Some challenges in modelling reliability of battery packs

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Outline

Problem description

Reliability modelling

Questions

Problem description: aim

Batteries

- compact way of storing energy
- extremely fast response times
- large scale production readily available
- expensive

Novel applications for batteries

- automotive (already in use, large expansion expected)
- grid-scale (experimental stage)

cost-effective design and maintenance of huge battery packs?

Problem description: designs

Notation

$$c_i = \text{capacity of cell } i$$
$$c = \text{system capacity}$$

Naive design

- all batteries in series
- only capacity of worst battery is available to all batteries

$$c = n \min_{i=1}^{n} c_i \tag{1}$$

- stupendously bad for large n
- requires substantially over-designed system
- enormous wastage of capacity, obviously bad use of material

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Problem description: designs

Power electronic design

- designed at Oxford by Dan Rogers [1]
- surrounds cells by clever power electronics which aims to extract their full capacity

$$c = \sum_{i=1}^{n} c_i \tag{2}$$

- electronics is expensive and can fail
- possibly not effective to use electronics for each individual cell

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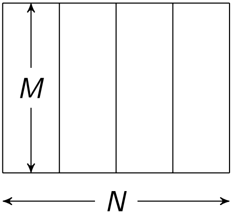
Problem description: designs

Flexible design

- organise batteries into N modules each containing M individual cells in series



- surround modules by power electronics

$$c = \sum_{i=1}^{N} M \min_{j=1}^{M} c_{ij} \tag{3}$$

- what is a good balance of N and M?
- how should the batteries be arranged?

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Reliability modelling: single cell

Simple model

$$C_{ij}(t) = [c_{ij}(0) - D_{ij}t]E_{ij}(t) \tag{4}$$

- $c_{ij}(0)$ initial capacity, known
- D_{ij} degradation rate, unknown
- $E_{ij}(t)$ random jump from 1 to 0, unknown (E for explosion)

Notes

- not physics based
- average trend in time rather than detail in time
- assumes uniform load cycling
- for simplicity we set $E_{ij}(t) = 1$ for the time being
- we might measure $C_{ij}(t)$ at certain points in time

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Reliability modelling: full system

Full system model

$$C(t) = \sum_{i=1}^{N} M \min_{j=1}^{M} C_{ij}(t) = \sum_{i=1}^{N} M \min_{j=1}^{M} (c_{ij}(0) - D_{ij}t) \tag{5}$$

Reliability criterion

$$\underline{P}(C(\tau) \geq \gamma) \geq \alpha \tag{6}$$

system must have capacity of at least γ at end of life time τ
with a guaranteed lower probability of at least α

- lower probability: we may not know all distributions
- may assume D_{ij} are i.i.d. (tenuous?)
- choice of τ, γ, and α depends on application
- analytical expression for probability *if all* $c_{ij}(0)$*'s are identical*

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Reliability modelling: decision problem

find cheapest N, M, and arrangement of cells
subject to our reliability criterion

- arrangement of cells = huge combinatorial problem!
- because of min expression per module, $C(\tau)$ will be largest when

$$C_{i1}(\tau) \simeq C_{i2}(\tau) \simeq \cdots \simeq C_{iM}(\tau) \tag{7}$$

- $c_{ij}(0)$ identical does not guarantee $C_{ij}(\tau)$ identical
  especially if D_{ij} has large variability

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Reliability modelling: interval analysis

- assume $D_{ij} \leq d$, nothing else
- $\underline{P}(C(\tau) \geq \gamma)$ is either 0 or 1

$$C(\tau) \geq \gamma \tag{8}$$

$$\iff \sum_{i=1}^{N} M \min_{j=1}^{M} (c_{ij}(0) - D_{ij}\tau) \geq \gamma \tag{9}$$

$$\iff \sum_{i=1}^{N} M \min_{j=1}^{M} (c_{ij}(0) - d\tau) \geq \gamma \tag{10}$$

$$\iff \sum_{i=1}^{N} M \min_{j=1}^{M} c_{ij}(0) \geq \gamma + MNd\tau \tag{11}$$

- simple deterministic analysis

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- we may have data on degradation rate, so more general model for D_{ij}
- typical distribution of $c_{ij}(0)$ in production?
- τ typically many factors larger than standard testing time
- theoretical question: can we evaluate

$$\overline{P}\left(\sum_{i=1}^{n}\min_{j=1}^{m}[x_{ij}+Y_{ij}]\right) \tag{12}$$

where x_{ij} is known and Y_{ij} are i.i.d. according to some imprecise probability model (say, independent natural extension)?

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Thank you!

Selected Publications I

[1] E. Chatzinikolaou and D. J. Rogers.
Cell soc balancing using a cascaded full-bridge multilevel converter in battery energy storage systems.
IEEE Transactions on Industrial Electronics, 63(9):5394–5402, September 2016.
doi:10.1109/TIE.2016.2565463.