Safety-Assured Collaborative Load Management in Smart Grids

Anna Olkhovskaia

Introduction:

What is a smart grid?

- An electricity supply network that uses digital communication technology to detect and react to local changes in power usage
  - Detects power outages, energy demand, optimizes electrical power grid

What happens when the power grid gets overloaded?

- Load shedding occurs causing power outages and inconveniencing/ putting customers at risk

Proposition:

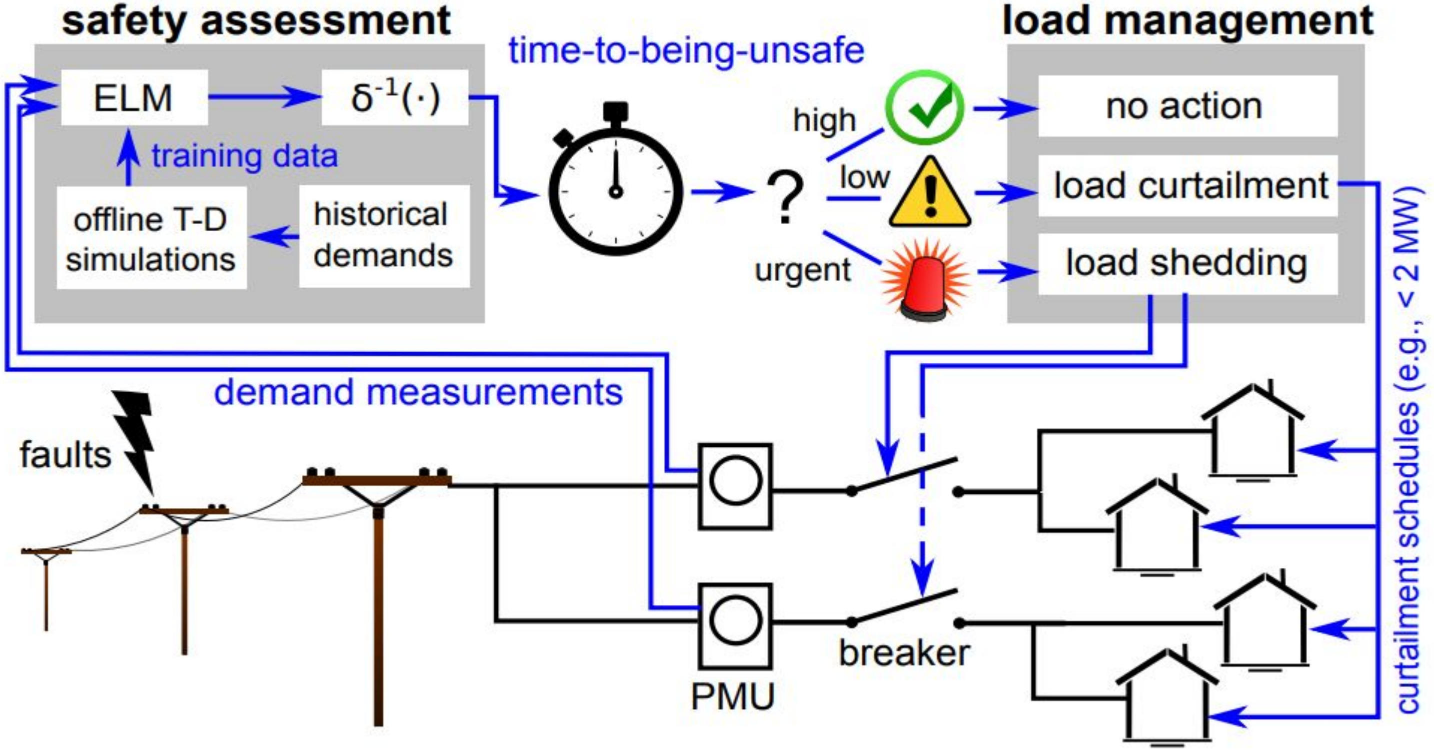
Two-phase load management scheme:

i) Giving the customers a chance to collaboratively reduce their energy demands so the grid can correct its supply while there are no immediate safety concerns

ii) Fall back on conventional load shedding in order to ensure safety once the grid enters a vulnerable state

Overview:

1) How the safety assessment works
2) Approach overview
3) Real Time safety measures; TTBU, design of ELM
4) The two-phase load management
5) Simulation results
6) Conclusion



safety assessment
ELM
δ-1(·)
training data
offline T-D simulations
historical demands
time-to-being-unsafe
high
low
urgent
?
load management
no action
load curtailment
load shedding
curtailment schedules (e.g., < 2 MW)
demand measurements
faults
PMU
breaker

Approach Overview

- Most current solutions use a centralized approach which is just load shedding
    - Unfair
    - Potentially hazardous
    - Uses a bipolar safety metric; either safe or unsafe

- The new approach would run side by side with existing technologies
    - When the TTBU drops below a certain threshold customers are given a chance to collaboratively fix the issue before the grid goes into an urgent state
    - ELM (extreme learning machine) calculates the TTBU according to current conditions

ELM:

- First the ELM is trained with offline simulations using historical data
- At runtime the ELM will calculate the TTBU using an algorithm
- It can be repeatedly invoked to assess candidate load management actions

Curtailment:

- An algorithm is used for the curtailment schedule
- A list of demand ceilings is computed for future time periods
- This lets customers collaboratively reduce the load
- This approach decentralizes the safety process

Downfalls:

- The curtailment schedules may not be realized because of limited customer involvement

Next Step:

- The system enters the already in-place load shedding phase
- Cuts off a subset of loads in order to prevent system failures and damage to infrastructure

Benefits:

- This approach runs side-by-side with existing technology
- This means the new programs can be introduced incrementally for selected subsets of customers

Time-to-Being-Unsafe:

Important Metrics:

L: (loading) demand vector at all load buses; indicates the level of stress imposed on a grid

- If the demand at each bus keeps growing the grid will at some point become unsafe

T: time to being unsafe

P: maximum amount of additional power each bus can draw without being classified as unsafe

$L \in R$ ^m ≥0 : this vector denotes the loading of a system with m buses

$\delta t0$ (Δt) = [δ1,t0 (Δt), δ2,t0 (Δt), . . . , δm,t0 (Δt)] :

- this calculates the ramp-up in demand of the buse i at time t0 + Δt
- t0 is any time instance
- Δt denotes the change in time

T : this factor exists when at time t0 + Δt with loading L + δt0 (Δt) if $\Delta t < T$ then the grid is considered safe

- If δi,t0 (Δt) is the max ramp-up in demand at each bus i
- Then T is the minimum remaining time before the grid with loading L at time t0
- T represents TTBU

P :

- We assume that each bus at any time t0 has the same max ramp-up function so under this simplification we can define P which is the maximum additional power that each bus can draw without being unsafe
- We define P as equal to δ(T)
- And as long as P is known we can take the inverse to calculate T = δ ^−1(P)

As long as an upper envelope is chosen for the ramp-up function δ(Δt), the resulting T will be a conservative estimate for the TTBU.

This is a general calculation and the safety assessment subsystem can be extended to admit a per-bus ramp-up function instead

Extreme Learning Machine:

The ELM is a single hidden layer feedforward neural network with a training algorithm much faster than conventional gradient based learning algorithms

- A feedforward neural network is where connections between the nodes do not form a cycle meaning the information moves in one direction only from the input to the output nodes

The design of the ELM focuses on the given input and produces one output generating a large number of data pairs <L,P>

Input: loading, L

Output: power distance to being unsafe, P

- The ELM is fed historic records of L from an operators database to train the ELM and generate a large amount of the <L,P> data pairs
    - In practice the ELM continually improves as more current load parameters become available
    - The measurements are collected using trusted metering devices such as PMU's in the grid core

- At run-time the ELM can quickly compute P and repeatedly look for the best control actions in real time to evaluate candidate actions
    - Since the computation is very high-speed the best control actions can be found in real time

- The system then uses P to quickly calculate T which is the min time to an unsafe state caused by any credible contingency

Practical Issues:

- If there is a planned change to the grid:
    - Ex: adding a transmission line or generator
    - The ELM will need to be retrained using new T-D simulations based on the new system model

- Multiple contingencies:
    - Ex: If the system wants to handle multiple contingencies at different locations
    - This can be fixed by using multiple ELM's in which each ELM is trained to find and address one safety criterion

Two-Phase load management:

Cycles:

- Safety assessment
- Load management

Two-phase load management:

- Load curtailment
- Load shedding

- Once T is known the system can determine the current phase and apply the appropriate management strategy
-
- The curtailment schedule at each at each bus is a list of suggested demand ceilings for several subsequent cycles
    - Furthermore demand ceilings can be further broken down into specific demand ceilings for individual customers

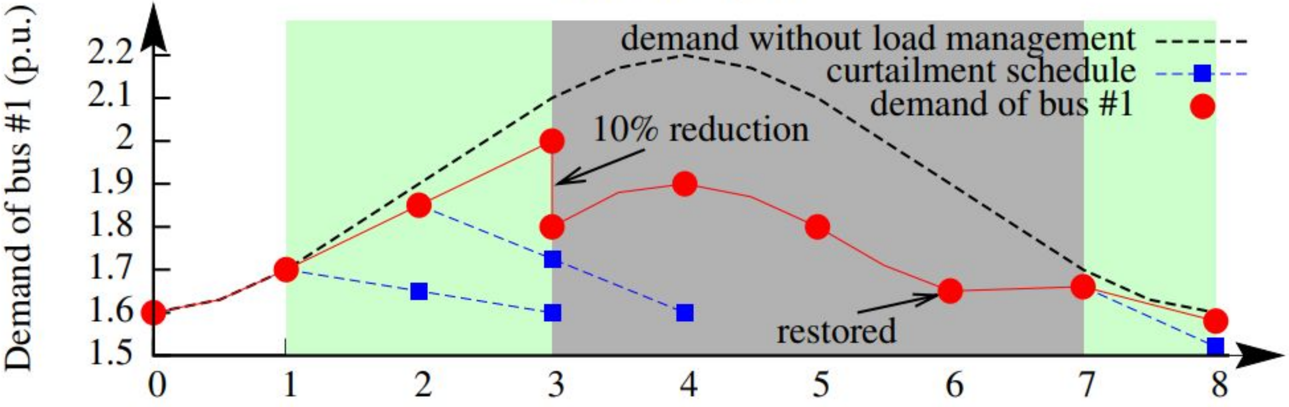
- The system enters and exits the curtailment phase by comparing T to thresholds:
    - Tw: warning threshold
    - Tr: restorative threshold
    - Te: emergent threshold

- Tw > Tr > Te

Cycle lengths should account for a tradeoff between:

1) The communication overhead of sending curtailment schedules to a large number of customers

2) Prediction accuracy, which typically degrades with longer cycles



(b) Time (cycle)

At time instant k = 0 as T > Tw the grid is safe

As k = 1 T drops below Tw and the the system enters a curtailment phase attempting to get T above Tw

At k = 3 T drops even lower now being below Te, the grid now enters an emergent condition, begins load shedding

At k = 7 the bus has been relieved from load shedding but since T is still under Tw the system goes back to the load curtailment phase

At k = 8 T is once again above Tw and no more management actions are needed

Curtailment Model:

- The operator of each bus i, maintains a curtailment schedule which is a FIFO queue of H demand ceilings
- It is represented by $S_i = [D_{i,1}, D_{i,2}, \cdots, D_{i,H}]$
  - $D_{i,1}$ is the oldest element and $D_{i,H}$ is the newest
  - H is the optimization horizon
- During the curtailment scheduling session the system computes the curtailment schedules and updates all elements in S_i
- After the session bus i uses $D_{i,1}$ as its demand ceiling
  - Ideally at the end of the cycle the demand of bus i is no higher than $D_{i,1}$
- The remaining elements are estimated demand ceilings for subsequent cycles
  - The bus can use these estimates to prepare for curtailments in the next cycle

Load Shedding:

- Load shedding is already a well-established technology in power grids
- The two thresholds Tr and Te serve as low and high watermarks
- If T is below Te a certain percentage of load at a selected bus is shed
- When T goes above Tr the previously disconnected load is restored
- When all previously disconnected loads have been restored the system leaves the load shedding phase
- Percentage of load shedding is based on:
    - The tolerable level of disturbance caused by disconnecting the load
    - Other constraints such as service agreements

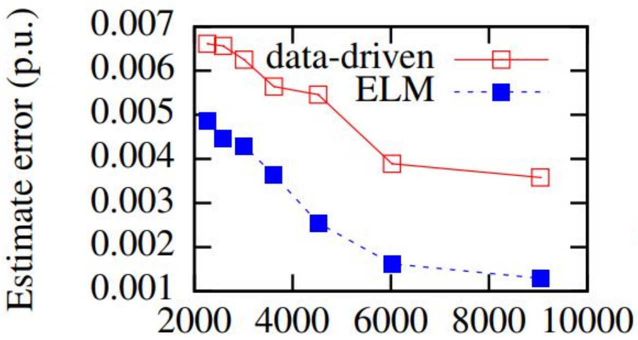
Things to consider:

- Te and Tr must guarantee that T will not reach 0
- Tw must be chosen to minimize the activations of load shedding
- Ultimately the effectiveness of load curtailment depends on the customers commitment to the schedule
- Tw can be adjusted depending on customer commitment levels
- At runtime the system should also update Tw periodically according to the observed commitment levels

Simulation Results:

All simulations are based on a 37-bus system

- When comparing the ELM approach to a baseline data-driven approach:
    - Baseline approach stores training data and finds data pair with L closest to input L
    - Both estimation errors decrease with training data
    - ELM is more accurate
    - Increase in data also increases delay in baseline approach



(a) Training data volume

based and data-driven safety assessments.

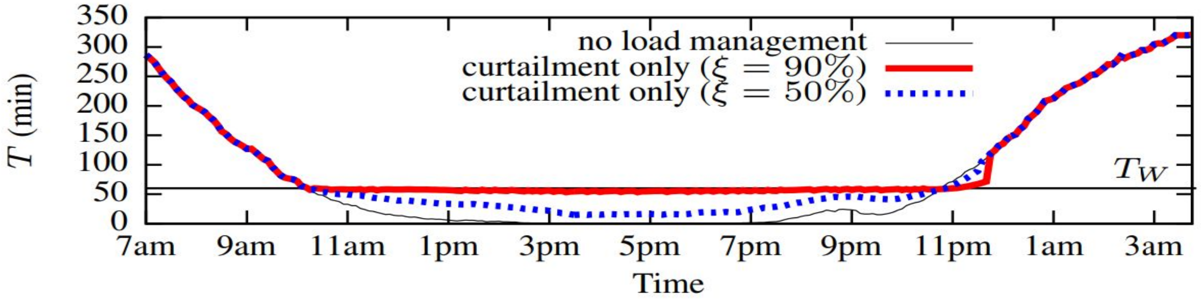


Figure 10: Peak hours of Aug 02, 2012 ($H = 3$).

This image shows the evolution of T during peak hours:

- With no load management the system is unsafe for 4 hours from 3-7pm (T=0)
- With load curtailment and a customer commitment of 50%, T does go below Tw but does not reach 0
- With load curtailment and a customer commitment of 90%, T is maintained around T
- If T is kept above Tw for a certain amount of time (0.5 hours) the system exits curtailment phase

Importance of customer commitment:

- With a low percentage of customer commitment prediction error significantly rises

- For a low commitment the demand ceiling for a cycle needs to be significantly changed due to the lowered prediction accuracy

- When a change needs to be made due to customer commitment it is referred to as a schedule revision
    - Schedule revisions decrease with commitment
    - When customers follow curtailment schedules their schedules change less in return
    - This helps mitigate the challenges of power consumption planning

Example:
- If Te is set to 10 minutes:
    - With a commitment level of:
        - 30% -> Tw = 90 mins
        - 60% -> Tw = 20 mins
        - 90% -> Tw = 13 mins

Conclusion:

- Instead of current load shedding scheme this article proposes a two-phase smart-grid load management scheme which switches between curtailment and conventional load shedding
- The switching is controlled by a safety metric called TTBU
- The grid is given a chance to correct its undersupply but relies heavily on user participation
  - Ex: With participation of 30% at most 8 buses need to be shed
    - With participation > 51% no buses need to shed their load
- If the grid cannot be successfully corrected the system falls back on conventional load shedding

Thank You For Listening

Any Questions?