Adaptive Learning-Based Battery Management for Grid-Scale Vanadium Redox Flow Batteries

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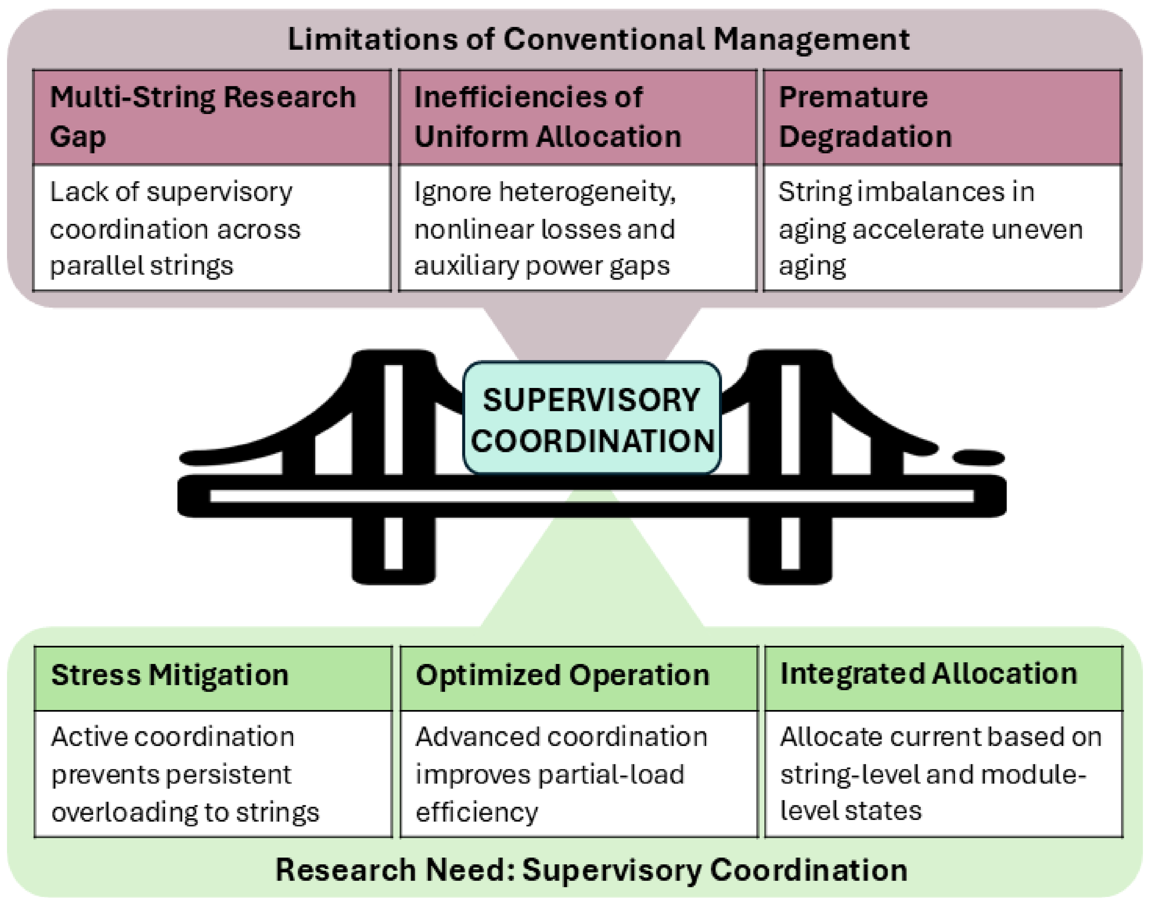
PROJECT PROFILE
Topic: Analytics & Tools Vertical: Grid Integration & Field Validation Strategic Pathway: Optimize Project start and finish: FY26 – FY26

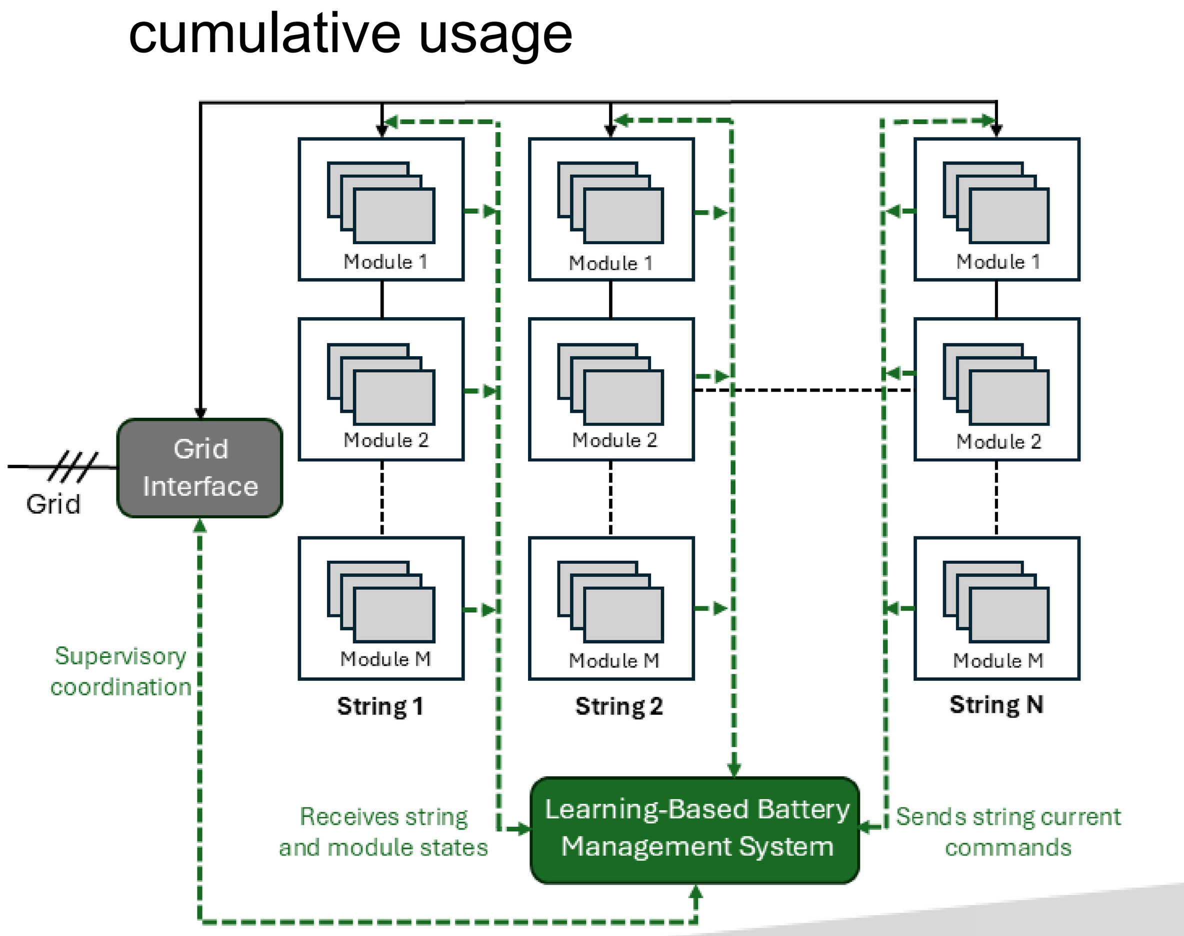
PROBLEM

- Opportunities for Enhanced Power Coordination in Multi-String VRFBs
  - ➢ Existing BMS strategies often use fixed equal power/current allocation across strings and modules
  - ➢ Uniform dispatch does not adapt to varying module/string conditions, operating status, efficiency, or degradation characteristics
  - ➢ Using all strings/modules under all operating conditions can limit the operating range and increase losses

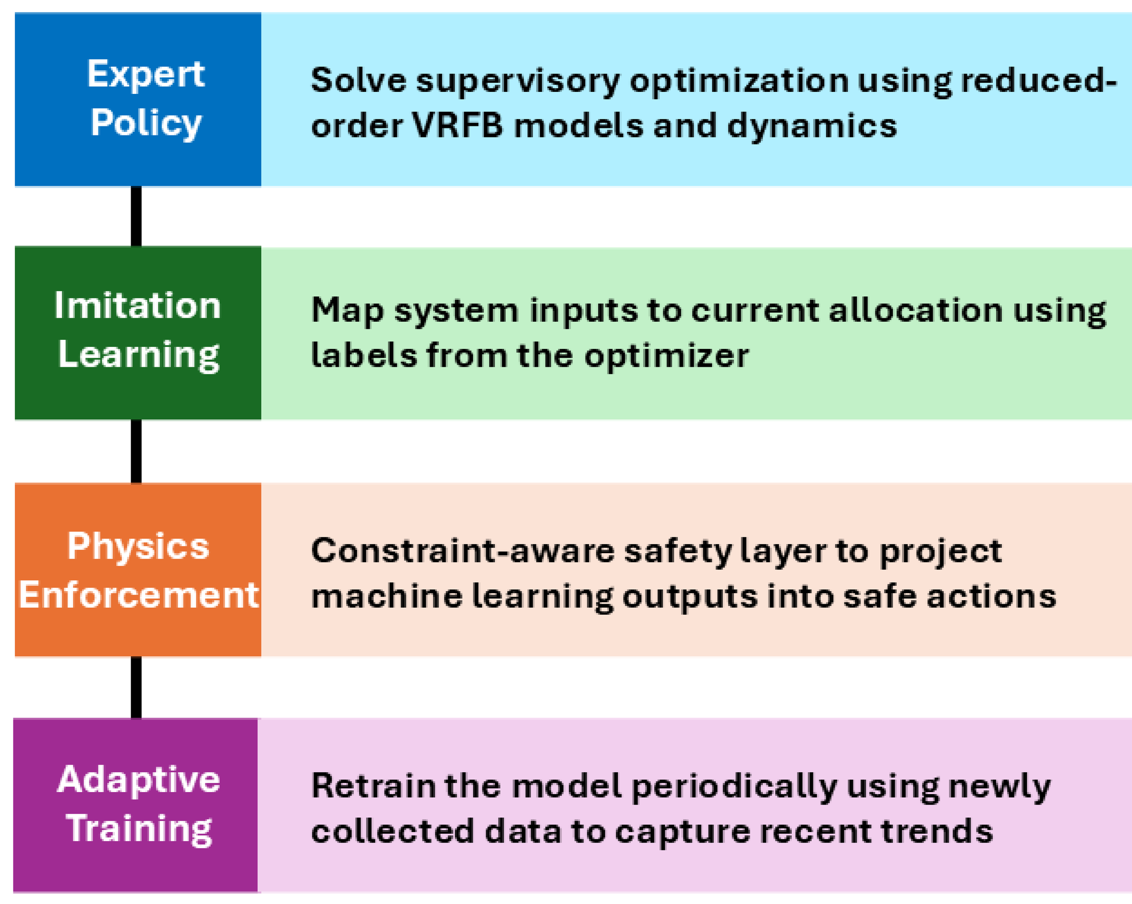


APPROACH

- The objective function captures
  - ➢ Internal electrical loss minimization
  - ➢ Auxiliary loss minimization
  - ➢ Thermal-stress penalty
  - ➢ Cumulative throughput balancing penalty
- Model combines module-level SOC and SOH, and string-level aggregated electrical, auxiliary-power, thermal, and cumulative usage

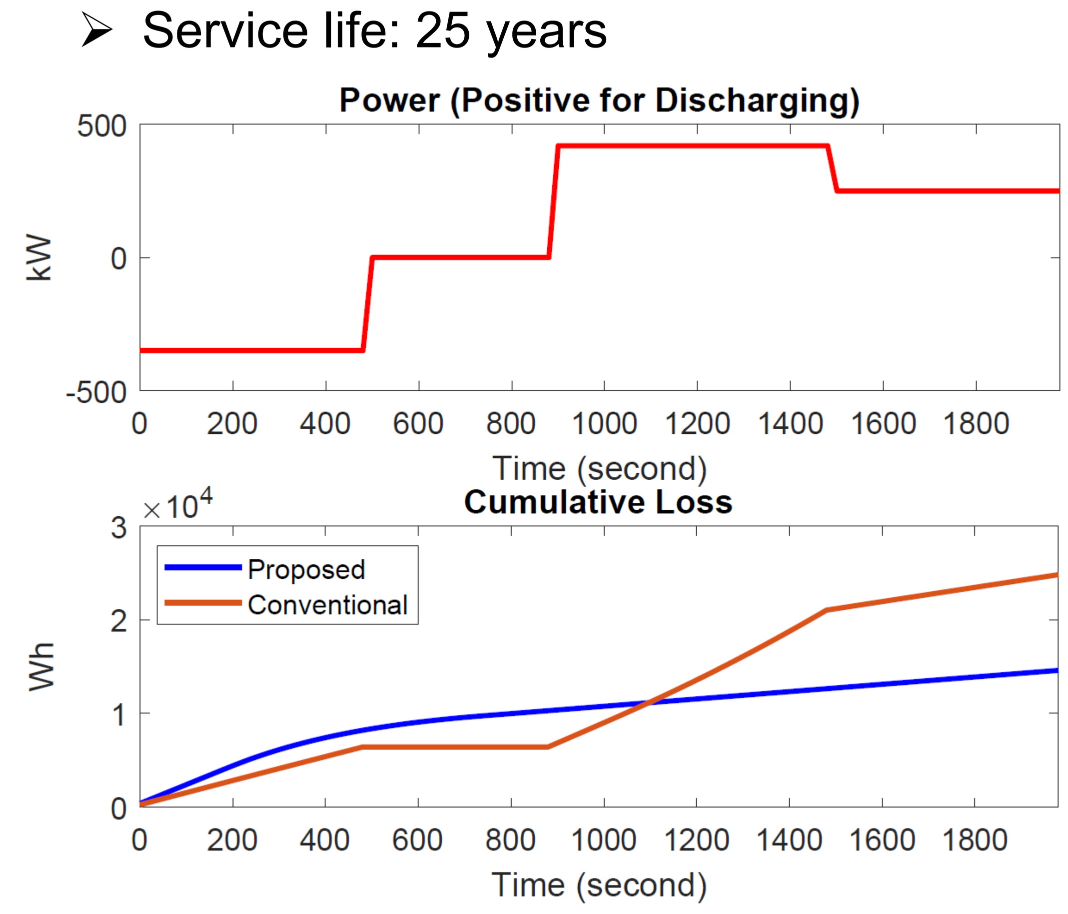


- Proposed BMS is powered by physics-guided imitation learning
  - ➢ Module-level states (SOC, SOH, voltage, temperature), together with aggregated string-level and system-level information, are used to train the neural policy
  - ➢ String current allocation commands pass through a physics-enforced safety layer to ensure healthy operation

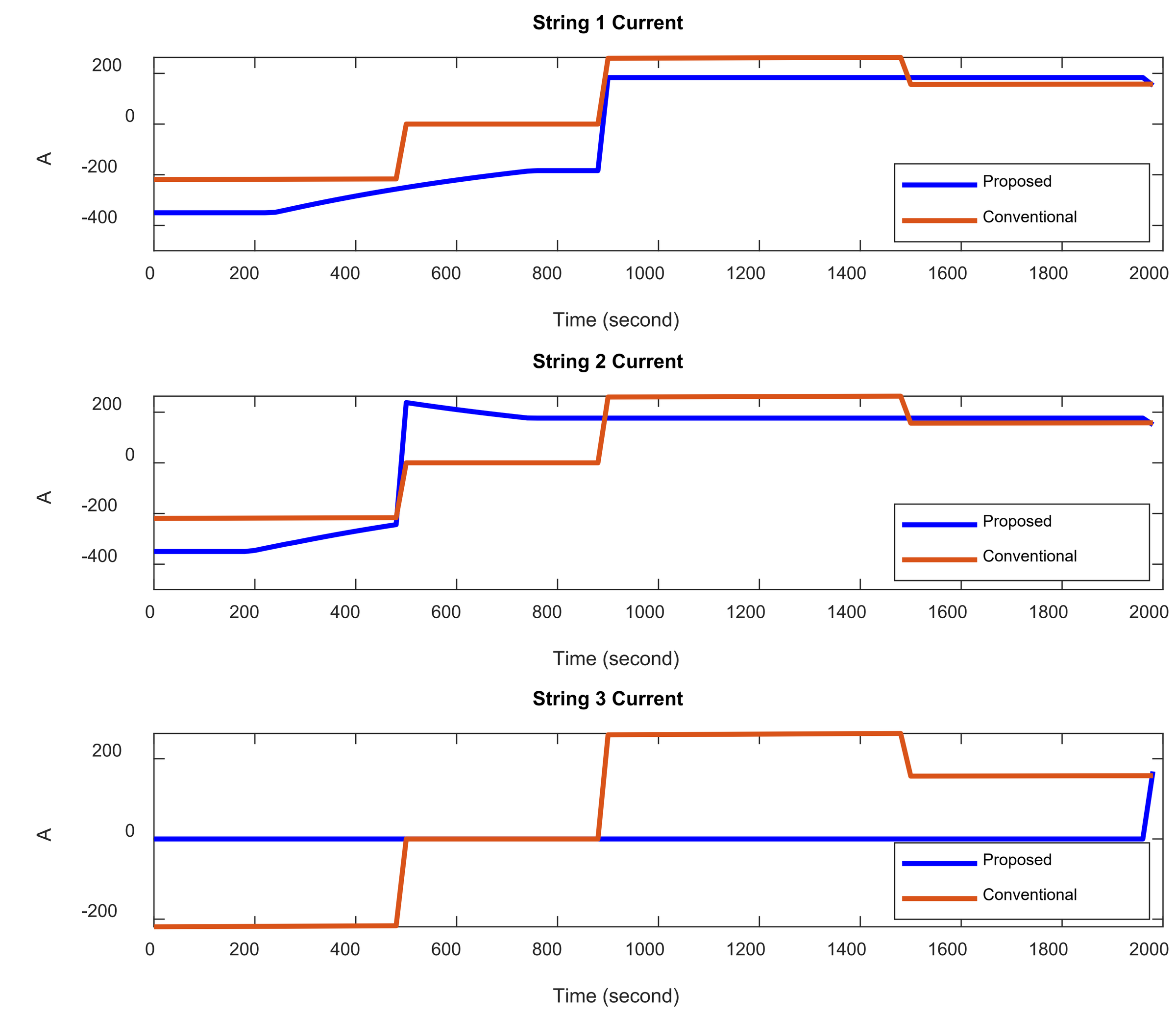


RESULTS

- Case studies: a three-string VRFB system
  - ➢ Module-level DC power: 75 kW
  - ➢ Energy capacity per module: 300 kWh
  - ➢ Number of modules per string: 2
  - ➢ Service life: 25 years



- Cumulative Loss Reduction
  - ➢ Conventional equal-sharing strategies do not leverage string-level electrical and thermal conditions to optimize power allocation and cooling operation
  - ➢ The proposed BMS achieved >40% reduction in cumulative losses by adaptively routing current away from high-resistance strings and proactively pre-cooling modules ahead of peak thermal stress



- Balancing Heterogeneous Assets
  - ➢ Conventional equal-sharing operation leads to greater imbalance in string utilization and stress
  - ➢ The proposed BMS adaptively allocates current across strings, reducing Ah throughput imbalance by ~10% while mitigating uneven string stress

CONCLUSIONS & IMPACT

- We developed a physics-guided, imitation learning-based BMS method for grid-scale VRFB systems
- Case studies demonstrate adaptive power coordination and supervisory control capabilities
  - ➢ Improved system efficiency, achieving >40% reduction in cumulative losses
  - ➢ Mitigated uneven electrical and thermal loading, reducing Ah throughput imbalance by ~10%

FUTURE DIRECTIONS

- Extend the proposed BMS to jointly optimize efficiency, degradation, and operational flexibility under broader grid service scenarios
- Validate the approach under larger-scale systems, heterogeneous operating conditions, and experimental / hardware-in-the-loop environments

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