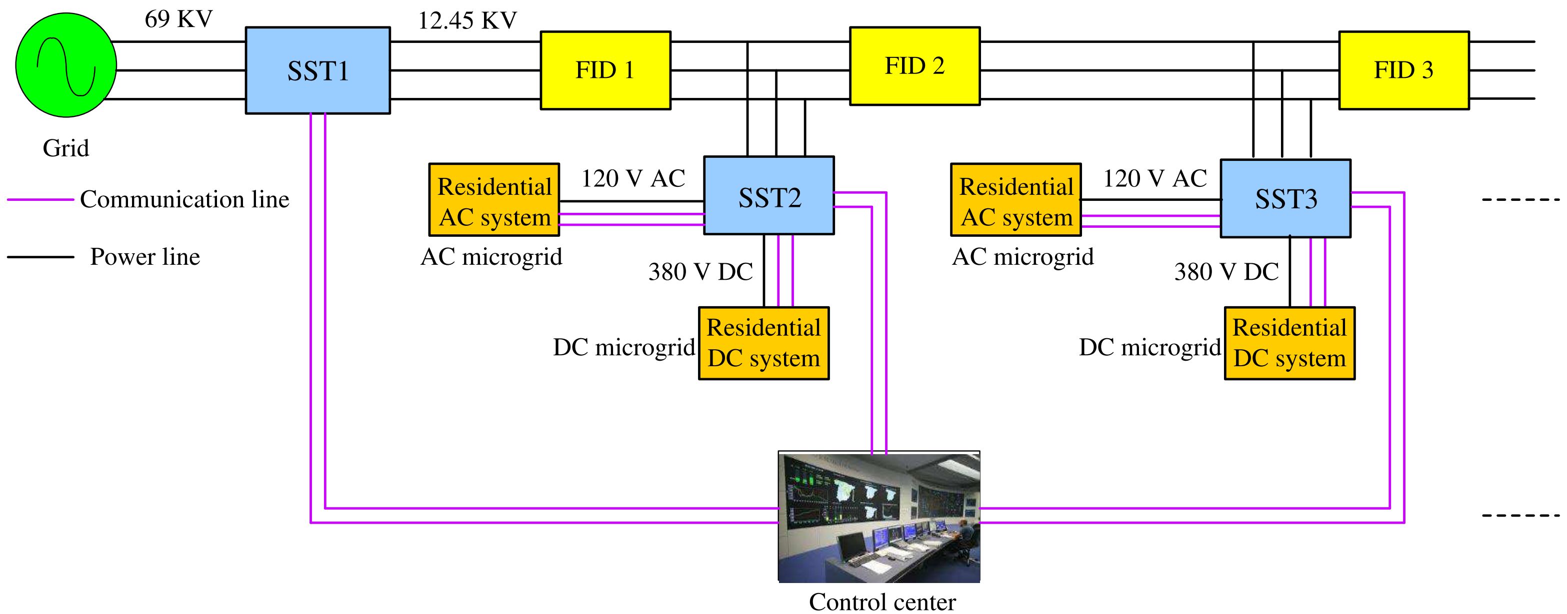
500 w DC/DC Converter for battery

200 w DC/DC converter for PV

Key hardware parameters

$L_{r\_battery}$	6 uH	I_{PV_MPPT}	2.5 A	$V_{PV\_shedding}$	395 V
L_{r_PV}	4 uH	f	50 kHz	V_{PV_back}	375 V
$V_{battery}$	48 V	V_b	380 V	$V_{load\_shedding}$	365 V
V_{PV_MPPT}	45 V	R_b	54	V_{load_back}	385 V

FREEDM Control Classification

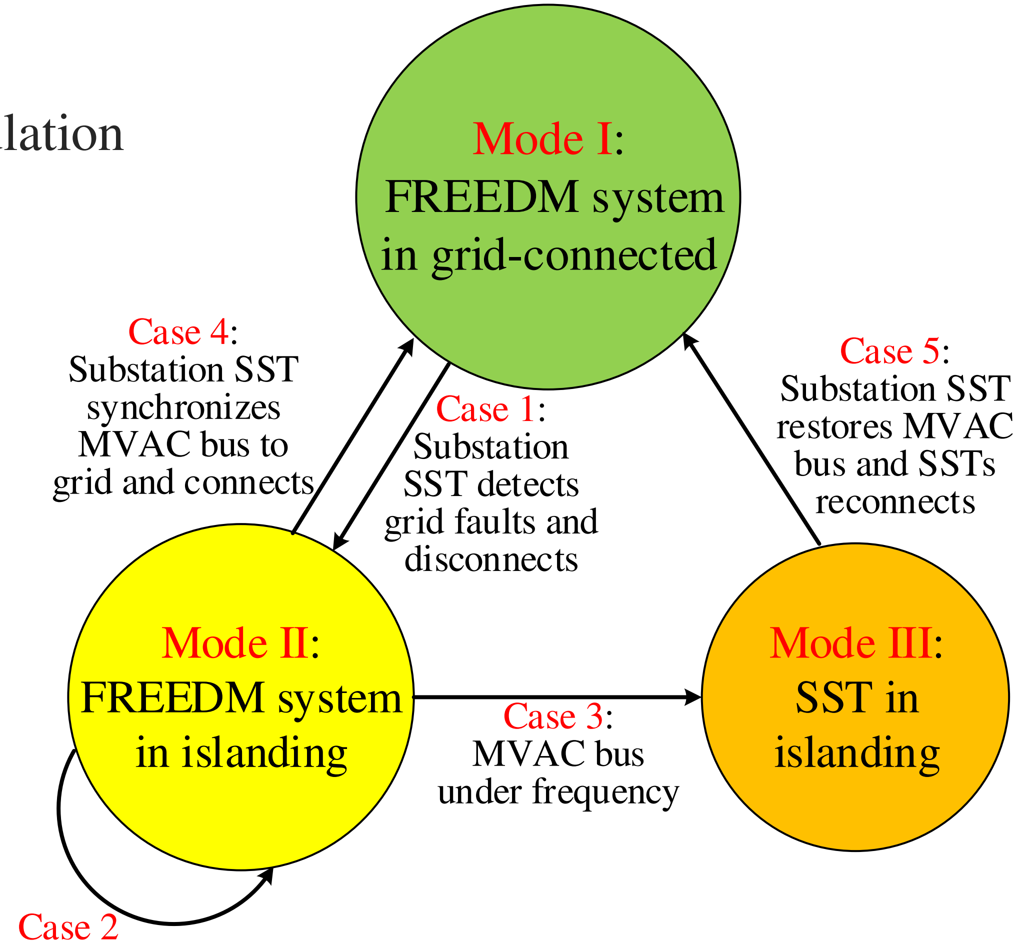


Key features of the innovative FREEDM system:

1. Plug-and-play AC and DC Microgrid that integrate distributed renewable energy resources (DRER) and distributed energy storage devices (DESD).
2. **Intelligent power management (IPM) through high bandwidth SST.**
3. Intelligent fault management (IFM) with ultra-fast and intelligent FID.
4. Intelligent energy management (IEM) via coordinated optimization and dispatch of distributed resources. **Slower communication can be used**

Intelligent Power Management (IPM) Control of FREEDM System

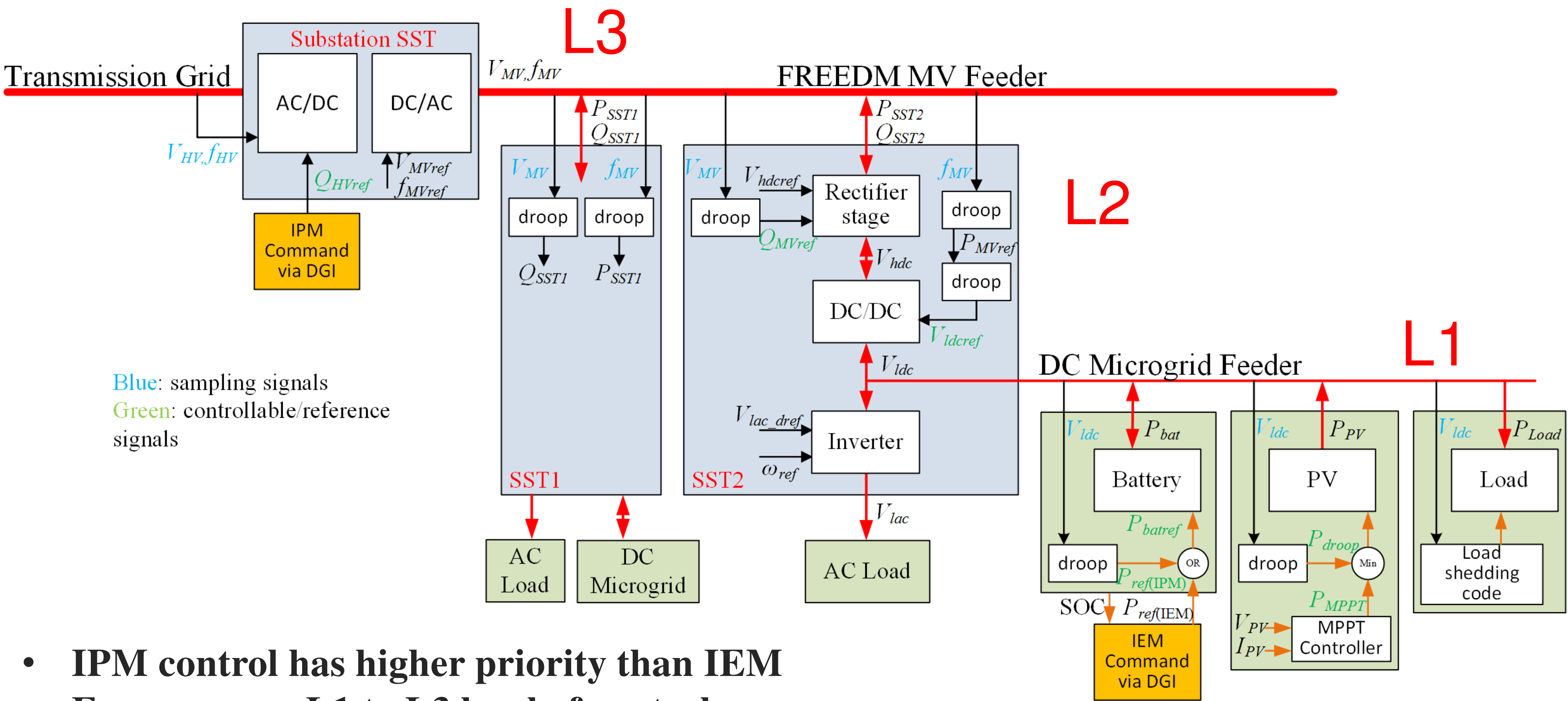
IPM Objective:
Voltage & Frequency Regulation



Operation modes and transitions

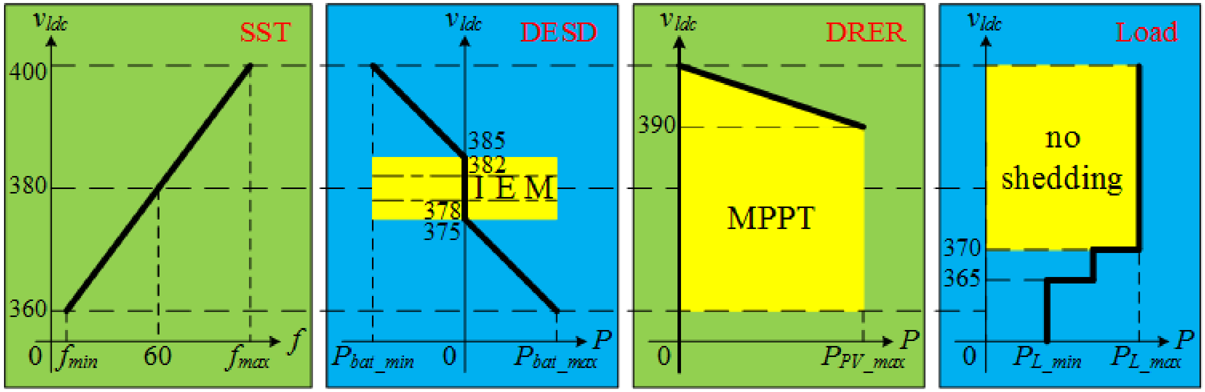
IPM Challenge: operate each component/subsystem in a distributed fashion while maintaining system stability under all operation conditions

Autonomous and Distributed IPM Control Strategy



- **IPM control has higher priority than IEM**
- **Encompasses L1 to L3 level of control**
- **L1 (energy cell) devices have it own control**
- **L2 (SST) has its own control**
- **Require no communication**
  - **Benefit from the inherent control bandwidth of the underlining power electronics**

Dual Droop Control Strategy for DC Microgrid

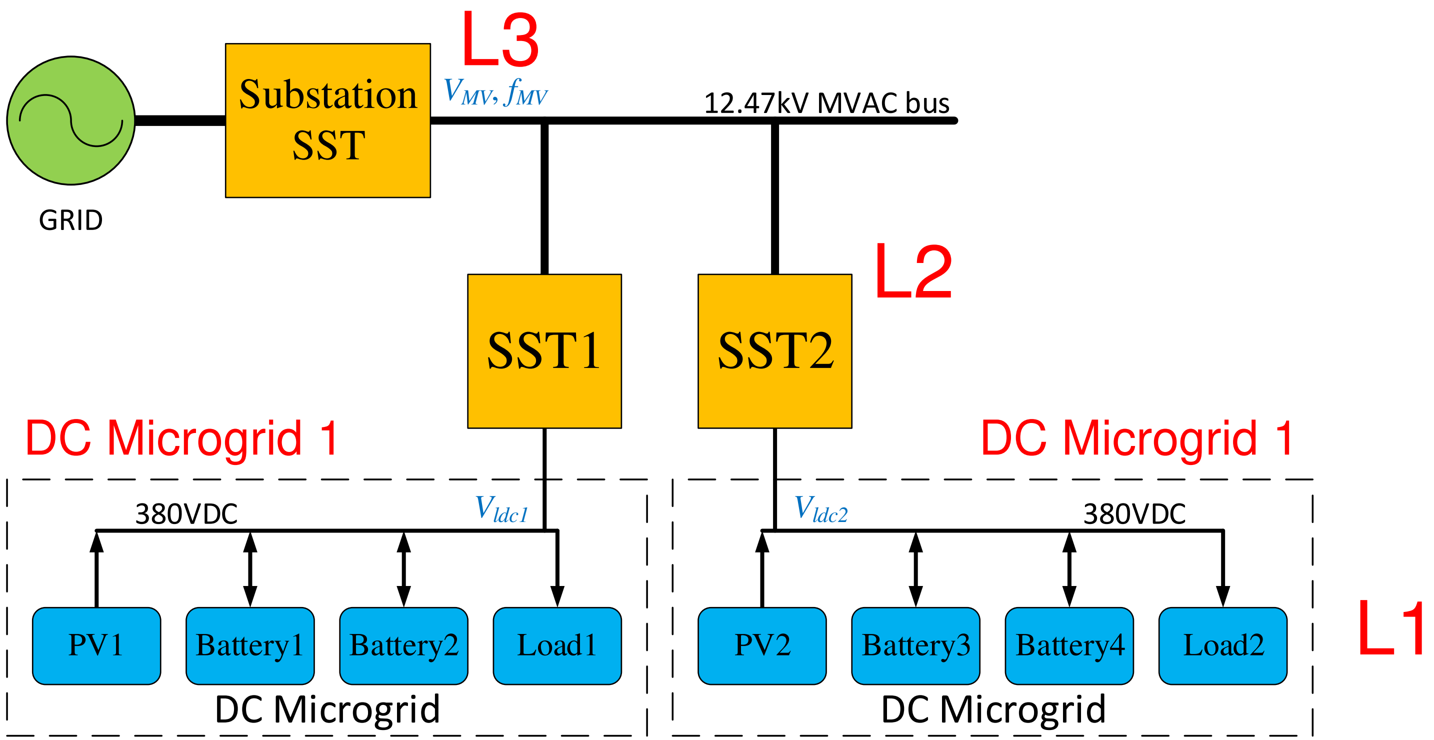


Dual droop control:

- **First droop for SST**: *f-P* droop (AC frequency to SST active power) and *P-Vldc* droop (active power to DC voltage) combine to form the first droop: ***f-Vldc*** (AC side frequency to DC side voltage); SST acts like a real transformer, only lets power flow through it.
- **Second droop for DC microgrid**:
  - DESD: ***Vldc-P*** droop; affording/absorbing power to/from SST according to the *Vldc* (upper level AC frequency *f* indeed);
  - DRER: normally MPPT control; ***Vldc-P*** droop when *Vldc* is too high;
  - Load: shedding at low *Vldc* point;

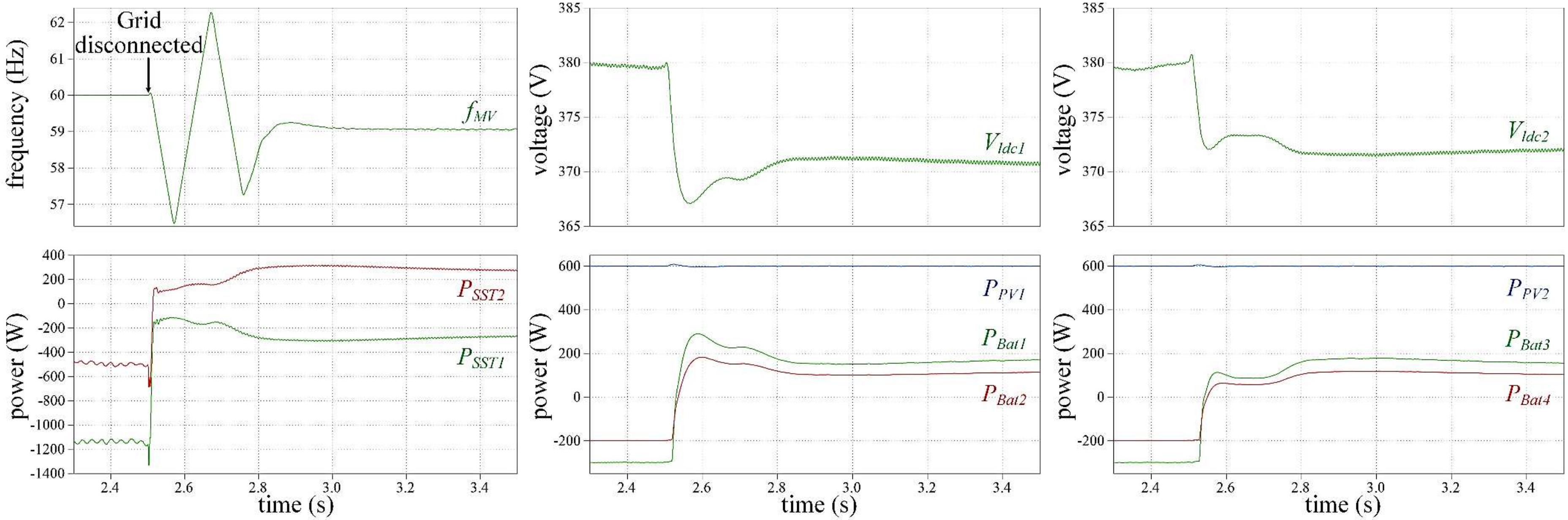
DESD, DRER are the only energy sources in system; the working point is determined by loads and available sources.

Simulated FREEDM System



Component	Rated Power	Component	Rated Power
Substation SST	6000VA	Battery1, Battery3	600W
SST1	1200VA	Battery2, Battery4	400W
SST2	1000VA	Load1	120Ω
PV1, PV2	600W	Load2	240Ω

Simulation Case 1: Mode I to II



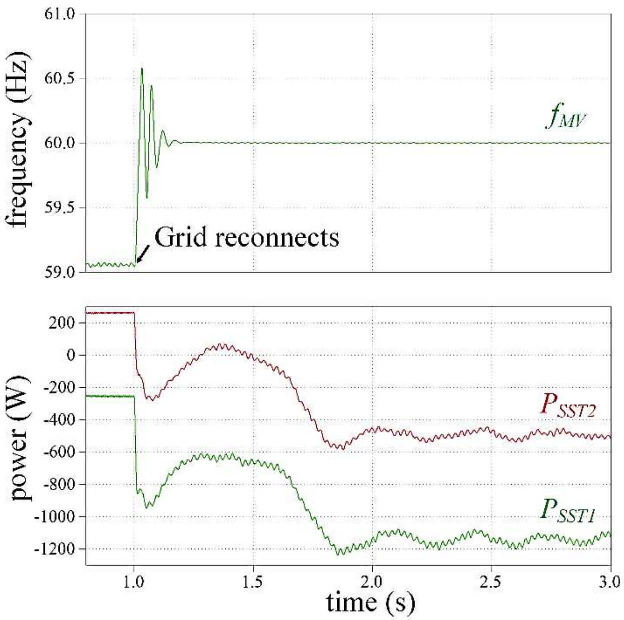
AC frequency and active power of SST1, SST2

Vldc1 and power of PV1, battery1, battery2

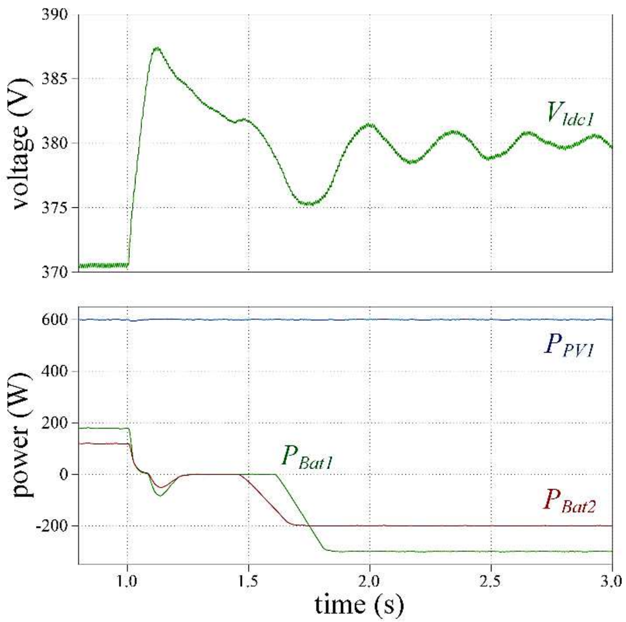
Vldc2 and power of PV2, battery3, battery4

- **1.7 kW grid power is lost at 2.5s**
- **Battery automatically change from charging to discharging following the double droop strategy**
- **Battery power sharing automatically achieved**
- **Power balance is reached within 0.1s**

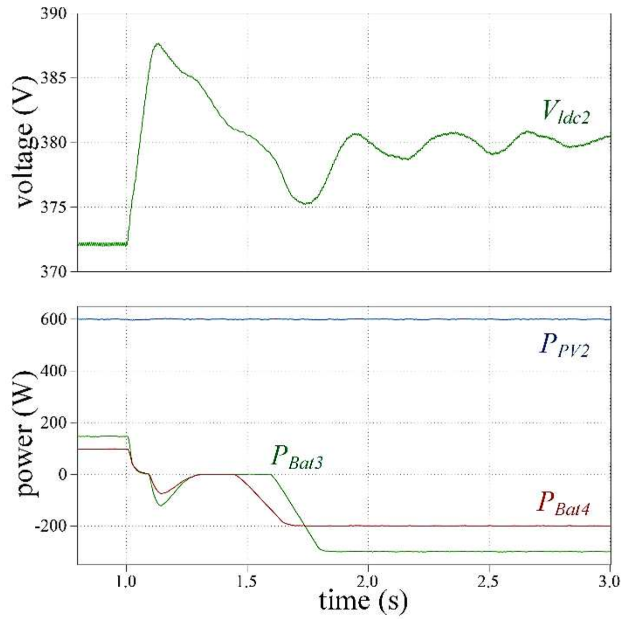
Simulation Case 4: Mode II to I



AC frequency and active power of SST1, SST2



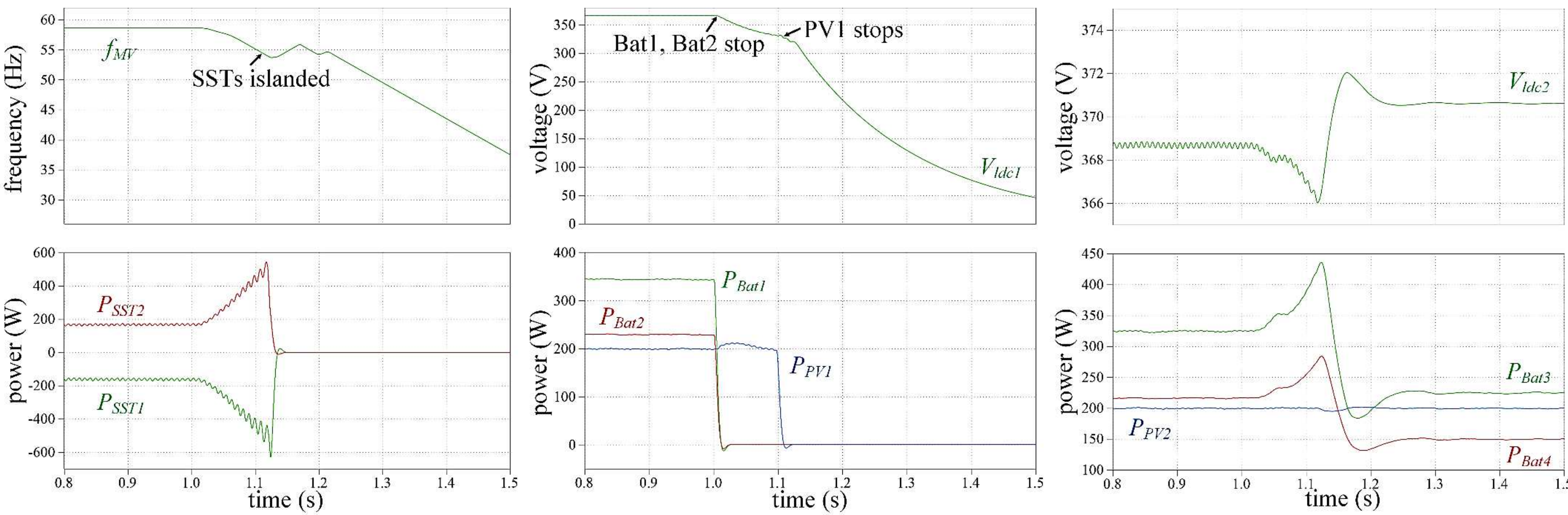
Vldc1 and power of PV1, battery1, battery2



Vldc2 and power of PV2, battery3, battery4

- **When MV grid recovers, dual droop re-balance the power flow . Battery in charging mode**

Simulation Case 3: Mode II to III



AC frequency and active power of SST1, SST2

Vldc1 and power of PV1, battery1, battery2

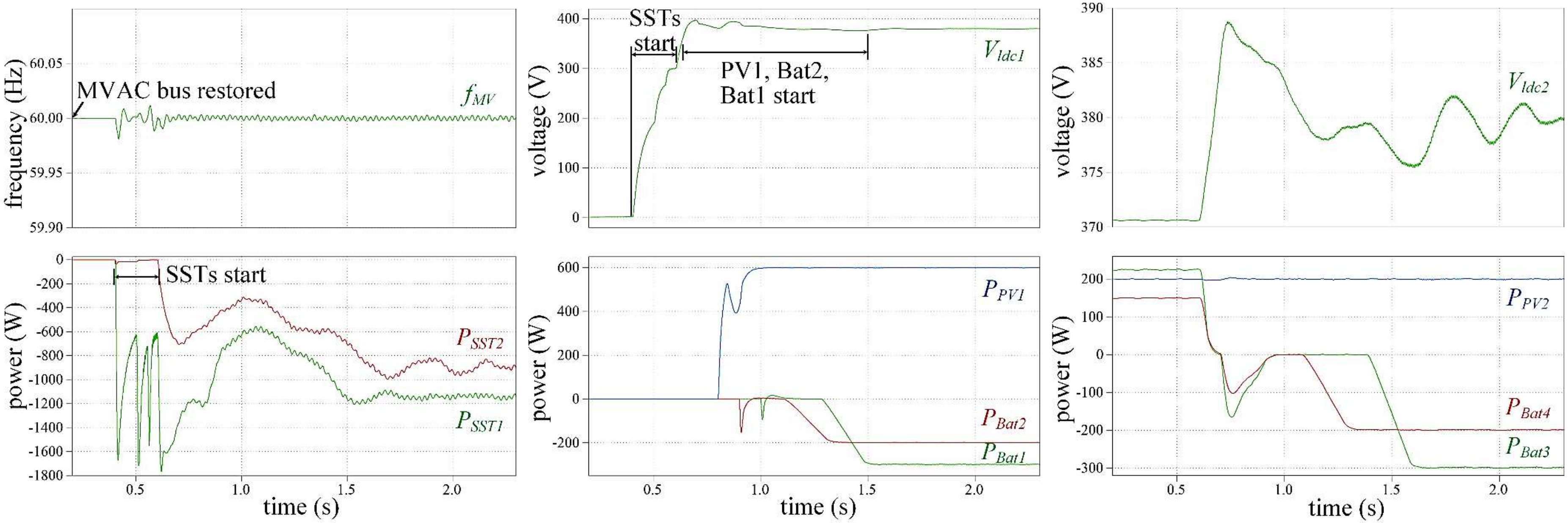
DC Microgrid 1

Vldc2 and power of PV2, battery3, battery4

DC Microgrid 2

- **DC microgrid 1 battery and PV production stops**
- **Available power not capable to regulate medium voltage frequency. SST1 and SST2 disconnect from medium voltage feeder**
- **DC microgrid 2 is capable to keep DC microgrid 2 operation**

Simulation Case 5: Mode III to I



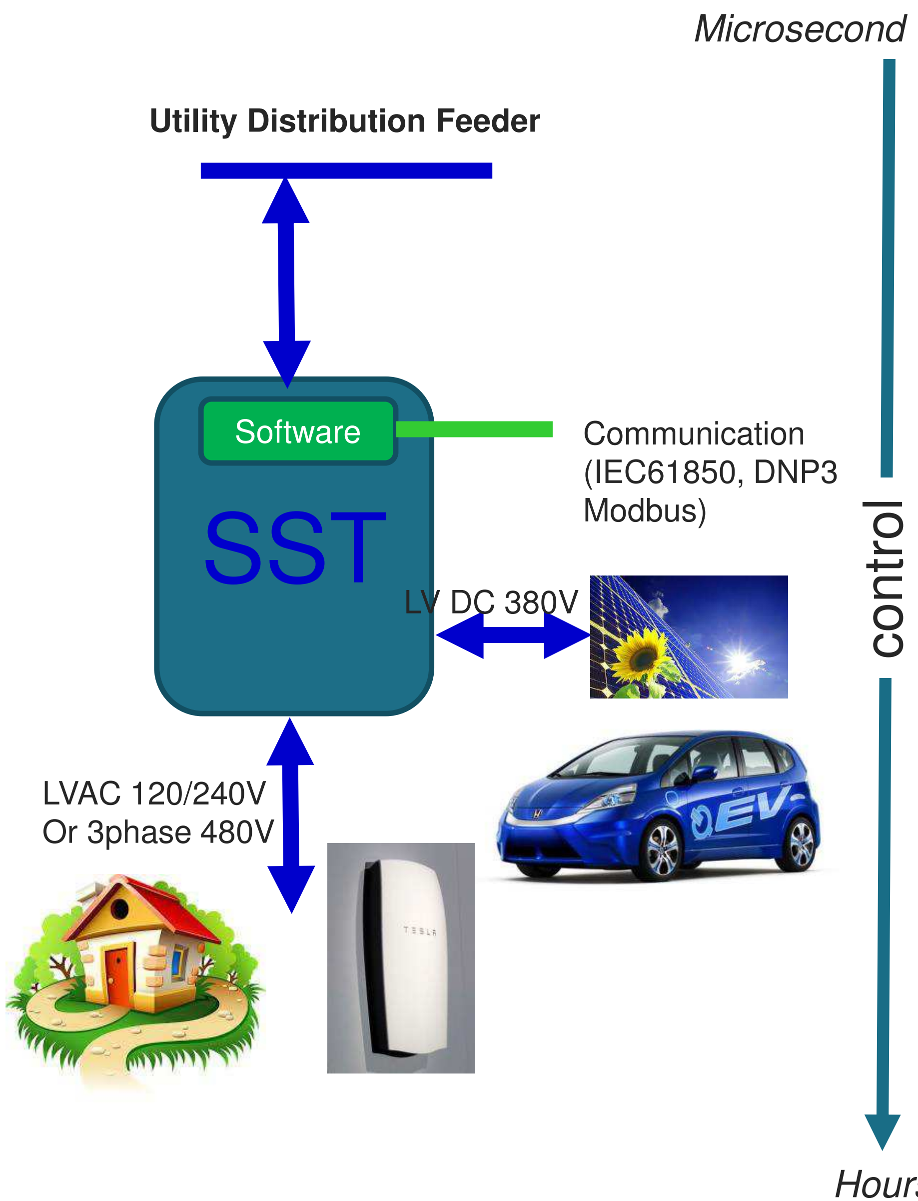
AC frequency and active power of SST1, SST2

Vldc1 and power of PV1, battery1, battery2

Vldc2 and power of PV2, battery3, battery4

- **When MV grid recovers, SST reconnect to the MV feeder**
- **dual droop re-balance the power flow .**
- **DC microgrid 1 restarts, battery in charging mode**
- **DC microgrid 2 battery moves into charging mode**

SST Winning Strategy for Smart Grid

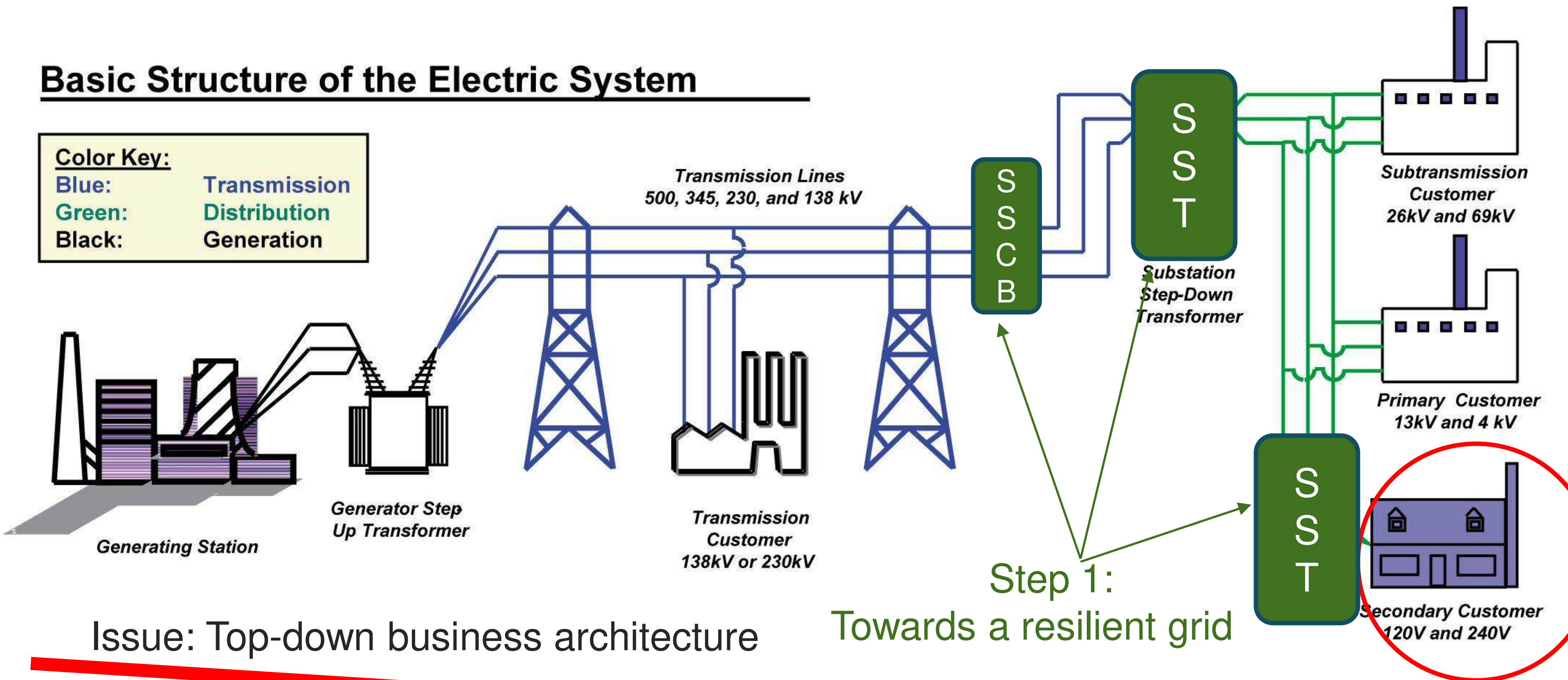


- **Fault management**
  - **Current limiting**
  - **Disconnect/reconnect**

- **Power Management:**
  1. **Control power factor/Var Injection**
  2. **Change/Control customer voltage**
  3. **Low voltage ride through**
  4. **Eliminate customer side harmonics**
  5. **Provide DC power/Forming DC Microgrid**
  6. **Bidirectional Power flow control via Energy Cell aggregation**
  7. **Supports advanced power managements and islanding modes**

- **Energy Management**
  - **Monitor energy usage (AMI)**
  - **Can control/dispatch power *via microgrids (Energy Cell)***
  - **Demand side management**

Electric Market Reality & Transformation

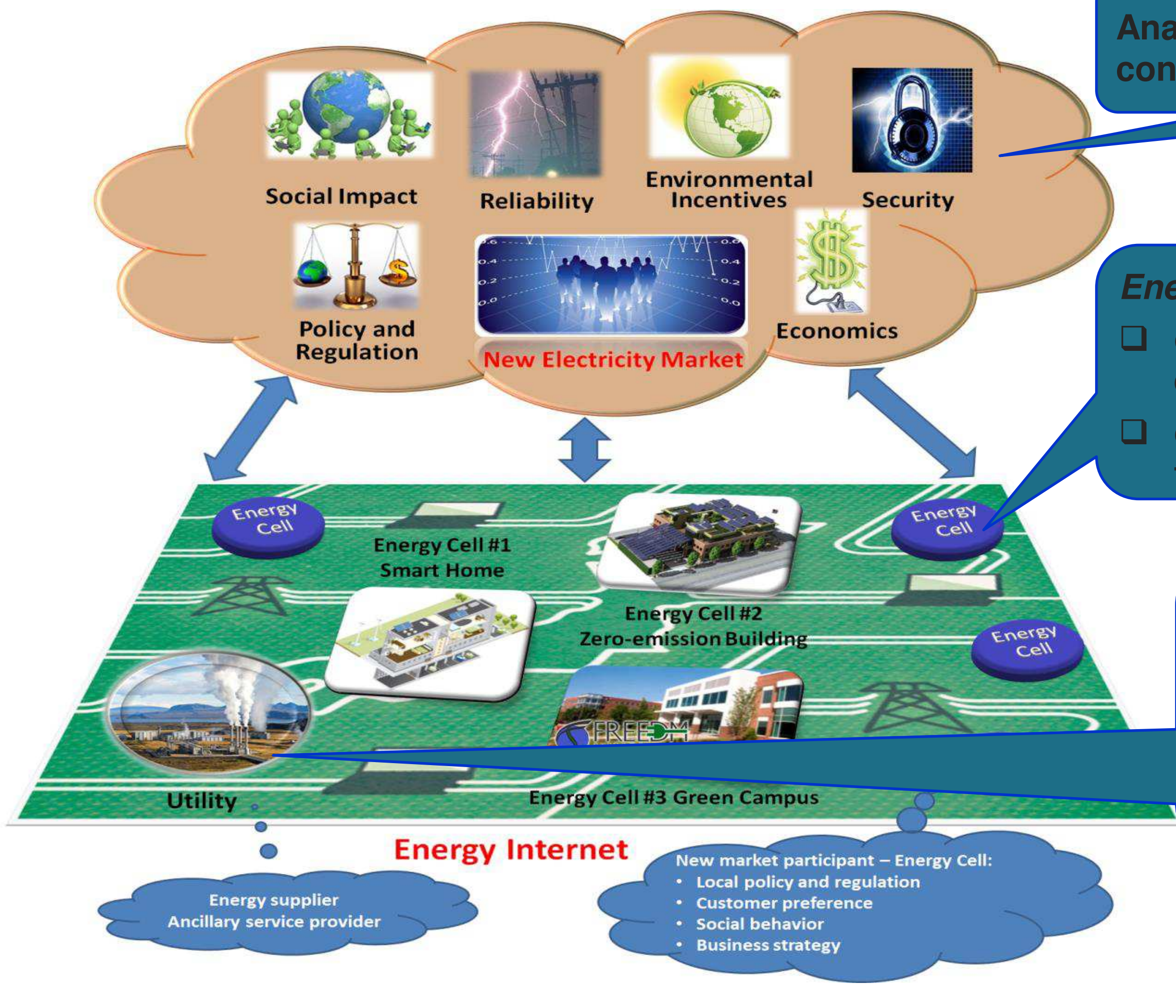


Where is the customer: You?

USA Residential Customer: 128m **$114/Per Month/Per Customer ~15B/per month**

Source: EIA

Step 2: Towards Energy Internet



Analogous to internet consumer-to-consumer commerce (eBay) or stock market

Energy Cells are to

- ❑ operate and manage local generators, energy storage, and dispatchable load
- ❑ compete with each other to maximize their own profits

Utilities are expected to make more profit on providing ancillary services to ensure the residential distribution system security and reliability, in addition to electricity transaction.

Who owns data rules

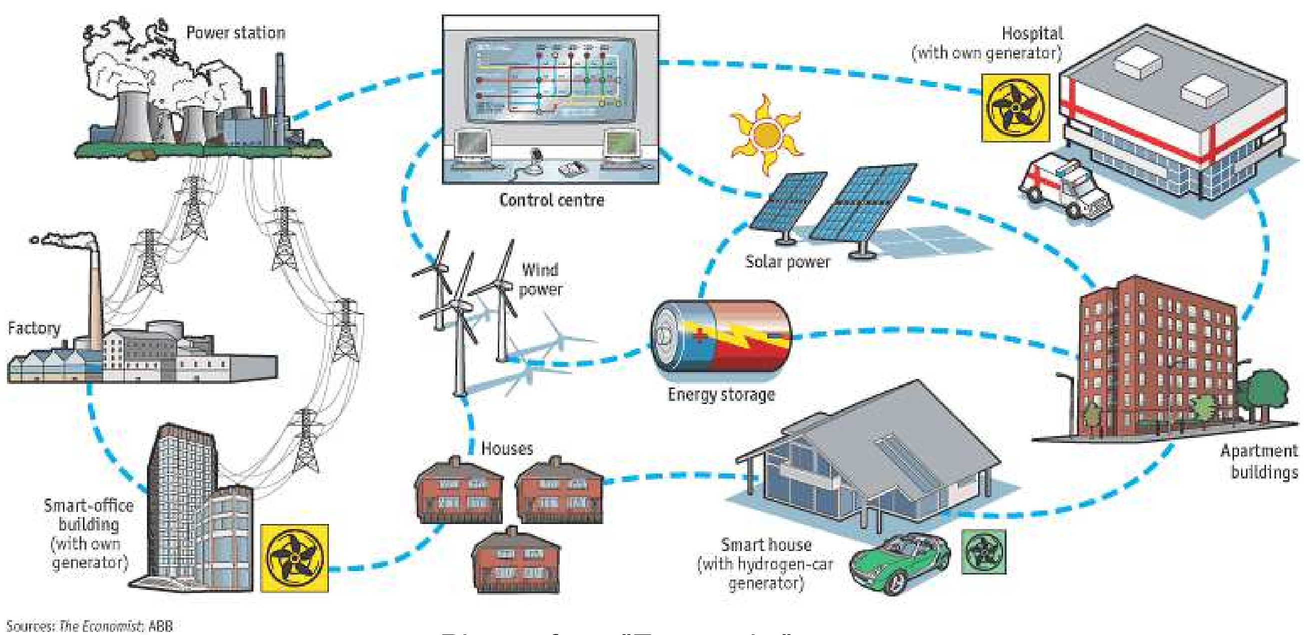
[1] Huang, A.Q.; Crow, M.L.; Heydt, G.T.; Zheng, J.P.; Dale, S.J.; , "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," *Proceedings of the IEEE* , vol.99, no.1, pp.133-148, Jan. 2011

[2] W. Su, and A.Q. Huang, "A Game Theoretic Framework for a Next-generation Retail Electricity Market with High Penetration of Distributed Residential Electricity Suppliers" *Applied Energy,* vol.119, pp.341-350, April 2014.

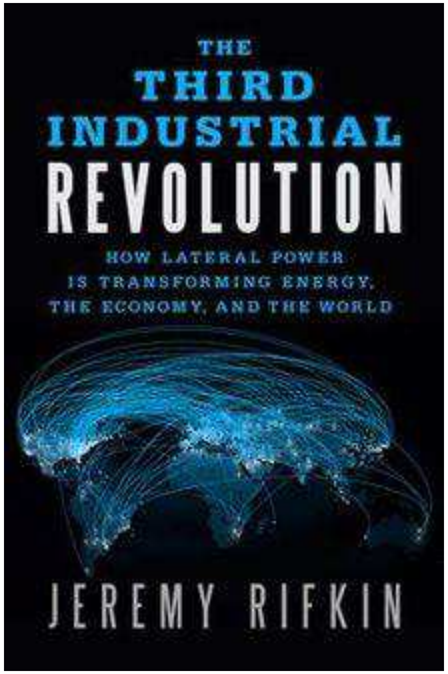
[3] W. Su, "The Role of Customers in the U.S. Electricity Market: Past, Present, and Future", *The Electricity Journal,* 2014. (invited)

The Third Industrial Revolution

“using Internet technology to transform the power grid of every continent into an **Energy Internet** that acts just like the Internet (when millions of buildings are generating a small amount of renewable energy locally, on-site, they can sell surplus green electricity back to the grid and share it with their continental neighbors); and”



Picture from ”Economist”



THANK YOU