Session L3

The FREEDM System: components, main functions, system control

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October 26, 2016

Topics for this tutorial

Lecture L3

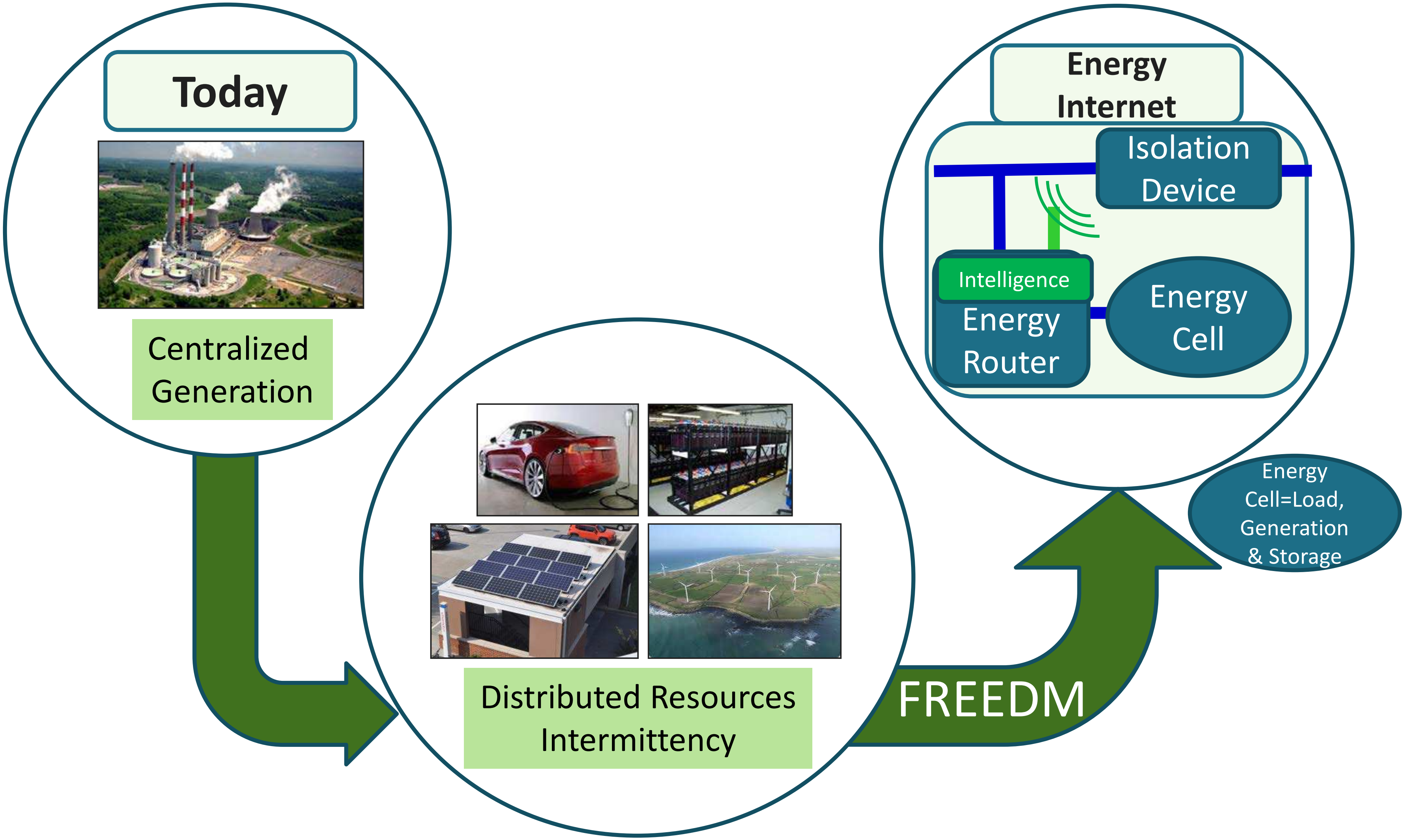
A. Traditional distribution systems, strengths, weaknesses

B. Overview of the FREEDM system and components

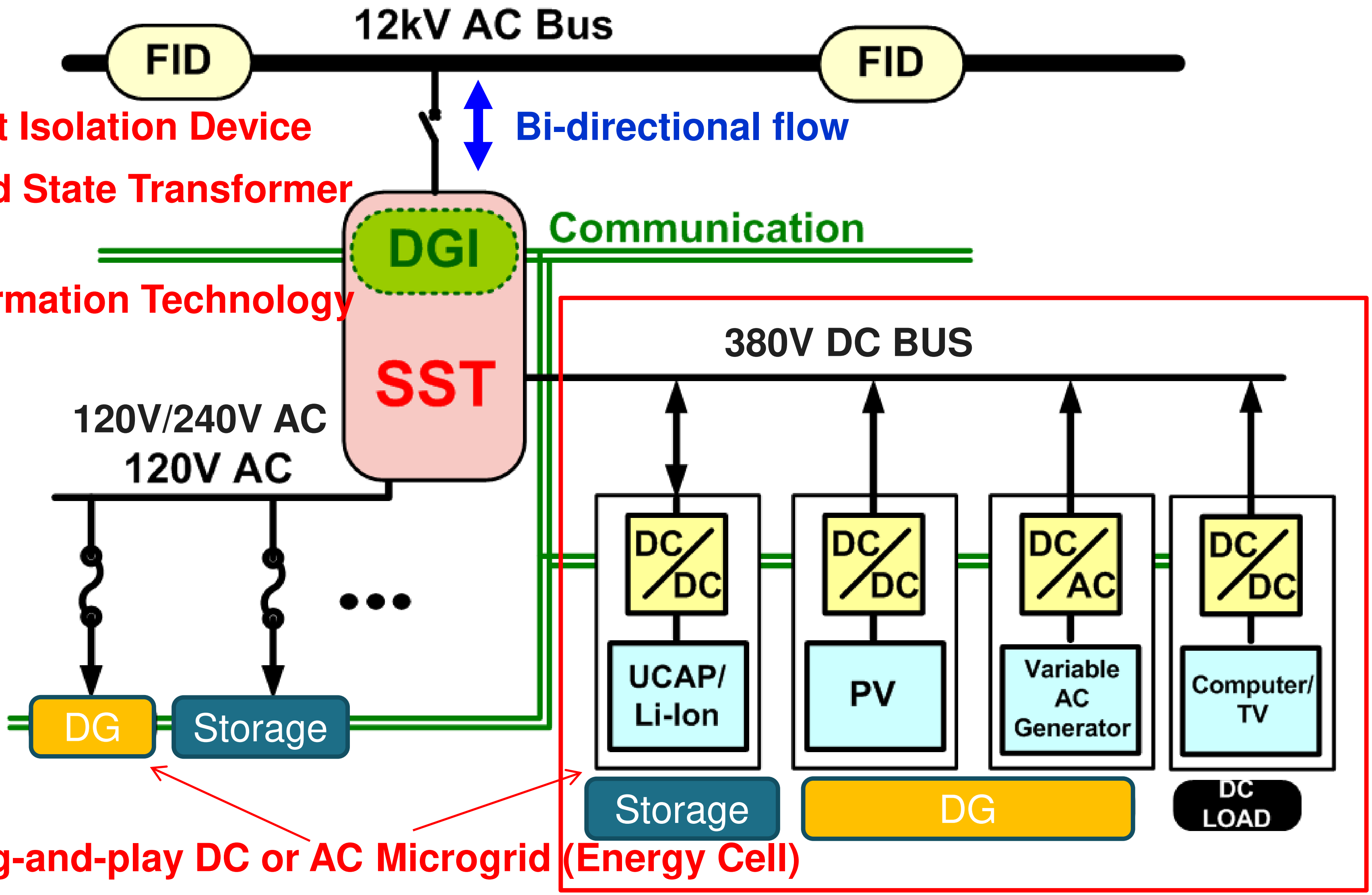
C. FREEDM system control and comparison with traditional systems

D. Some features of the distribution system of the future: pricing, cost / benefit, reliability

FREEDM Vision



The FREEDM Solution



1. Fault Isolation Device

1. Solid State Transformer

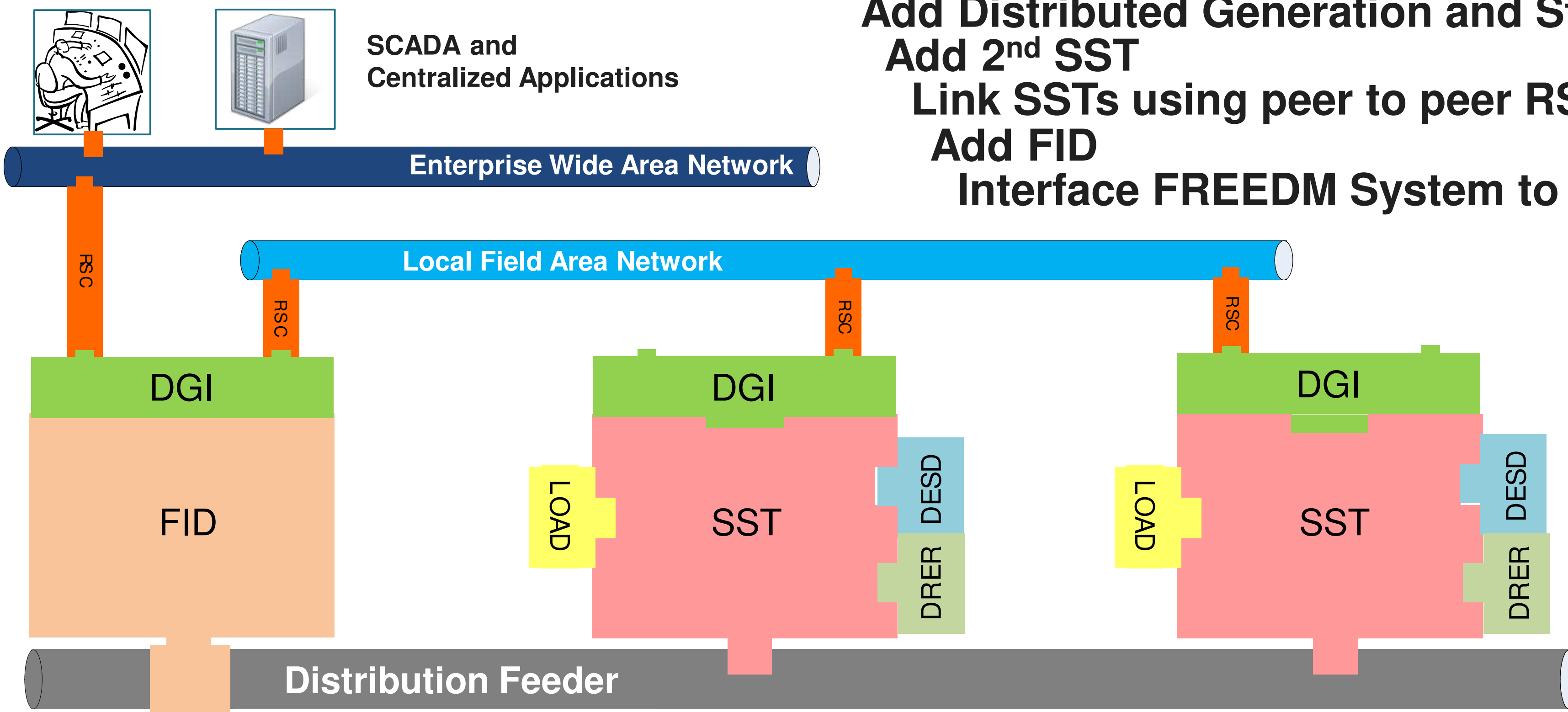
3. Information Technology

2. Plug-and-play DC or AC Microgrid (Energy Cell)

4. Robust and Automated Power, Energy and Fault Management

FREEDM System Scalability

System can be as small as one SST
- Add Distributed Generation and Storage
  - Add 2nd SST
    - Link SSTs using peer to peer RSC
      - Add FID
        - Interface FREEDM System to Utility



- Power distribution system built from ground up using FREEDM System devices.

DGI: Distributed Grid Intelligence **SST: Solid State Transformer** **FID: Fault Isolation Device**

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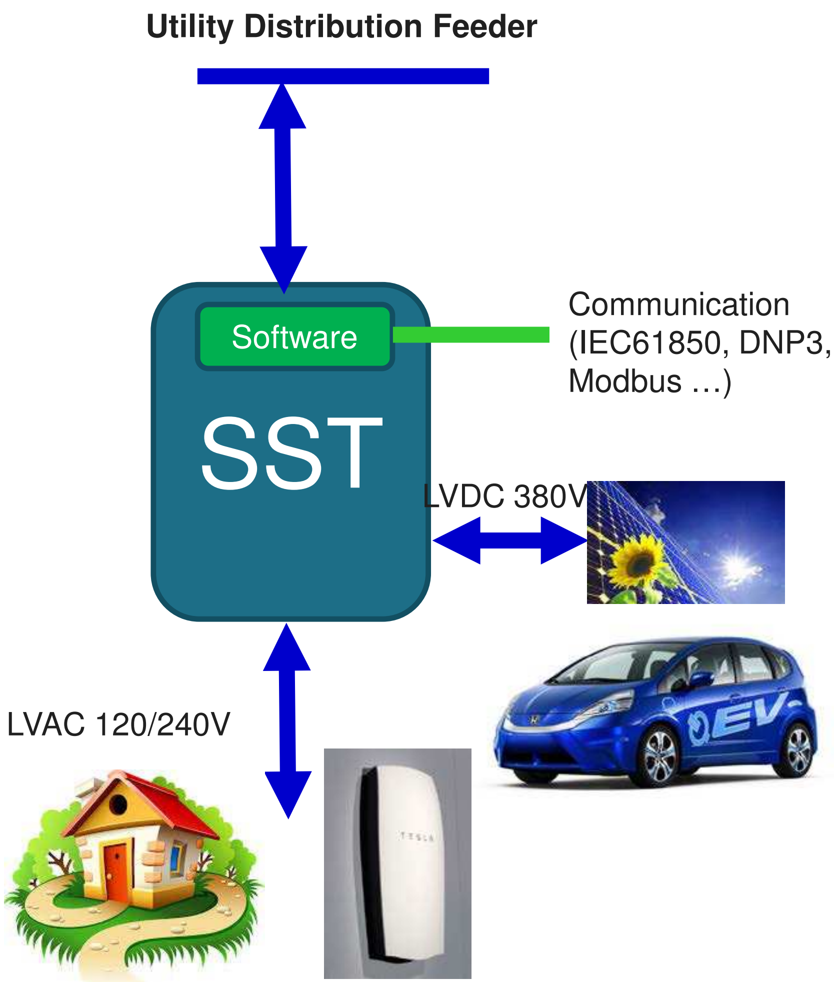
SST Enabled Smart Grid Features



Microsecond

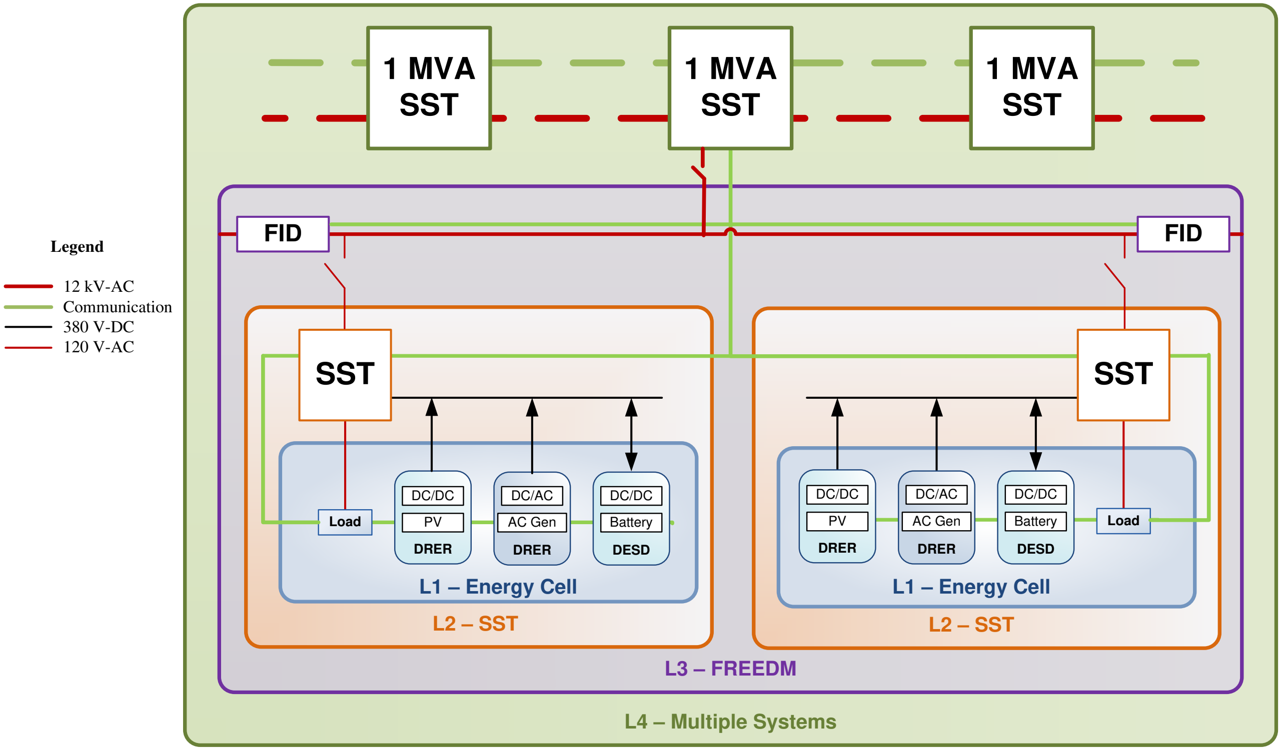
control

Hours

- **Fault management**
  - **Current limiting** ✓
  - **Disconnect/reconnect** ✓
- **Power Management:**
  - **Control power factor** ✓
  - **Change/Control customer voltage** ✓
  - **Provide DC power** ✓
  - **Eliminate harmonics** ✓
  - **Low voltage ride through** ✓
  - **Supports multiple islanding modes**
- **Energy Management**
  - **Monitor energy usage (AMI)**
  - **Can control/dispatch power *via microgrids (Energy Cell)***
  - **Demand side management**

✓ Features demonstrated in GEH using Gen I &II SSTs

FREEDM Physical Level Definitions



Level 1 – Energy Cell (Microgrid)

Coordination of local load, generation, and storage on SST secondary for maintaining instantaneous power balance.

Level 2 – Single SST

Interaction of a single SST with medium-voltage FREEDM system based on localized measurements and control.

Level 3 – FREEDM System

Interaction of multiple SSTs and FIDs within a single FREEDM system based on peer to peer communications and distributed control. Note “1 MVA SST” corresponds to Substation SST.

Level 4 – Multiple FREEDM Systems

Interaction of multiple FREEDM systems interconnected to form a medium-voltage distribution system.

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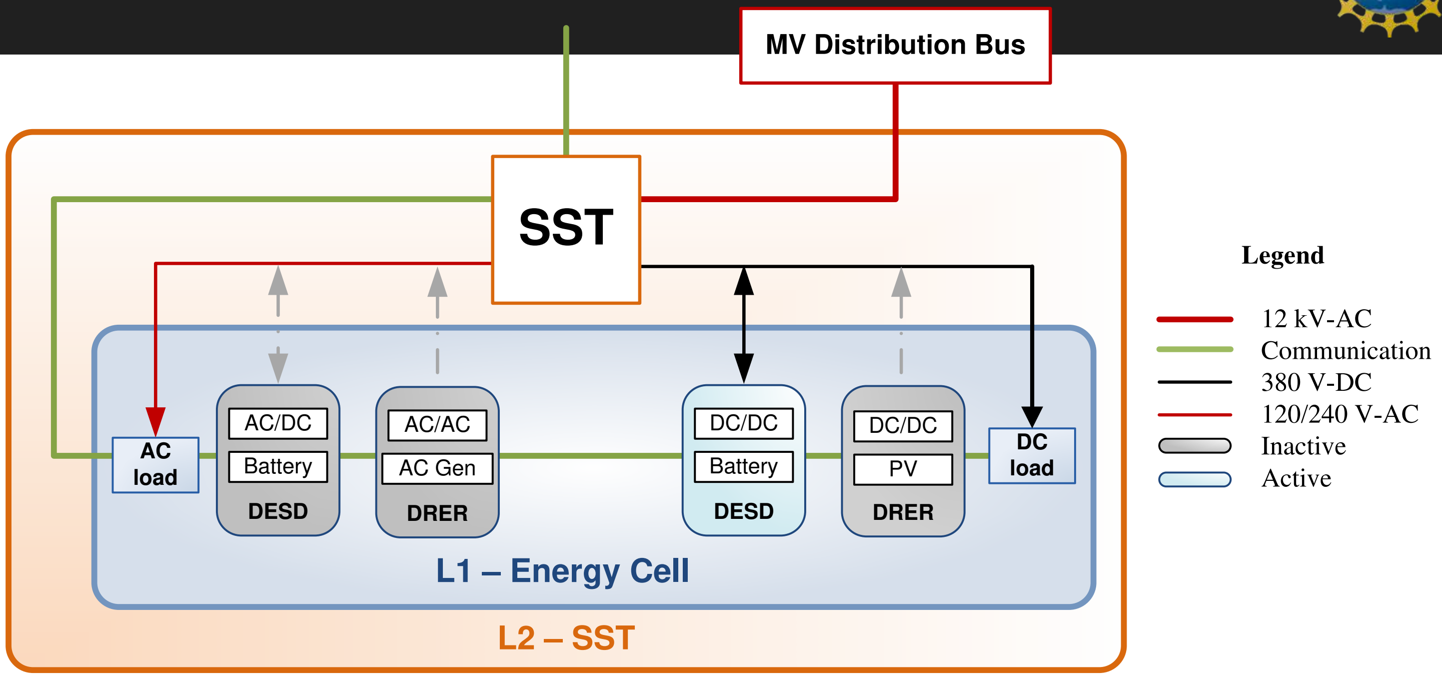
FREEDM Use Cases

- UC1: Plug and Play Functionality
- UC2: IEM when FREEDM System is Grid Connected
- UC3: IEM when FREEDM System is Islanded
- UC4: IEM when SST is Islanded
- UC5: IPM when FREEDM System is Grid Connected
- UC6: IPM when FREEDM System is Islanded
- UC7: IPM when SST is Islanded
- UC8: IFM for FREEDM System

L1 - Grid-Connected FREEDM



Use Case 5: IPM When FREEDM is Grid Connected

- L2 SST controls low voltage V_{ac} and V_{dc}
- Charge DESD
- Renewable generation should do MPPT
- No load shedding

Implementation:

- Communication: Local
- Time constants/constraints: ms
- Major control loops:
  - MPPT Control for PV/Wind
  - Constant Current /Constant Voltage
  - Charge Control for DESD

Low-Cost SST with LF Transformer for Power Distribution

❑ Alternative to MV SST Technology

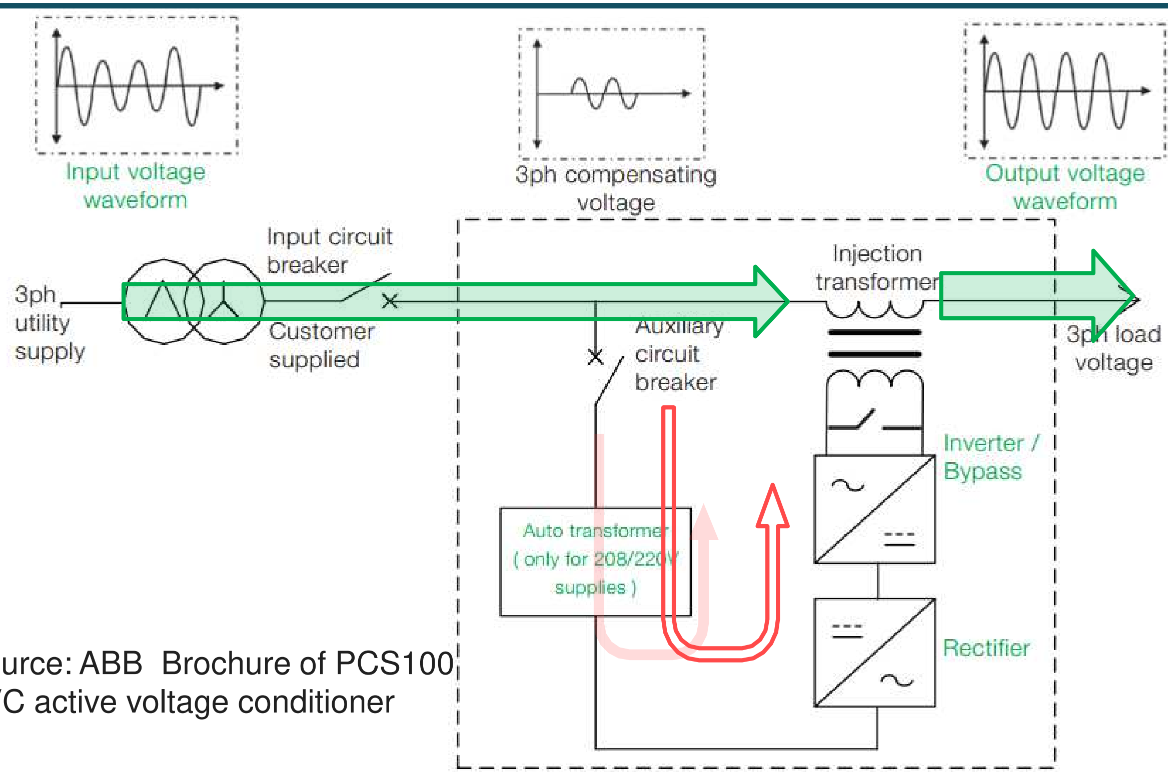
- ✓ LFT with SST solution : AC-DC-AC low power SST + high power LF transformer

❑ Comparison LFT-SST solution and the conventional 50/60 Hz transformer

- ✓ Alternative candidate for future smart grid applications
- ✓ This SST do NOT process the full power flow, which results in significant cost saving vs. normal SST
- ✓ Combining controllability of SST and low cost of LF transformer
  - Voltage scaling & galvanic isolation
  - Correction of voltage sags, unbalances and phase angle errors
  - Reactive power compensation
  - Can be extended to bidirectional power flow control

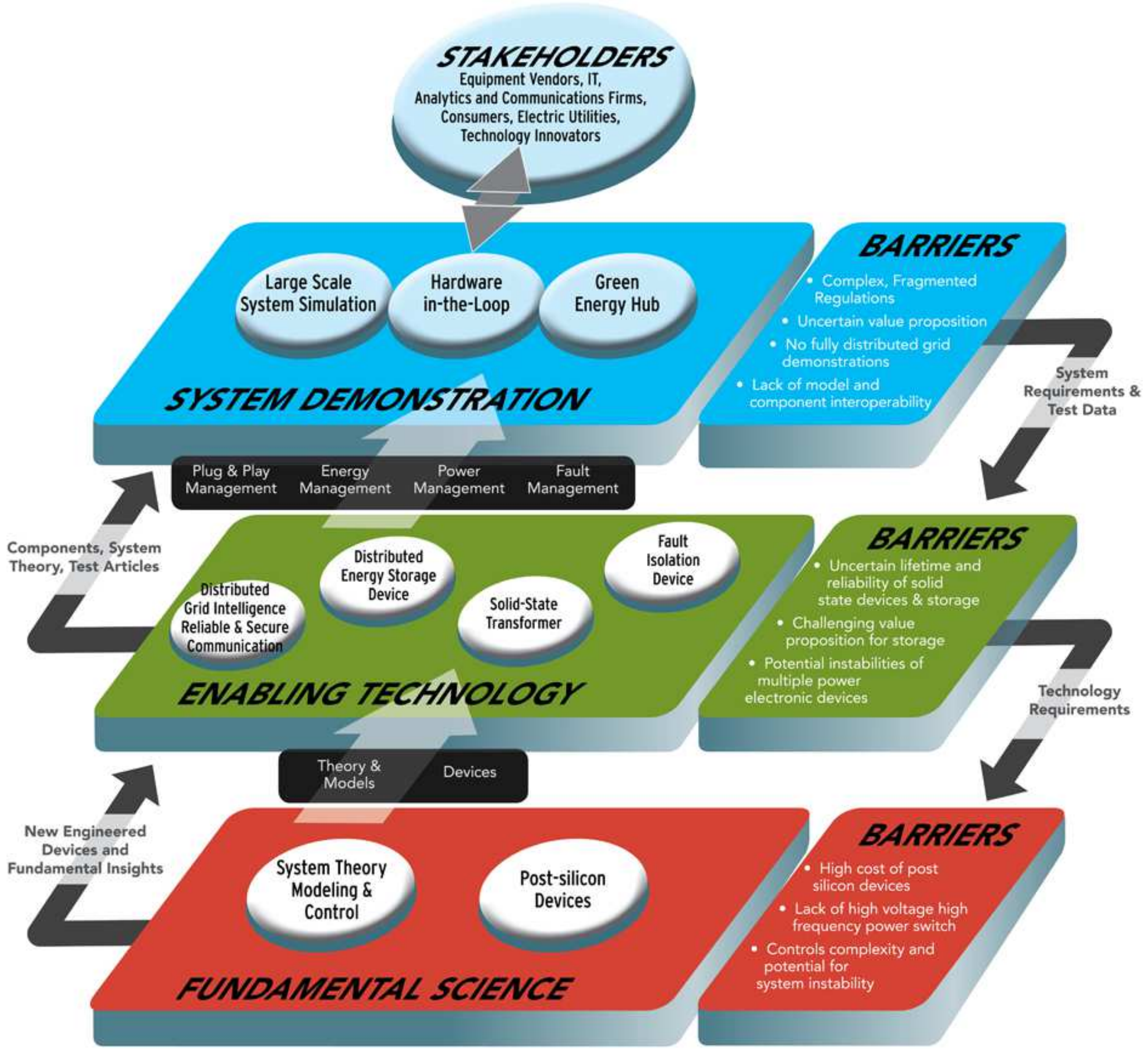
❑ Comparison with MV SST Technology (FREEDM System)

- ✓ Limited controllability of the essential smart grid features
- ✓ Bi-directional power flow
- ✓ Do not enable DC distribution system
- ✓ Space and weight penalty
- ✓ Do not take advantage of the emerging WBG technologies



Source: ABB Brochure of PCS100 AVC active voltage conditioner

Strategic Research Plan



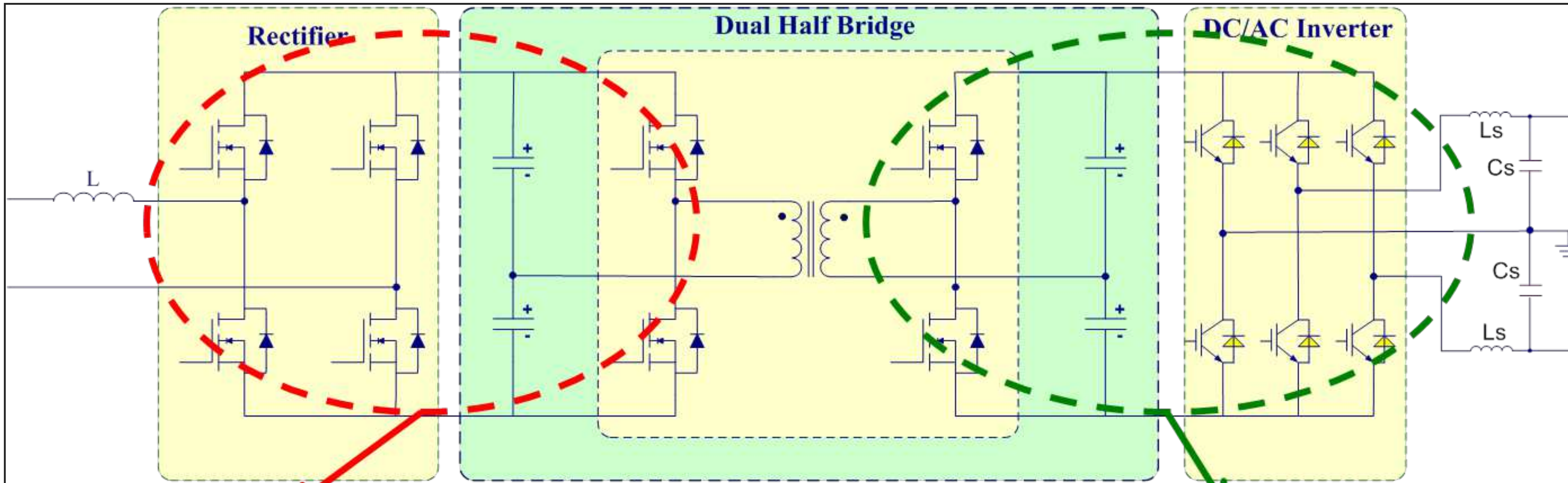
Gen-II Solid State Transformer

Specifications:

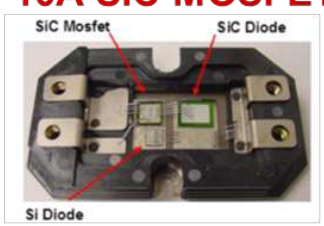
- Input: 7.2kVac
- Output: 240Vac/120Vac; 400Vdc
- Power rating: 20kVA

Tested:

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



15kV 10A SiC MOSFET



1200V 100A SiC MOSFET

Gen III Solid State Transformer (Y7-Y8)

A more reliable and cost-effective Gen-III Solid State Transformer (SST) with improved energy efficiency, power density, isolation capability, robustness and controllability

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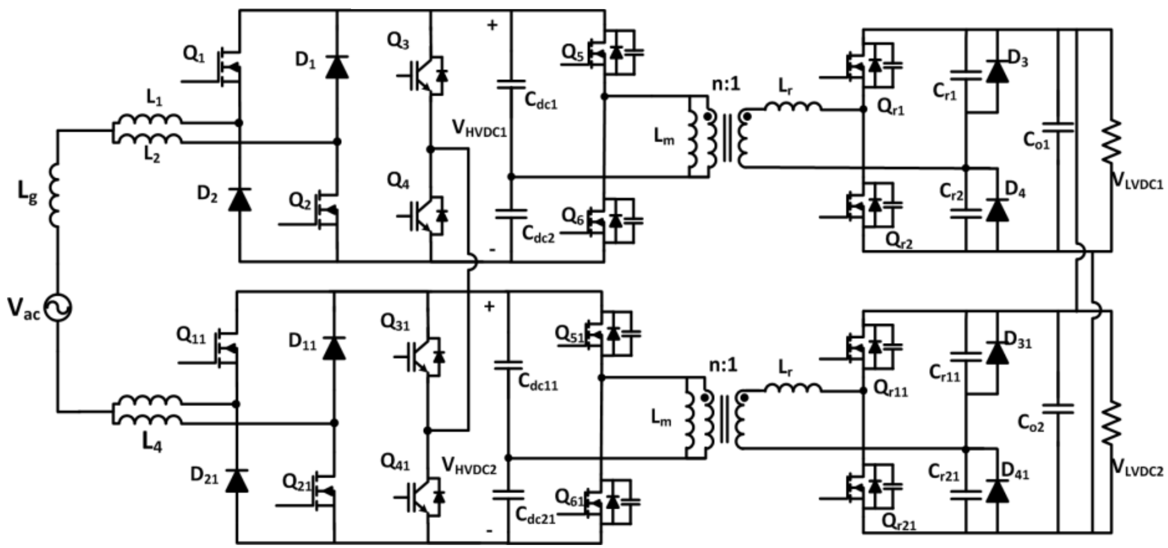
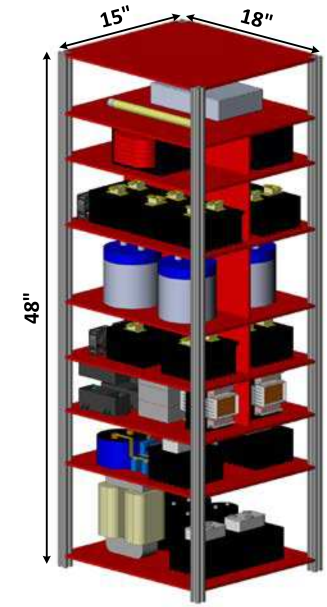
Three stage power conversion





Major Accomplishments:

- HV/HF transformer with >20kV isolation capability (invention disclosure)
- World record 6kV-400V 10kW 40 kHz DC-DC converter based on LLC/DAB hybrid (APEC2015)
- Shoot through free AC-DC topology (APEC2016)

Major Challenges:

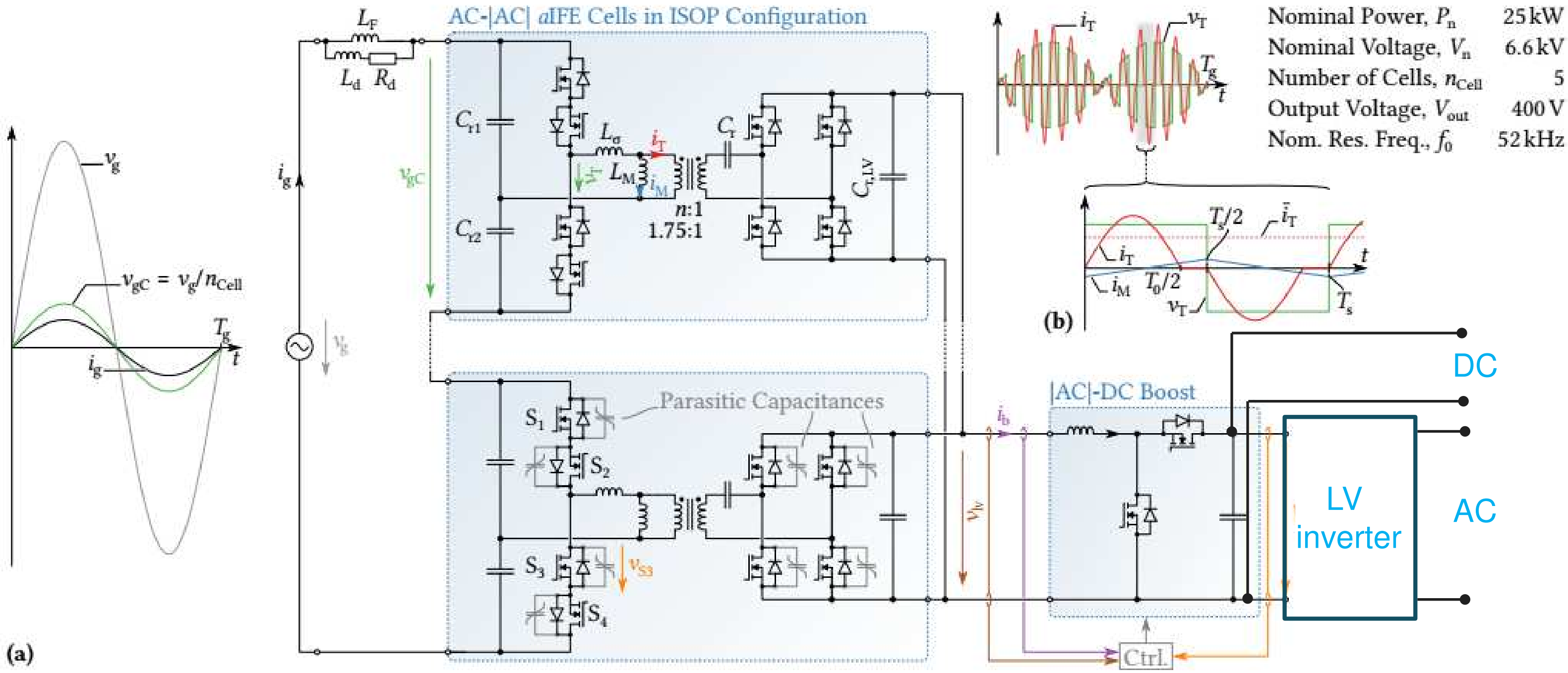
- Three stage power conversions as in Gen-I & II.
- MV rectifier stage hard switched & ultra high device turn-on stress
- Still large number of HV devices needed: Higher cost.

New Approach

Three-Stage AC/AC & DC SST

❑ Key technologies

- ✓ Three-stage solution : multi-level resonant AC-DC with fixed gain+ boost dc-dc + LV inverter
- ✓ The simplest high-voltage-side topology and the simplest system-level control

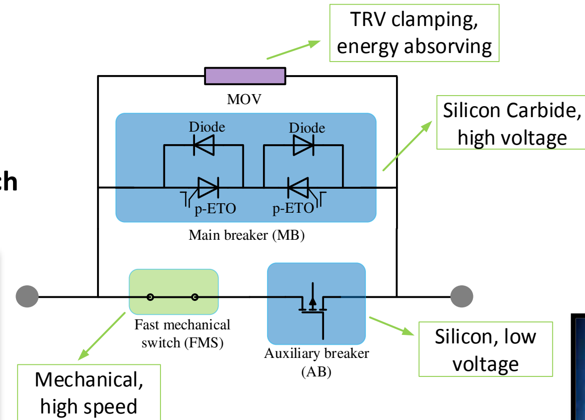


❑ International Collaboration with FREEDM partners

J. E. Huber, D. Rothmund, L. Wang, and J. W. Kolar, "Full-ZVS modulation for all-SiC ISOP-type isolated front end (IFE) solid-state transformer," in Proc. IEEE ECCE, Sep. 2016.

Gen III Hybrid FID Development

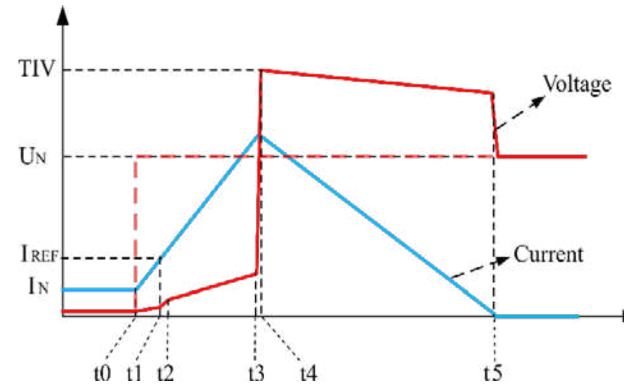
200A, 15 kV mechanical disconnect switch
Open in < 1ms



15 kV, 200 A, SiC p-ETO, bi-directional

200 (400) A, MOSFET
Rds(on) < 1mOhm
Vbr = 100 2

Hybrid Fault Isolation Device



$$t = t_{CS} + t_{FMS} + t_{MB} + t_{MOV}$$

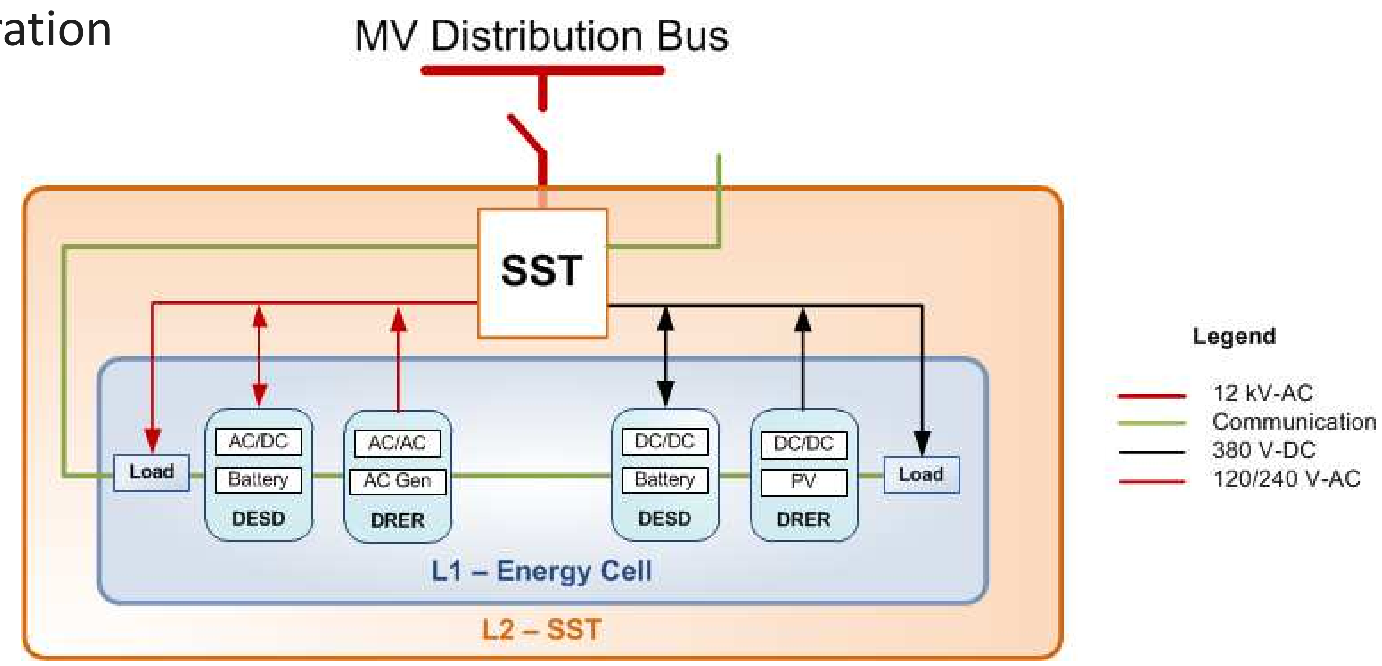
$$t \approx t_{FMS} + t_{MOV}$$

Hybrid CB V-I transient

- Hybrid FID designed combining a fast mechanical switch (FMS) in series with a low loss Si Mosfet with a parallel branch for the SiC ETO high voltage switch
- Low conduction losses by **bypassing the semiconductors**
- HV SiC ETO device (> 13kV) lowers the on-state and switching losses
- Only as fast as the mechanical switch
- No arcing in the mechanical switch

Distributed Energy Storage Devices

- DESD supports IEM and IPM functions by providing an energy buffer with bi-directional power flow capability.
- Efficient converter interfaces between storage devices and FREEDM DC and AC ports
- DESD Supports
  - Renewable Integration
  - Islanded Operation



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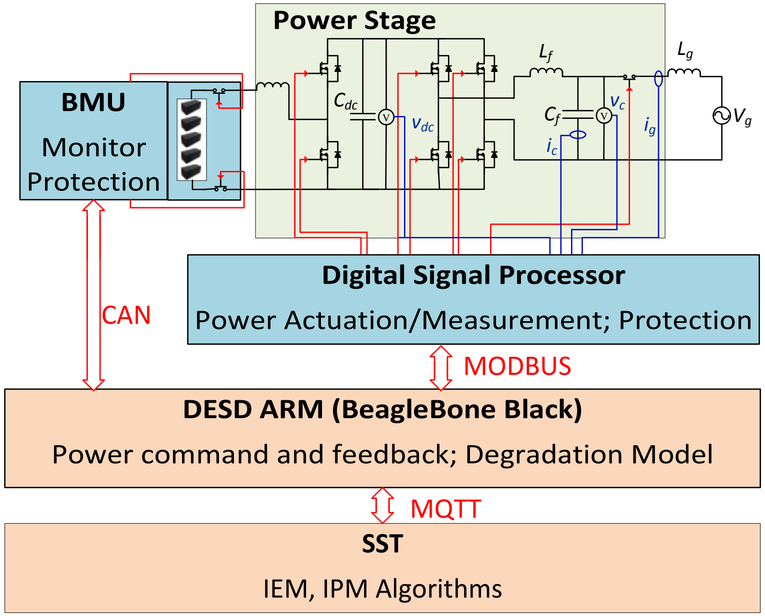
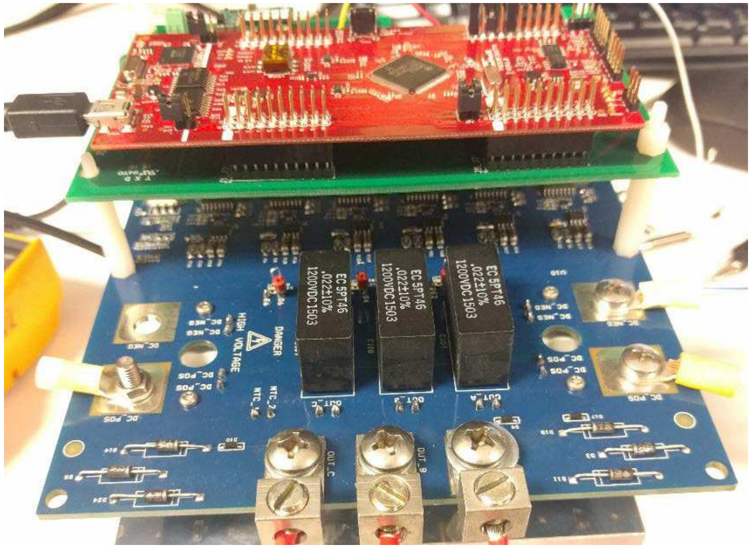
DESD Standardization

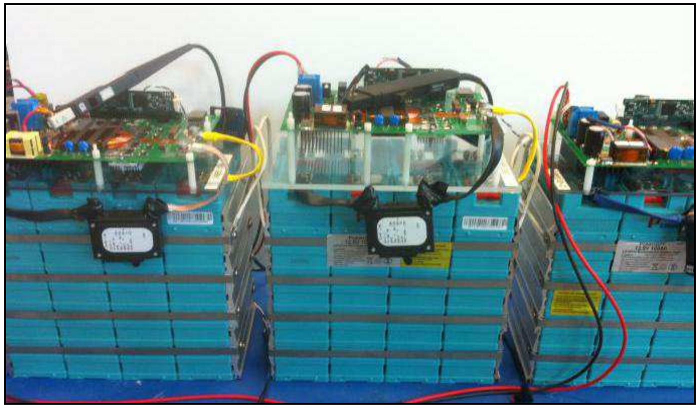
- SiC Boost/Inverter power stage
- DESD Integration Platform
  - Low-cost **ARM** for DESD-specific Apps; **DSP** for power control
  - **MQTT** Communication backbone to SST
  - **CAN** communication to battery management system (BMU)
  - **MODBUS** link between power electronics controller and high-level apps



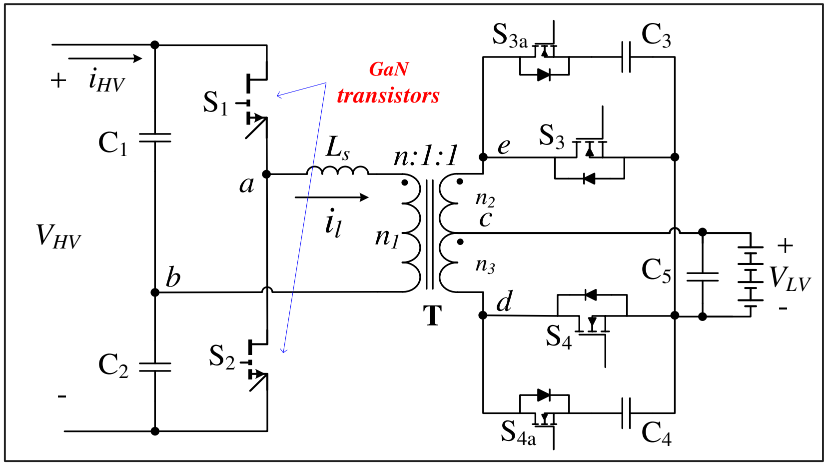


Major Achievements
Power Electronics

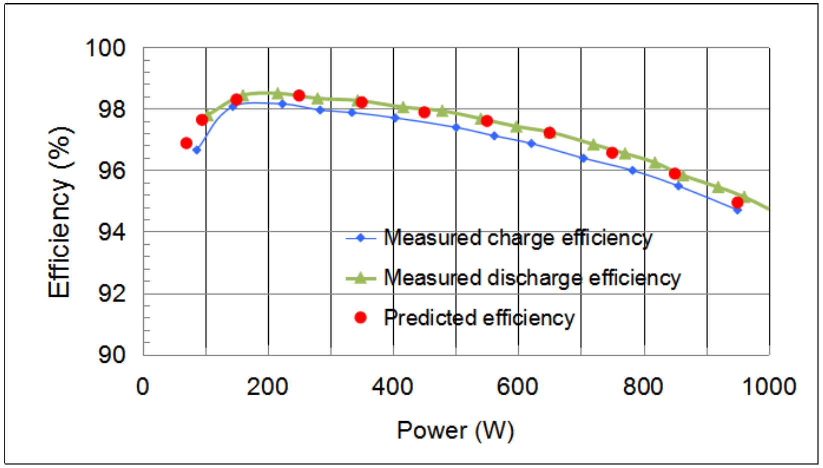
- High efficiency high power density DC/DC Converter
- Integrates a 12V battery to 380V DC
- Stacks 1kW building blocks
- Uses GaN Devices on the high-voltage side



Converter prototype integrated with battery



Selected topology using GaN transistors

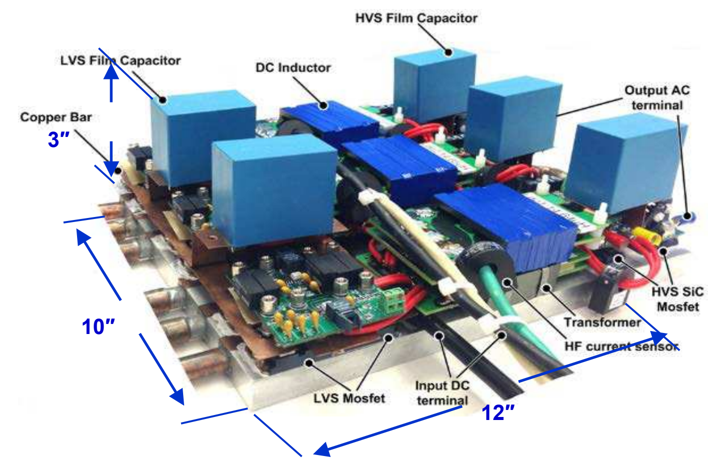


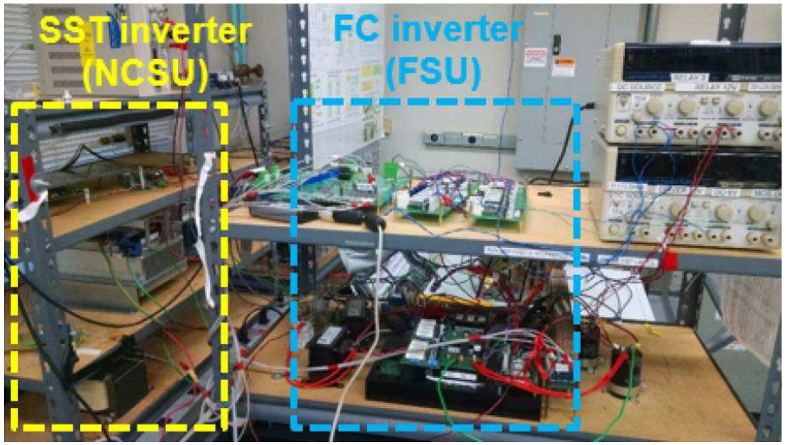
Converter prototype efficiency

F. Xue, R. Yu, W. Yu and A. Q. Huang, "Distributed energy storage device based on a novel bidirectional Dc-Dc converter with 650V GaN transistors," *2015 IEEE 6th Int. Symp. on Power Electronics for Distributed Generation Systems (PEDG)*, 2015, pp. 1-6.
F. Xue, R. Yu, W. Yu and A. Q. Huang, "GaN transistor based Bi-directional DC-DC converter for stationary energy storage device for 400V DC microgrid," *DC Microgrids (ICDCM), 2015 IEEE First International Conference on*, Atlanta, GA, 2015, pp. 153g-153l.
Fei Xue, R. Yu, W. Yu, A. Q. Huang and Yu Du, "A novel bi-directional DC-DC converter for distributed energy storage device," *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Charlotte, NC, 2015, pp. 1126-1130.

Major Achievements
Power Electronics

- Gen II DC/AC converter with reduced DC-bus Capacitor
  - Interfaces 100Vdc energy storage system to 120Vac output
  - Two stage solution; very low current ripple from storage system
  - DC cap reduced 90% through control; allows for the use of film capacitors
- System integrated with SST inverter, showing a stable interaction

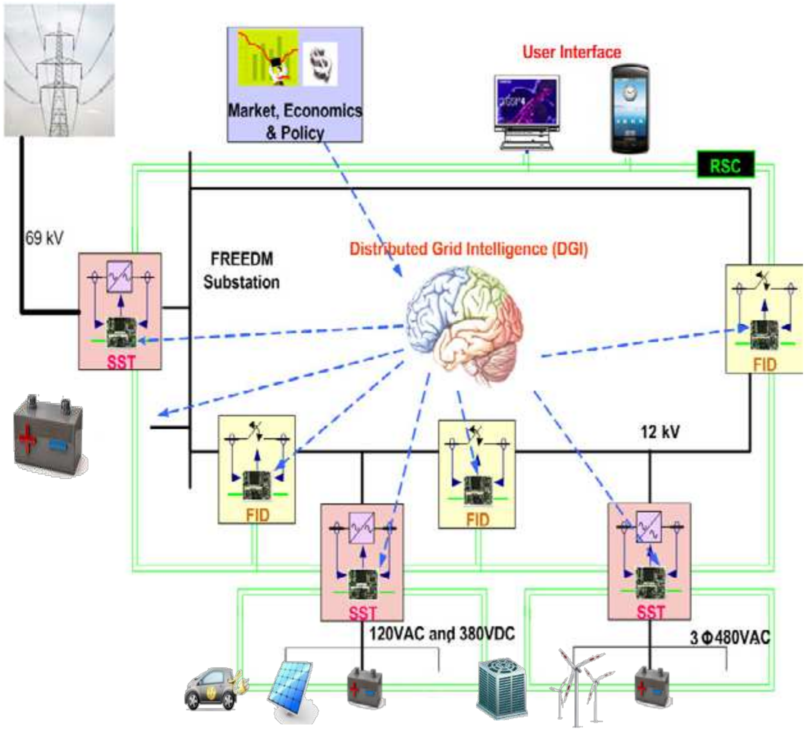




X. Liu and H. Li, "An Electrolytic-Capacitor-Free Single-Phase High-Power Fuel Cell Converter With Direct Double-Frequency Ripple Current Control," in *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 297-308, Jan.-Feb. 2015.
Q. Ye and H. Li, "Stability analysis and improvement of solid state transformer (SST)-paralleled inverters system using negative impedance feedback control," *2016 IEEE Applied Power Electronics Conference and Expo.*, 2016, pp. 2237-2244.
Q. Ye, R. Mo, Y. Shi and H. Li, "A unified Impedance-based Stability Criterion (UIBSC) for paralleled grid-tied inverters using global minor loop gain (GMLG)," *IEEE Energy Conversion Congress and Exposition*, Montreal, QC, 2015, pp. 5816-5821.

FREEDM System Intelligence and Control

- Decentralized control and monitoring of FREEDM devices, load, storage and generation at distribution transformer and feeder level.
- Each FREEDM device (SST and FID) has a Distributed Grid Intelligence (DGI) processor.
- Reliable and Secure Communications (RSC) is the local, peer-to-peer and utility communications needed to support the DGI.
- DGI supports both single-node and group applications for:
  - Plug and Play functionality
  - Intelligent Power Management
  - Intelligent Energy Management
  - Intelligent Fault Management
- Decentralized architecture supports both grid-connected and islanded (isolated Microgrid) functionalities.



Green Energy Hub Testbed

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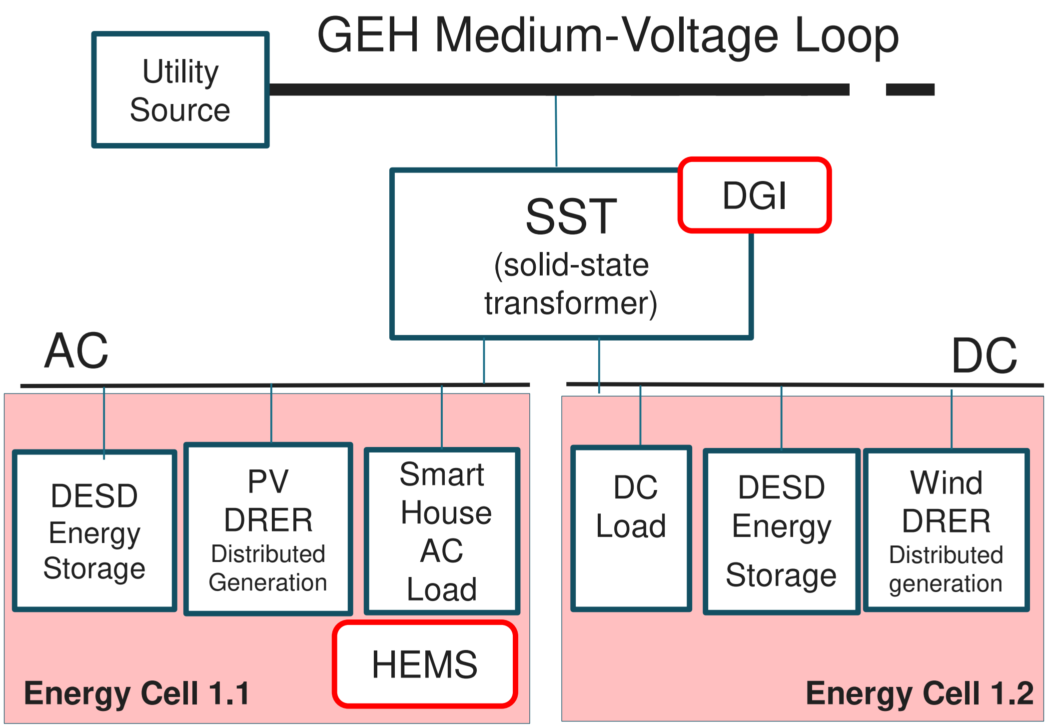
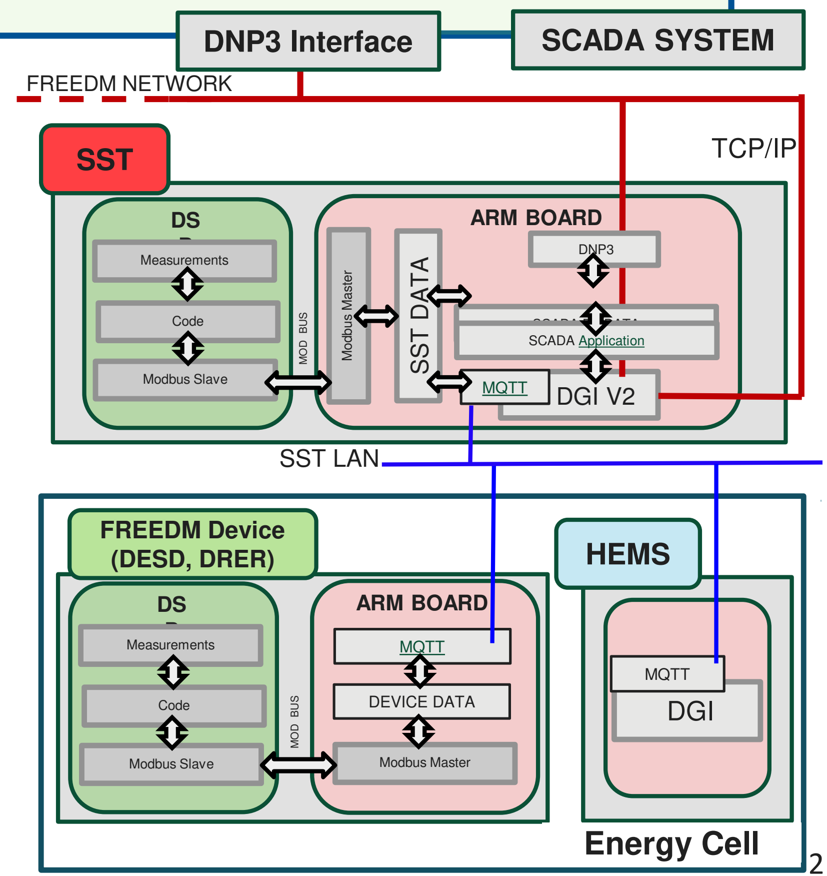
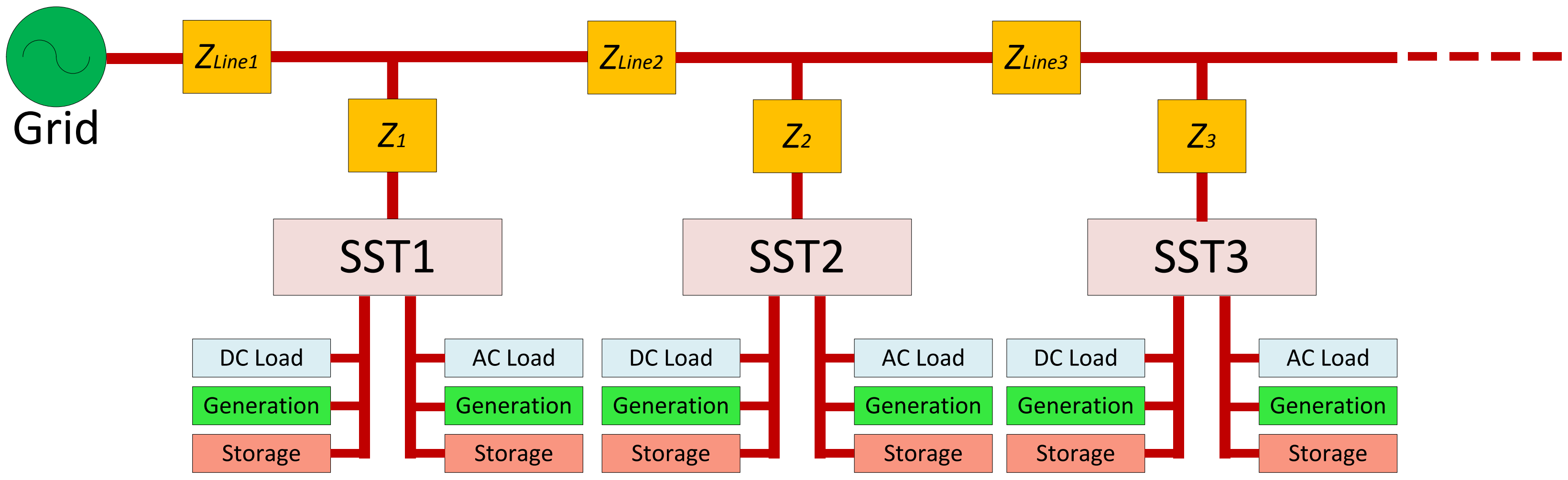
- Demonstration of FREEDM System functionalities including islanding, black start, load control, frequency regulation in GEH
- GEH testbed enhanced with Distributed Grid Intelligence (DGI) software platform for hosting applications and includes
  - MQTT-based local device data transfer
  - DNP3 protocol support for enterprise



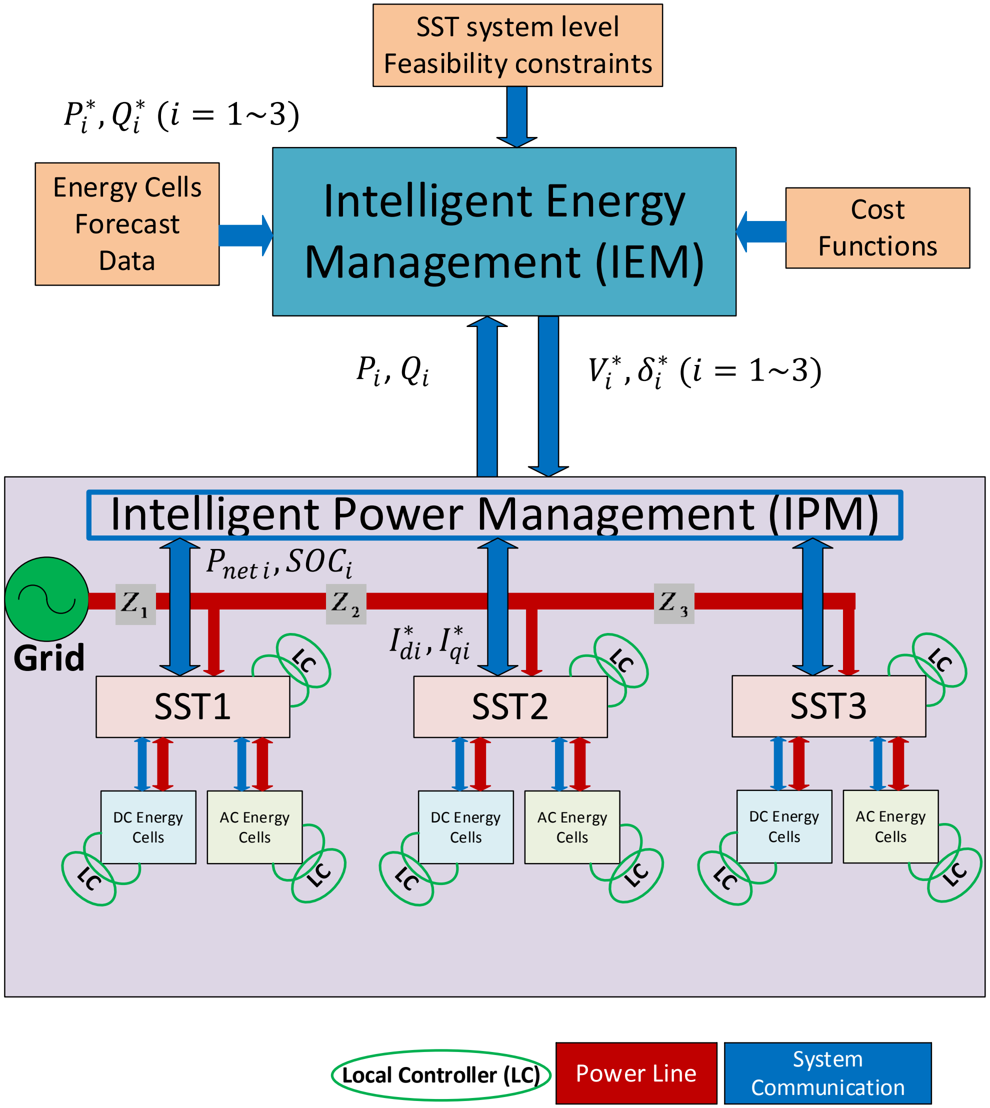


FREEDM Systems Controls



- FREEDM system is an engineered, non-linear, hybrid, multivariable system having its challenges for identifying suitable analysis techniques
- FREEDM System Analysis:
  - Comprehensive state space model development
  - Equilibrium and feasibility Analysis
  - System controller development and stability analysis

Technical Approach



Hierarchical Schematic of FREEDM System

Apply model reduction techniques to reduce the complexity and order of the model

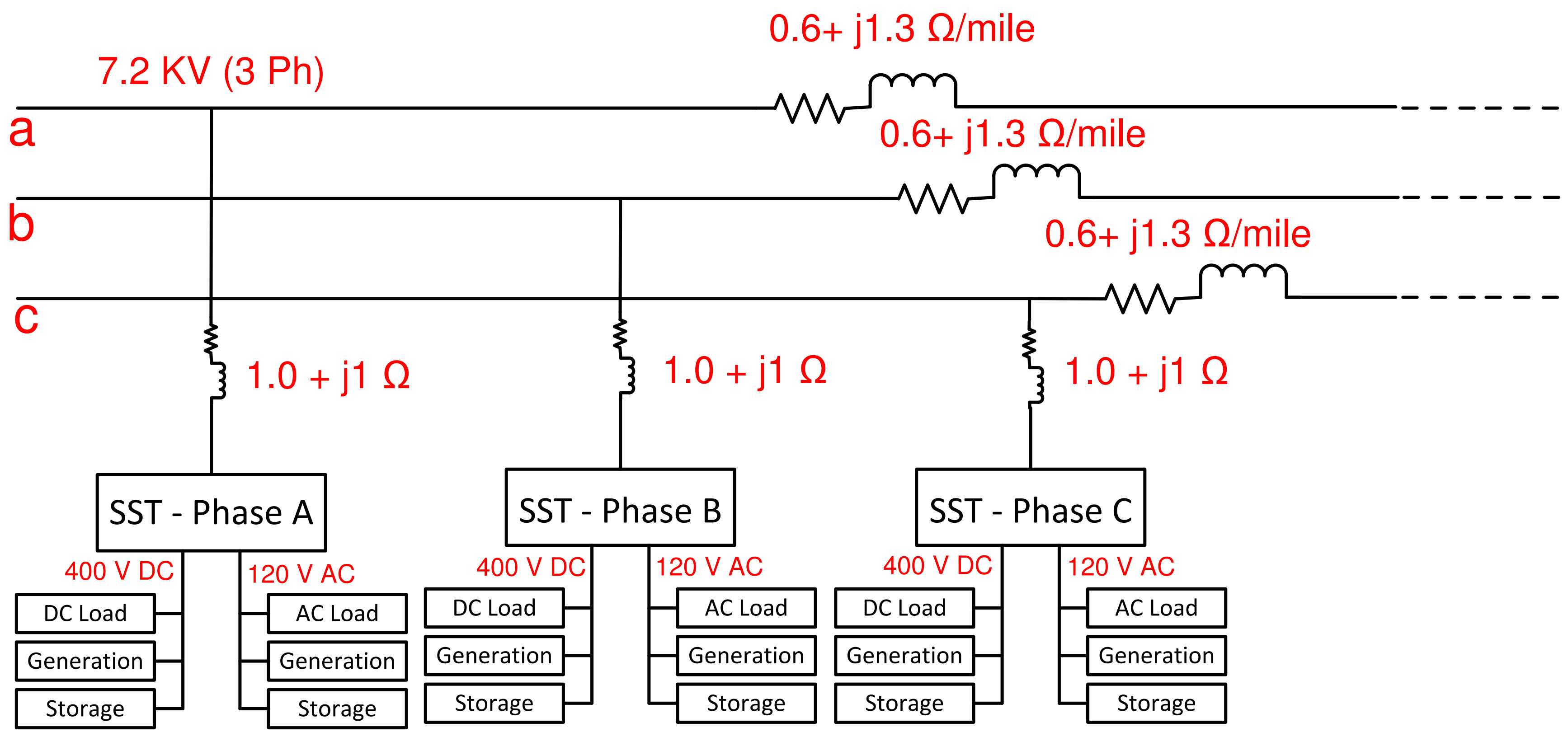
Types of reduced analytical models:

- Large signal: State space models
- Small signal: Linearized models at operation points
- Dynamic phasors: For analyzing large systems with many power converters

Control Hierarchy:

- IEM provides the power reference commands for IPM based on forecast data and real time measurements
- IPM sets the current commands for each FREEDM system based on IEM reference signals
- Local controllers in each FREEDM system will maintain the voltage and frequency at its desired level

High Fidelity Model for Simulation



FREEDM System in LSSS Model

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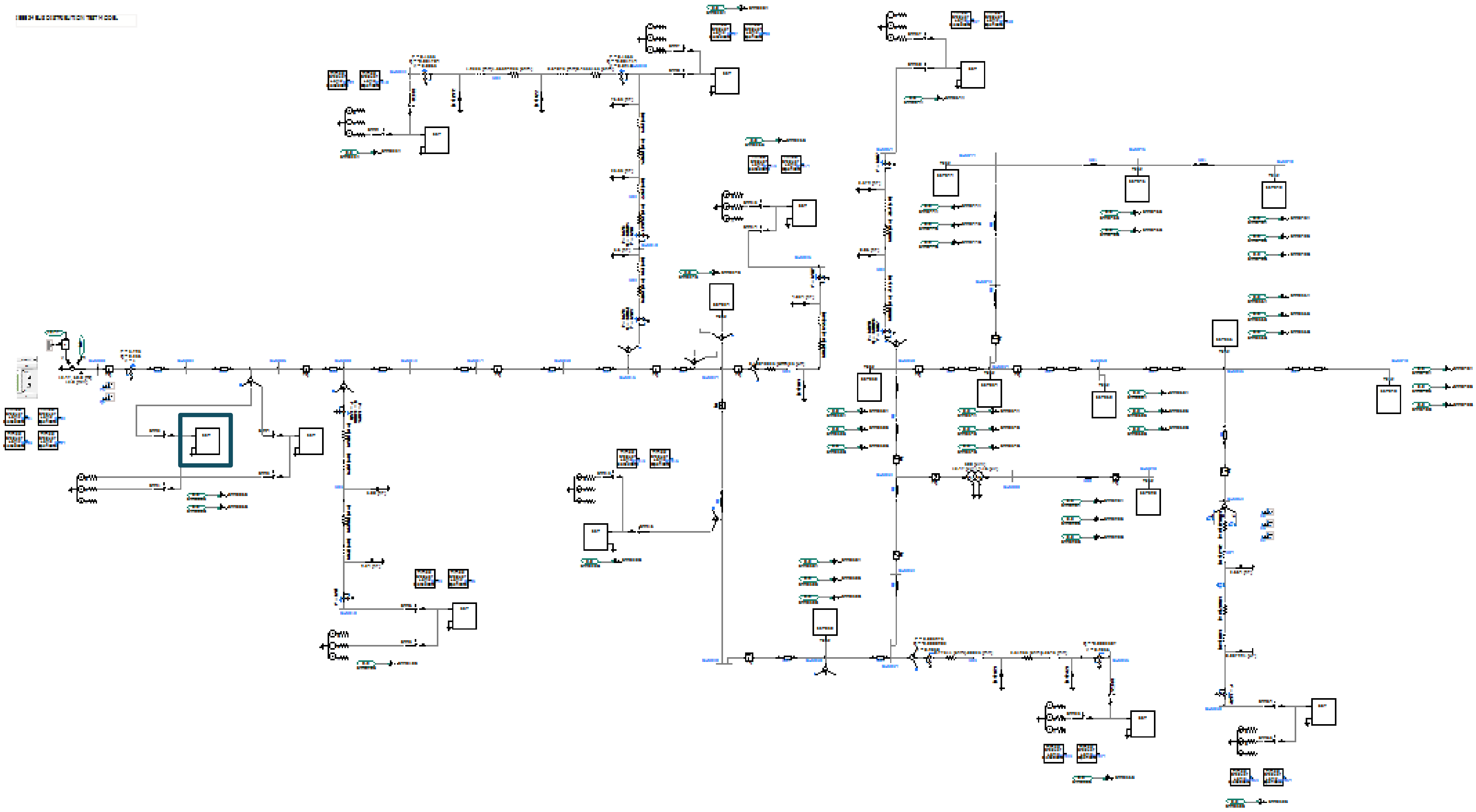
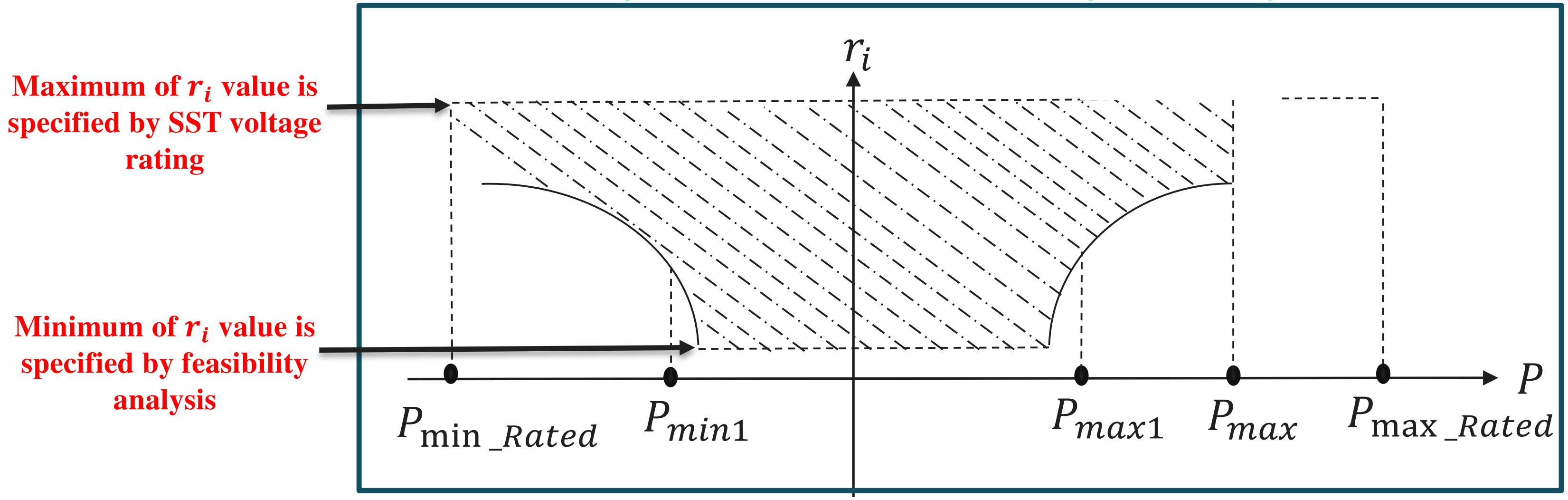
LSSS Model (Radial System)

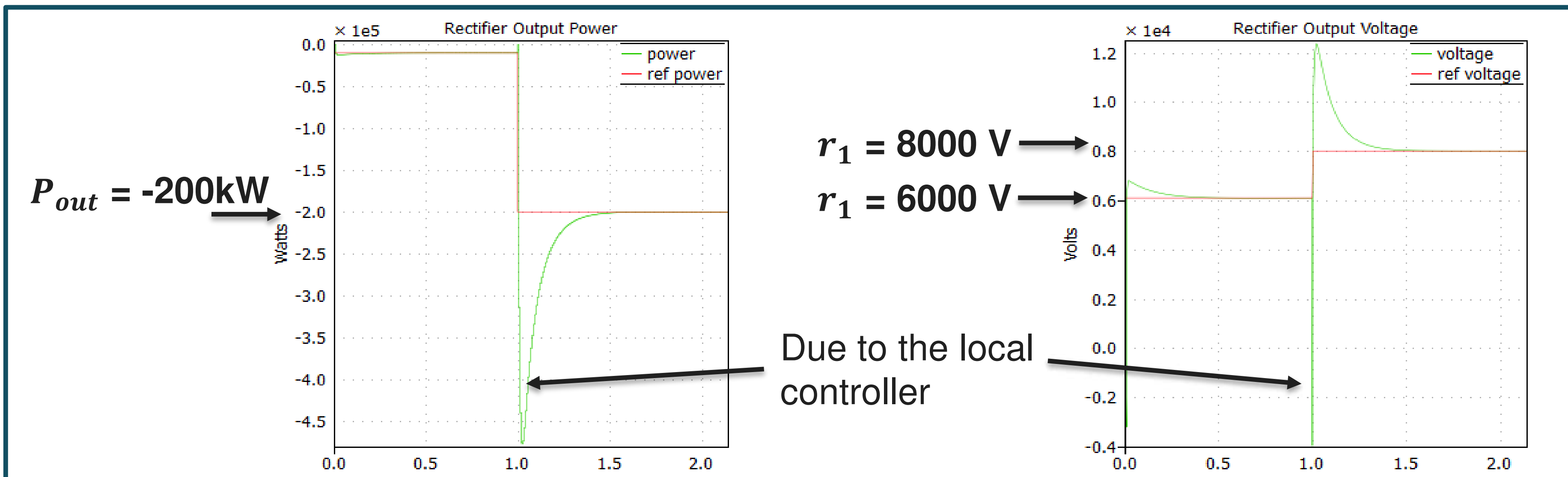


FREEDM System Equilibrium Analysis

Feasibility range can be increased by changing the rectifier output voltage r_i.

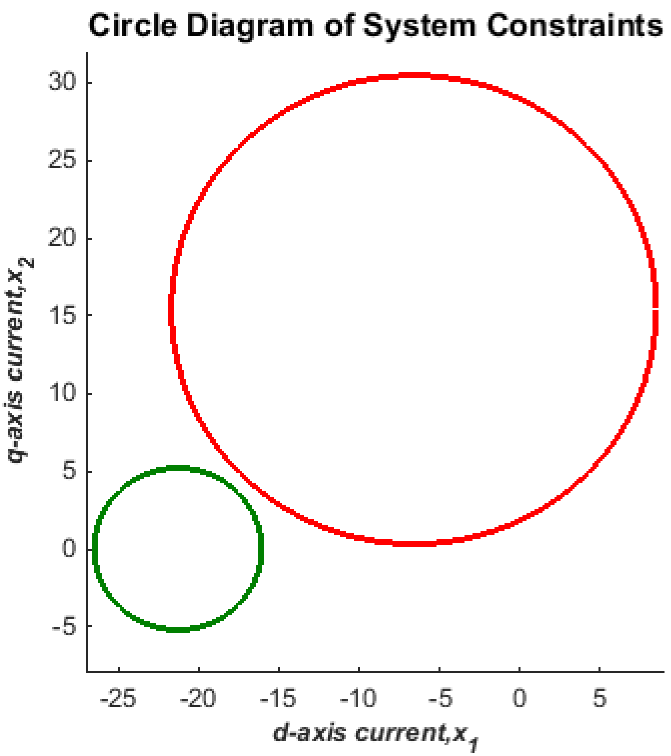
Droop control of rectifier output voltage reference



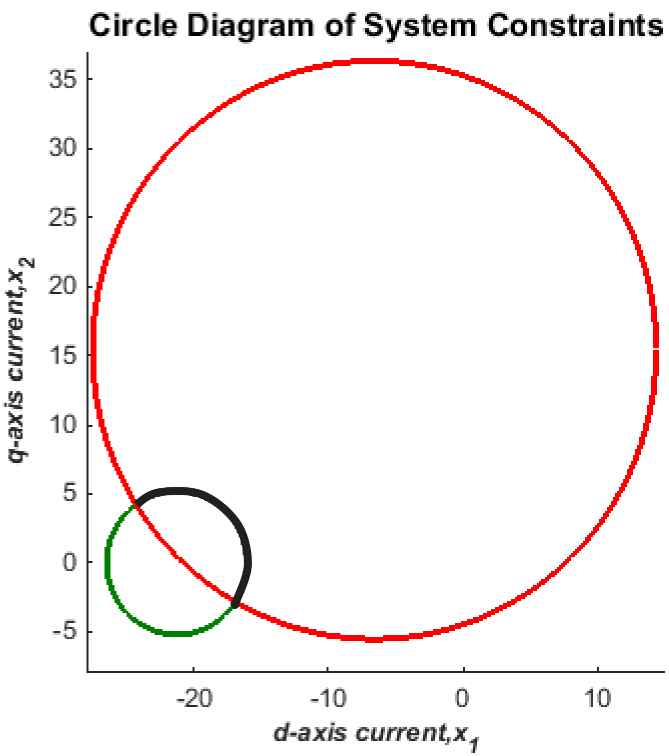


LSSS model – Feasibility Analysis

- Feasibility analysis in LSSS model to transform infeasible SST into feasible one.
- Infeasibility is observed in node 40 of LSSS model and then, rectifier output voltage reference is tuned to make it feasible.
- Voltage reference can be changed instantaneously for each individual SST from IPM controller based on system status.

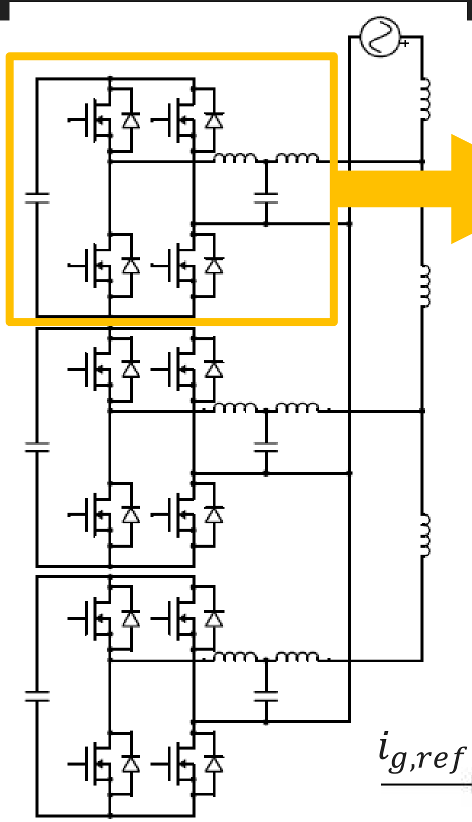


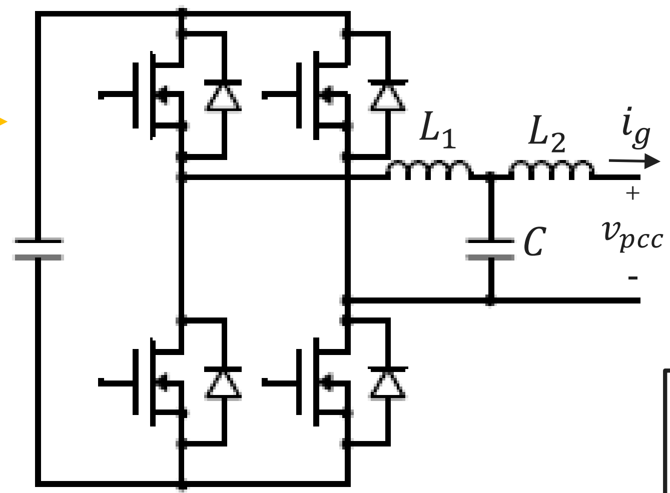
Infeasible system at node 40 @ P = 10 KW



Feasible system at node 40 @ P = 10 KW

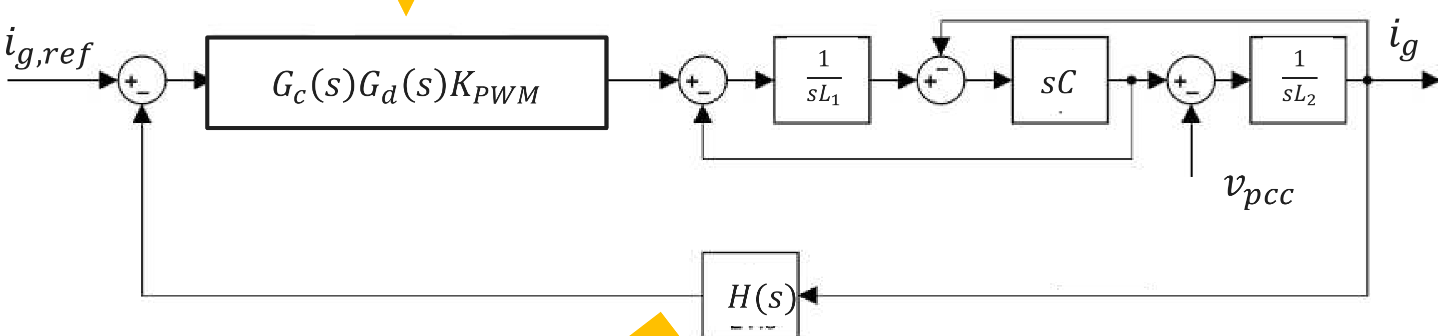
Current PV Integrated Distribution System





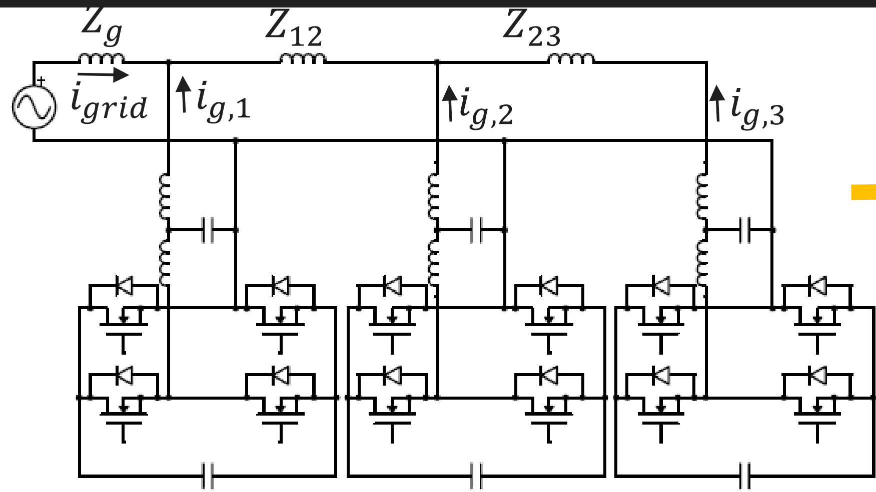
Only the front-end rectifier/inverter stage of SSTs are considered assuming that the DC link ensures decoupling with the later stages

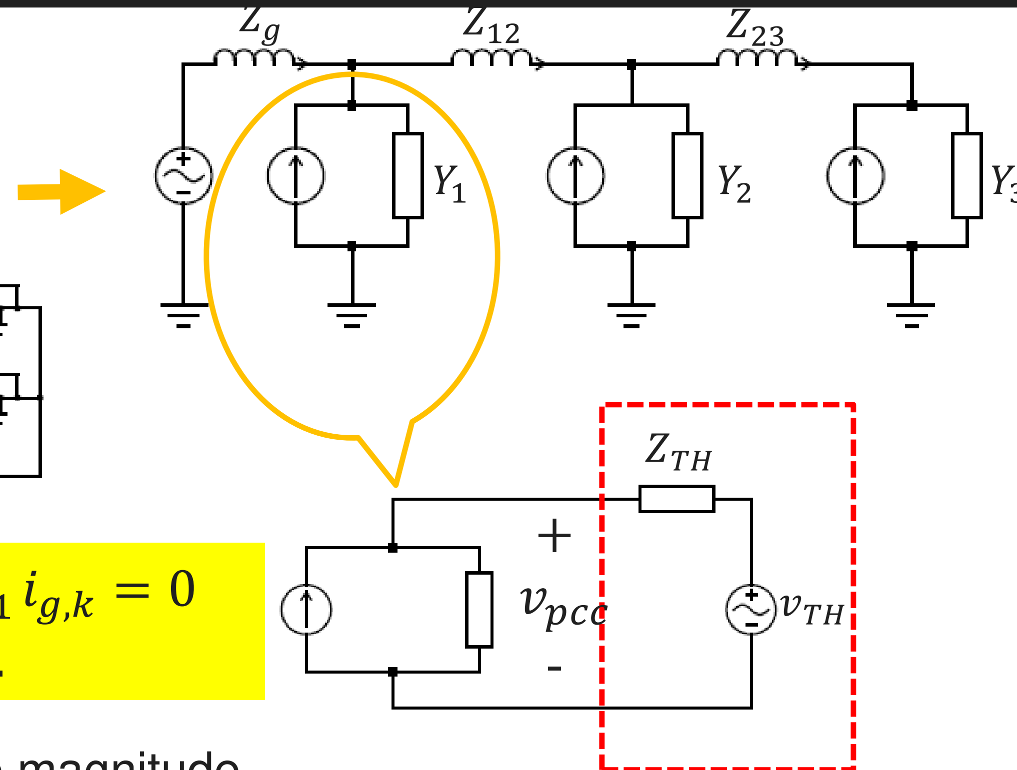
- $G_c(s)$= Controller (PR or PI)
- $G_d(s)$= Delay due to sampling and computation
- K_{PWM}= PW Modulator gain
- Normalized by DC bus voltage



$$i_g = \left[\frac{G_c(s)G_d(s)K_{PWM}}{s^3L_1L_2C + s(L_1+L_2) + G_c(s)G_d(s)K_{PWM}H(s)}\right] i_{g,ref} - \left[\frac{s^2L_1C+1}{s^3L_1L_2C + s(L_1+L_2) + G_c(s)G_d(s)K_{PWM}H(s)}\right] v_{pcc}$$

Controller Stability





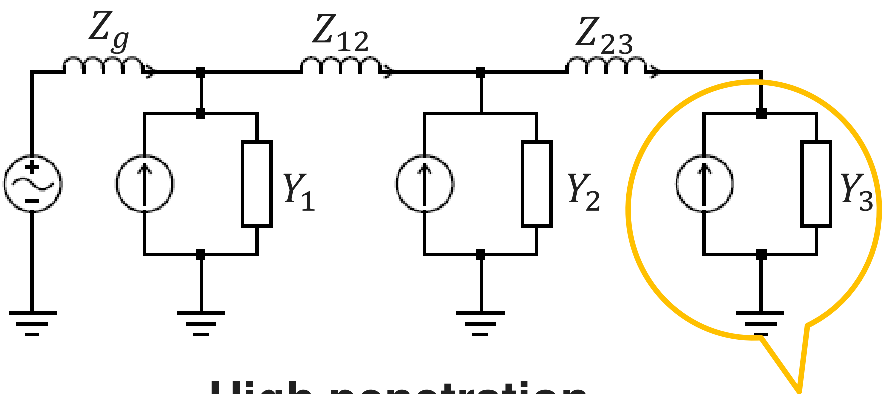
Feasibility: To ensure, $i_{grid} + \sum_{k=1}^{3} i_{g,k} = 0$
Work done by SMC thrust.

$Z_{TH} = \mathrm{f}(Y_1, Y_2, Y_3, Z_g, Z_{12}, Z_{23})$

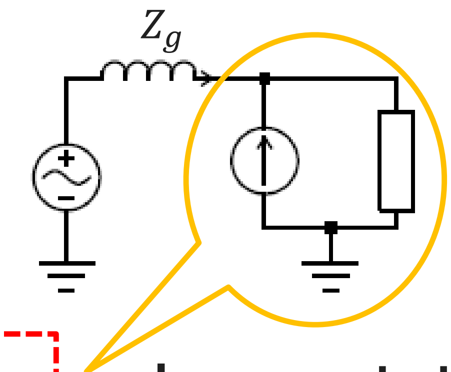
- Feasibility of achieving target voltage magnitude and frequency depends on the premise of local controller stability and only when local controller, i.e. $G_c(s)$, is stable then tracking of $i_{g,ref}$ is ensured.

- **v_{pcc} is no longer an independent disturbance, rather a function of i_g. The effective grid impedance that the converter sees looking into the point of common coupling, i.e. Z_{TH}, plays a vital role in converter dynamics.**

High Penetration of Power Electronic Converters

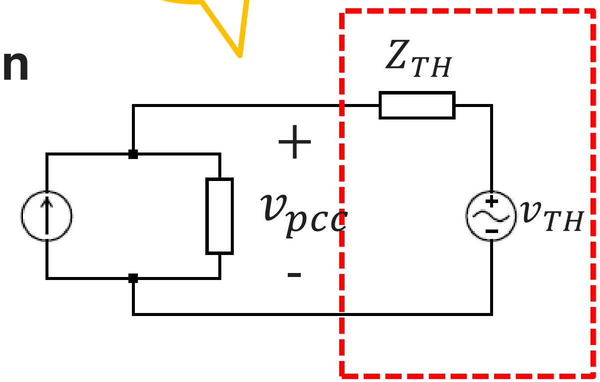


High penetration



Low penetration

$Z_{TH} = \mathrm{f}(Y_1, Y_2, Y_3, Z_g, Z_{12}, Z_{23})$ **where $Y_1(s), Y_2(s), Y_3(s)$ are all active, the interaction among which leads to extremely complex system dynamics**



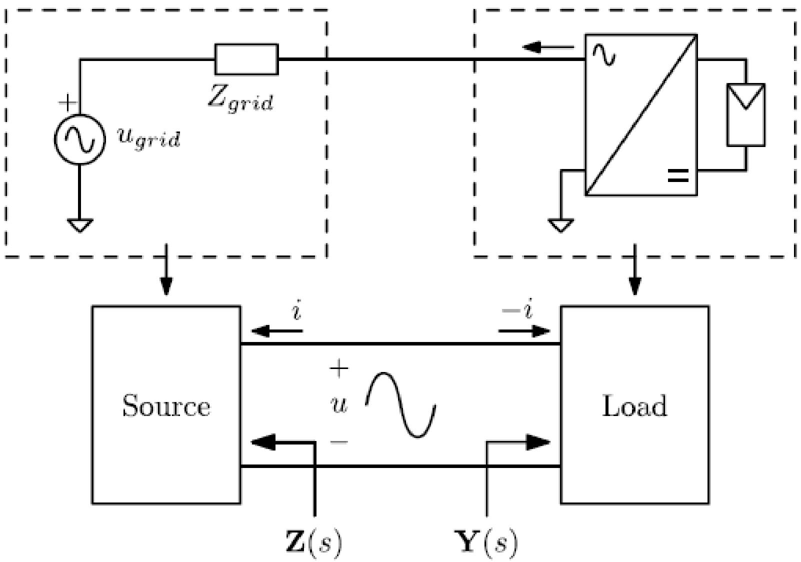
Thevenin Equivalent

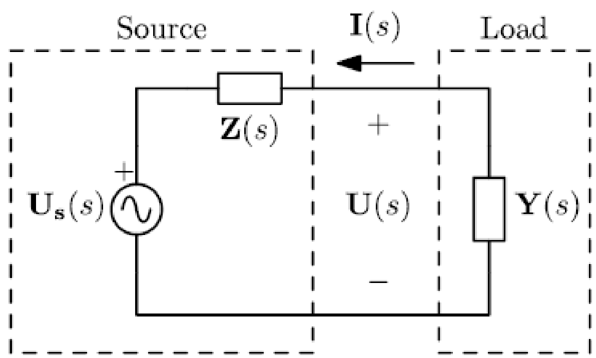
$Z_{TH} = Z_g =$ **Equivalent transmission line impedance, i.e. passive components only - L, C, R**

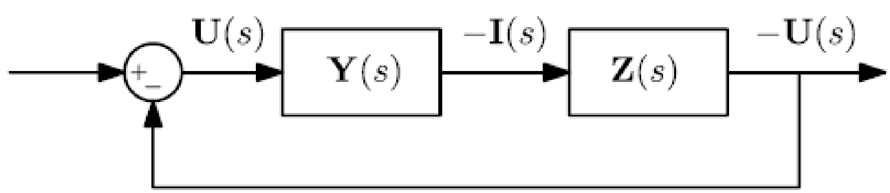
- Any system similar to FREEDM that includes heavy penetration of power electronic converters, adds significant complexity to the design of local controllers.
- Significant research is being done on how to make local controllers less sensitive to grid impedance variation.

Stability Analysis: Middlebrooks Criterion

- In 1976, Middlebrook introduced a stability criterion for cascaded DC systems [2].
- Middlebrook's criterion has been extended to study stability of AC systems for both 3 phase and single phase systems [3].





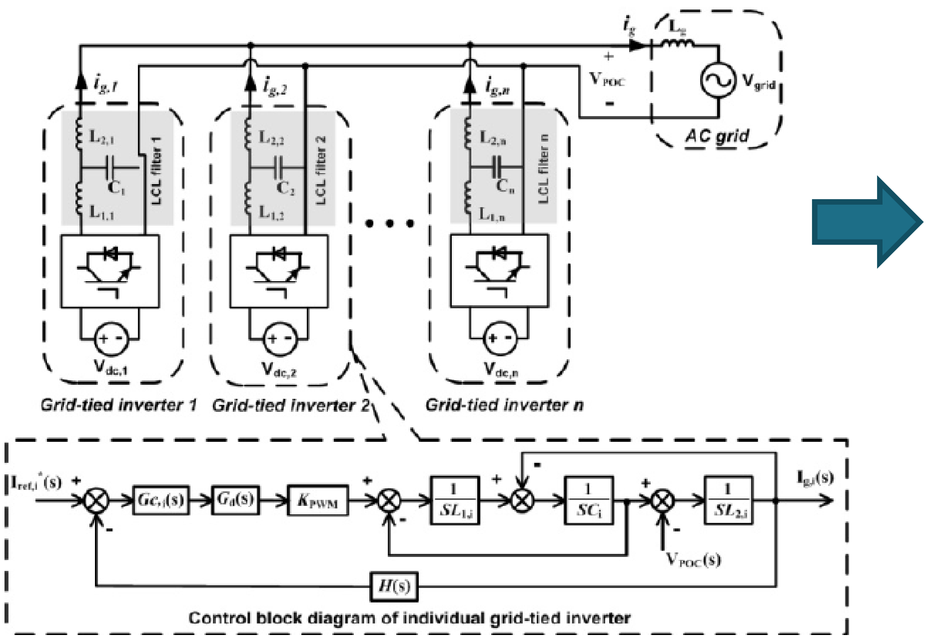


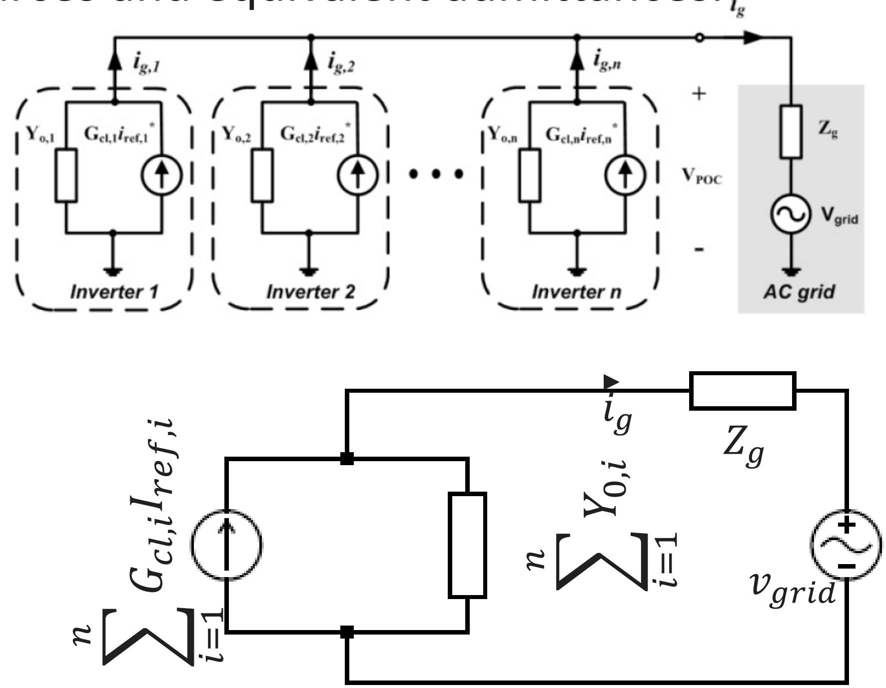
System poles defined by: $\mathbf{1 + Y(s)Z(s)=0}$

[1] R. D. Middlebrook, "Input filter considerations in design and application of switching regulators," in Proc. IEEE Ind. Appl. Soc. Annu. Meeting, 1976, pp. 366–382.
[2]S. Lissandron, L. Dalla Santa, P. Mattavelli and B. Wen, "Experimental Validation for Impedance-Based Small-Signal Stability Analysis of Single-Phase Interconnected Power Systems With Grid-Feeding Inverters", *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 1, pp. 103-115, 2016.

Impedance Based Controller Design: Global Minor Loop Gain Method

- Li et. al. from Florida State University developed an impedance based criterion for designing controllers for parallel inverters with knowledge of all inverter parameters.
- Impedance Based Controller Design: Global Minor Loop Gain Method
- Through detailed mathematical analysis they reach the total system stability criterion to be defined by the characteristic equation: $\mathbf{1 + Z_g \sum_{i=1}^{n} Y_{0,i} = 0}$
- The same conclusion can be readily reached using Middlebrook's criterion by combining all the equivalent current sources and equivalent admittances.





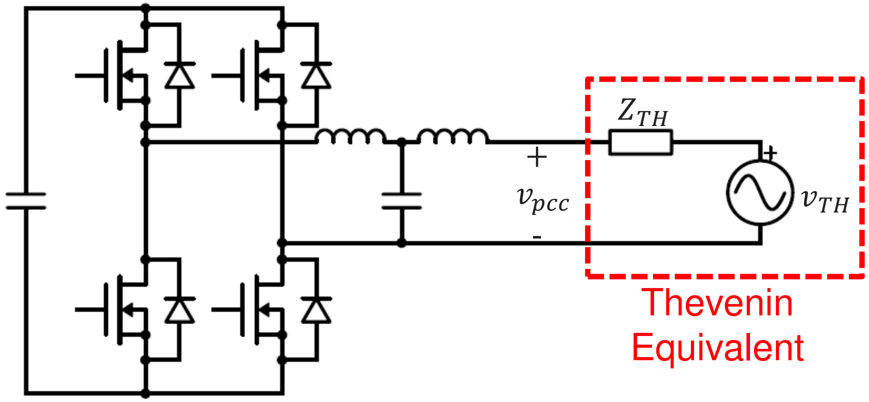
[3] Q. Ye, R. Mo, Y. Shi and H. Li, "A unified Impedance-based Stability Criterion (UIBSC) for paralleled grid-tied inverters using global minor loop gain (GMLG)", *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015.

Smart Inverter Controllers

- Assuming $Z_{TH}(= L_g)$ to be predominantly inductive, the worst case can be studied considering no resistive damping in the system.
- C, L_1 and $(L_2 + L_g)$ constitute a 3rd order system with a resonant frequency of

$$\omega_{res} = \sqrt{\frac{L_1+L_2+Lg}{L_1(L_2+L_g)C}}$$

- Even without variation in L_g, this resonance needs to be actively (or passively) damped to achieve sufficient controller bandwidth.

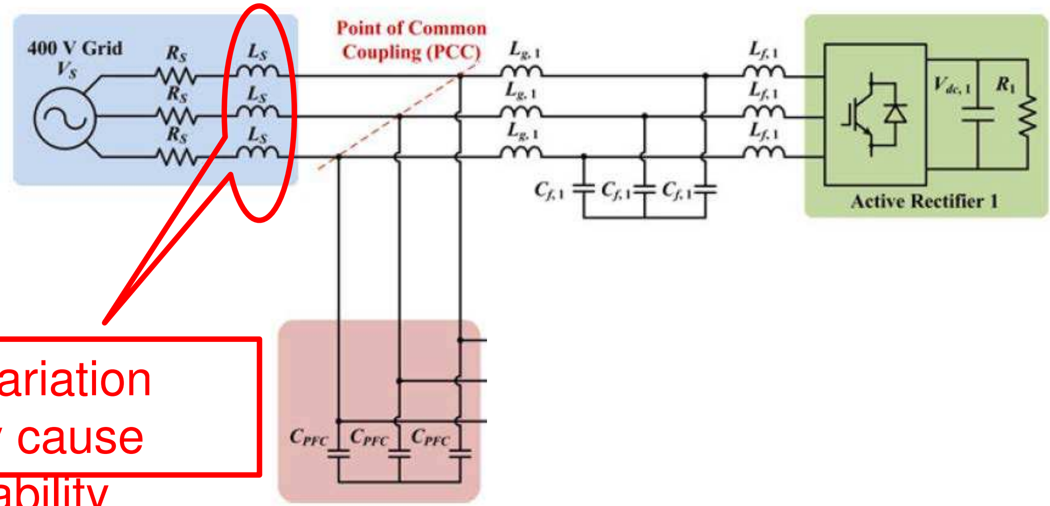


- Passive Damping: These techniques can reduce controller sensitivity to variation in grid inductance at the cost of increased loss and lower attenuation at high frequency [4]
- Active Damping: These approaches provide resonance damping without reducing efficiency, but suffers from lower damping performance in case of parameter variation. Also known as virtual impedance methods [5]. The approaches have critical limits of grid impedance variation, beyond which they fail.

[4] R. Beres, X. Wang, F. Blaabjerg, M. Liserre and C. Bak, "Optimal Design of High-Order Passive-Damped Filters for Grid-Connected Applications", *IEEE Transactions on Power Electronics*, vol. 31, no. 3, pp. 2083-2098, 2016.
[5] X. Wang, F. Blaabjerg and P. Loh, "Grid-Current-Feedback Active Damping for LCL Resonance in Grid-Connected Voltage-Source Converters", *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 213-223, 2016.
[6] L. Zhou, W. Wu, Y. Chen, J. Guerrero, Z. Chen, A. Luo and X. Zhou, "Robust two degrees-of-freedom single-current control strategy for LCL-type grid-connected DG system under grid-frequency fluctuation and grid-impedance variation", *IET Power Electronics*, 2016.

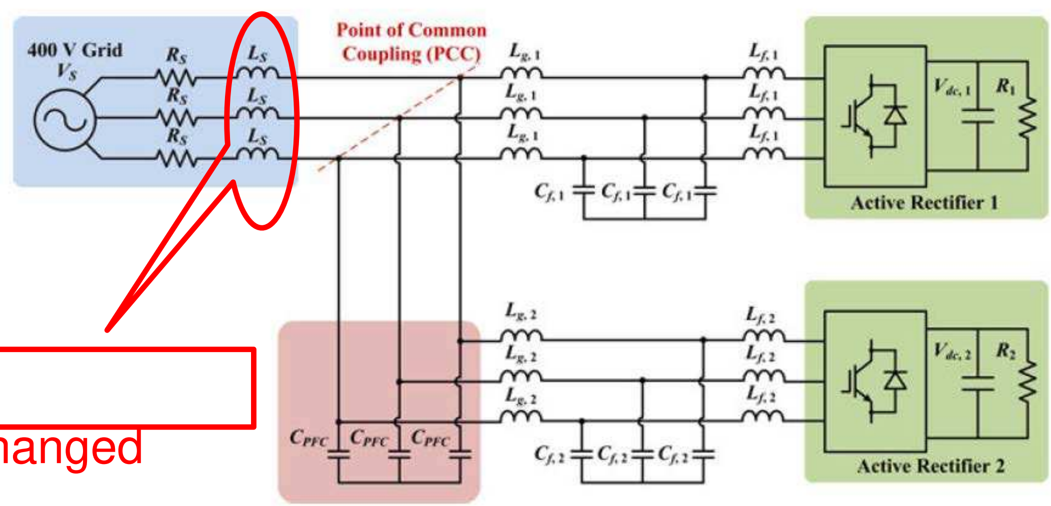
Two Types of Instability

- **Grid Impedance Variation:** Only one rectifier is connected at PCC along with PFC capacitors. The single rectifier can become unstable due to variation of L_s



L_s variation may cause instability

- **Interaction between two converters:** For the same grid impedance, interaction between two converters may cause instability



L_s is unchanged

[7]X. Wang, F. Blaabjerg, M. Liserre, Z. Chen, J. He and Y. Li, "An Active Damper for Stabilizing Power-Electronics-Based AC Systems", IEEE Transactions on Power Electronics, vol. 29, no. 7, pp. 3318-3329, 2014.

Controller Challenges for FREEDM Architecture

- Impedance based controller design techniques are feasible for systems in a closely contained systems with power electronic converters; however, controller design must take into account the variation in Z_g.
- Reported works consider Z_{TH} to be dominantly inductive contributed by transmission lines and transformers. Therefore, by variation of grid side inductor, the effect of grid impedance variation is emulated.
- In a FREEDM like architecture neighboring SSTs directly contribute to actively shape the impedance that one SST sees looking into the point of common coupling.
- For a SST based distribution system, the objective is to design local controllers for readily deployable SSTs without retuning existing SSTs
- Design technique for local controllers that are less sensitive to grid impedance, i.e. Z_{TH}, variation needs to be developed.

Topics for this tutorial

Lecture L3

A. Traditional distribution systems, strengths, weaknesses

B. Overview of the FREEDM system and components

C. FREEDM system control and comparison with traditional systems

D. Some features of the distribution system of the future: pricing, cost / benefit, reliability