Overcoming the Barrier of Deploying Second-Life EV Batteries for Storage Applications

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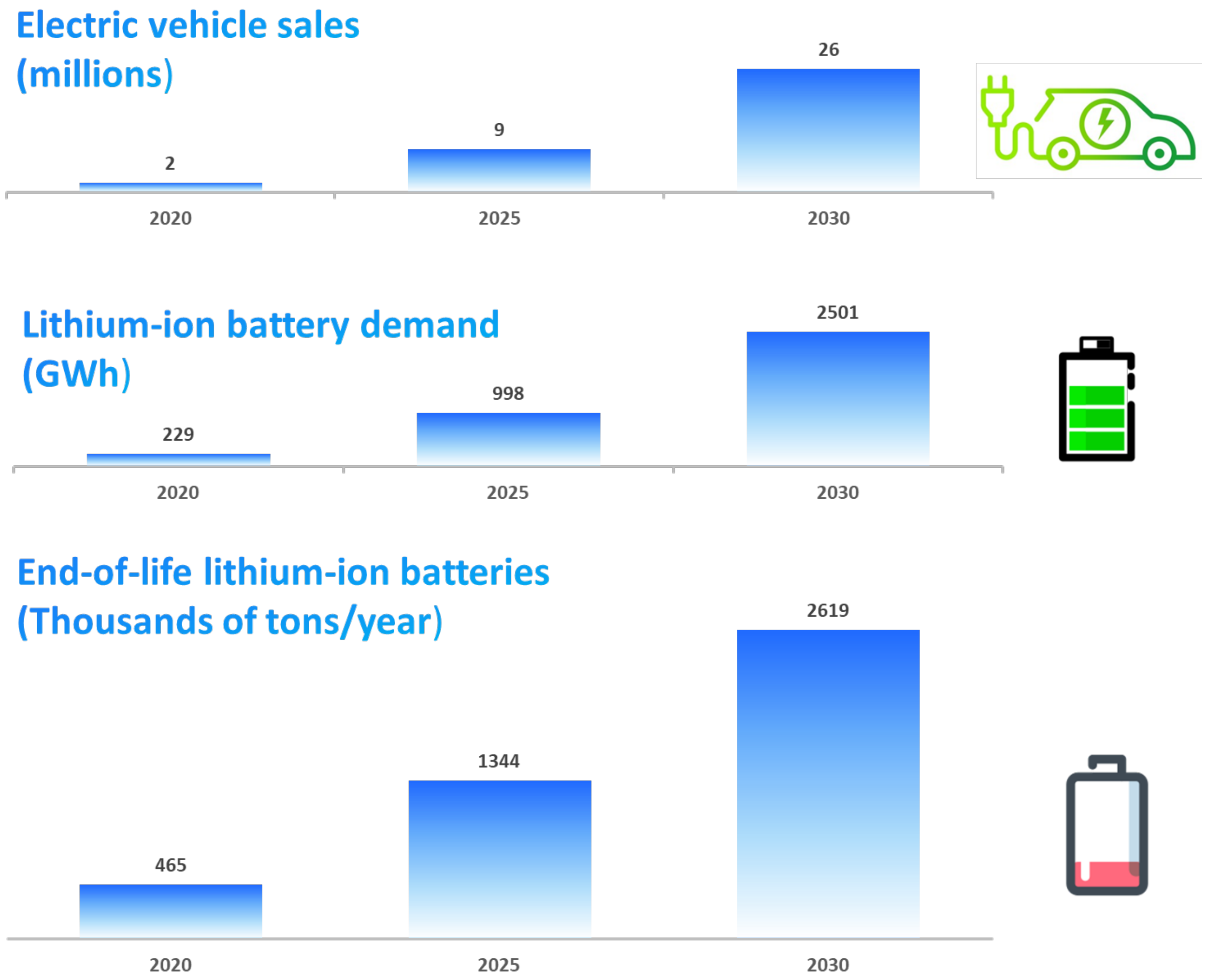
Outline

- **Needs of energy storage in renewable energy systems**
- **Second-life batteries (SLBs)**
- **Aging of second-life EV batteries**
- **Energy storage system design with SLBs**
- **Standards for the use of second-life EV Batteries**
- **Recycling of EV Lithium Ion Batteries**
- **The project is to answer three questions:**
  - Can spent EV batteries be used for storage applications?
  - If yes, how can they be used?
  - How can the system be designed to be safe, reliable, and cost effective?

Electric Vehicle & Battery Growth

- **EV battery market has 750GWh, $126+ Billion USD in 2023 (14M+ vehicles produced)**
    - Assuming $150/KWh and 60KWh battery pack per vehicle -> $9, 000 /EV
- **15 % (HEV + EV) Penetration annually**
- **It will likely triple to reach US$300 billion by 2030, or 2.25 TWh**



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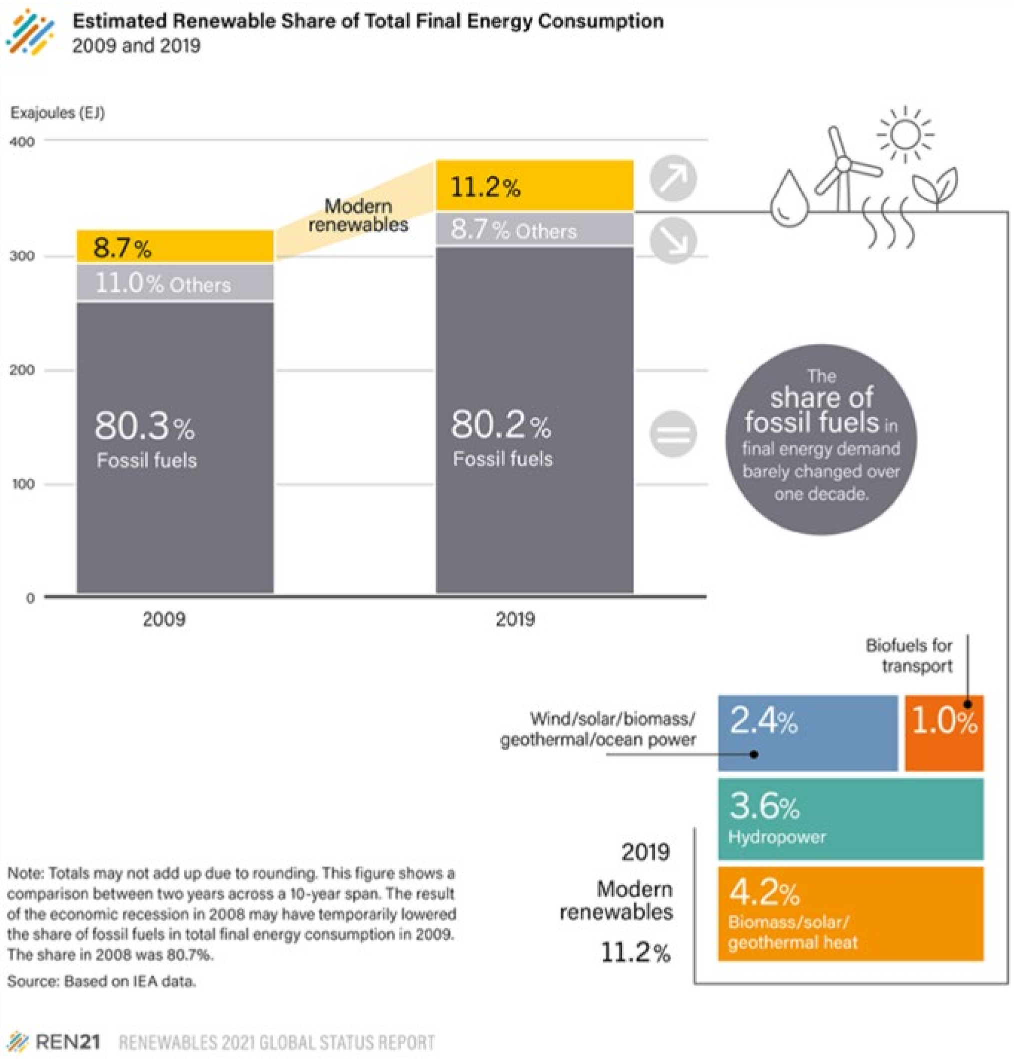
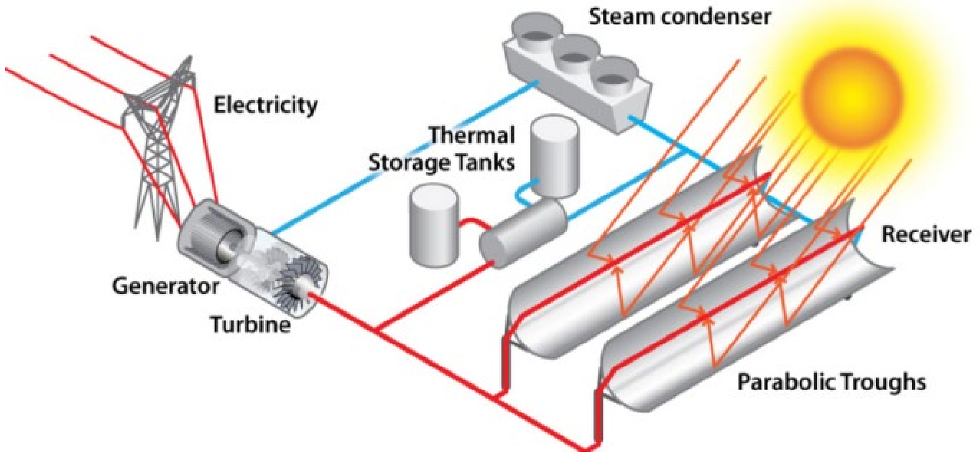
Source: Global Battery Alliance; World Economic Forum; McKinsey analysis

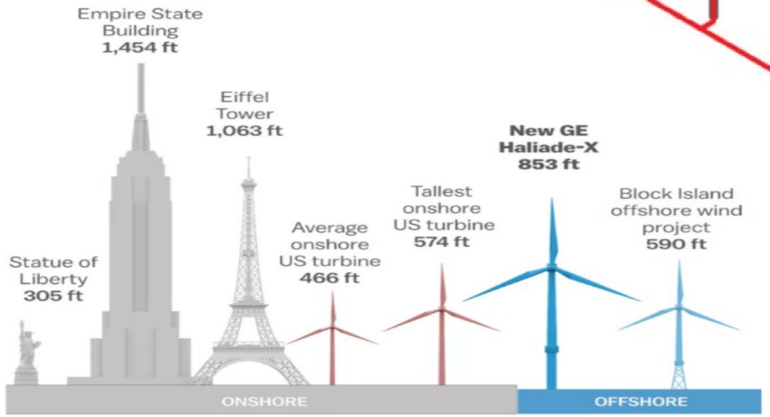
Demand for EV batteries reached more than 750 GWh in 2023, up 40% relative to 2022.

Renewable Energy Growth



- **Added together, lithium-ion batteries will reach 7 TWh/year by 2030 or US$ 1 trillion**





https://www.c2es.org/content/renewable-energy/#:~:text=At%2Da%2Dglance,percent%20from%202000%20to%202020).

Second-life EV batteries

- **Second-life EV batteries include those that**
  - are discarded EVs due to degraded conditions;
  - in-warranty replacements;
  - road accidents;
  - test vehicle batteries; and
  - unsold batteries.
- **These batteries may have energy for other purpose before being recycled. Use of these batteries in Grid BESS**
  - extend the life cycle of batteries after their first life in EVs
  - improve the environment
  - reduce EV ownership cost by selling them for second-life use
  - reduce the cost of BESS in renewable energy systems

Using the pack as a storage unit

- **Multiple packs connected in series and/or parallel using various power electronics converters.**
- **Advantages:**
  - Easy to obtain
  - Easy installation
  - Low cost for grouping the system

- **Disadvantages:**
  - Cells inside the pack may be unbalanced – need to address balancing issues
  - No access to cell monitoring
  - Access the CAN messages of the onboard BMS is not possible – a GATEWAY is necessary

Disassemble the pack and obtain battery cells

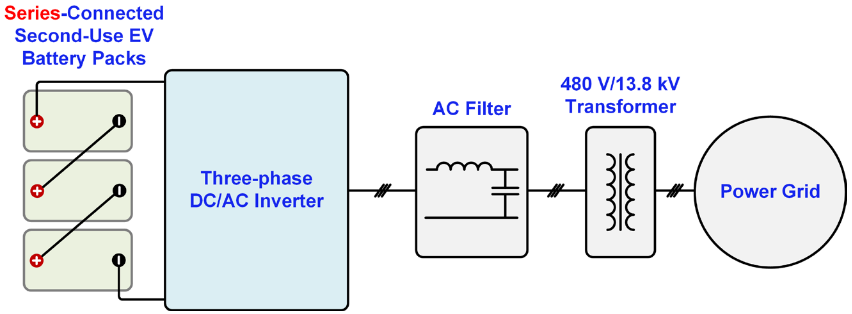
- **Advantages**
  - Cells can be grouped based on their SOH
  - Bad cells are discarded for recycling
  - Maximize the new BESS capacity and longer life span
- **Disadvantages**
  - Labor intensive to disassemble packs
  - Damage can happen during disassembling
  - Dangerous for the disassembly process itself
  - Difficult to test and store the cells
  - A new BMS is needed for the new BESS
  - May not be cost-effective

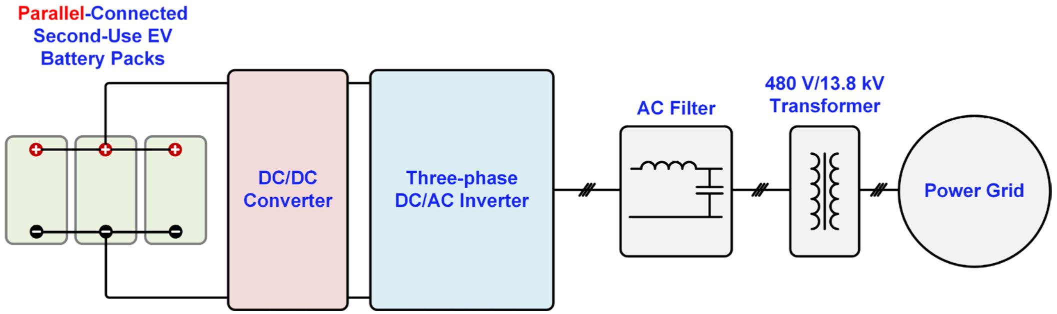
SDSU System Deployed at UCSD Warehouse

- Six Nisan Leaf Gen 3 packs
- Total 372 kWh nominal
- Used packs as is
- No balance issues

System Design Considerations

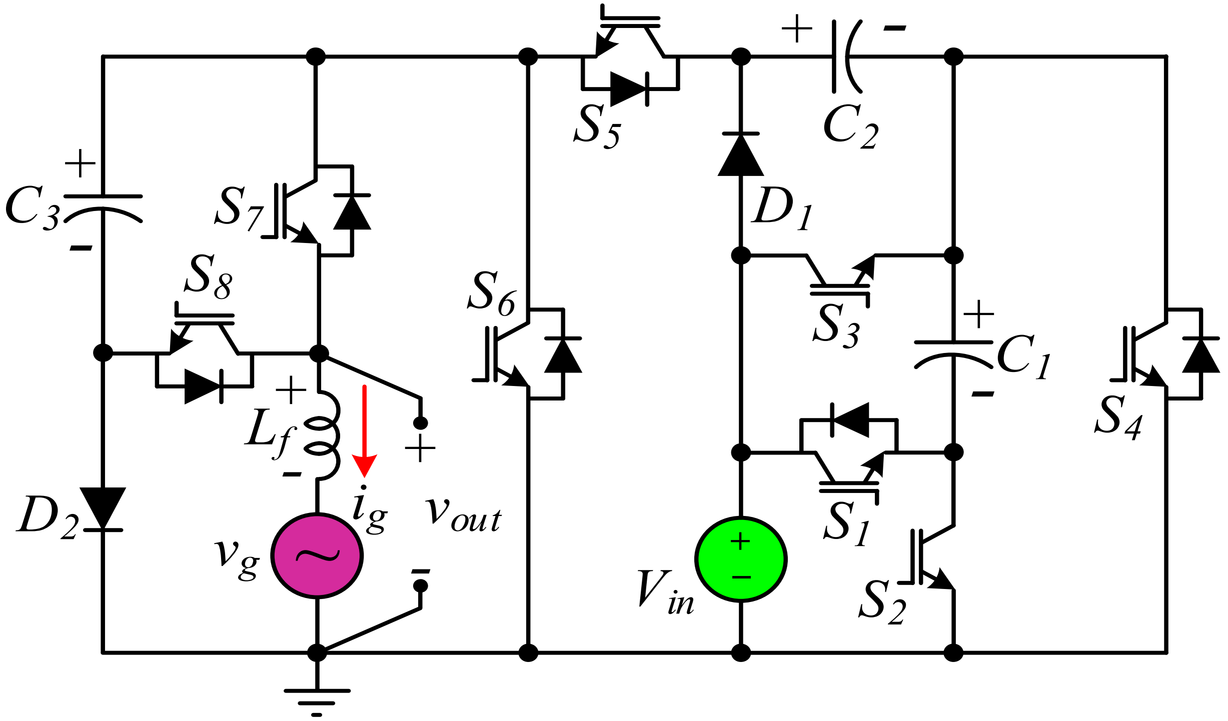
- **EV battery packs are typically 300-400V**
- **Single pack connected to inverters will only support 208V/3-phase grid.**
- **While the minimum DC-link voltage required for a 480V/3-phase grid is 750V (= 480 * $\sqrt{2} * 1.1$)**
  - Option #1: two to three packs needs to be connected to series
  - Option #2: Connect each pack or paralleled packs with a DC-DC, and the output of the DC-DC could be fed to an inverter





Proposed switch-capacitor (SC) converter

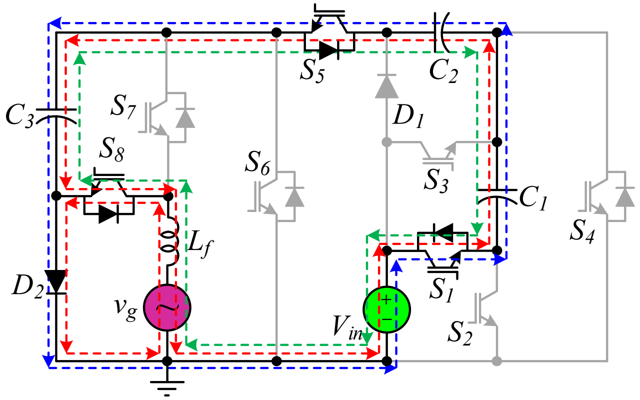
- **Seven-level voltage at the output terminals**
- **Three times boosting factors**
- **Common ground features**
- **Reactive power supporting**



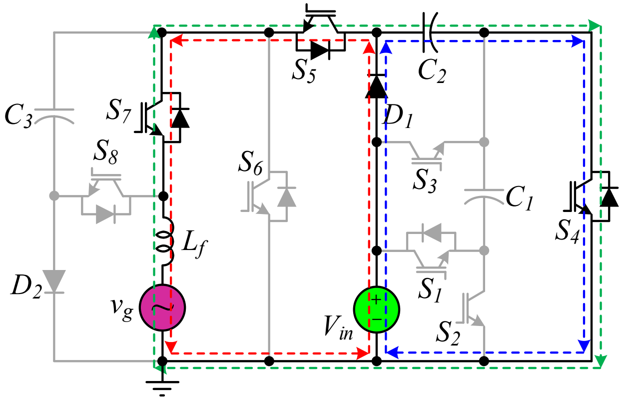
Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

Journal: Energies 2024, 17(13), 3115; https://doi.org/10.3390/en17133115

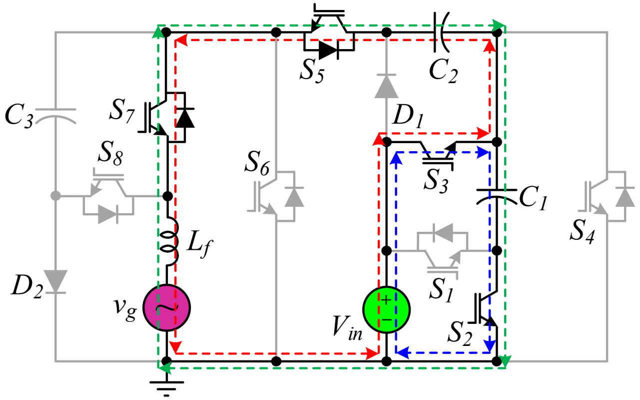
Operation modes of the proposed topology-positive half-cycle



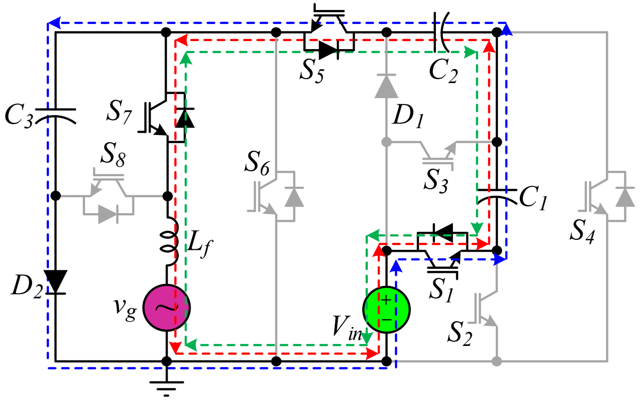
$V_{out} = \pm 0$



$V_{out} = V_{in}$



$V_{out} = 2V_{in}$



$V_{out} = 3V_{in}$

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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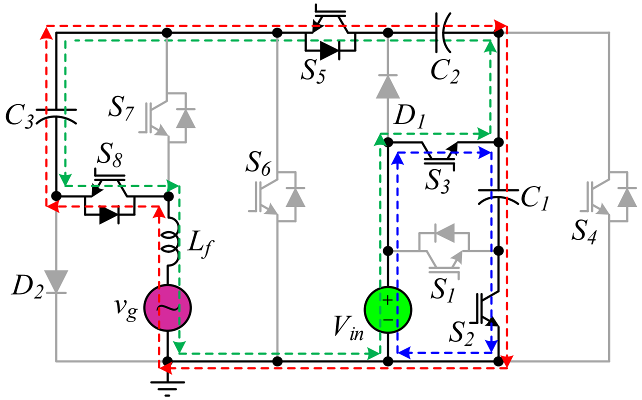
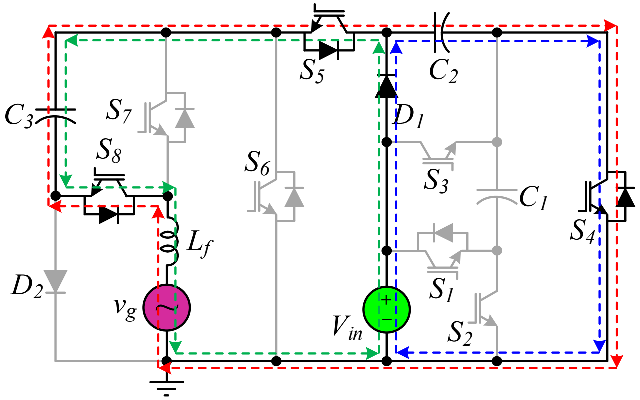
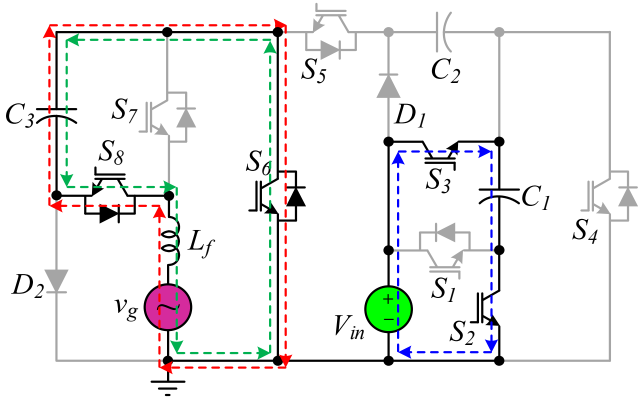
Operation modes of the proposed topology-negative half-cycle



$V_{out} = -V_{in}$



$V_{out} = -2V_{in}$



$V_{out} = -3V_{in}$

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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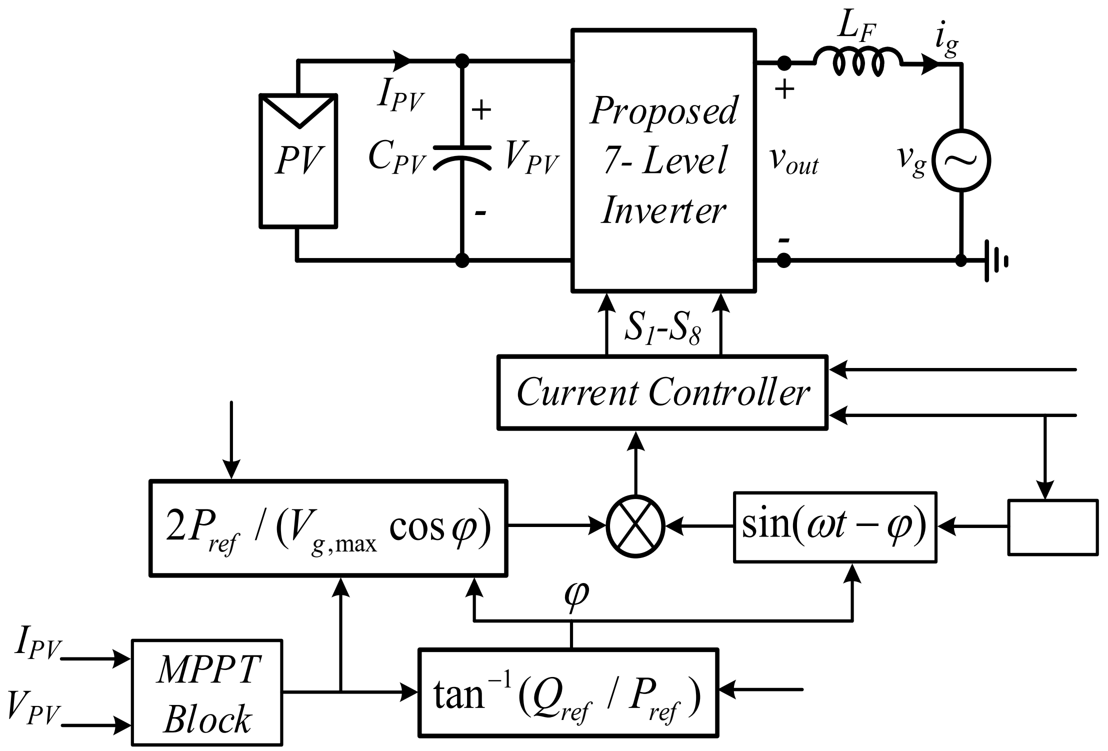
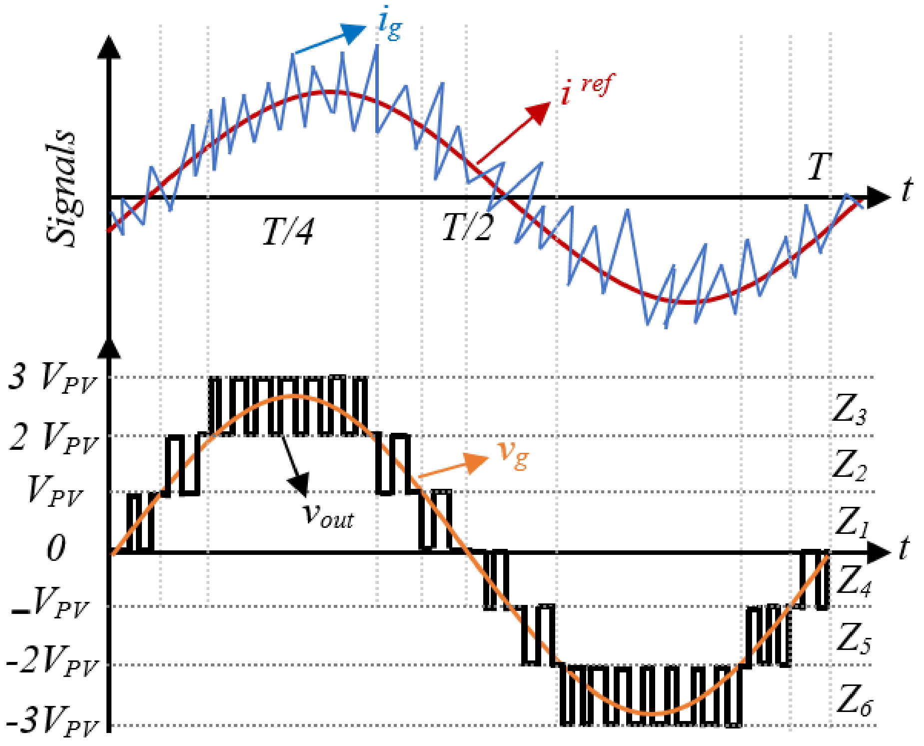
Peak Current Control (PCC) Strategy



The control system of the proposed inverter



Output voltage, grid voltage, grid current, and reference current

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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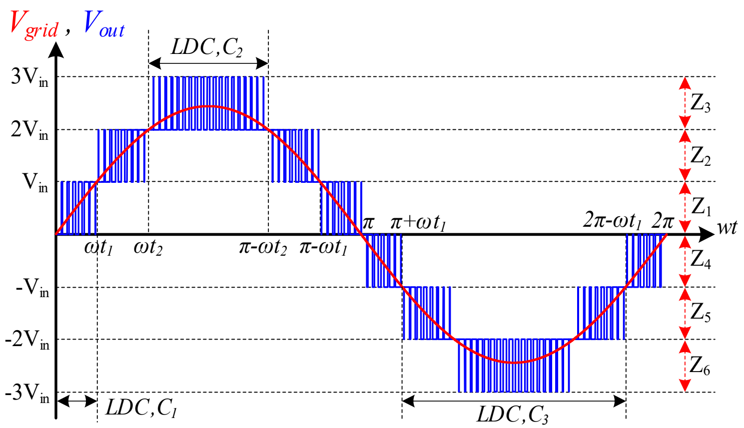
Design of passive components



$$d_1(t) = \frac{v_g(t)}{V_{in}} = \frac{V_{max}}{V_{in}} \cdot \sin \omega t \quad ; \quad 0 \le t < t_1$$

$$d_2(t) = \frac{v_g(t)}{V_{in}} - 1 = \frac{V_{max}}{V_{in}} \cdot \sin \omega t - 1 \quad ; \quad t_1 \le t < t_2$$

$$d_3(t) = \frac{v_g(t)}{V_{in}} - 2 = \frac{V_{max}}{V_{in}} \cdot \sin \omega t - 2 \quad ; \quad t_2 \le t < \frac{T}{2} - t_2$$

$$L_f = \left(5V_{max} - \left(V_{max}^2 / V_{in}\right) - 6V_{in}\right) / \left(\Delta I_{L_f,max} \cdot f_s\right)$$

$$C_1 = \frac{\int_0^{\omega t_1} i_{C1} d\omega t}{\Delta V_{C1,max}} = \frac{I_{max}\left(1 - \cos \omega t_1\right)}{\Delta V_{C1,max}} = \frac{2P_{out}\left(1 - \cos\left(\sin^{-1}\left(\frac{V_{in}}{V_{max}}\right)\right)\right)}{\Delta V_{C1,max} \cdot V_{max}}$$

$$C_2 = \frac{\int_{\omega t_2}^{\pi - \omega t_2} i_{C2} d\omega t}{\Delta V_{C2,max}} = \frac{2I_{max} \cdot \cos \omega t_2}{\Delta V_{C2,max}} = \frac{4P_{out} \cdot \cos\left(\sin^{-1}\left(\frac{2V_{in}}{V_{max}}\right)\right)}{\Delta V_{C2,max} \cdot V_{max}}$$

$$C_3 = \frac{\int_{\pi + \omega t_1}^{2\pi - \omega t_1} i_{C3} d\omega t}{\Delta V_{C3,max}} = \frac{2I_{max} \cdot \cos \omega t_1}{\Delta V_{C3,max}} = \frac{4P_{out} \cdot \cos\left(\sin^{-1}\left(\frac{V_{in}}{V_{max}}\right)\right)}{\Delta V_{C3,max} \cdot V_{max}}$$

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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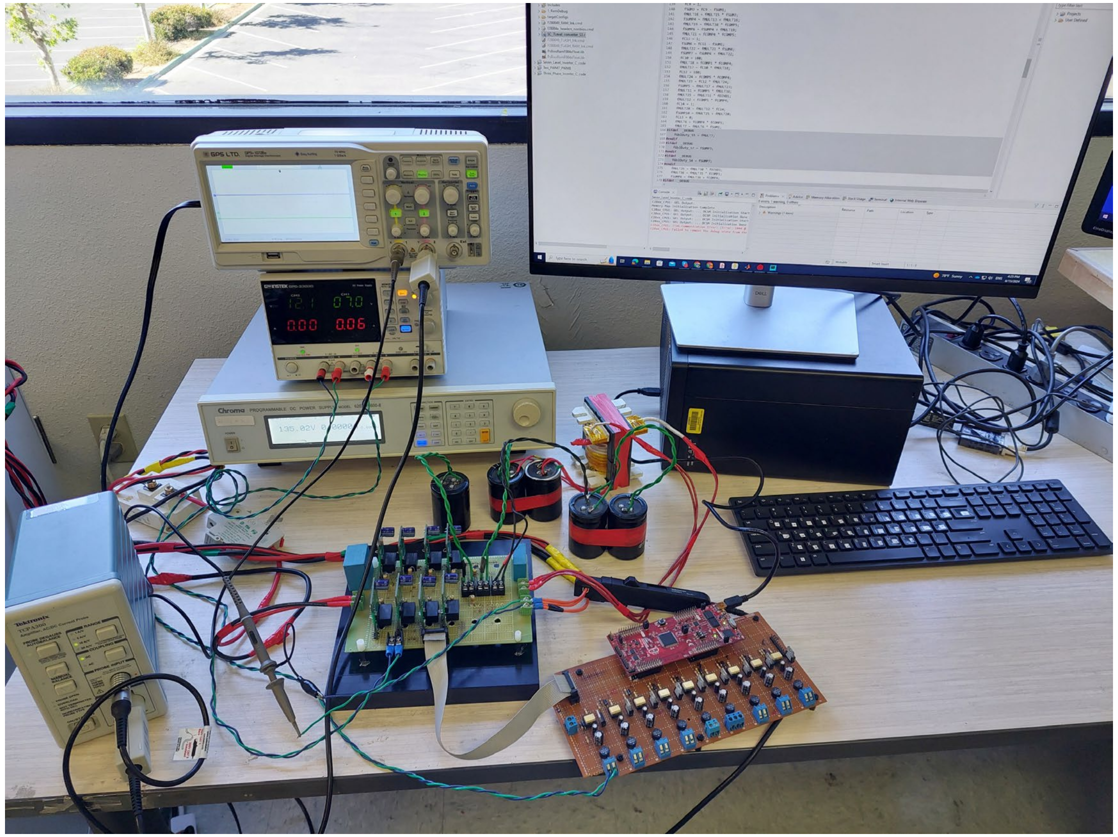
Experimental Verifications

Parameter Values of Experimental Analysis

Parameter	Value	Parameter	Value
Input Voltage	135 V_{dc}	C_1	1 mF
Output Voltage	220 V_{rms}	C_2	2.2 mF
Power Diodes	APT75DQ60BG	C_3	2.2 mF
Power Switches	G3R40MT12K	L_f	1.5 mH
Gate Driver	TLP250	C_f	2.2 µF
Microcontroller	TMS320F28069	Load	62 Ω



Experimental Setup

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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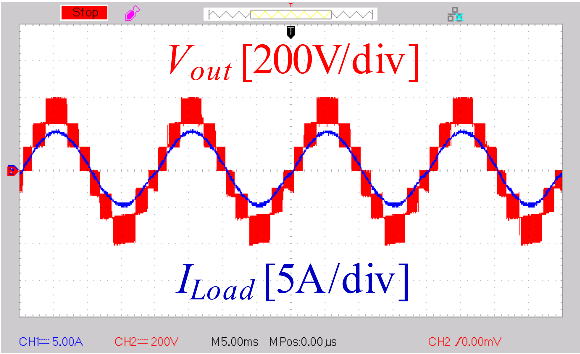
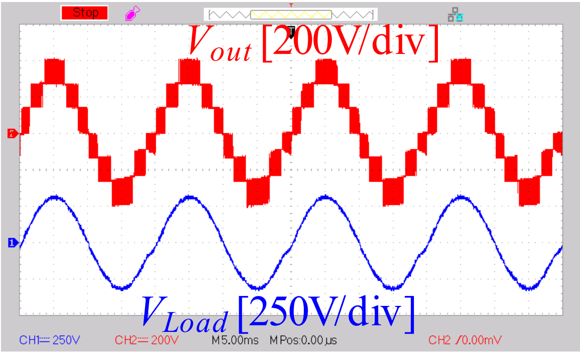
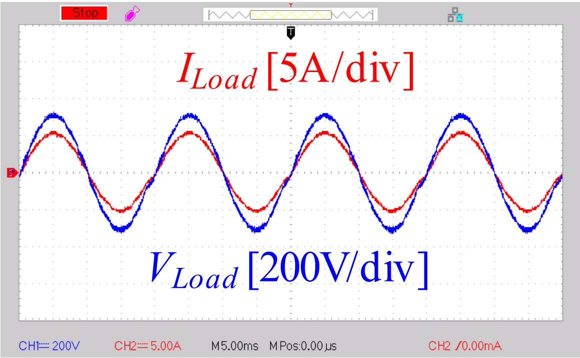
Experimental Verifications- 1 kW output power



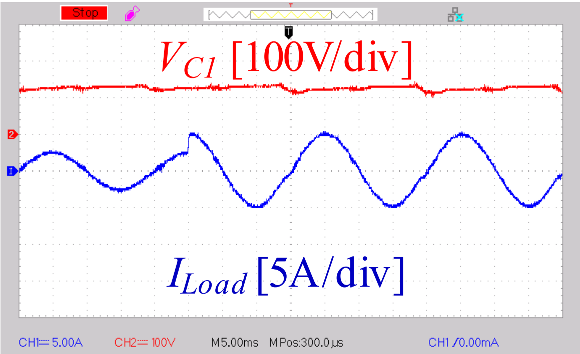
Output voltage and load current



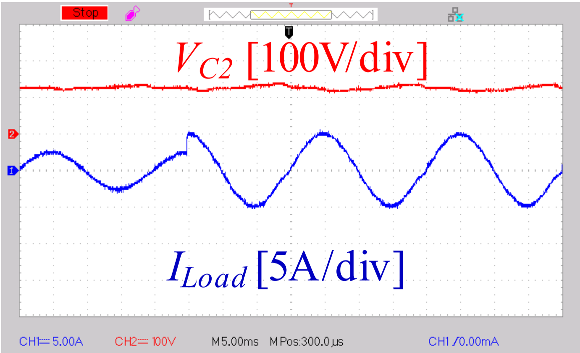
Output voltage and load voltage



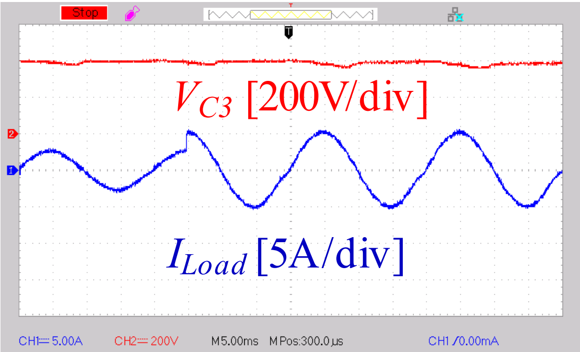
Load voltage and load current



Capacitor C1 voltage and load current



Capacitor C2 voltage and load current



Capacitor C3 voltage and load current

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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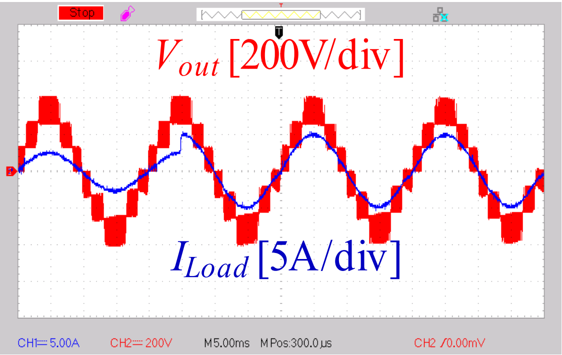
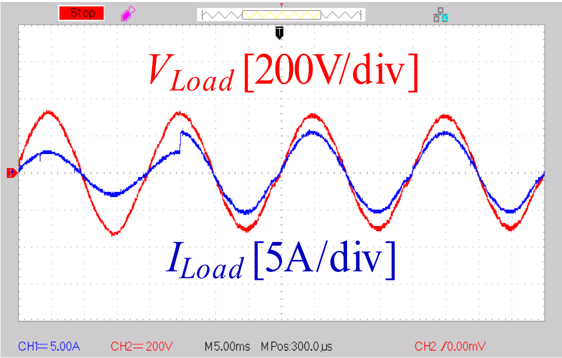
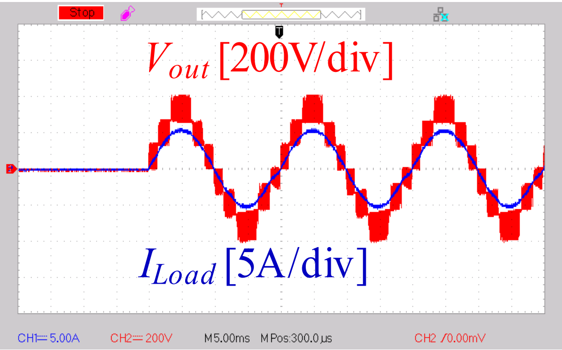
Experimental Verifications- 1 kW output power



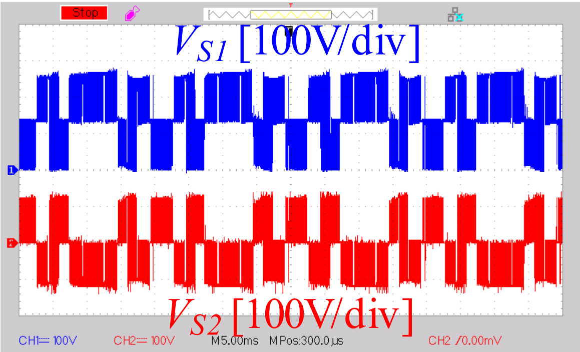
Output voltage and load current- step change conditions



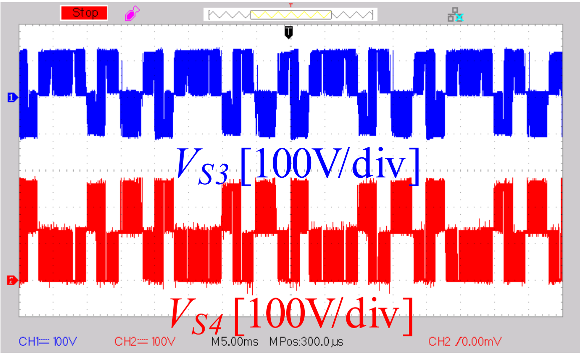
Load voltage and load current- step change conditions



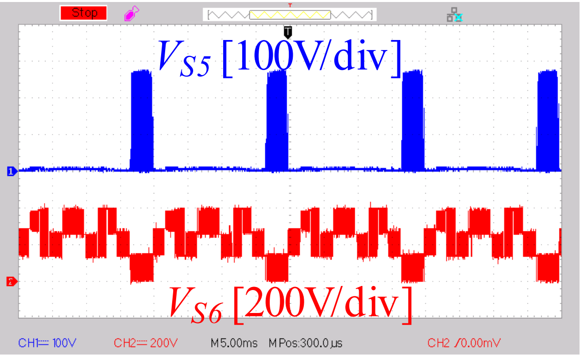
Output voltage and load current- step change conditions



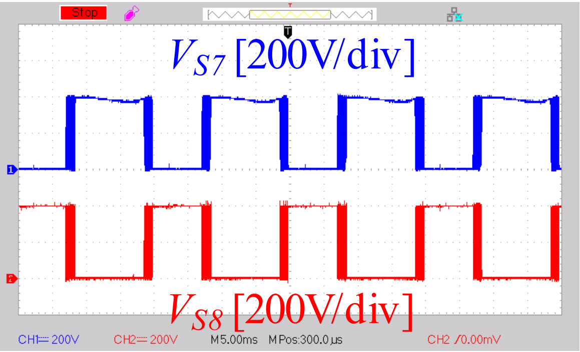
Voltage stress of switches S1 & S2



Voltage stress of switches S3 & S4



Voltage stress of switches S5 & S6



Voltage stress of switches S7 & S8

Source: Transformer-Less Seven-Level Inverter with Triple Boosting Capability and Common Ground

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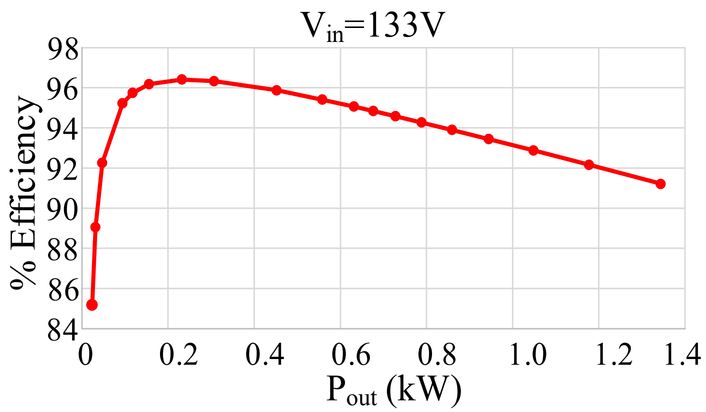
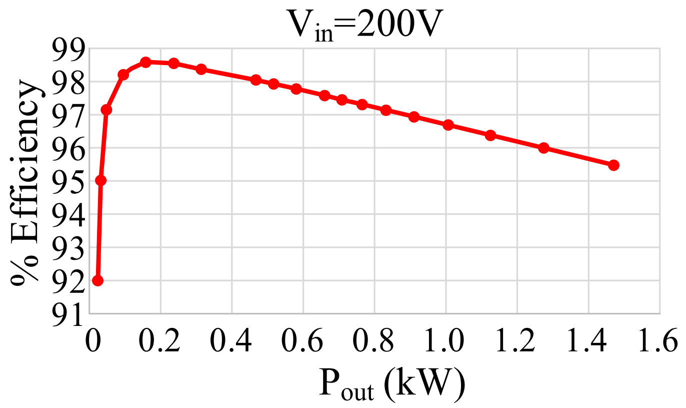
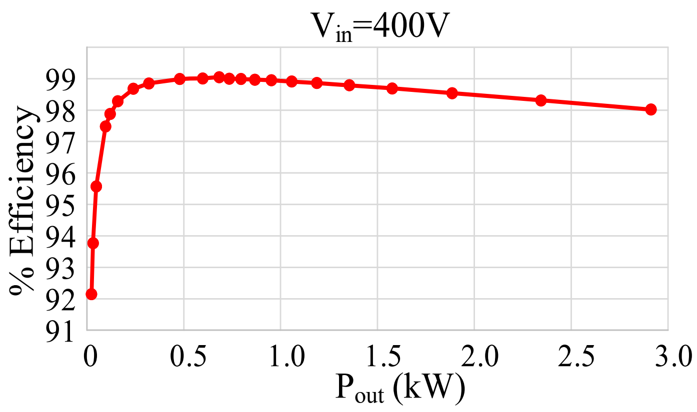
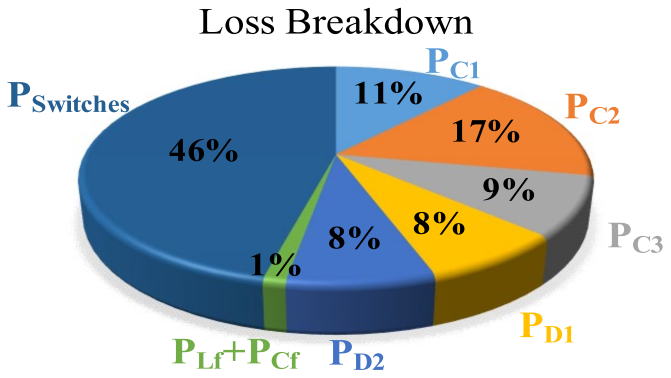
Efficiency Curves- Simulation results









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Conclusions

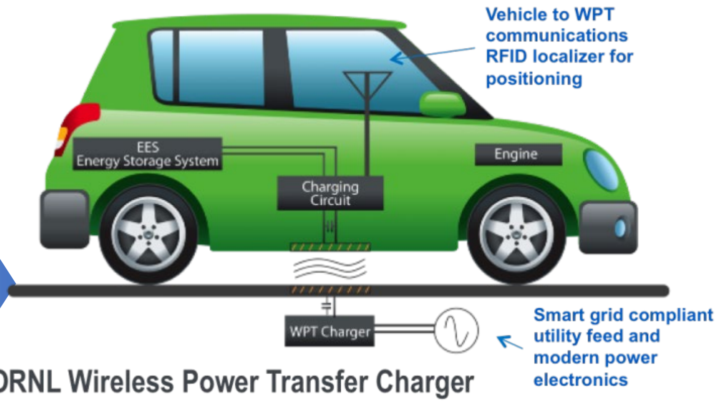
- The common ground capability of the proposed inverter eliminates the leakage current in photovoltaic systems.
- The ability to handle the return current by the proposed inverter makes it possible to feed non-unity power factor loads or perform voltage control at the point of common coupling of the power grid.
- The ability to boost voltage with three times the gain means that there is no need for an additional boost converter, and at input voltages lower than the peak output voltage, power transfer is performed in a single-stage power processing.
- The proposed inverter can inject power into the output power grid in a wide range of input voltage.
- There is no need for an additional voltage sensor or a complex control system to control the voltage of the capacitors in the inverter.
- It offers high efficiency suitable

Wireless Charging

Electric safety is of concern: electric shock due to rain, etc.

Charge station, plug and cable can be easily damaged, stolen

Charge/swap station takes a lot of space and affect the views



ORNL Wireless Power Transfer Charger

Collaboration with DOE, DENSO, LG

Solid State Batteries

40 Layers
(15Ah)

<1 ATM

5mA/cm^2

-40 to 90ºC

350Wh/kg

SOLiD ENERGIES

STATE OF CALIFORNIA ENERGY COMMISSION

High weight percent Si-C anode increase capacity over 3000mAh/g

SUSTAINABLE

cobalt-free, easily sourceable materials

FLEXIBLE

flexible solid electrolyte with extreme low temperature performance

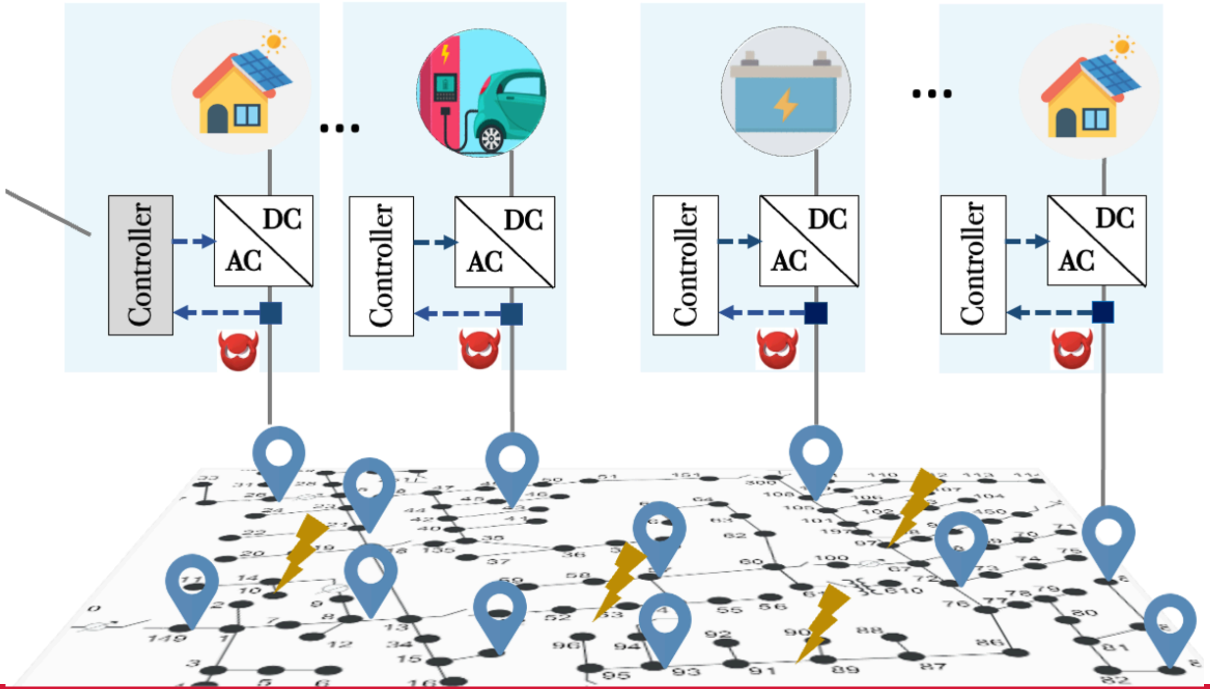
Proven Scalability

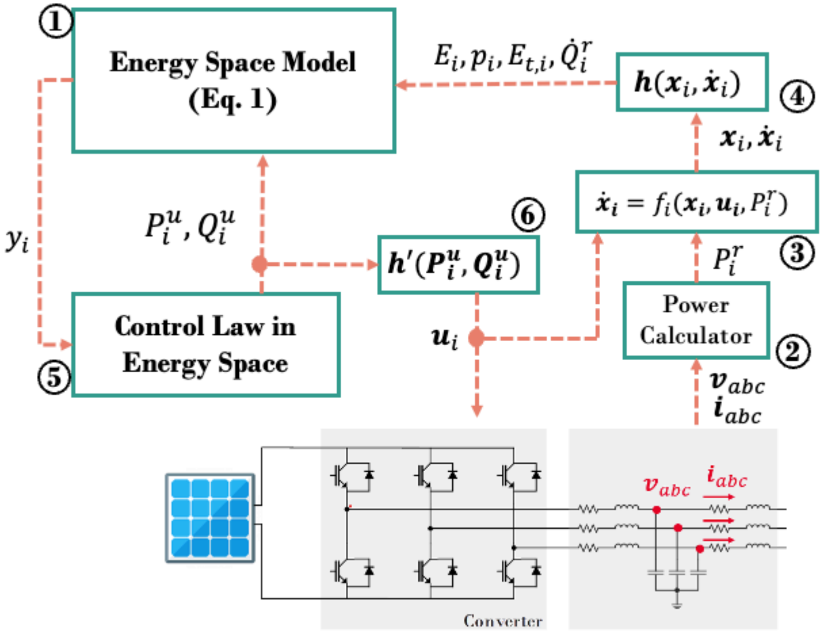
industry-leading
16Ah, 3.8 V
50-layer pouch cells

Collaboration with Dr. Tim Lin, Solid Energies Inc., Funded by California Energy Commision

Cyber Security of Power Systems

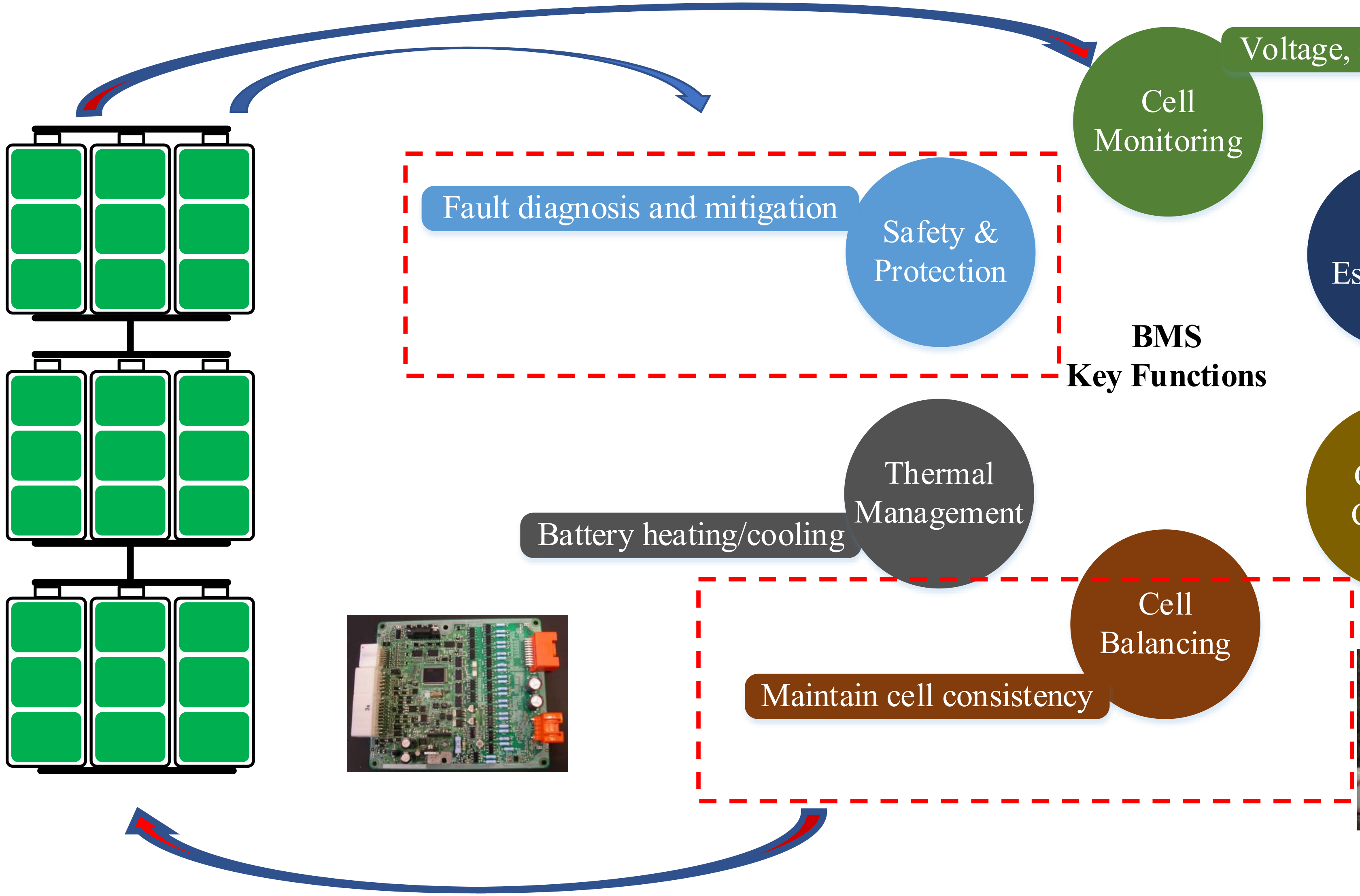
- **Resilience of power electronics (PE)-dominated power distribution systems is an increased concern**
- **There exists physical disturbances and/or cyberattacks**
- **Use unified, energy space-based modeling framework to identify disturbances, cyber attacks, and mitigate the risks**



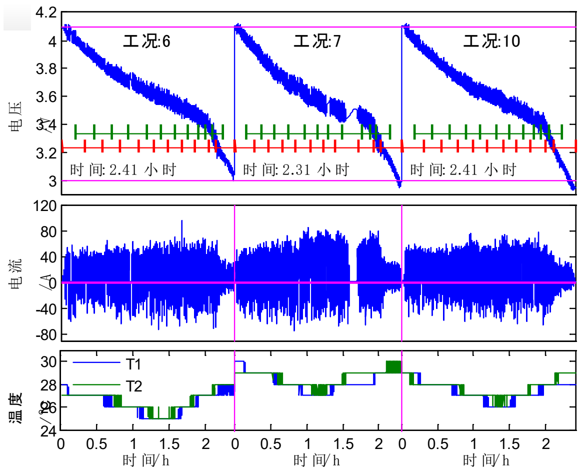


Collaboration with Dr. Tong Huang, SDSU, Marija Ilich, MIT, Funded by NSF

Wireless Battery Management Systems



Joint SOH & parameter estimation



Step Three:
Parameter Identification for Battery Cells

1. Raw data selection and pre-treat
2. Calculation for "unit data pieces"
3. Generate "Parameter-Ah" curves;
4. Battery cell parameter report;

Step Two:
Data is uploaded to Calculation platform;

Step Four:
Battery Package Analysis

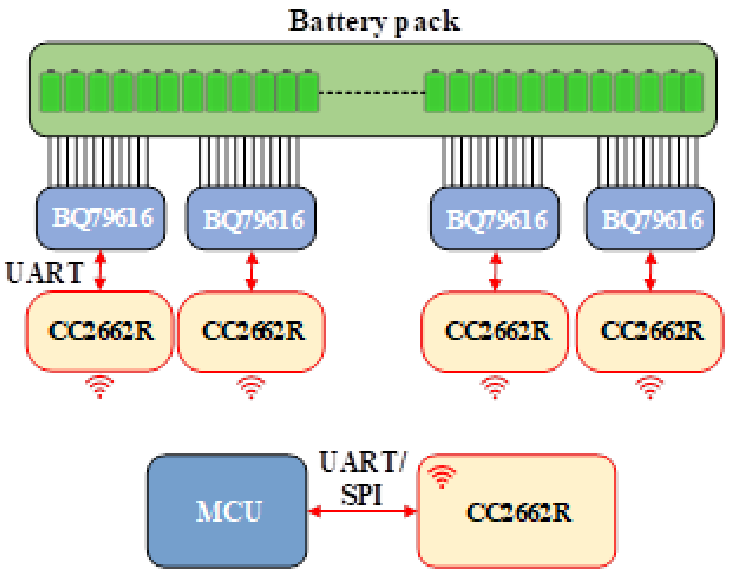
Step One:
Vehicle data is upload to manufacture's database;

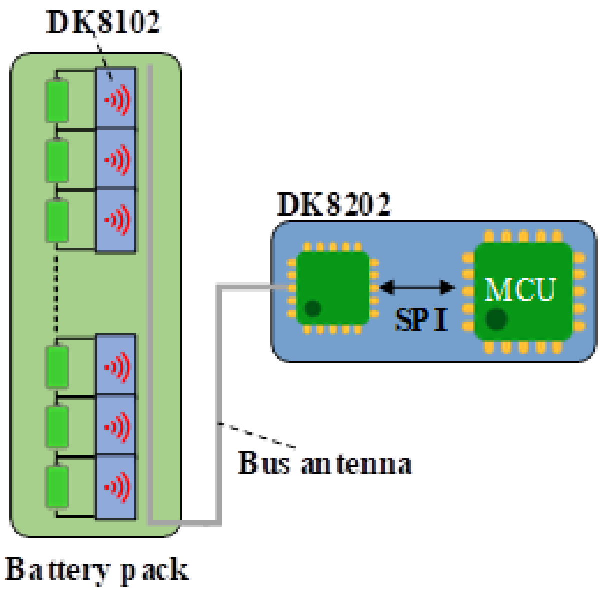
5. Balance analysis — Balance strategy
6. Battery failure analysis
7. Remaining of life and residual value analysis

Raw Data Recorded:
- Current
- Cell Voltages
- Temperatures

Step Five: Report Send Back

Wireless BMS





- Elimination of physical connections
- Natural galvanic isolation
- Reduced weight
- Simplified packaging
- Enhanced flexibility and reliability
- Easy to reuse and repurpose

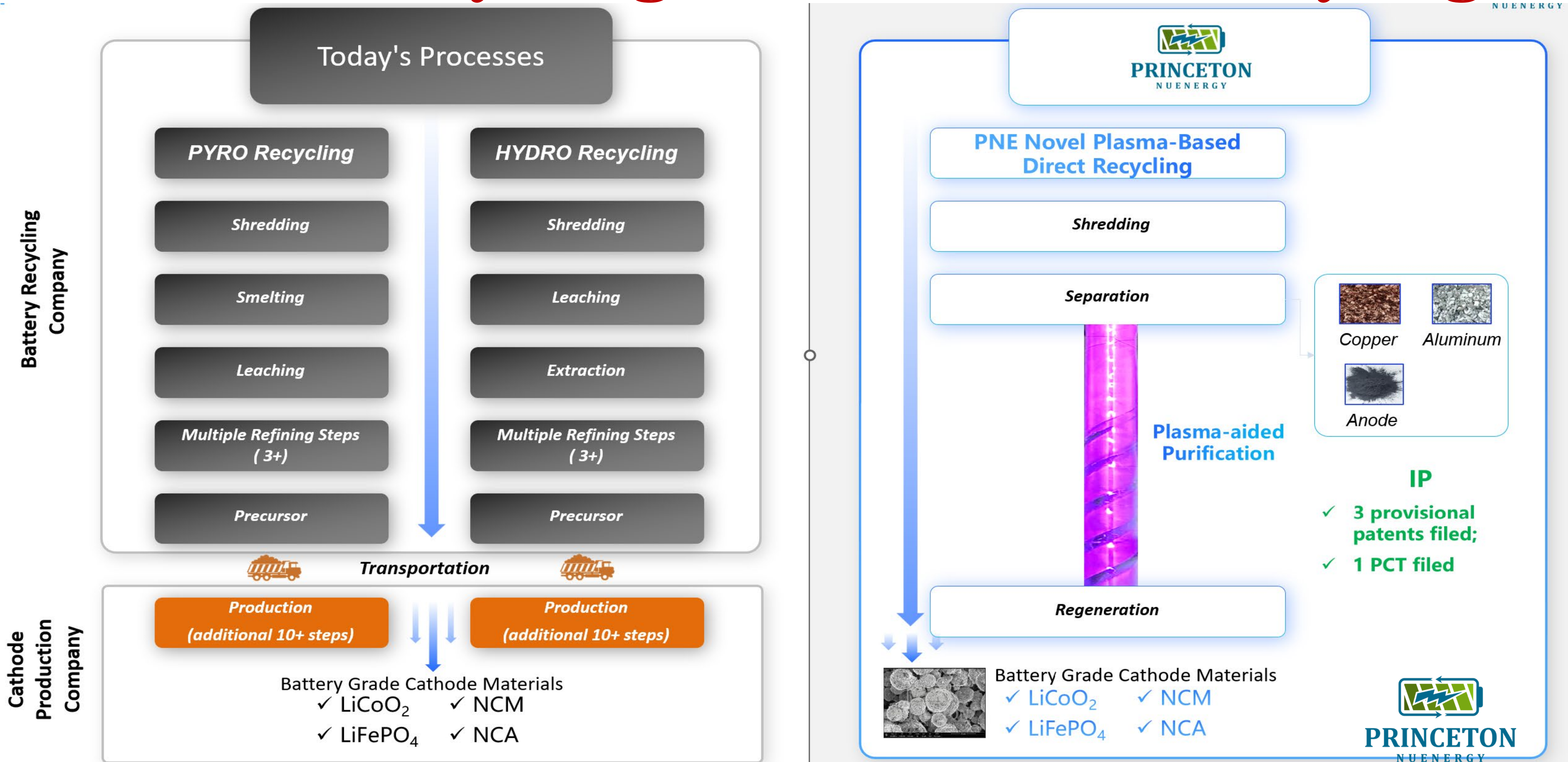
SDSU Collaboration with Dukosi, Solid Energies, Funded by the California Energy Commision & Gotion

Second-Life EV Battery

Step	 • Nissan Leaf Gen1 24 kWh LiMO2	 • Nissan Leaf Gen3 62 kWh LiNMC	 • Electric Forklift LFP 100Ah battery	 • Electric Bus LFP 270Ah battery
1: Initial SOH	60%~67%	89~97%	Cell: 89% SOH Pack: 50%~60% SOH	Cell: 79% SOH Pack: 52% SOH
2: Balance State	< 5% minor	< 5% minor	30% serious	27% serious
3: Capacity degradation speed ▪ *Fast / Vehicle* ▪ *Slow / BESS*	20% / 1000 cycles 4% / 1000 cycles	20% / 1000 cycles 3.6~5.9% / 1000 cycles	9.3% / 1000 cycles 5.0% / 1000 cycles	Balance Issues exist
4: Aging Knee	No aging knee	Aging knee at 75% SOH (1500 cycles)	No aging knee	
5: Estimated 2nd life	10~15 years 3000~5000 cycles 10 years / 3000 cycles high performance	10 years 3000 cycles 80% Dod <0.4C-rate	30 years 9000 cycles 100% Dod 0.5C charge/ 1C discharge	>10 years 3000 cycles Enhanced balance system is needed

SDSU Funded by the California Energy Commission.

Direct Recycling vs. Traditional Recyling



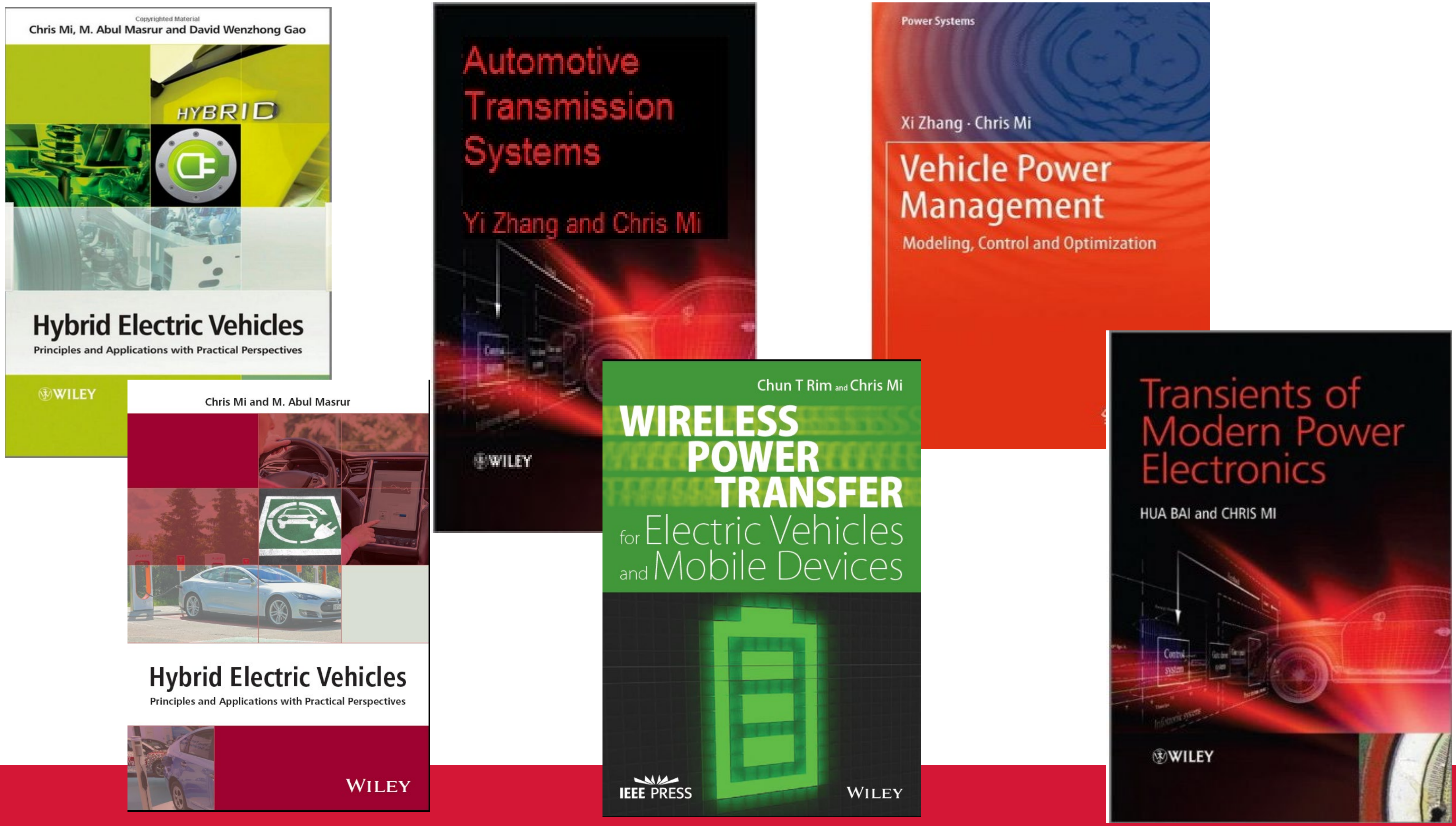
Project: flying cars/electric airplanes

- Aviation accounts for 2% of CO_2 emissions and 3% of all greenhouse gases globally, and in the long term
- EVTOL seems to be ready; long haul large body electric airplane may never come to fruition

NASA ULI

In Collaboration with John Hwang, UCSD, funded by NASA ULI program

We are committed to conduct research to improve performance, efficiency and safety of electric vehicles



To learn more about WPT

- https://www.youtube.com/c/[WirelessPowerTransfer](https://www.youtube.com/c/WirelessPowerTransfer)