Modelling and Control of Highly Distributed Loads

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Load modelling overview

• The behaviour of loads during large disturbances affects system transient response.
  – This is well known, and has been for a long time.
  – Many, many, many studies have been undertaken, and papers written, on estimating load-model parameters.

• Typical models are a composite representation of large numbers of diverse devices.
  – Loads are continually varying, so deterministic models can never be correct.
  – But stochastic models are inconsistent with traditional large-disturbance simulation techniques.
  – Computational challenge: assessing uncertainty in large-scale, nonlinear hybrid dynamical systems (e.g. power systems.)

• Loads that have high penetration (e.g. residential AC, power electronics, energy efficient lighting) can display synchronized behaviour in response to particular events.
Load control overview

- Non-disruptive load control is standard in communications so why not in electricity delivery.
- Load control offers enhanced system responsiveness at the local, regional and system-wide levels.
- There are many open questions on how to design controls that interact appropriately across these three levels, and with other controllable devices.
- Incorporating load control (and distributed generation) into load models is extremely challenging.
Traditional load modelling

- The WECC load model has around 120 parameters, all of which are unknown, and most of which are not identifiable.
- It was motivated by the desire to capture the effects of disparate types of loads.
- A particular driver was the phenomenon known as “Fault induced delayed voltage recovery” (FIDVR).
FIDVR

- FIDVR involves progressive stalling of residential ACs in response to a (seemingly) benign voltage dip.
- A spatially continuous PDE model of feeder dynamics has been developed to better understand the phenomenon.

From Duclut, Backhaus, Chertkov: Hysteresis, phase transitions, and dangerous transients in electrical power distribution systems.
PEV charging load

- The response of PEV chargers to power quality events is governed by SAE Standard J2894:
  - PEV chargers must remain energized if the supply voltage drops to 80% of nominal for up to 2 sec.
  - PEV chargers must ride through a complete loss of voltage for up to 12 cycles.
  - Nothing stated about situations where voltages sag below 80% but remain nonzero.

- Probability of PEV charger tripping was modelled by:

\[
P(\text{PEV trips during } T) = 1 - e^{-\lambda(\Delta V)T}, \quad \Delta V = 0.8 - V > 0
\]
Uncertainty in nonlinear hybrid dynamics

• Increasingly important to map parameter uncertainty along the trajectory.
  – Including uncertainty in communications latency.

Phase portrait

Time domain
Load control

- Competing objectives:
  - Local control objective, e.g.,
    - Maintain temperature close to setpoint.
    - Deliver required charge to PEV by specified time.
  - System service, e.g.,
    - Balance renewable generation output.

- Load control strategies must be consistent with the legacy system operating philosophy.
- Centralized control of large numbers of loads is impractical.
Electric vehicle charging

- Charging control strategies will be vitally important for ensuring large-scale adoption of plug-in EVs does not cause generation scheduling problems.

**MISO summer load demand**

**Time-based charging strategy**

- Total demand, including PEVs
- Underlying demand
Electric vehicle charging (continued)

- Price-based charging strategy: charge when price falls below a lower threshold, cease charging when price rises above an upper threshold.

![Graphs showing demand for different numbers of PEVs](image_url)
Decentralized control of PEVs

Theorem: A collection of charging strategies $u$ for an infinite population of PEVs is a Nash equilibrium, if (i) $u_n$ minimizes the cost function,

$$J_n(u_n; z) = \sum_{t \in T} \left( p_t(z_t)u_{nt} + \delta(u_{nt} - z_t)^2 \right) + h_n(|u_n|_1)$$

with respect to a fixed $z$, and (ii) $z_t = \bar{u}_t$, for all $t \in T$, i.e., $z$ can be reproduced by averaging the individual optimal control trajectories of all PEV agents.

Under certain mild assumptions, the Nash equilibrium:
- Exists and is unique.
- Can be obtained by a convergent iterative process.
- Satisfies a “valley filling” property which gives globally optimal cost.
Undamped interactions between PEVs

- If the damping term $\delta$ is zero:
Decentralized charging control

- Damping $\delta$ is a small positive value:
Hysteresis-based load control: residential air conditioning

- Steady-state temperature distribution for 10,000 cooling loads.
- Temperature behaviour modelled according to:
  \[ \theta_{n+1} = a\theta_n + (1-a)(\theta_{amb} - m_nK) + w_n \]

- Regions:
  - ‘a’ contains only loads in the off state.
  - ‘b’ contains loads in both the on and off state.
  - ‘c’ contains only loads in the on state.

- Control strategy:
  - Increase load by lowering setpoint.
  - Decrease load by raising setpoint.

From Callaway: Tapping the energy storage potential in electric loads.
Load control: tracking wind variations

- Controlling 60,000 AC loads to follow wind variations.

From Callaway: Tapping the energy storage potential in electric loads.
Hysteresis-based control of PEV load

- Hysteresis-based load control can be extended to loads that require a certain amount of energy, but have some flexibility in when they receive that energy.
  - PEV charging, refrigeration, dehumidifiers, pool pumps.

![PEV charging pattern](image1)

![Power consumption of 20,000 PEVs](image2)
PEV charging control: tracking

Tracking wind variability

- Actual state of charge
- Nominal state of charge
- Deadband
- Power consumption

Aggregate demand (kW)

Actual demand
Desired demand

Shift in deadband

Time (hr)

State of charge (kWh)

Time (min)
State-space modeling of hysteretic control

- State-space modelling results in a nonlinear hybrid dynamical system.
  - Nonlinear because states and inputs multiple together.
  - Hybrid due to the influence of rapidly changing inputs.

Period-3 orbit,
Input period = 15.6 min

Period-4 orbit,
Input period = 12.4 min
Distribution network overloads

• Plug-in electric vehicles:
  – Charging: 10-80 Ampères per PEV
  – Typical household connection 10-20A (@ 240V)
  – Scenario: *en masse* over-night charging

Uncoordinated PEV charging  
=  
distribution network overload!
Dynamical model of PEV charging

- SOC dynamics / charging of \( N \) vehicles
  \[ \dot{s}_n(t) = \tilde{\eta}_n p_n(t) = \tilde{\eta}_n V_{AC} i_n(t) \]

- Aggregated current
  \[ i(t) := i_d(t) + \sum_{n \in N} i_n(t) \]

- Transformer temperature dynamics
  \[ \dot{T}(t) = \frac{1}{C} \left\{ R_c i^2(t) - \frac{T(t) - T_a(t)}{R} \right\} \]
Iterative, distributed solution

- Open-loop coordinated charging, driven by pseudo-price $\lambda^{(p)}$

PRICE MANAGER (subgradient step)

$$\lambda^{(p+1)} = \left[ \lambda^{(p)} + \alpha^{(p)} \left( \Phi \Delta T[0] + \Psi \left( \sum_{n \in \mathcal{N}} i^{(p)}_n \right) + \Psi_d \hat{d} - T_{\text{max}} \mathbf{1}_K \right) \right] +$$

PEV SCHEDULER (local optimization)

$$i^{(p)}_n = \arg \min_{i_n \in \Pi_n \left( s_n[0] \right)} \hat{J}_n(i_n) + (\lambda^{(p)})^\top \Psi i_n, \quad n \in \mathcal{N}$$

Centralized solution is recovered for $p \to \infty$
Case study: temp and load profiles

Temperature within limits, despite 5% inaccuracy in background load
Wireless testbed for PEV charging algorithms

• A testbed has been developed to investigate PEV charging control algorithms.
• Each charger communicates with each other and a “transformer” using a Zigbee wireless mesh network.
Conclusions

• Modelling of load behaviour has always been challenging.
  – This is further complicated by synchronizing events driven by a high penetration of similar devices.
  – Distributed generation and controllable loads provide other nontrivial complications.

• Significant actuation can be achieved through coordinated non-disruptive control of highly distributed loads.
  – Technical issues: control structure, nonlinearity (bifurcations), latency, interoperability, data security, …
  – Social issues: incentives for consumers to participate in (non-disruptive) fast-acting, demand response schemes.
Primary references


