On the Impact of Storage in Residential Power Distribution Systems

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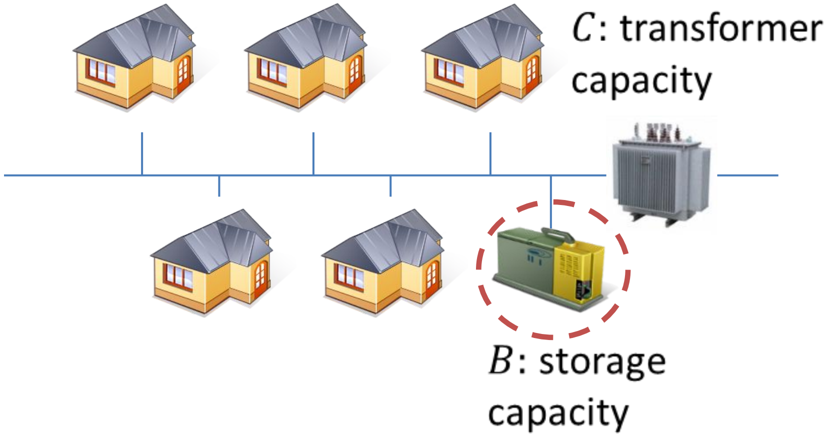
A power distribution network consists of:

- 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

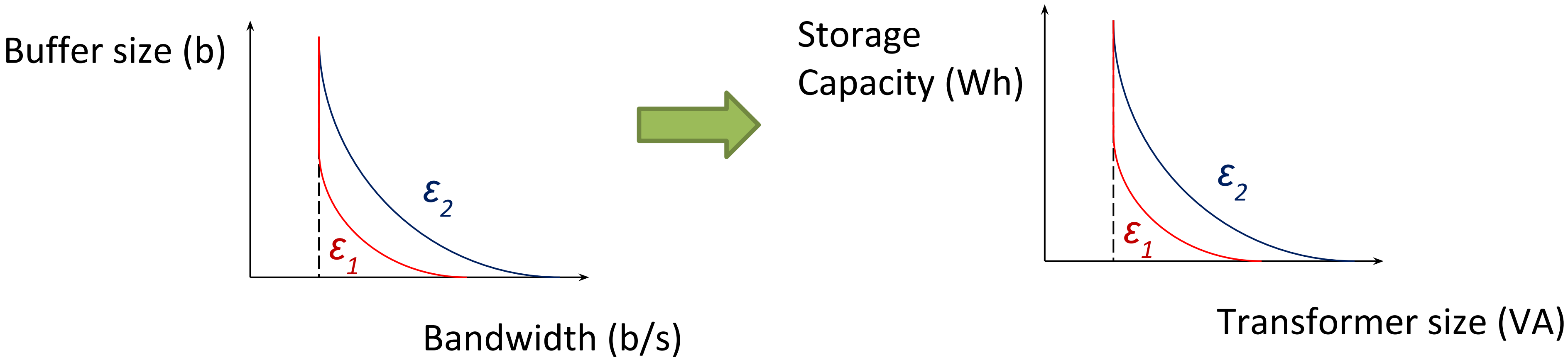
- Storage can partially supply the demand when the transformer is overloaded
  - Smoothing the demand curve
- Instead of sizing a pole-top transformer for the peak, it can be sized closer to the long-term average demand of the neighbourhood
  - The same reliability level is maintained
  - Transformer upgrade can be deferred
- A trade-off between the transformer size and the storage capacity

Contributions

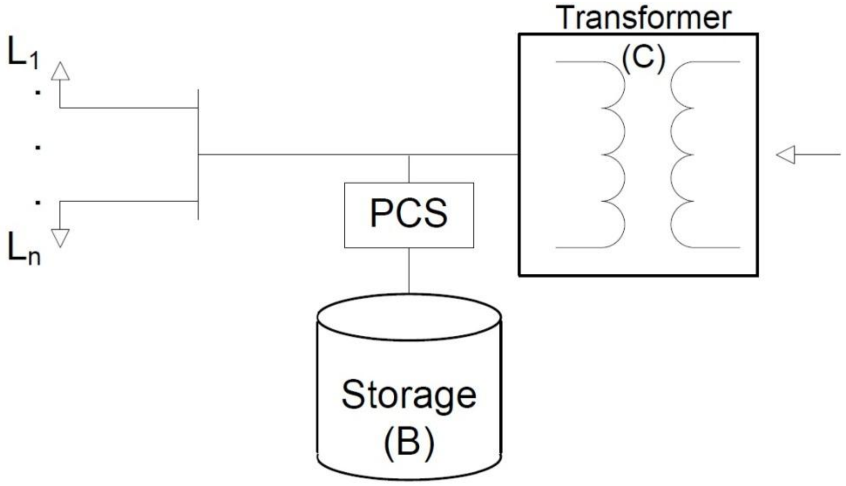
- We present a theoretical foundation for joint sizing of storage and transformers
- We demonstrate how to map electricity demand to the standard dual leaky-bucket parameters
- We present a joint sizing guideline in a residential neighbourhood and show the impact of the aggregate load parameters on this 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

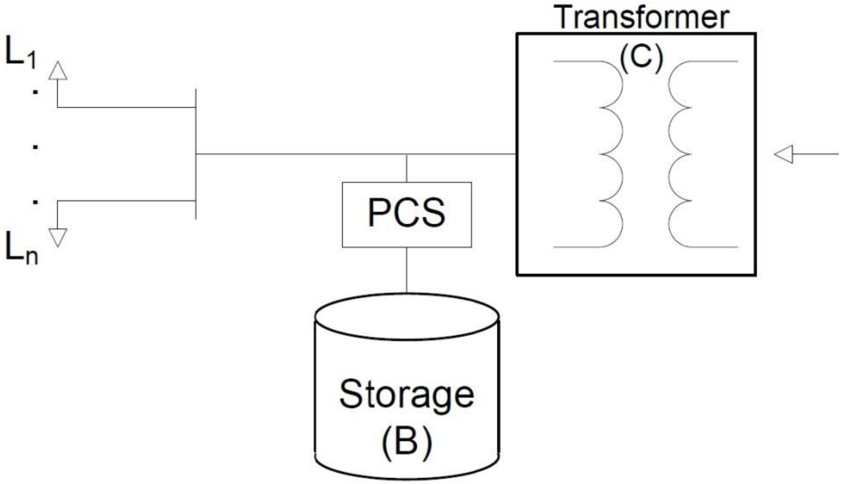
A fluid queueing model can be associated to a radial power distribution network

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

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

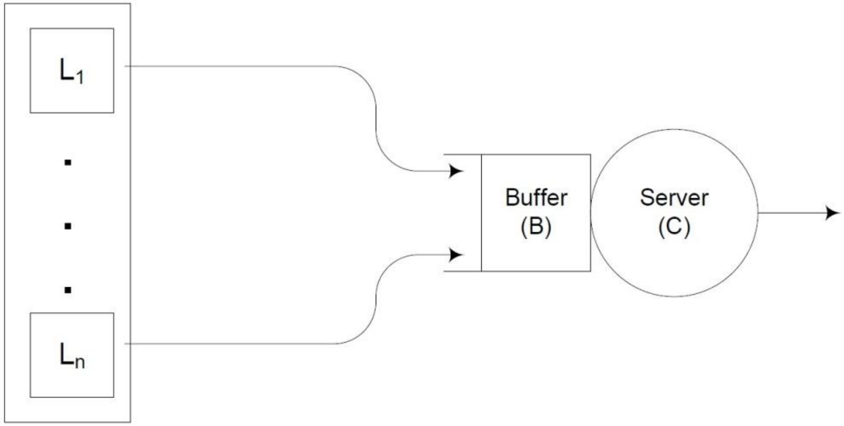
- Unfortunately teletraffic analysis does not deal with this question

A dual queueing model



ε: storage underflow probability

The Equivalence Theorem



buffer overflow probability $\cong \varepsilon$

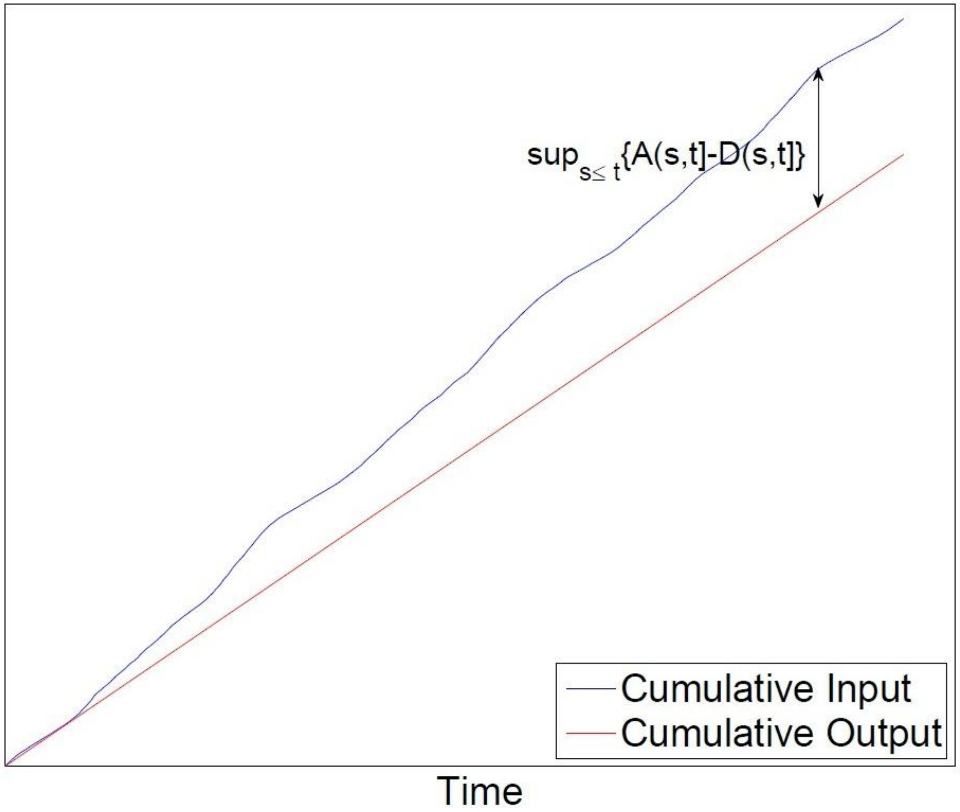
A deterministic upper bound on the content of the store

- 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) [†]

- Upper bound on the stationary probability of crossing level B in an infinite capacity queueing system[*]
  - $\mathbb{P}(Q(0) \geq B) = \dfrac{\sigma - \frac{\pi-\rho}{\pi-C}B}{\frac{C}{\rho}\sigma - B}, \quad \rho < C < \pi, \quad \dfrac{\pi-C}{\pi-\rho}\sigma \geq B$

[†] Y. Ying, F. Guillemin, R. Mazumdar, and C. Rosenberg. "Buffer overflow asymptotics for multiplexed regulated traffic". Performance Evaluation, 65:555-572, July 2008.

[*] G. Kesidis and T. Konstantopoulos. "Extremal shape-controlled traffic patterns in high-speed

Admissible region

- Admissible region for a given reliability requirement ε:

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

Definition: S(B) is the minimum transformer size such that (B,S(B)) ∈ $Admissible\ region$

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:

$$\pi = \mathrm{S(0)f}$$

$$\left.\begin{aligned} \rho_1 &= \bar{L}_{peak\ day} \\ \rho_2 &= \bar{L}_{peak\ week} \\ \rho_3 &= \bar{L}_{peak\ month} \end{aligned}\right\} \text{3 estimators for } \rho$$

$$\left.\begin{aligned} \sigma_1 &= (\pi - \rho)T \\ \sigma_2 &= \{\min B \mid (B, \rho/f) \in Admissible\ region\} \end{aligned}\right\} \text{2 estimators for } \sigma$$

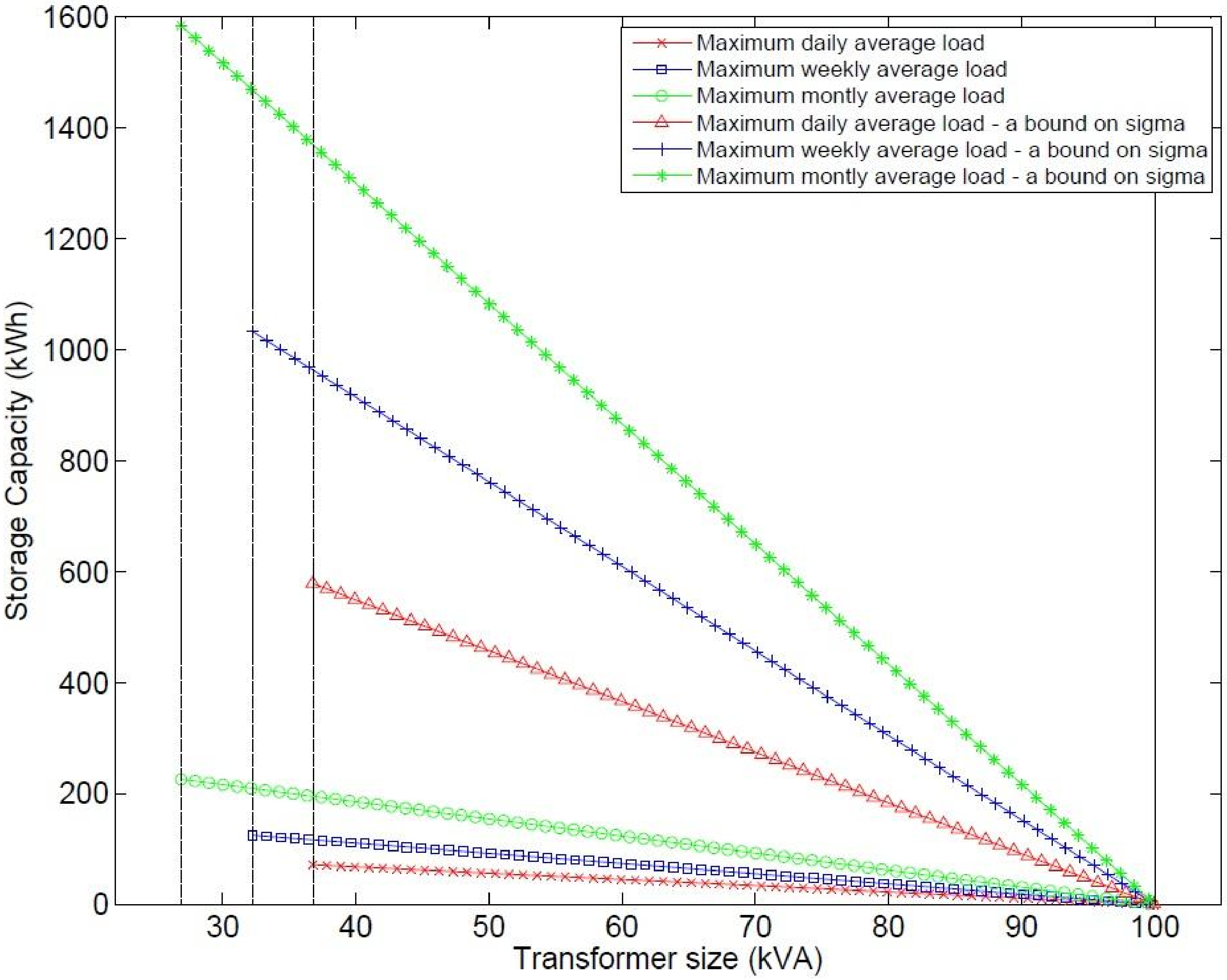
Results

- 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)=100kVA for this neighbourhood)

- The power factor is set to 0.95

Results



Maximum daily average load
Maximum weekly average load
Maximum montly average load
Maximum daily average load - a bound on sigma
Maximum weekly average load - a bound on sigma
Maximum montly average load - a bound on sigma
Storage Capacity (kWh)
1600
1400
1200
1000
800
600
400
200
0
30
40
50
60
70
80
90
100
Transformer size (kVA)

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]

[1] O. Ardakanian, S. Keshav, and C. Rosenberg. "On the use of teletraffic theory in power distribution systems". In Proc. e-Energy, May 2012.

[2] J.-Y. Le Boudec and D.-C. Tomozei. "A demand-response calculus with perfect batteries". In WoNeCa, 2012.

[3] K. Wang, S. Low, and C. Lin. "How stochastic network calculus concepts help green the power grid". In IEEE Smart Grid Communications 2011, pages 55-60, October 2011.

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