On the Impact of Storage in Residential Power Distribution Systems

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A power distribution network consists of:

- Homes with stochastic electricity demand
- Shared lines, transformers, and storage (installed at different levels)

A certain level of “reliability” is guaranteed
Reliability of the grid

• Loss of load probability is one measure of reliability
• Loss of load *may* happen when a transformer is *overloaded*
Outline

• Introduction
• Background
• Upper bounds on the content of storage
  – Deterministic
  – Stochastic
• Load modelling
• Experimental Results
• Related work
• Conclusion
Motivation

- Electric utilities will install storage in power distribution and transmission networks to
  - Enhance DG integration
  - Reduce the peak demand
  - Defer system upgrade
  - ...

- Its impact on the distribution network is not well-studied
  - How it affects the loading of neighbourhood pole-top transformers
  - How much it can reduce the aggregate peak demand
Transformer upgrade

• A transformer is overloaded when the load supplied by it is higher than its nameplate rating
  – An overloaded transformer may overheat and fail
  – This decreases reliability of the grid

• Even low levels of EV adoption may increase the number of overloaded transformers depending on their charging strategies

• Distribution system upgrade is unaffordably expensive
Transformer and storage

• Storage can partially supply the demand when the transformer is overloaded
  – Smoothing the demand curve

• Instead of sizing a pole-top transformer for the peak, it can be sized closer to the long-term average demand of the neighbourhood
  – The same reliability level is maintained
  – Transformer upgrade can be deferred

• A trade-off between the transformer size and the storage capacity
Contributions

• We present a theoretical foundation for joint sizing of storage and transformers

• We demonstrate how to map electricity demand to the standard dual leaky-bucket parameters

• We present a joint sizing guideline in a residential neighbourhood and show the impact of the aggregate load parameters on this guideline
Background

- Equivalence Theorem
- The buffer/bandwidth trade-off
Observations:

- Storage is a buffer
- A transformer charges storage as traffic sources fill the buffer
- Loads discharge storage as a router empties the buffer
- The loss of load probability is similar to the packet loss probability
A fluid queueing model can be associated to a radial power distribution network

- A fluid queue with constant arrival rate and arbitrary service rate

- We want to quantify the buffer (storage) underflow probability in this model

- Unfortunately teletraffic analysis does not deal with this question
A dual queueing model

\[ \varepsilon: \text{storage underflow probability} \]

The Equivalence Theorem

buffer overflow probability \( \cong \varepsilon \)
A deterministic upper bound on the content of the store

- Arrival curve $A$
  - e.g., $A(s, t] = \max\{\pi(t - s), \rho(t - s) + \sigma\}$

- Service curve $D$
  - e.g., $D(s, t] = C(t - s)$
  Where $\rho < C < \pi$

- To guarantee no overloading
  $B \geq \sup_{s \leq t}\{A(s, t] - D(s, t]\}$
A probabilistic upper bound

- Loss probability in a finite queueing system (with capacity B) can be approximated with the probability of up-crossing the level B in an infinite queueing system (under some conditions) \(^\dagger\)

- Upper bound on the stationary probability of crossing level B in an infinite capacity queueing system\(^*\)

\[
- \mathbb{P}(Q(0) \geq B) = \frac{\sigma - \frac{\pi - \rho}{\pi - C} B}{\frac{\pi - C}{\rho}} \sigma \geq B, \quad \rho < C < \pi, \quad \frac{\pi - C}{\pi - \rho} \sigma \geq B
\]


\(^*\)G. Kesidis and T. Konstantopoulos. “Extremal shape-controlled traffic patterns in high-speed
Admissible region

Admissible region for a given reliability requirement $\varepsilon$:

$$Admissible\ region = \{(B,S) | B \geq \frac{\sigma(1 - \varepsilon \frac{sf}{\rho})}{\frac{\pi - \rho}{\pi - sf} - \varepsilon}\}$$

**Definition:** $S(B)$ is the minimum transformer size such that $(B,S(B)) \in Admissible\ region$
Mapping electricity demand to the standard dual leaky-bucket parameters

• Utilities have a guideline to size transformers when it is not supplemented with storage (i.e., $S(0)$)

• We set:
  \[
  \pi = S(0)f \\
  \rho_1 = \overline{L}_{\text{peak day}} \\
  \rho_2 = \overline{L}_{\text{peak week}} \\
  \rho_3 = \overline{L}_{\text{peak month}} \\
  \sigma_1 = (\pi - \rho)T \\
  \sigma_2 = \{ \min B \mid (B, \rho/f) \in \text{Admissible region} \}
  \]

  3 estimators for $\rho$

  2 estimators for $\sigma$
Results

- **Measurement nodes**
  - Are installed at a residential neighbourhood consisting of 20 homes
  - Active power consumption of each home is measured every 6sec
  - The measurement period includes peak day, peak week, and peak month of year

- **Homes are classified into 4 classes**
  - Each class is associated with a unit value
  - Total unit value of the neighbourhood determines the transformer size ($S(0)=100\text{kVA}$ for this neighbourhood)

- The power factor is set to 0.95
Results
Related work

• Proving the Equivalence Theorem and showing its application in sizing distribution transformers\(^1\)

• Sizing storage for ‘demand response via quantity’ applications\(^2\)

• Joint sizing of storage and renewable energy sources\(^3\)


\(^{2}\) J.-Y. Le Boudec and D.-C. Tomozei. “A demand-response calculus with perfect batteries”. In WoNeCa, 2012.

Conclusions

• A theoretical foundation for joint sizing of transformers and storage is presented

• A mapping from electricity demand to standard dual leaky bucket parameters is proposed

• The impact of the aggregate load parameters on the sizing guideline is shown using 6 trade-off curves obtained for the same neighbourhood