Adaptive Thermal Management for Portable System Batteries by Forced Convection Cooling

Qing Xie[1], Siyu Yue[1], Donghwa Shin[2], Naehyuck Chang[2] and Massoud Pedram[1]

[1]University of Southern California, Los Angeles, CA, United States

[2]Seoul National University, Seoul, South Korea.

USC Viterbi School of Engineering — Ming Hsieh Department of Electrical Engineering

SPORT lab — System Power Optimization and Regulation Technology

Low Power Laboratory — Seoul National University

Motivation

Battery Cycle Life Largely Varies with the Operating Conditions such as Temperature and Current

- The temperature of battery varies in a large range during continuous charging and discharging process.
- ***State-of-Health*** (SoH) significantly degrades at elevated temperature.
- This work proposed to use a *forced-convection cooling* mechanism for batteries in portable systems.
- This work proposed ***Adaptive Thermal Management*** policy that achieve the maximum *cumulative workload completion* over the *designed system life* using ***Dynamic Programming*** and ***Reinforcement Learning***.

Modeling the Batteries

State of Health (SoH)

- Figure of merit captures the general condition of a battery and its ability to store and deliver energy compared to its fresh condition.
- SoH of the fresh battery is 100%, typically 80% is used as a measure of end of battery life.

SoH Degradation Rate vs. Temperature

- A super-linear function (Figure B):

$$L(T) = L_0(DoD, SoC_{avg}, SoH) \cdot exp(\frac{U_0}{k} \cdot \frac{T - T_{ref}}{TT_{ref}})$$

Temperature Variation during Operation

- Heat generation: Ohmic heat Q_p, entropy change heat Q_s

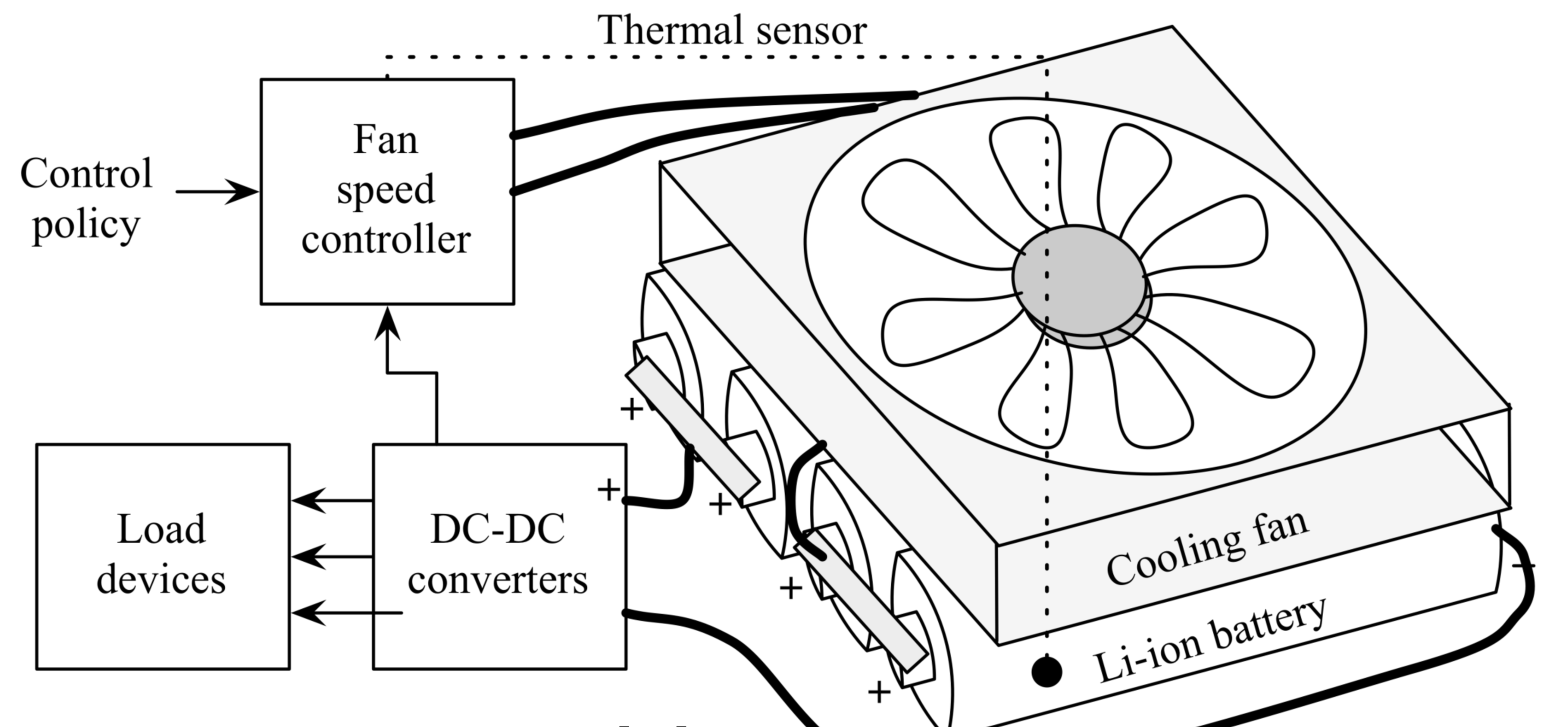
$$mC_p \frac{dT}{dt} = -\frac{(T - T_{amb})}{R_{th}} + Q_s + Q_p,$$

- Temperature variation in a discharge process (Figure C).

Proposed Cooling Mechanism

Apply an active cooling device, e.g., a cooling fan, together with the battery pack in portable system, as shown in Figure A.

- The cooling fan is also powered by the batteries.
- How to determine the fan status, i.e., on/off and speed, according to battery temperature, load demand and *state of charge* (SoC), in order to maximize the *Cumulative Workload* completed by the system.



(A)

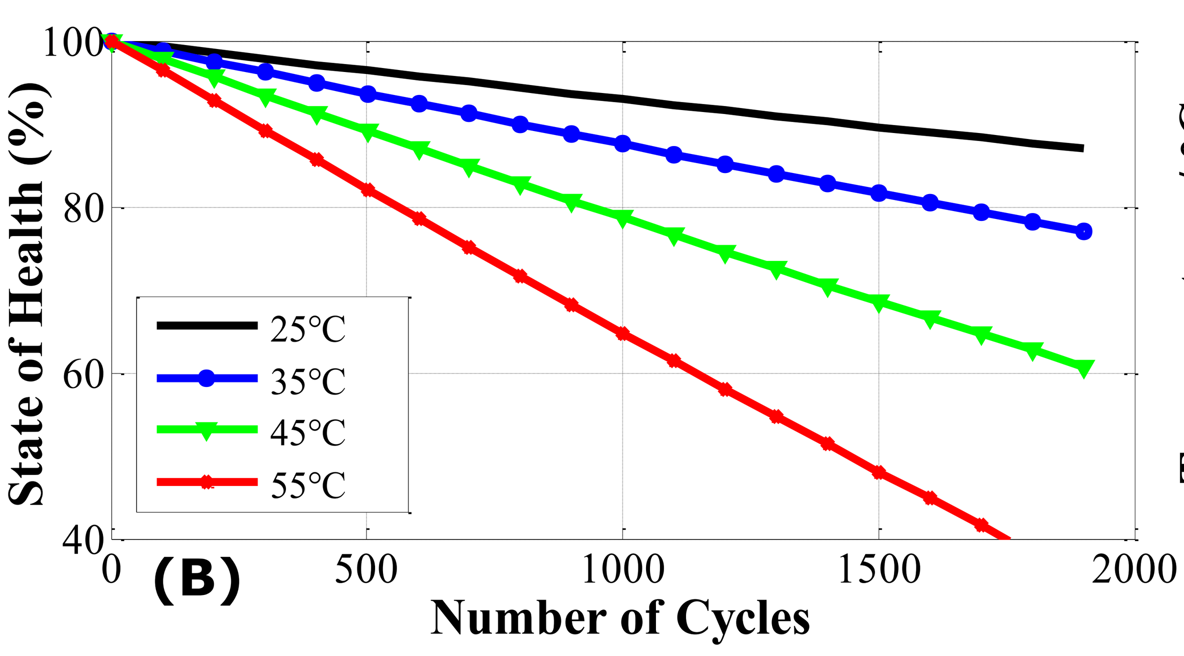
Forced Convection Cooling

Thermal Resistance:

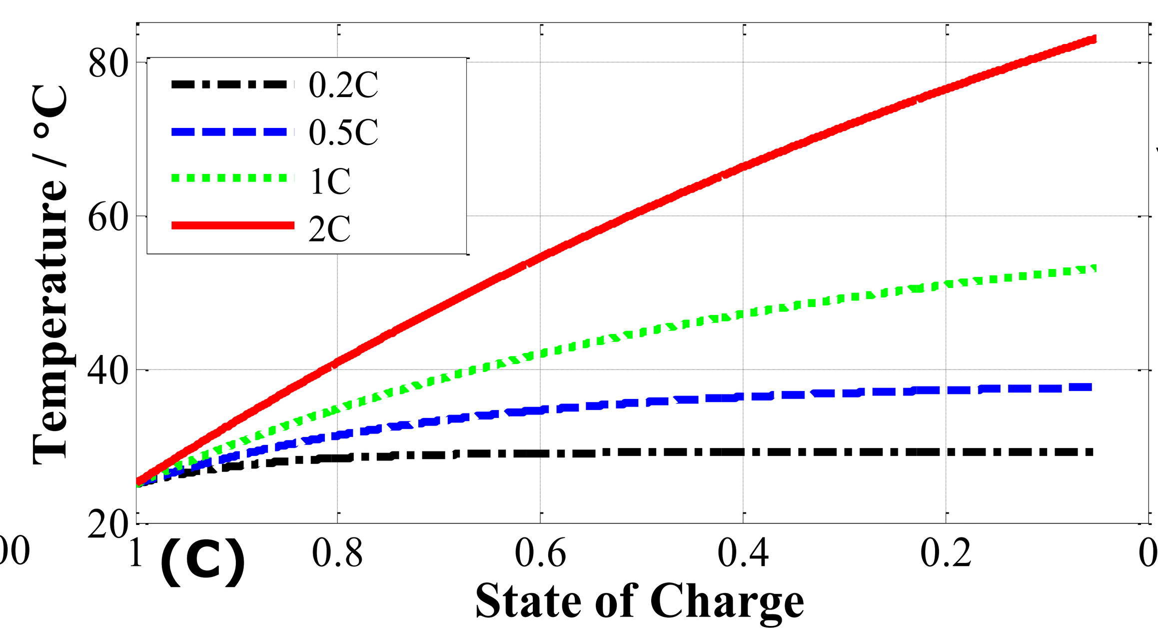
- *Natural thermal resistor* in parallel with *forced convection thermal resistor*, which depends on the specific heat capacity c_{ap} and flow rate of media m.

$$R_{th} = \frac{1}{hA_{eff}} \, || \, \frac{1}{2\dot{m}c_{ap}},$$

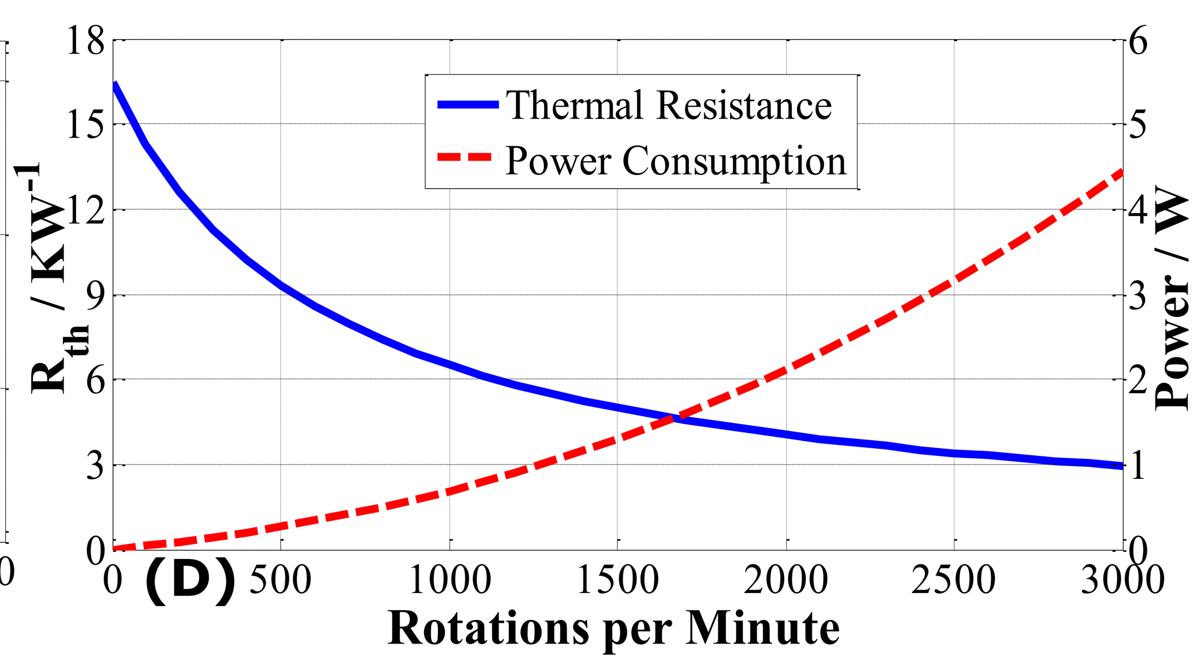
- Simulated thermal resistance and power consumption vs. fan speed levels (Figure D).



(B)



(C)



(D)

Proposed Algorithm

Objective Function:

- ***Cumulative Workload Completion (CWC)*** – *total* energy requested by the load devices at downstream of power converter over the designed system lifetime T_{dsl}.

Hierarchical Algorithm – Upper Level

- Given a designed system lifetime T_{dsl}, determine the optimal SoH degradation for each cycle (or equivalent, day) to maximize the CWC.
- Dynamic Programming: construct matrix *W(n,m)*, where each element implies maximum workload completed by the system after *n* cycles with SoH degradation of ΔL_m.

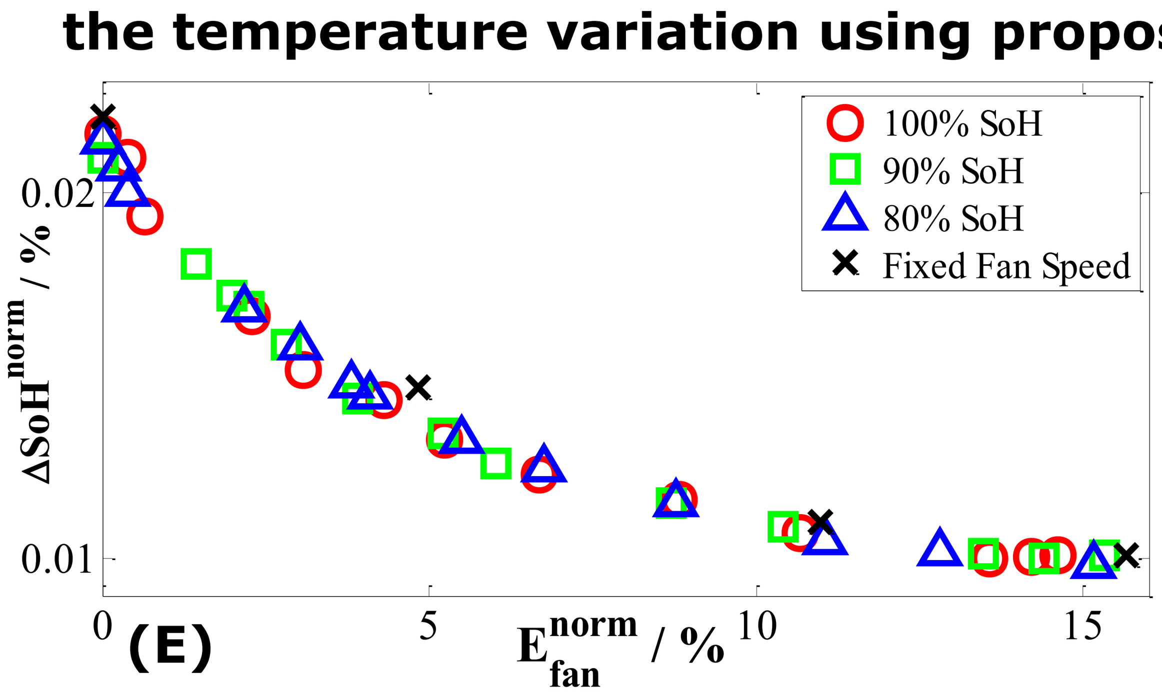
Hierarchical Algorithm – Lower Level

- Given a fixed amount of SoH degradation, determine the optimal cooling strategy considering battery SoC, temperature and load demand intensity.
- Reinforcement Learning:
  - Action set: *K* fan speed levels, [F_1, F_2, …, F_K].
  - State set: {*T*}X{*SoC*}X{P_{load}}, with quantized temperature levels {*T*}, SoC levels {*SoC*}, and load demand levels {P_{load}}.
  - Penalty function (*both terms following are normalized):

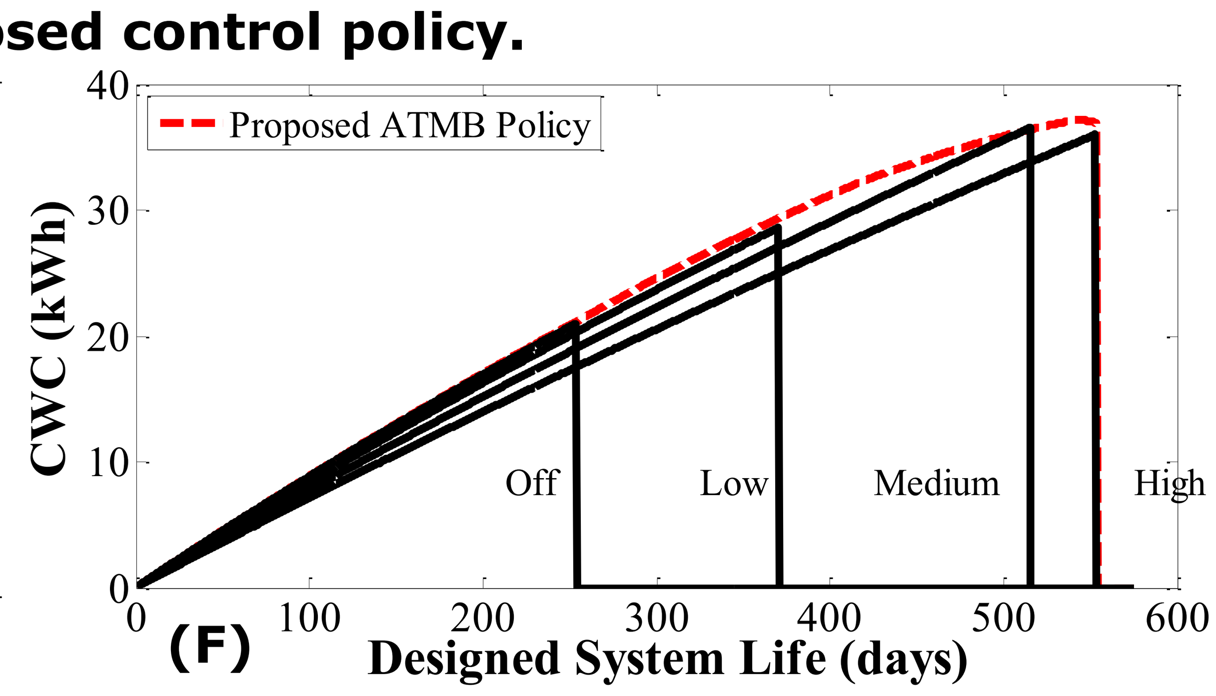
$$\lambda \cdot (\text{fan power usage}) + (1-\lambda) \cdot (\text{SoH degradation})$$

Simulation Results

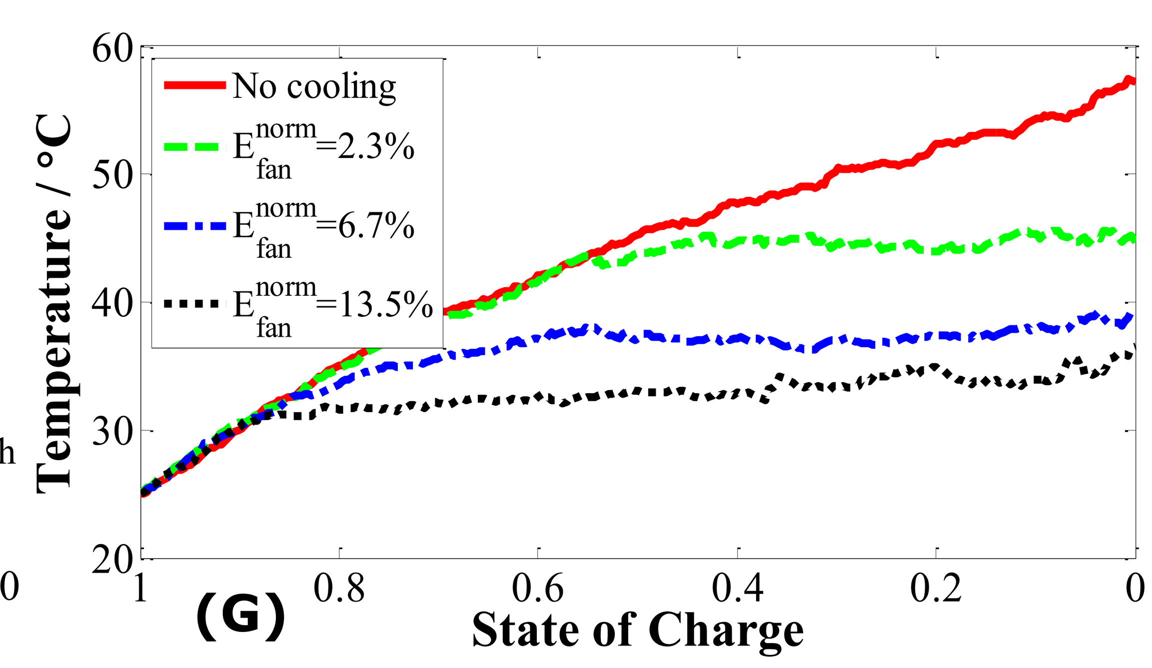
- We achieved better trade-off options (Figure E), improved the total CWC by up to 2.08X (Figure F). Figure G shows the temperature variation using proposed control policy.



(E)



(F)



(G)