PACE
ACCELERATING ELECTRIFICATION

Development of Medium Voltage Intelligent Power Stage (IPS) — Phase II

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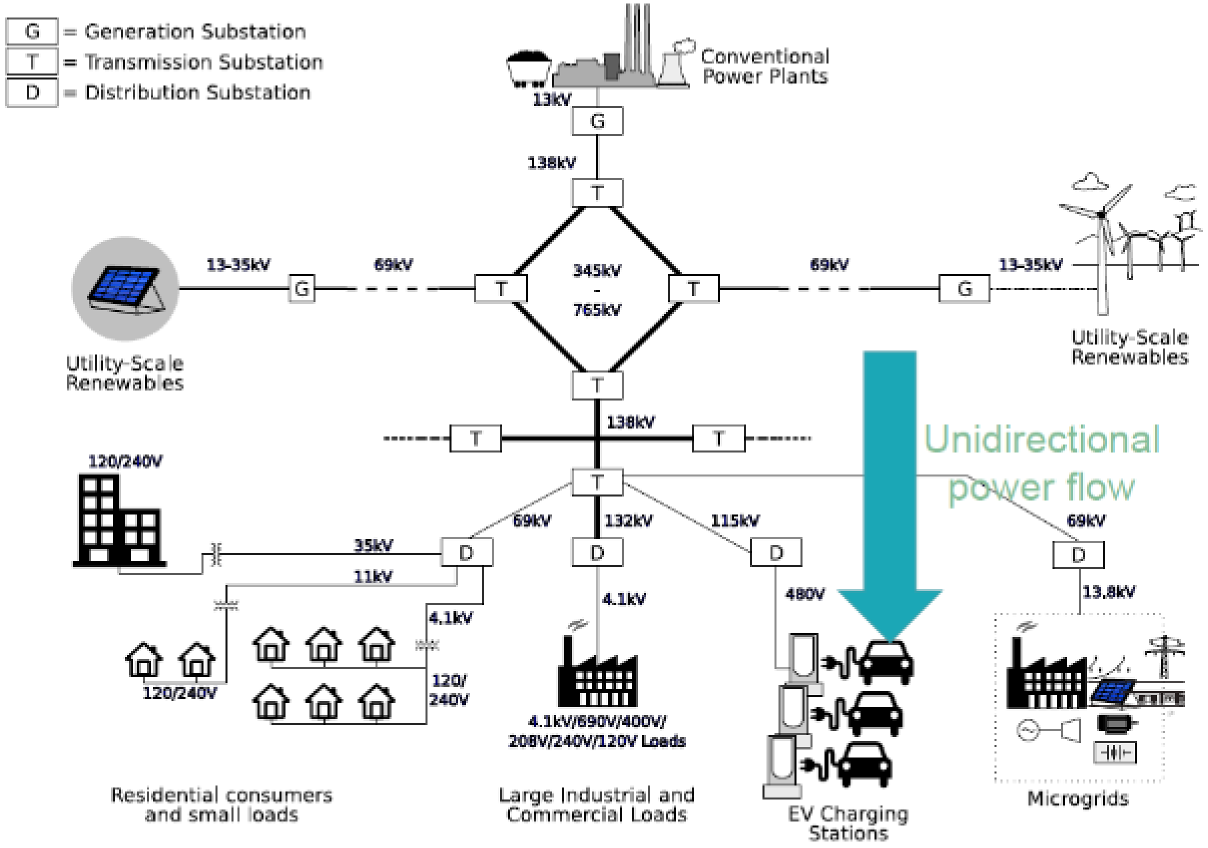
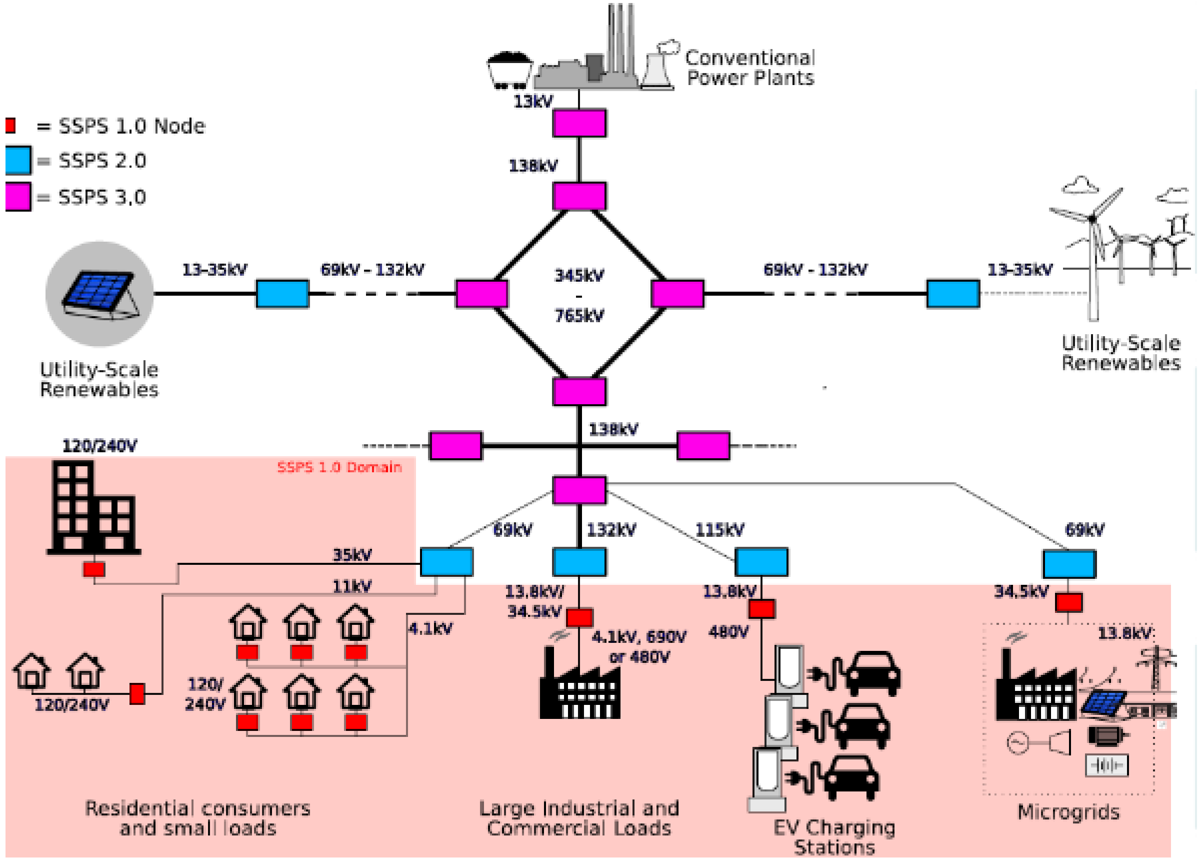
Affiliation: Center for Power Electronics Systems (CPES)
Virginia Tech

Function of Present and Future Substations

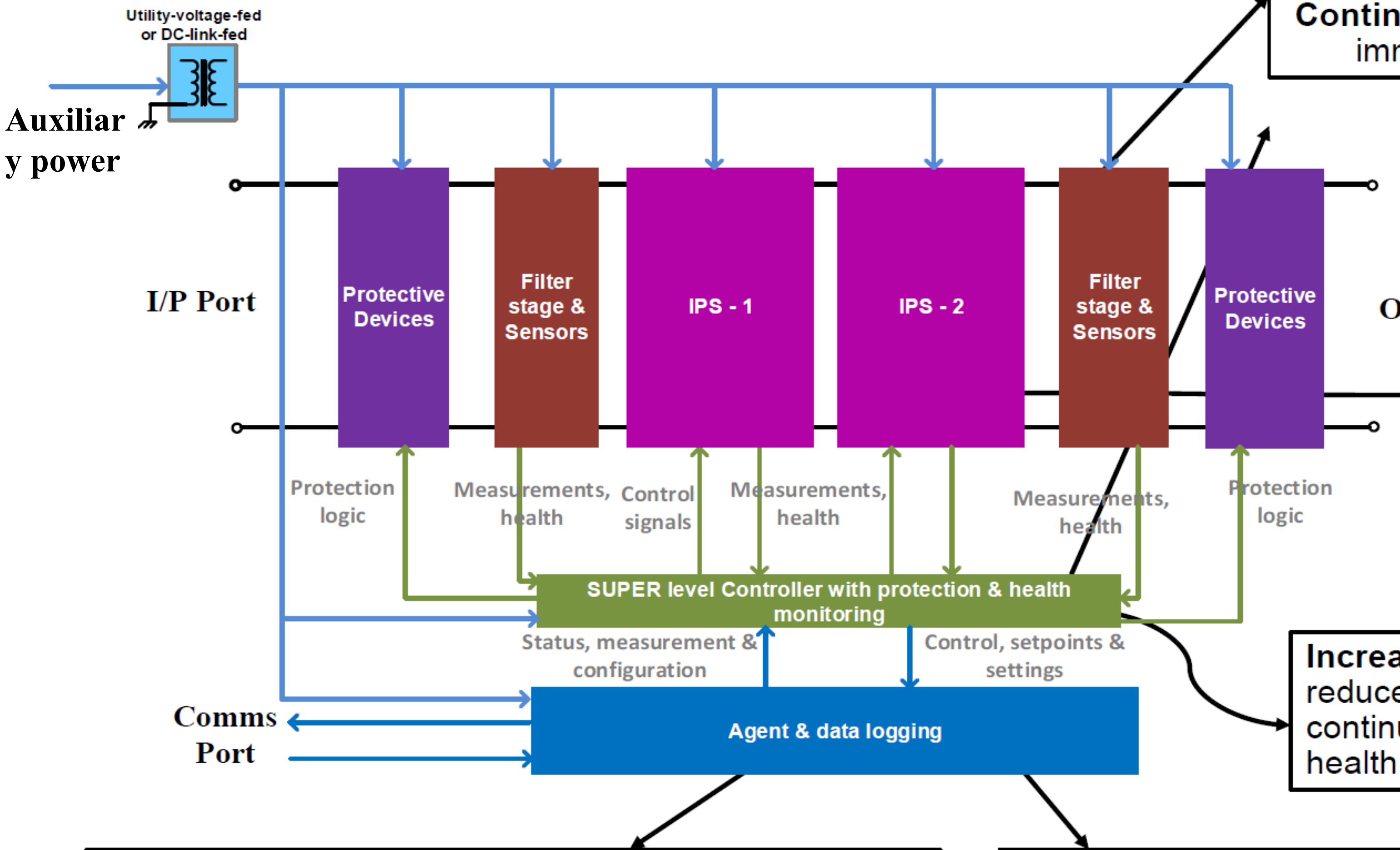


Present Substations



Future Solid State Power Substations (SSPS)

SSPS and the SUPER + IPS Vision



Continuously monitors the POC and acts immediately on nodal abnormalities

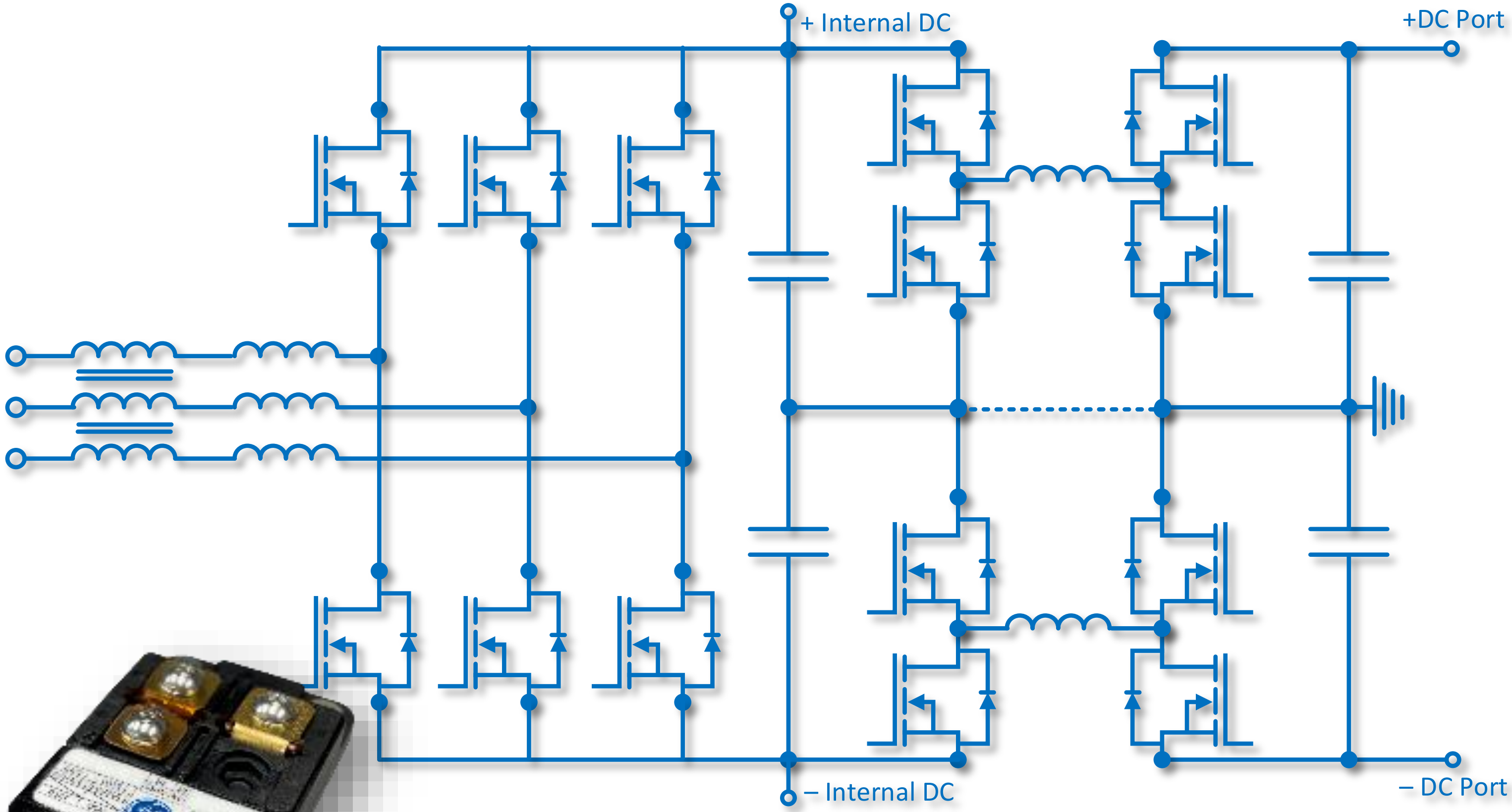
Self contained power stages with passives, aux power, sensing etc. to decouple parasitic loops, noise loops etc.

Increases system reliability, reduces downtime by continuously monitoring the health of the components

Enables transactive function for P & Q
Embedded intelligence for fault tolerant operation etc.

Enables **autonomous operation** & **maximizes grid support**. Enables dynamic voltage & frequency regulation etc.

E.g., Silicon-Carbide (SiC) Based IPS Topology



1.2 kV SiC MOSFET
GE12047CCA3

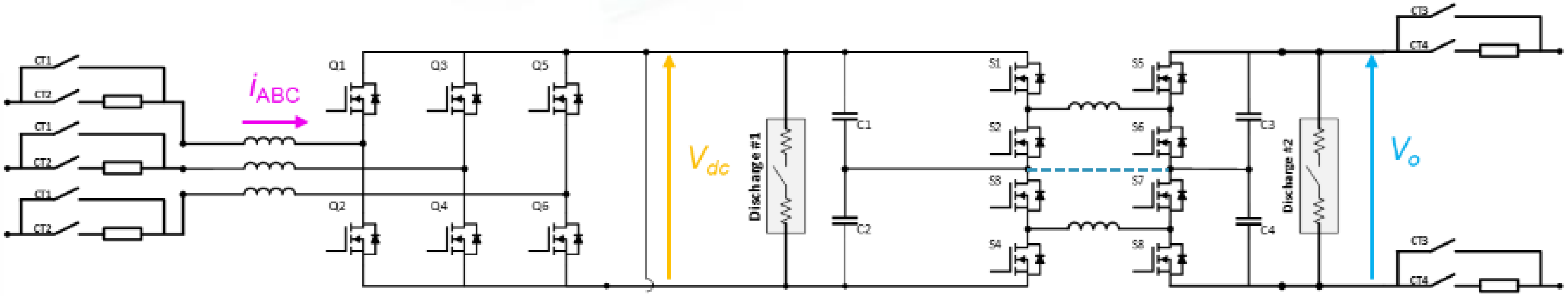
- AC-DC
  - 2-level voltage-source converter with split dc-bus
- DC-DC
  - 3-level buck-boost dc-dc converter
  - Accessible internal dc bus

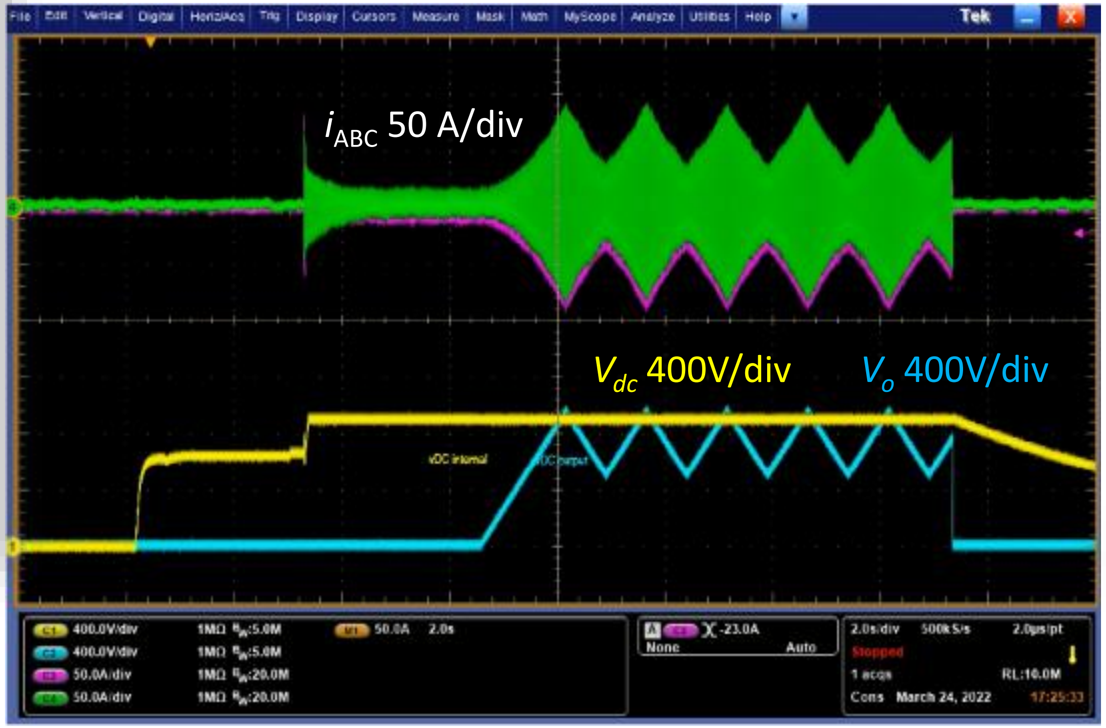
Specifications

- 50 kW, 75 kVA
- 480 V ac, 60 Hz
- 900 V dc-in
- 500 – 1,000 V dc-out
- f_{sw} = 30 kHz, η = 98 %

IPS Demonstration

75 kVA IPS Unit
in NEMA Enclosure





3-Level Buck-Boost
DC-DC Stage

Project Summary

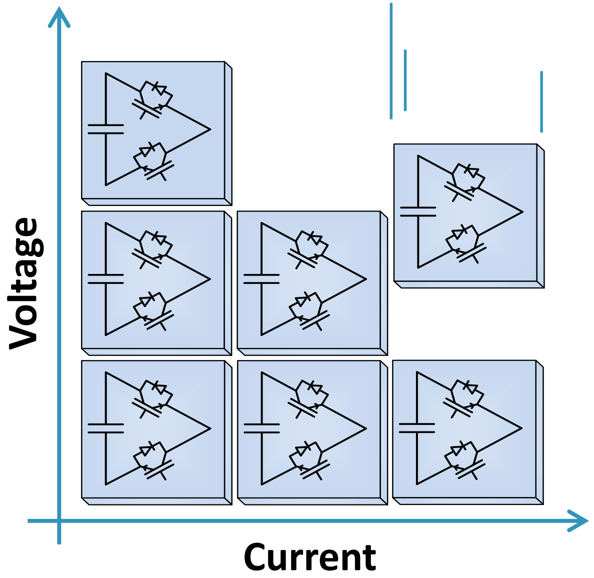
Objective

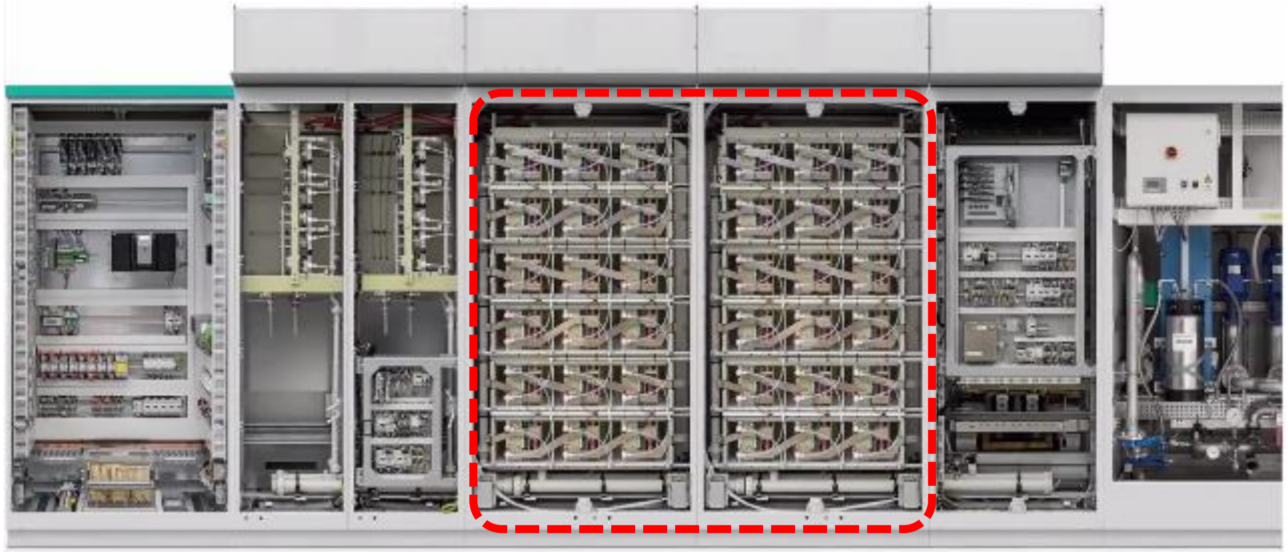
- To showcase the inherent increase in resiliency and reliability that IPS units can bring, not just to IPS-based solid state power substations (SSPS), but to the electrical power system (EPS) where they operate

Scope

- Failure mode and effect analysis (FMEA) of IPS and IPS-based SSPS
- Devising the corresponding protection systems commensurate with their fast dynamics
- Developing the insulation strategy necessary for the IPS unit to operate in electrical systems of up to 33 kV rms
  - The main IPS power supply concept will be developed, which should withstand the peak voltage with respect to ground

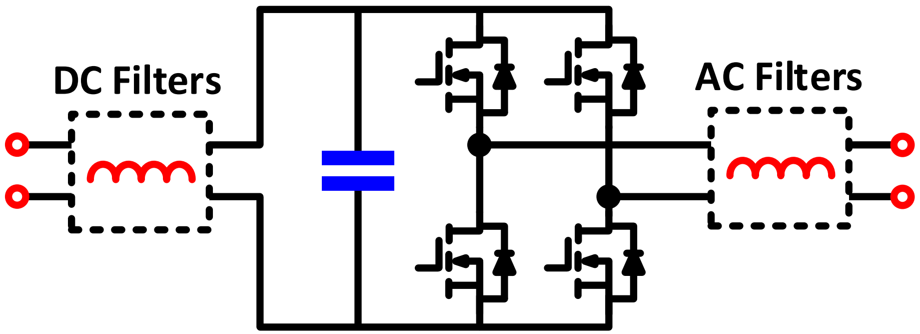
Modular Power Conversion Principle— Why?





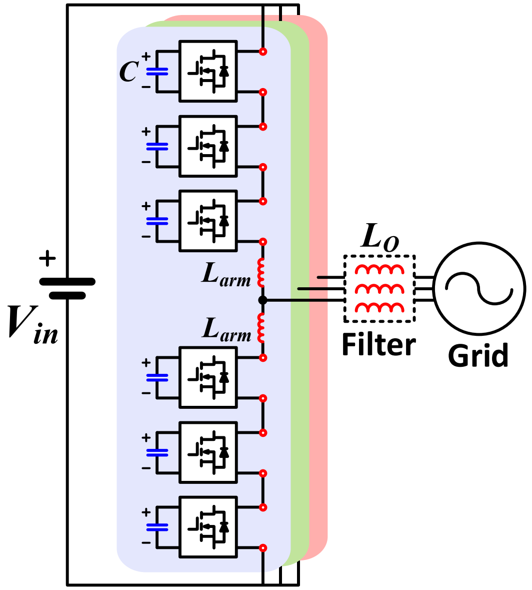
- **Principle**
  - ➢To ease the voltage and current scaling capability of power converters
- **At the system level**
  - ➢To improve the flexibility and expedite the integration of electrical systems

E.g., Modular Power Converter Topologies

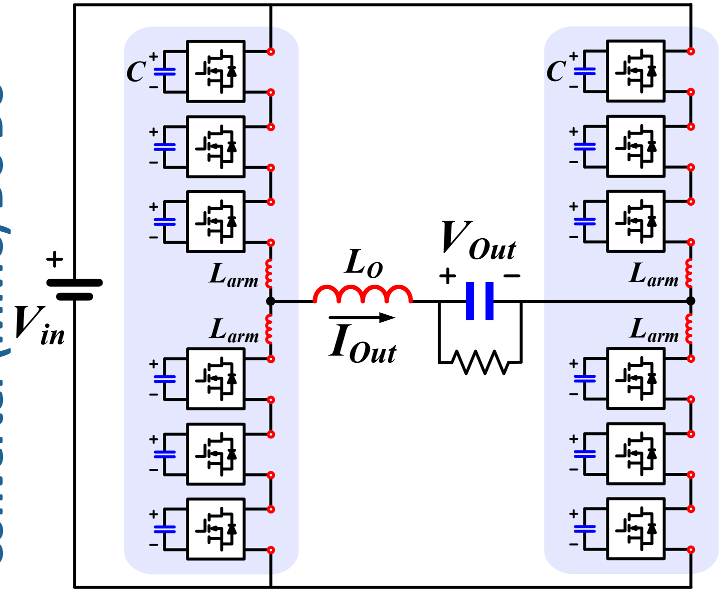


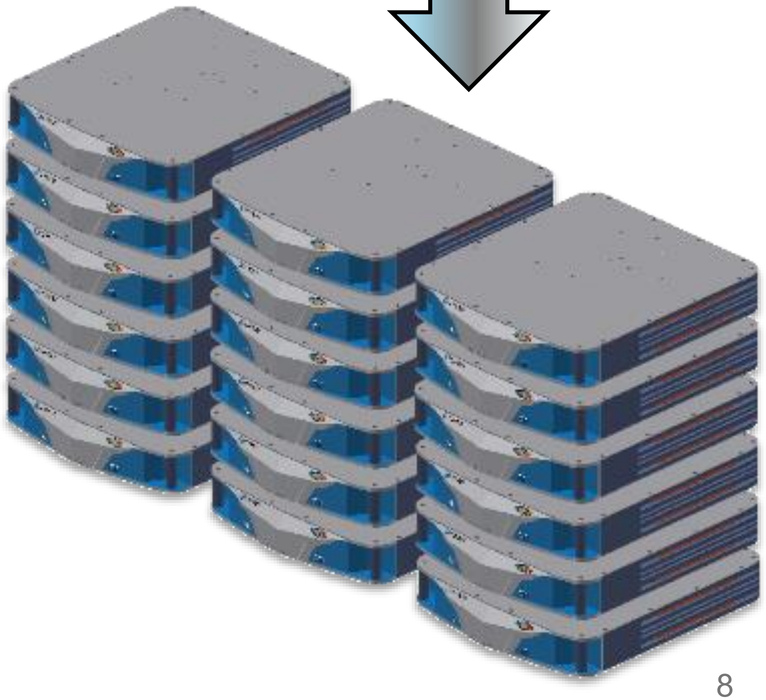
Power Electronics Building-Block

Modular Multilevel Converter (MMC) DC-AC



Modular Multilevel Converter (MMC) DC-DC

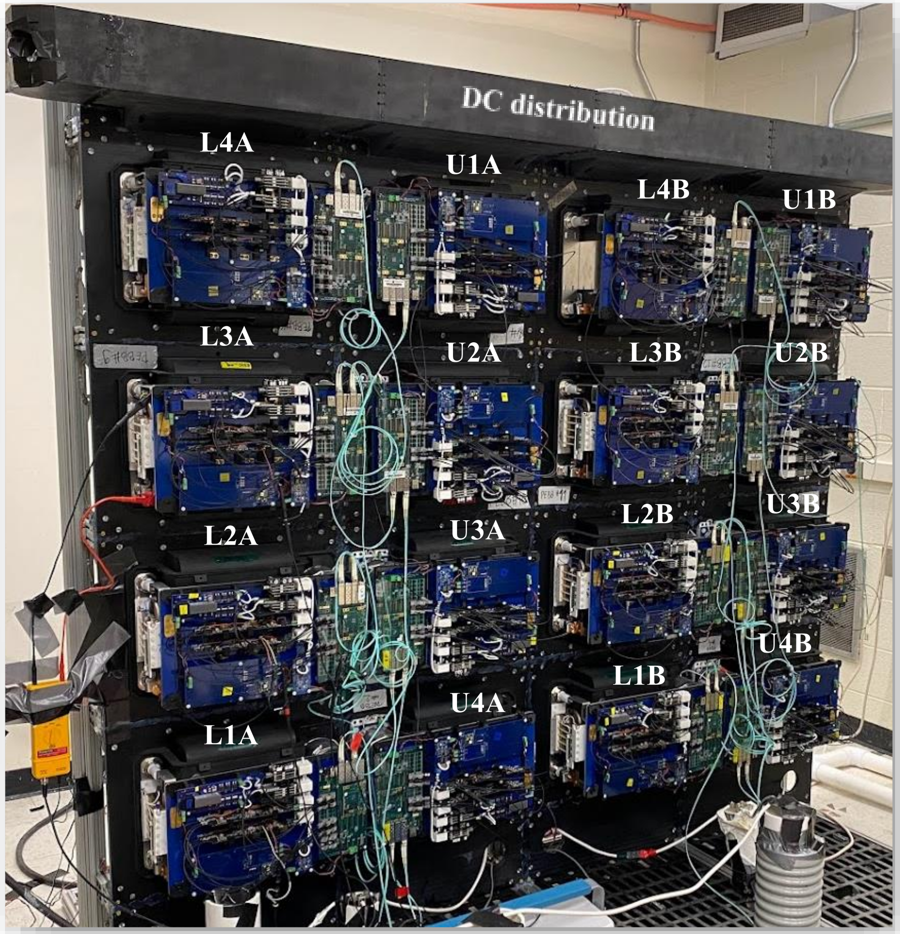




Modular SiC-based MV Converters

Impedance Measurement Unit (IMU)
10 kV, 120 A, Gen1 SiC MOSFET modules
4.16 kV AC, 2 MVA
3 PEBB units in series or parallel

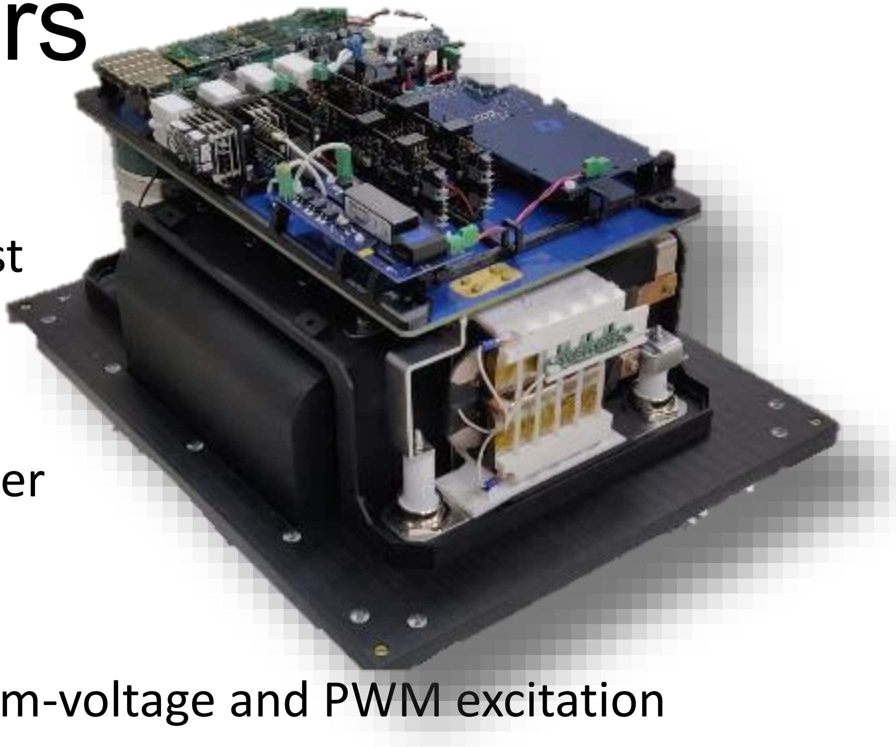
3-Phase AC-DC MMC
1.7 kV, 200 A SiC MOSFET
1 kV, 200 kW
6 PEBB units in bridge



H-Bridge MMC Demo
10 kV, 240 A SiC MOSFET
24 kV DC, 2 MW

16 x 6 kV PEBB

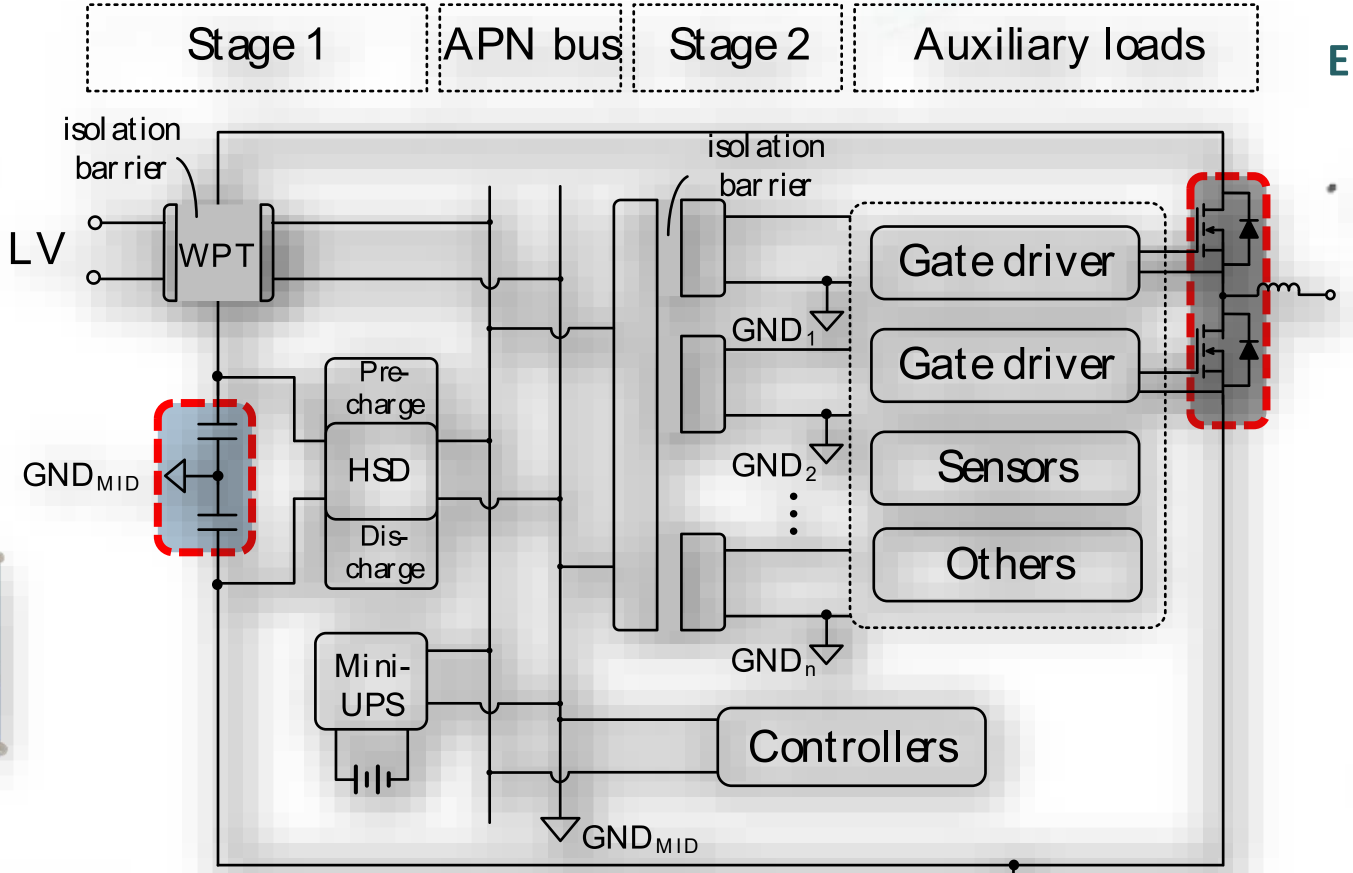
Design Challenges in High Power Density Modular Medium Voltage Power Converters



- **Electromagnetic Compatibility**
  - Heightened EMI emissions due to the high switching frequency, fast dv/dt, and large parasitic capacitances to ground
- **CM Ground Currents**
  - Pervasive CM currents that can alter the power flow in the converter operation
- **Insulation**
  - Lack of insulation strategies and guidelines compatible with medium-voltage and PWM excitation
- **Electromagnetic Devices & Ancillary Circuitry**
  - Lack of power components and ancillary circuitry designed to operate in medium-voltage and PWM excitation
  - ➢ E.g., inductors, capacitors, bus bars, interconnects, gate-drivers, sensors, power supplies, controllers

E.g., Auxiliary Power Architecture of MMC PEBB

WPT



Enhanced Gate-Driver

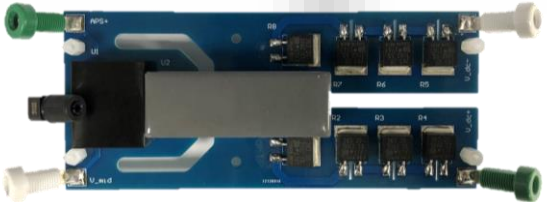
Mini-UPS

Distribution Primary

Sensor

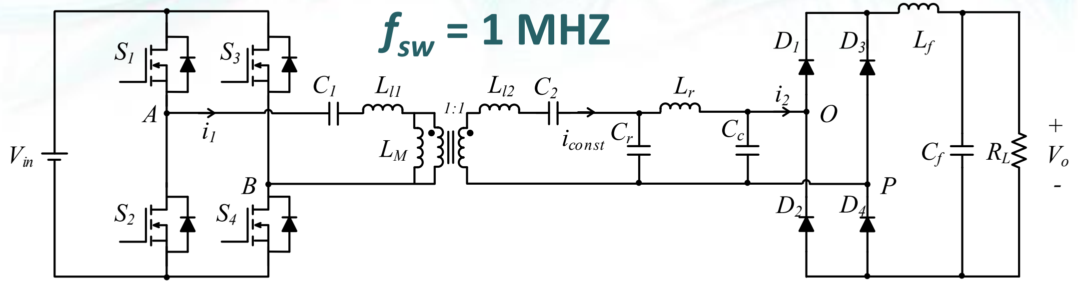
Pre-charge

Discharge



Distribution Secondary

Technical Specifications

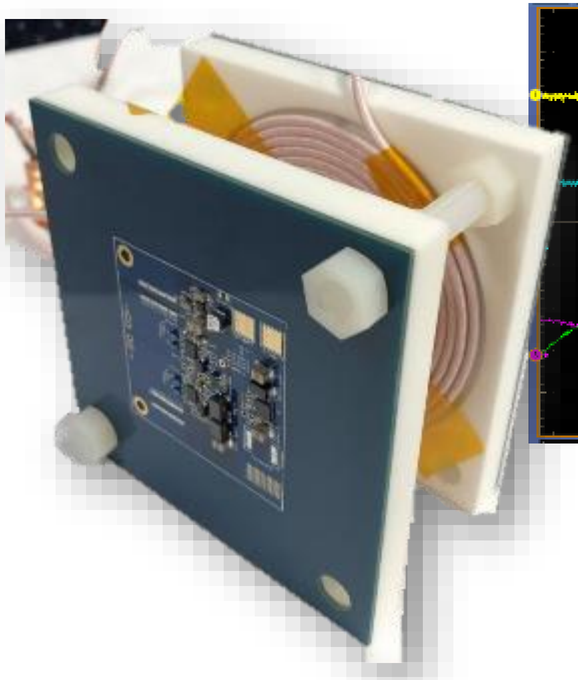


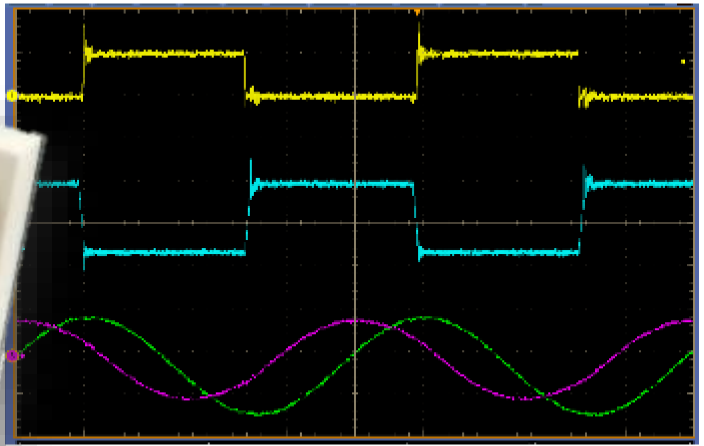
AC System

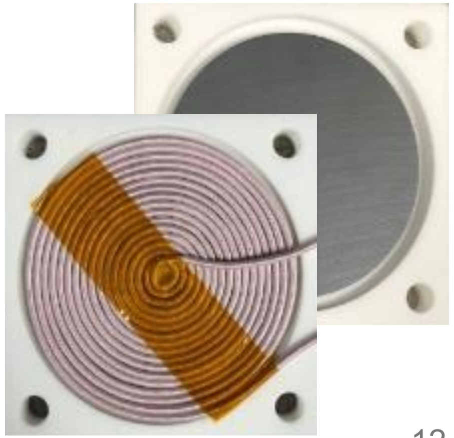
- Line voltage: 33 kV rms

IPS Auxiliary Power Supply

- Insulation voltage: 50 kV
- Partial Discharge Inception Voltage (PDIV): > 55 kV peak
- Output power: 100 W
- Input voltage: 48 V
- Output: 48 V



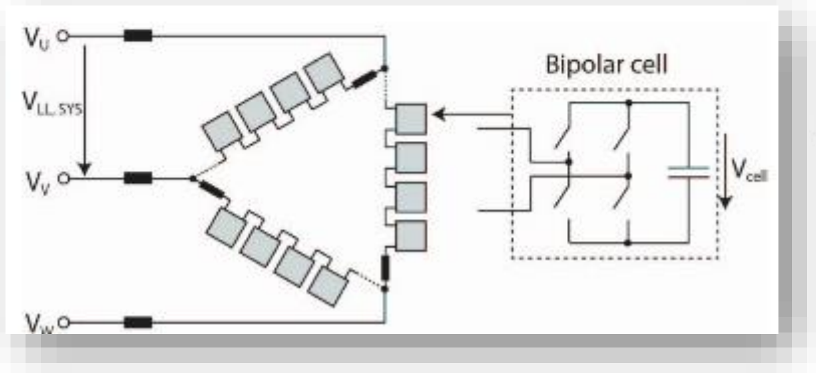




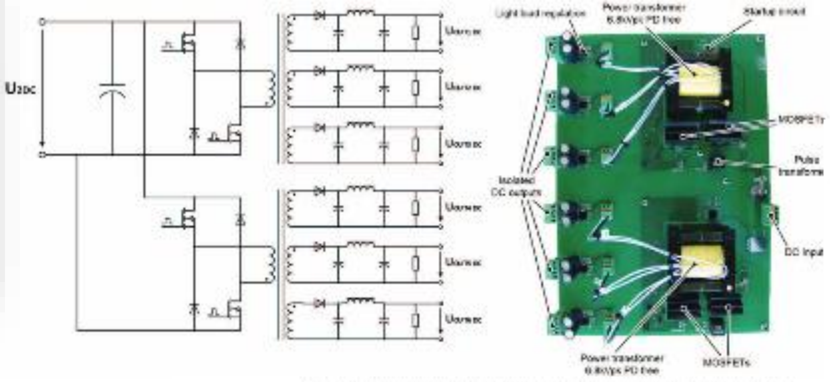
Wireless Power Supply
100 W, 48 : 48 V
PDIV : 30 kV

Literature Survey

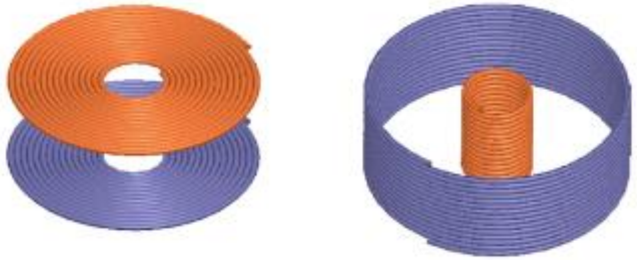
MMC

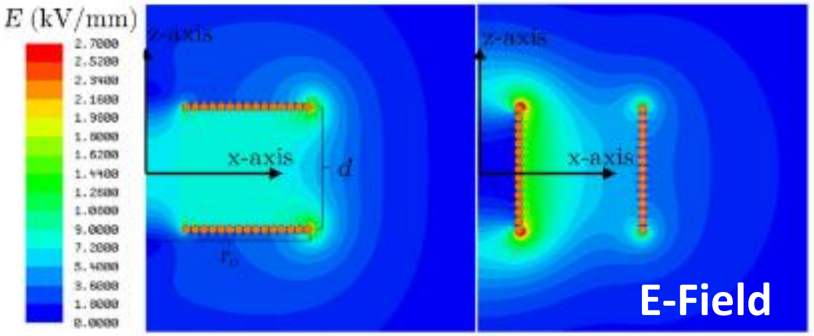


Series-Parallel Resonant Converter

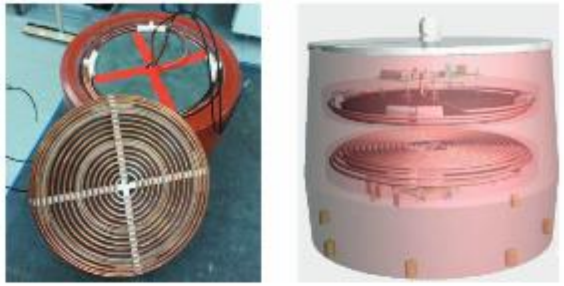


Parallel and Coaxial Coils

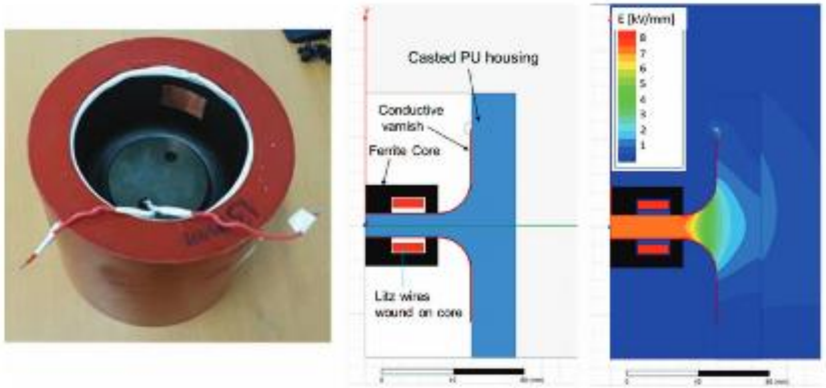




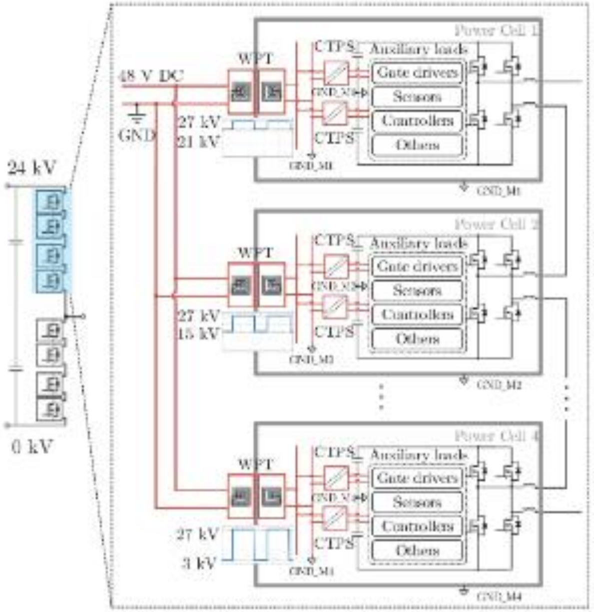
Potted Air-Core Coils



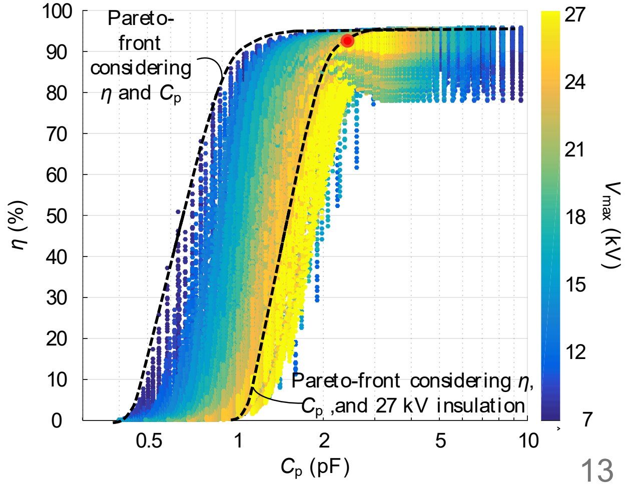
Embedded Ferrite



WPT Power Supplies

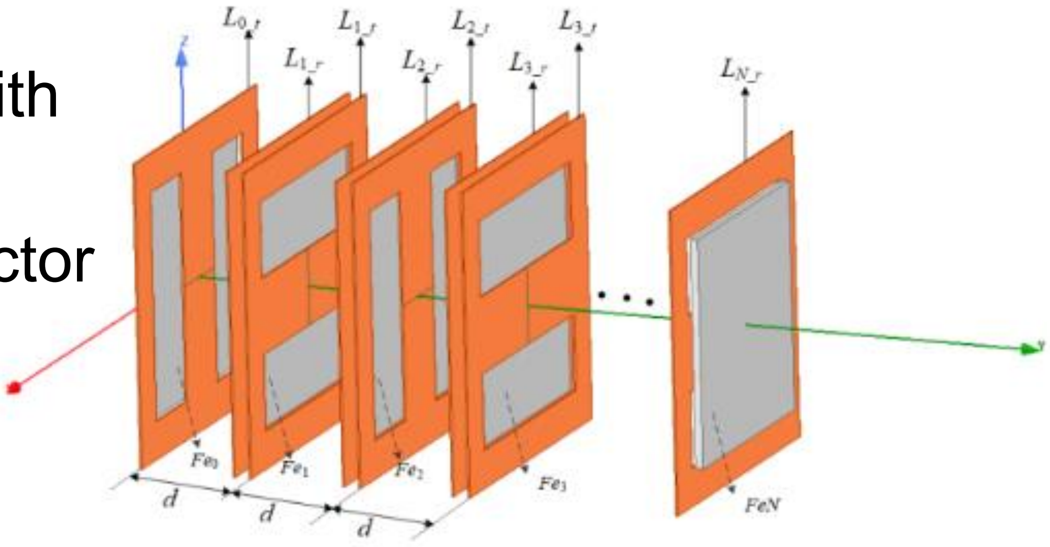


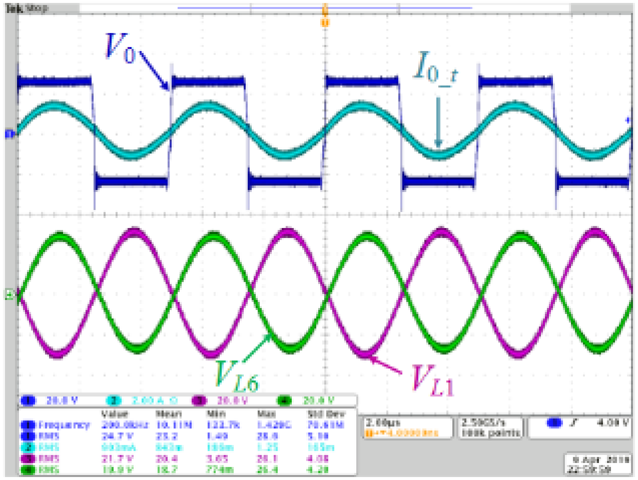
Multi-Objective Optimization



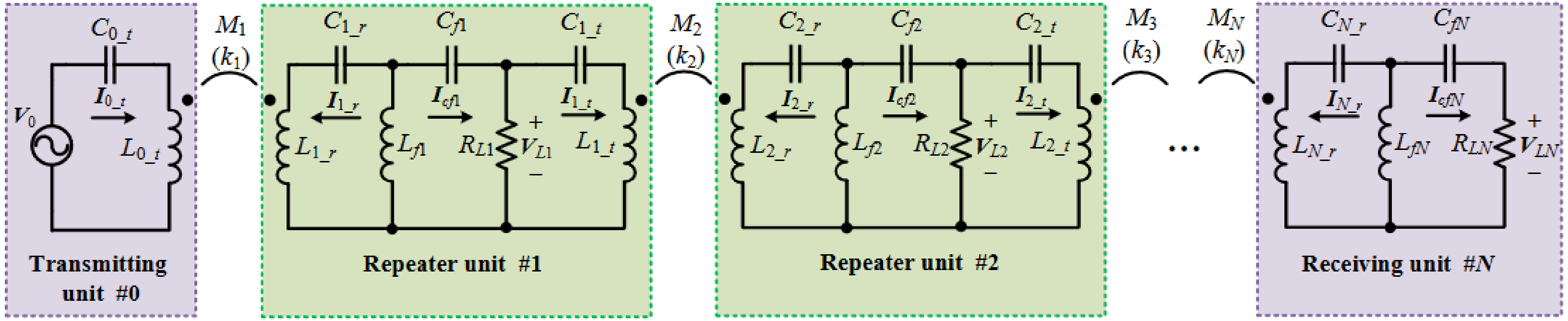
Literature Survey—Multi-Stage WPT

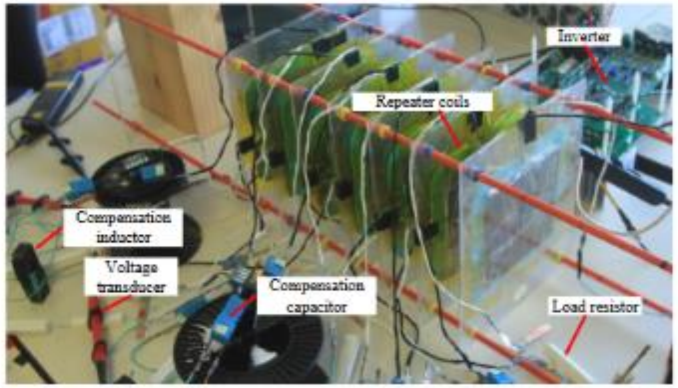
- Multi-stage WPT unit with repeater coils
- Compensation via inductor and capacitors can be designed
- Ferrite end-terminal shields



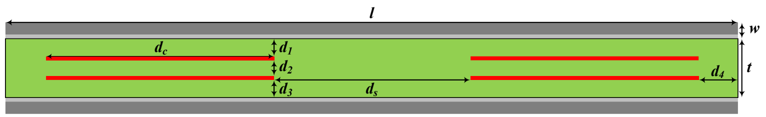


200 kHZ Operating Frequency

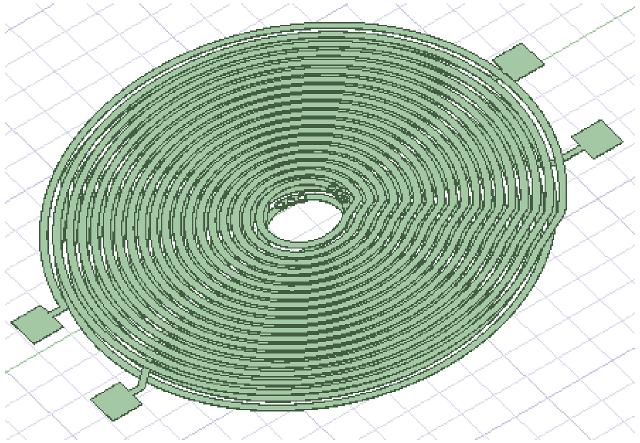




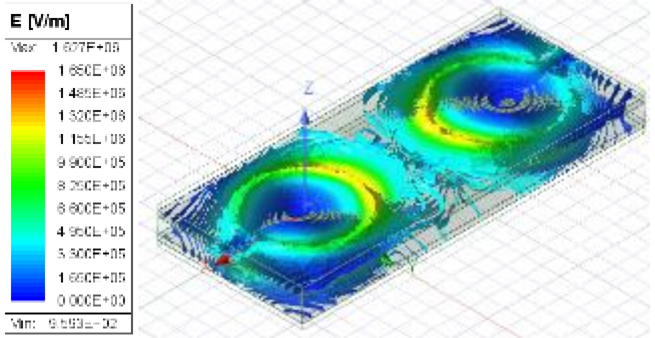
PCB-Embedded Multi-Stage WPT Unit



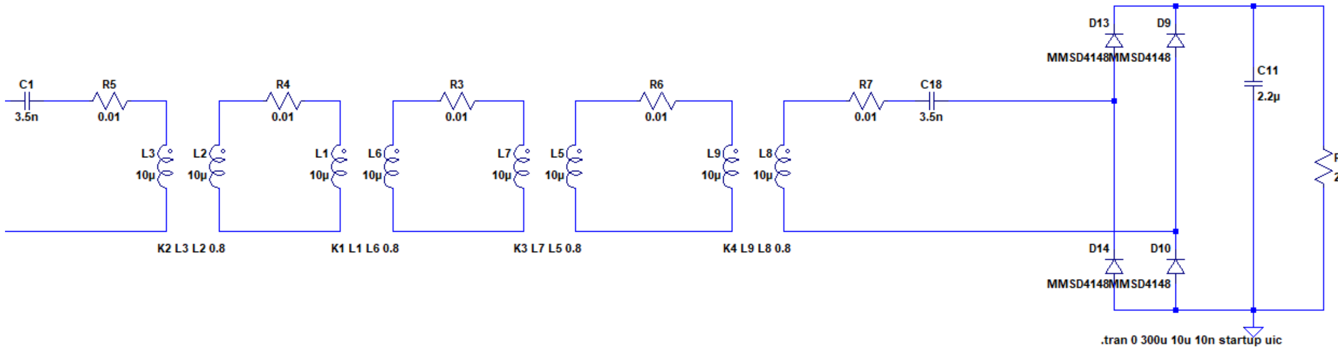
PCB-Embedded Series Coils

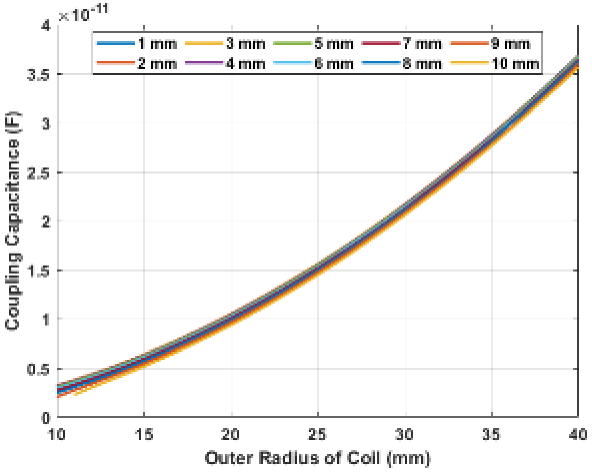


E-Field in Air < 1.6 kV/mm



4-Coil WPT Dc-Dc Converter

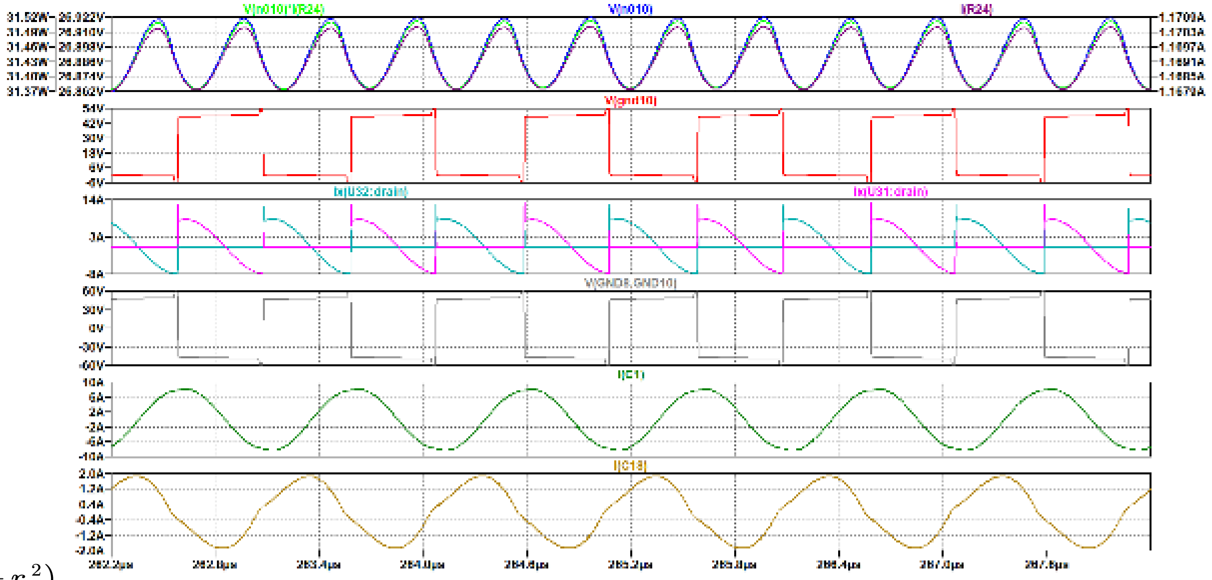




Inter-Winding Capacitance

$$C = \frac{5\pi\varepsilon_0\varepsilon_{FR4}}{3}\frac{\left(r_o{}^2 - r_i{}^2\right)}{X}$$

$$X = \int_0^{\pi}\int_{r_i}^{r_o}\int_{r_i}^{r_o}\frac{xydxdyd\theta}{\sqrt{x^2+y^2-2xy\cos\theta}} - \int_0^{\pi}\int_{r_i}^{r_o}\int_{r_i}^{r_o}\frac{xydxdyd\theta}{\sqrt{d^2+x^2+y^2-2xy\cos\theta}}$$



Voltage & Current Sims @ 1 MHz

Next Steps

PCB-Embedded WPT Unit

- Improve coil-to-coil impedance compensation network to increase efficiency and voltage gain
- Optimize design to meet electric field constraints, minimize input-output capacitance, and maximize efficiency and power density
- Build and demonstrate power supply

SSPS Impact on Resiliency and Reliability

- Failure mode and effect analysis of the IPS and SSPS
- SSPS and EPS Computer and Real-Time Simulations-Based Resiliency and Reliability Improvement Quantification

ACKNOWLEDGMENTS

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