Predicting Reliability, Improving Safety and Resiliency in Grid Connected Battery Energy Storage Systems

Presented by:
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Objectives

- To improve the **safety**, **resiliency** and **reliability** aspects of lithium ion based Battery Energy Storage System (BESS), using the power converter and its control, interfaced to the grid.
  - To develop modular, transformer-less multilevel inverter topologies for grid integration of BESS.
  - To develop self-battery management system (BMS) using power converter performing state of charge (SoC) balancing scheme.
  - To address resilient operation of energy storage system with the interfacing converter under adverse grid scenarios.
  - To develop accurate equivalent circuit models of Li-ion batteries for State of Charge and State of Health estimation.
  - To identify component level reliability parameters for SiC MOSFET, battery, etc, by performing accelerated life tests.
  - To evaluate the component-level remaining useful life (RUL) index for SiC-FET and Li-ion batteries; and to predict the system-level RUL for grid connected modular BES converter system.

Fig. 1. Grid connected BESS.
## Milestones and Targets

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestones</th>
<th>Deliverables</th>
<th>Target</th>
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<tbody>
<tr>
<td>Year I</td>
<td>• To develop a grid connected multilevel converter topology for BESS with self-battery management system.</td>
<td>• A single phase 1kW laboratory scale hardware prototype using CHB converter to verify the proposed <strong>SoC balancing</strong> scheme</td>
<td>☑ To achieve more than 50% <strong>improvement</strong> in rate of SoC balancing using rated current operation compared to Unity Power Factor (UPF) operation at half the power exchange.</td>
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<td>• To achieve more than 50% improvement in rate of SoC balancing using rated current operation compared to Unity Power Factor (UPF) operation at half the power exchange.</td>
<td>• Improved equivalent circuit model of Li-ion batteries considering effect of SoC and temperature.</td>
<td>☑ To develop SoC and temperature dependent equivalent circuit model (ECM), with model accuracy improvement above 50%.</td>
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<td></td>
<td>• To develop reliability evaluation model of SiC power MOSFETs.</td>
<td>• Reliability evaluation procedure for SiC devices at high temperatures.</td>
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<td>Year II</td>
<td>• To address resilient BESS operation through power converter under adverse grid conditions; • To identify state of health indicators of power electronic components in a BESS.</td>
<td>• Prediction algorithm to evaluate overall reliability and RUL of power devices and batteries for safe operation of</td>
<td>☑ To predict system level BESS RUL with an estimation error of less than 500 Hrs. in about 20 years.</td>
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<td>• To develop an integrated approach to predict system level RUL of BESS using power converters</td>
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Resilient BESS Operation under Adverse Grid Scenarios

Resilient BESS under Asymmetric Grid Voltage Scenarios through Active Power Balancing

- BESS needs to provide resilient operation while providing grid voltage support/var compensation during adverse grid voltage conditions.
- Example: low voltage ride-through (LVRT) operation of BESS during adverse grid voltage scenarios such as undervoltage and voltage sag.
- Developed a Modular Multilevel Converter (MMC) topology to achieve resilient operation for BESS using active power balancing scheme.

**Active Power Deviation**

**Active Power Balancing**

Fig. 3. (a) Grid voltages; (b) MMC leg power without power balancing; (c) average per phase SOC without power balancing; (d) MMC per-phase power with power balancing; (e) average per phase SOC with power balancing.
Characterization and Modeling of Li-ion Batteries

• Improved equivalent circuit models (ECM) is developed to obtain accurate state of charge (SOC) and state of health (SOH).

• The circuit parameters are obtained through subspace identification:
  o Methodology 1 (RC-Model): uses the whole dataset to find a unique model.
  o Methodology 2 (RC-SOC Model): uses dataset at every SOC to find several models.

• Obtained ECMs are used to correlate the parameters with the SOC and temperature through polynomial regression, to develop unique ECM.

• The developed model improves the accuracy of the terminal voltage estimation by approximately 50%.

<table>
<thead>
<tr>
<th>Error</th>
<th>Model</th>
<th>1RC</th>
<th>2RC</th>
<th>1RC-SOC</th>
<th>2RC-SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>T=35°C</td>
<td>17.6 mV</td>
<td>14.4 mV</td>
<td>8.3 mV</td>
<td>7.3 mV</td>
</tr>
<tr>
<td>RMSE</td>
<td>T=25°C</td>
<td>23.3 mV</td>
<td>18.8 mV</td>
<td>9.9 mV</td>
<td>8.4 mV</td>
</tr>
<tr>
<td>RMSE</td>
<td>T=15°C</td>
<td>35.5 mV</td>
<td>30.3 mV</td>
<td>15.5 mV</td>
<td>13.1 mV</td>
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Remaining Useful Lifetime (RUL) Prediction of Power Converters

Device Level Reliability Evaluation at High Temperature

- Component-level reliability evaluation needs degradation dataset. We take the evaluation procedure to next level through reliability evaluation at high temperature.

- High-Temperature Component-level RUL prediction involves:
  - Power and Thermal cycling on SiC-MOSFET Devices-Under-Test (DUT)
    - Injecting maximum DC current and heat to DUT during ON time operation.
  - Junction temperature and $R_{DS(ON)}$ measurement of DUT as temperature-sensitive electrical-parameters (TSEP).
  - Evaluation of RUL of DUT based on captured degradation data.

- Health indicator $R_{DS(ON)}$ is fitted to an exponential equation ($R_{DS(ON)} = a \times e^{bt}$) to model the component level behavior during the operational lifetime.

Fig. 6. The test setup for SiC-MOSFET degradation (a) Schematic (b) experimental Tamb =75°C.

Fig. 7. The schematic of degradation cycle (power and thermal cycling).

Fig. 8. The captured $R_{DS(ON)}$ data for DUT degradation at Tamb=75°C (a) DUT1 (b) DUT2.
Converter Level Reliability Evaluation under Thermal Equilibrium

- Developed a new reliability evaluation of power FETs based on thermal equilibrium during mission profile characterization through converter operation.

- H-Bridge power converter is cycled through a mission profile consisting of different current steps, operated at different ambient temperatures.

- DUTs are cycled until the device fails or the reliability parameters such as RDS(ON) and the equilibrium junction temperature exceed a certain threshold value.

- Degradation data are captured for post data processing to evaluate Remaining-Useful-Lifetime (RUL).

  ➢ The proposed approach offers a new, efficient, reliability evaluation procedure for power FETs, considering ambient temperature variations and mission profile.
Conclusion and Next Steps

• Developed a multilevel level inverter topology with active power balancing scheme to achieve resilient BESS operation under adverse grid conditions.

• Developed an improved equivalent circuit model (ECM) considering SoC and temperature dependency, with more than 50% model accuracy improvement.

• Developed a method for reliability evaluation of SiC MOSFETs using data obtained through experimental degradation at high temperature.

• Ongoing:
  o Working on a new, efficient power FET reliability evaluation test procedure for SiC devices using thermal equilibrium characteristics, through power converter operation.

• Next Steps:
  o To obtain state of health indicators of Li-ion batteries under realistic mission load profile (as function of SoC and temperature) for component level RUL prediction.
  o To develop an integrated approach to predict system level RUL of BESS using power converters with an estimation error of less than 500 hours for about 20 years.