Network-aware Demand Response in the Presence of Uncertainties

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Outline

- Introduction
- Motivations
- Objectives
- Main Contributions
- Conclusions
- Publications

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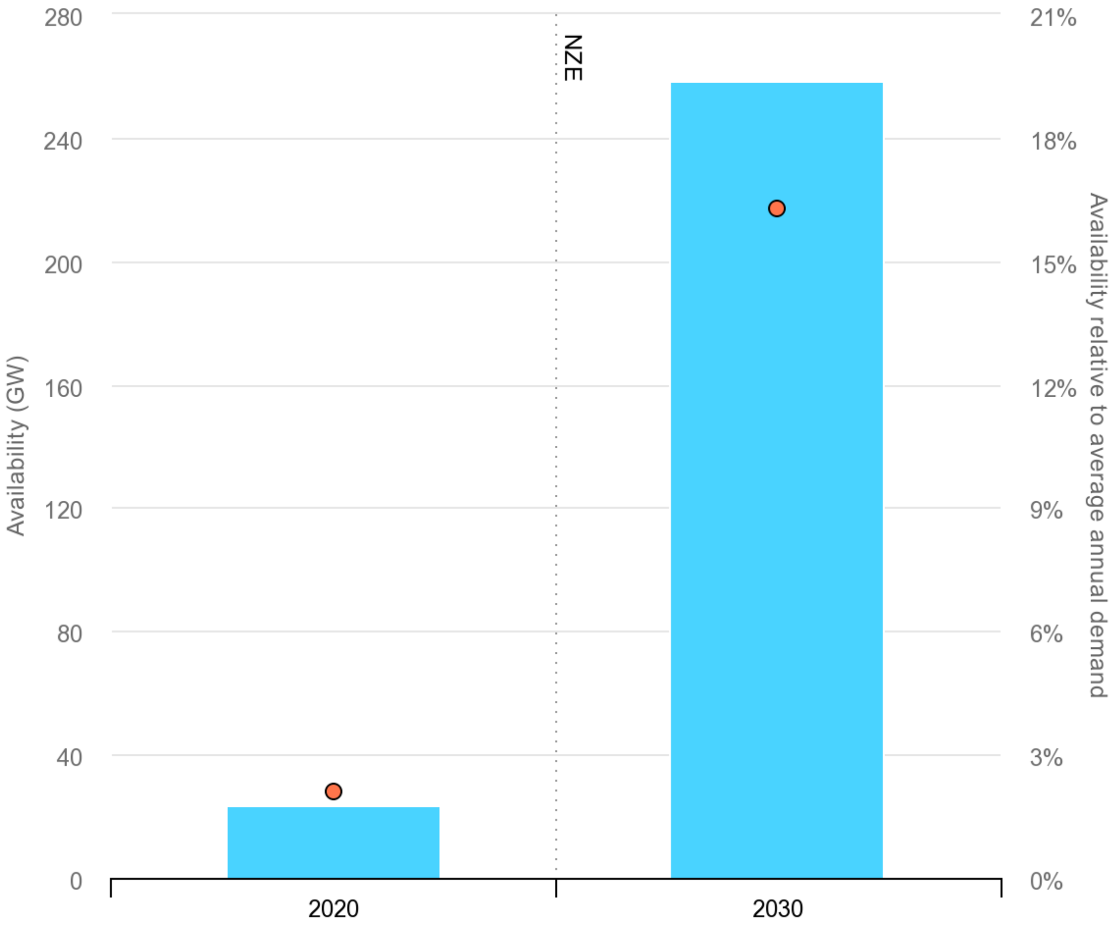
Demand Response



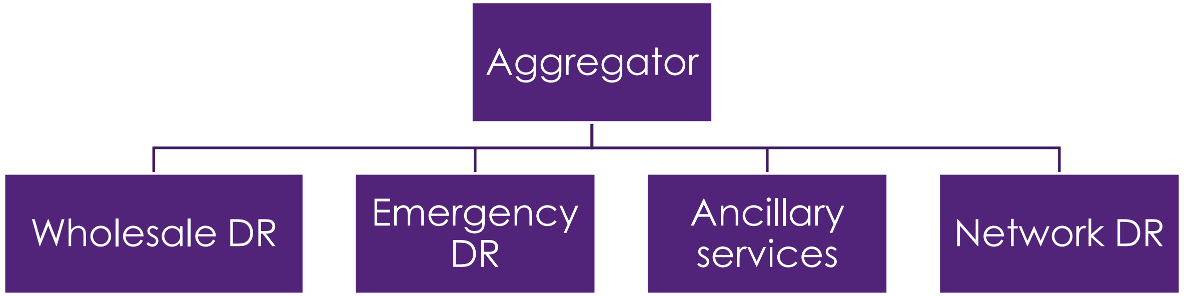
Demand response availability at times of highest flexibility needs and share in total flexibility provision

Consumer-centric approach

Changes in electricity usage from nominal consumption in response to:

- Price signal
- Incentive payment

For power markets,



Aggregator

Wholesale DR

Emergency DR

Ancillary services

Network DR

https://www.iea.org/data-and-statistics/charts/demand-response-availability-at-times-of-highest-flexibility-needs-and-share-in-total-flexibility-provision-in-the-net-zero-scenario-2020-and-2030, IEA.

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Motivations

Problem 1

Aggregator

Ancillary services

Emergency DR

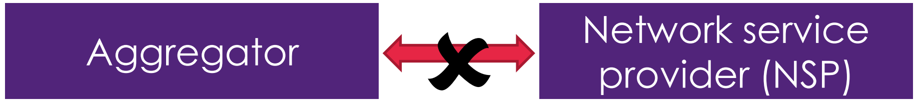
If bids cleared,
<u>commitment is mandatory</u>

Non-compliance →

Presence of uncertainties ???

DR aggregator is no longer able to deliver contracted demand in real-time

Problem 2



Aggregator

Network service provider (NSP)

No knowledge of the network

Only knows network information

No proper coordination between Aggregator and NSP

If households export PV to the grid on top of DR

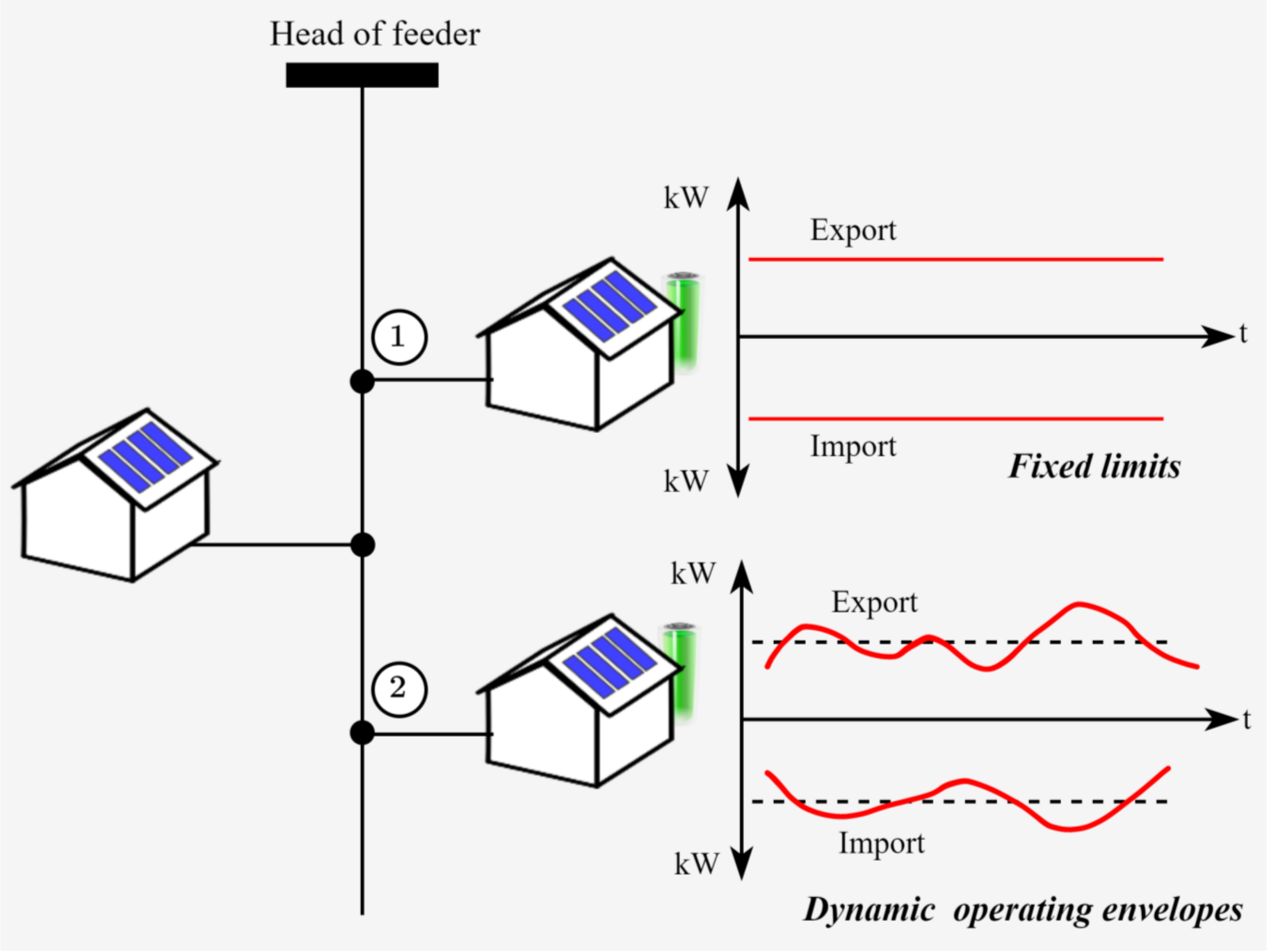
↓

Over-voltage issues and thermal overloading are inevitable

Network-agnostic DR schemes lead to network technical limit violations!

Network-aware DR schemes that account for uncertainties are vital for real-world implementation

Dynamic operating envelopes (DOE)



"Operating envelopes vary import and export limits over time and location based on the available capacity of the local network or power system as a whole." [1]

More emphasis on DOE for export power management

How feasible is it to adopt the DOE framework for DR applications?

[1] Dynamic Operating Envelopes Working Group, "Outcomes Report." Mar. 2022, [Online]. Available: https://arena.gov.au/assets/2022/03/dynamic-operating-envelope-working-group-outcomes-report.pdf.

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- Future Work
- Thesis timeline
- Publications

1. **To develop control strategies for residential DR to participate in grid services under uncertainties.**

2. **To propose techniques to establish dynamic operating envelopes in low-voltage distribution networks to ensure network integrity.**

3. **To develop network-aware control schemes for residential DR to participate in grid services under the dynamic operating envelopes framework.**

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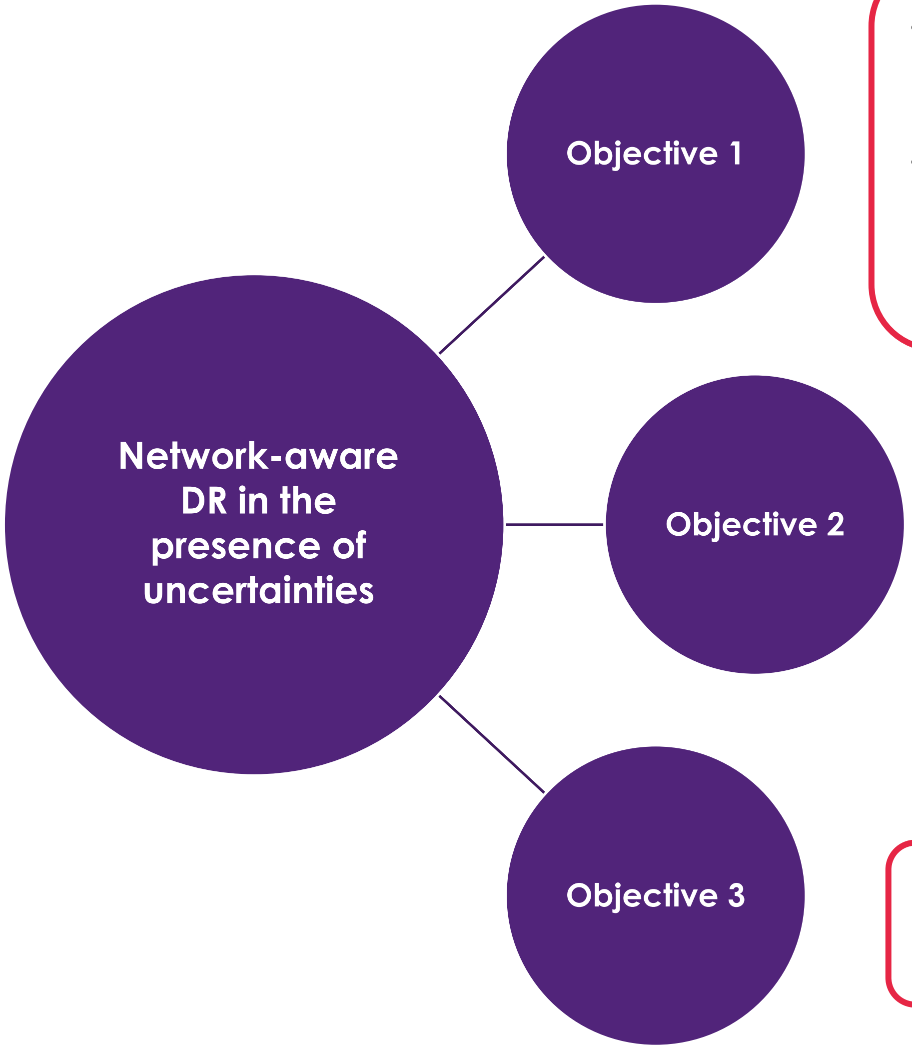


Network-aware DR in the presence of uncertainties

Objective 1

- Centralised control schemes for residential DR to participate in grid services under uncertainties
- Distributed control frameworks for an aggregator to provide DR in real-time markets under uncertainties

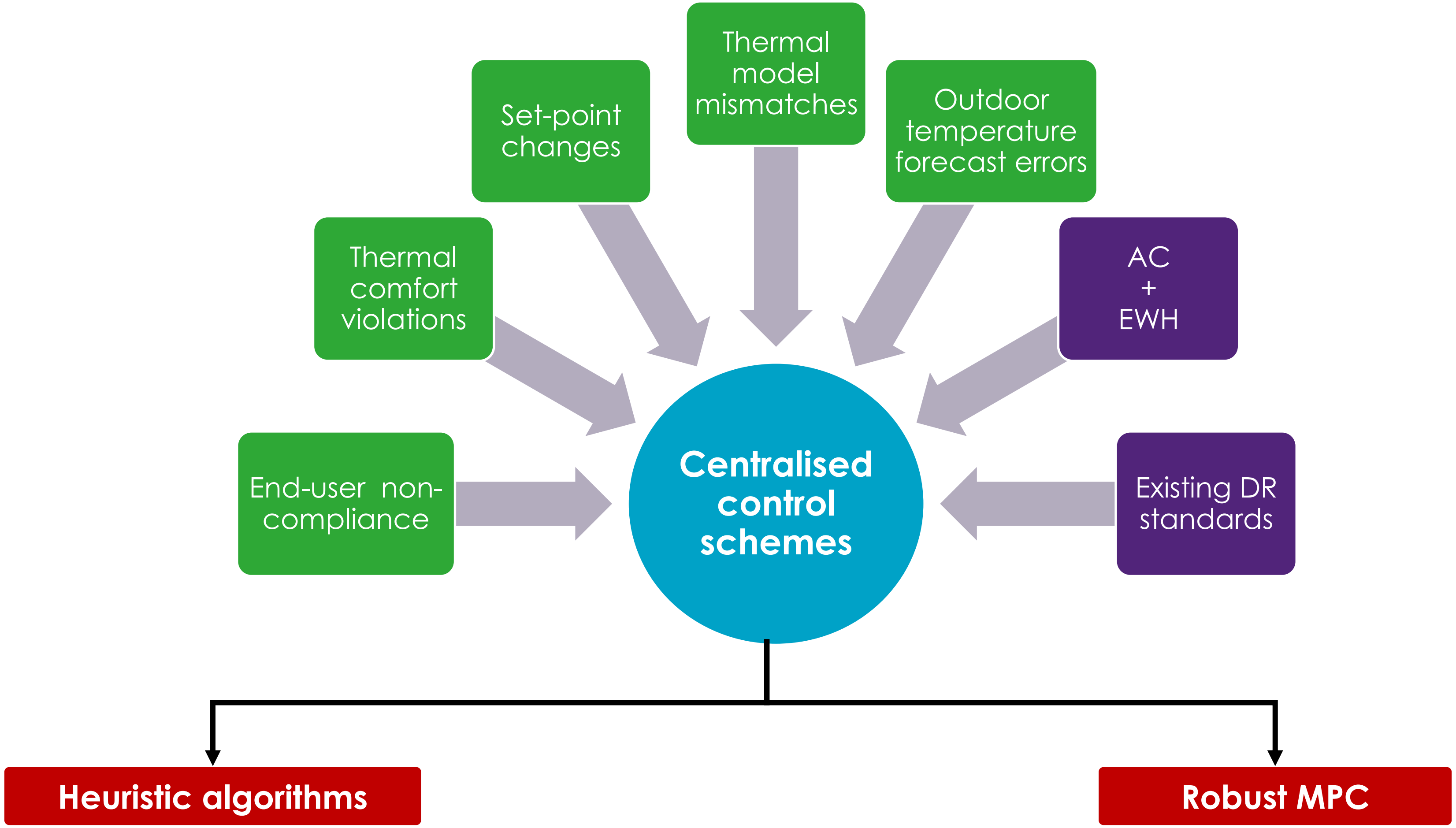
Objective 2

- Techniques to establish dynamic operating envelopes in low-voltage distribution networks

Objective 3

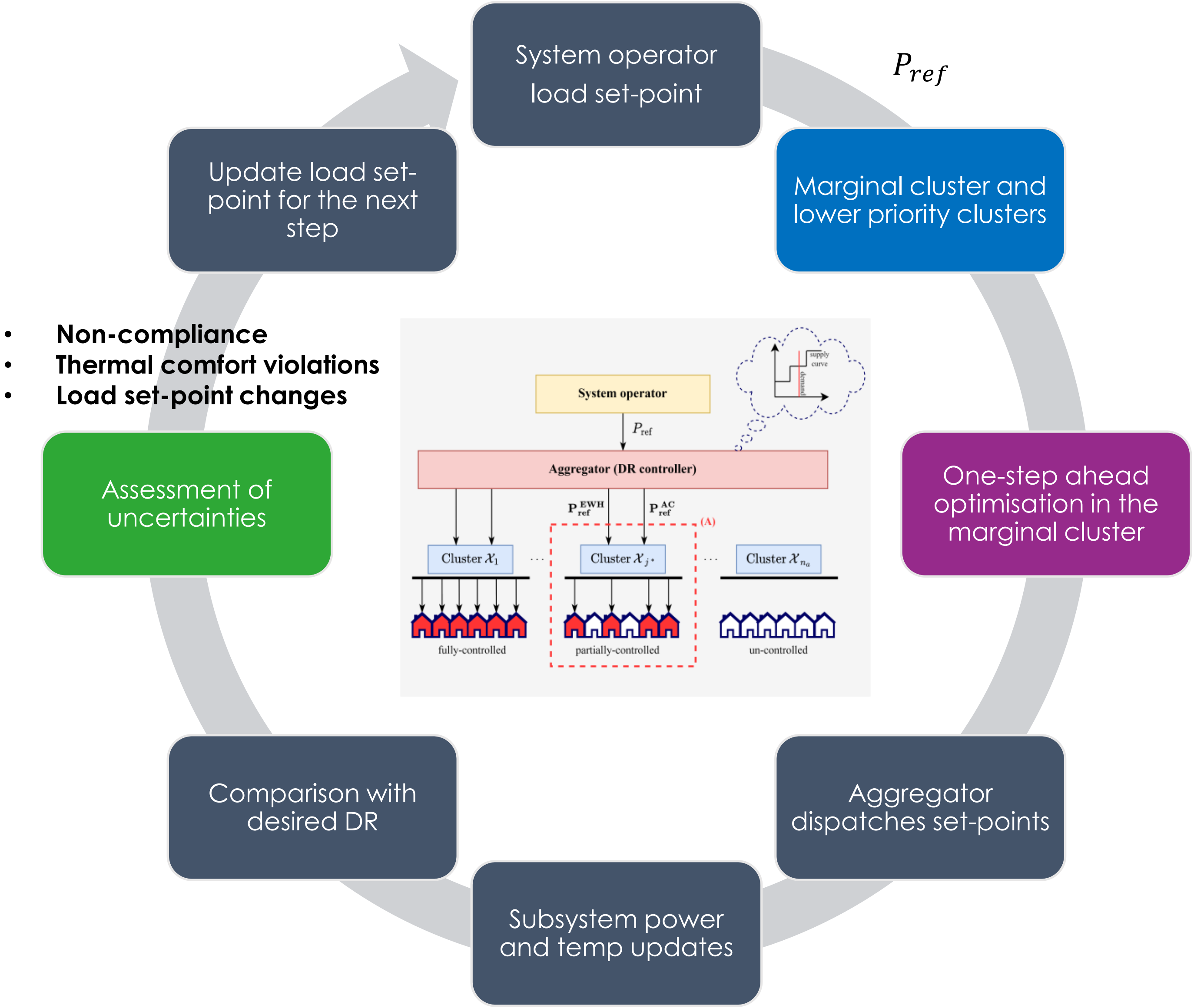
- A coordinated control scheme for dynamic operating envelopes-enabled demand response in low-voltage distribution networks

Contribution 1: Centralised control schemes for residential DR to participate in grid services under uncertainties



- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control algorithms to mitigate the effect of uncertainties in residential demand management," *Applied Energy (Elsevier)*, vol. 306, p. 117971, 2022, doi: 10.1016/j.apenergy.2021.117971.
- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "Control of Residential Air-conditioning Loads to Provide Regulation Services under Uncertainties," in *IEEE Power and Energy Society General Meeting*, 2021, vol. 2021-July, pp. 1–5, doi: 10.1109/PESGM46819.2021.9637890.

Approach: Heuristic scheme



System operator load set-point

P_{ref}

Marginal cluster and lower priority clusters

One-step ahead optimisation in the marginal cluster

Aggregator dispatches set-points

Subsystem power and temp updates

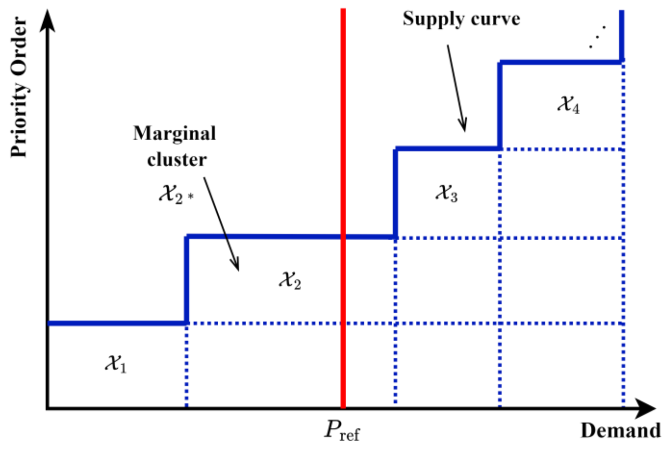
Comparison with desired DR

Assessment of uncertainties

- **Non-compliance**
- **Thermal comfort violations**
- **Load set-point changes**

Update load set-point for the next step

Conceptual priority-based ranking mechanism and supply curve emulation



One-step ahead optimisation

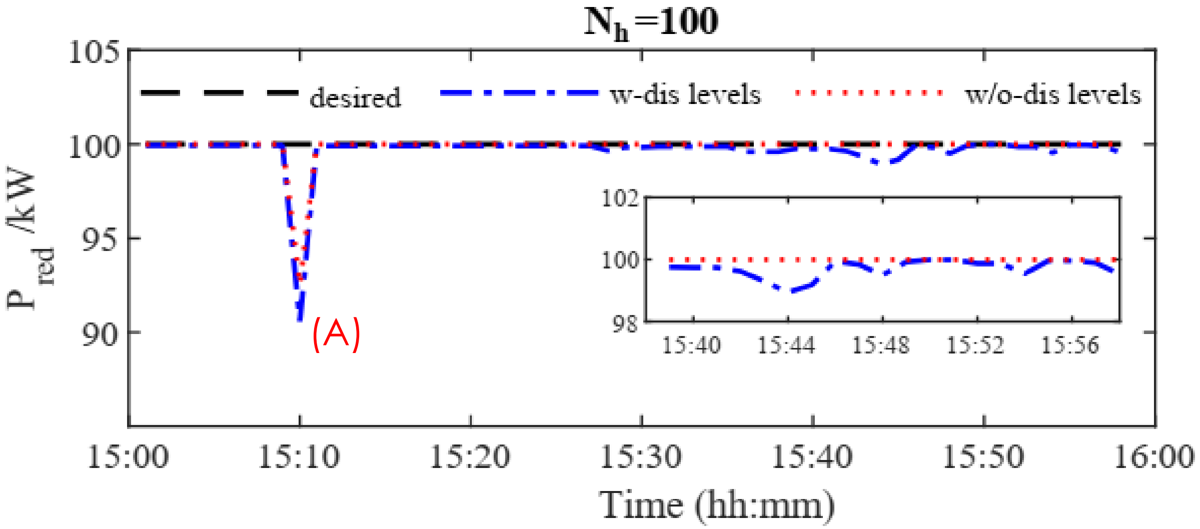
Min. (cost + thermal discomfort)

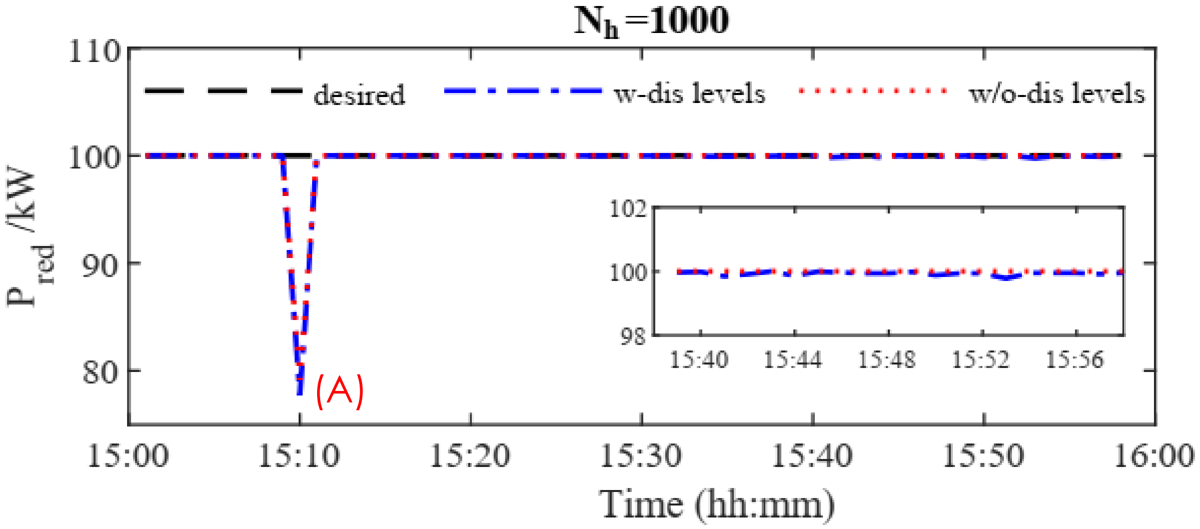
subject to:

Reference power tracking
AC and EWH power limits
DRM compliance

Results

customer override event (A)

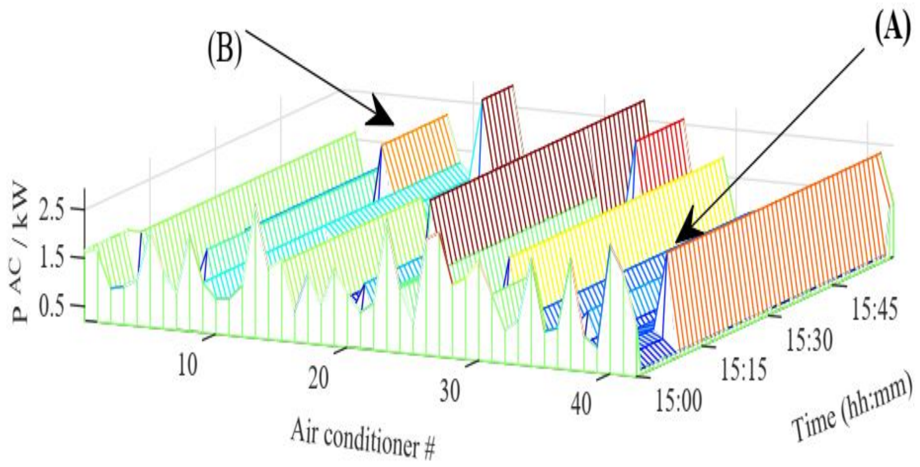




The tracking performance increases as the population size increases.

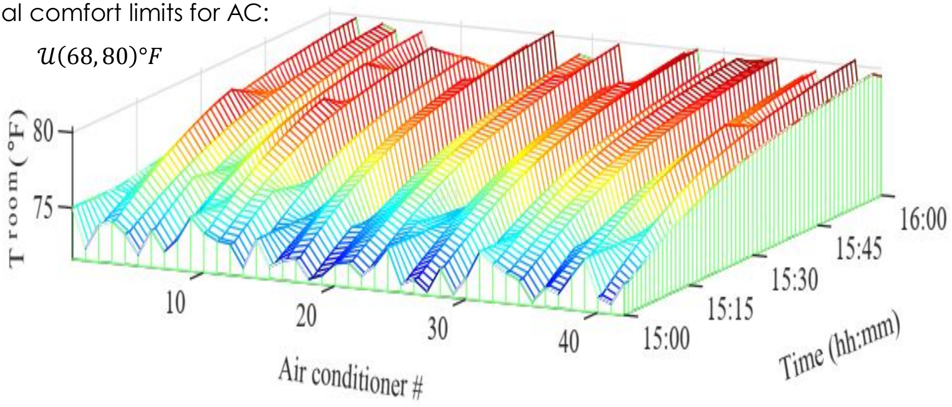
Resuming operation after temperature violations

override event



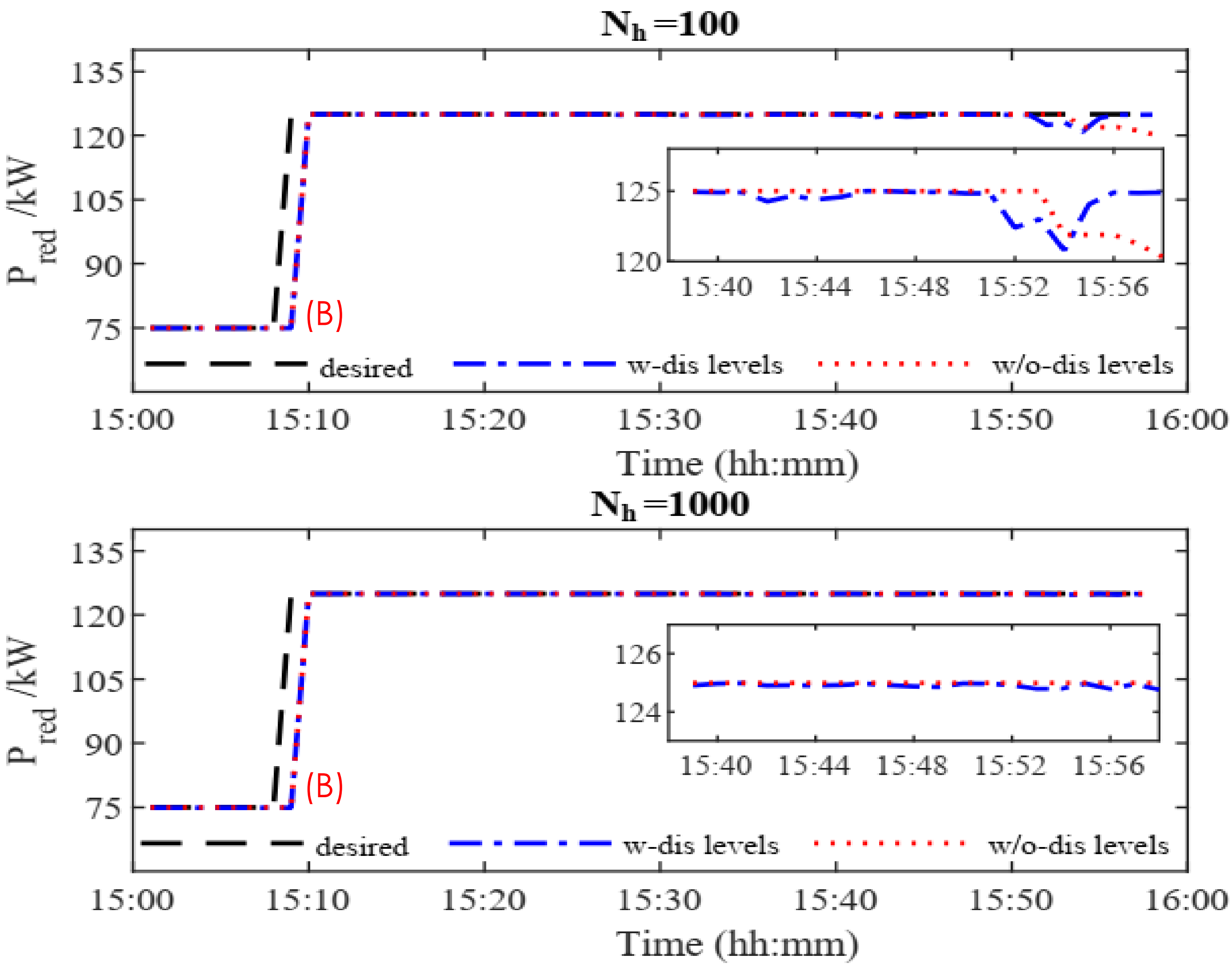
Thermal comfort limits for AC:

$\mathcal{U}(68, 80)°F$



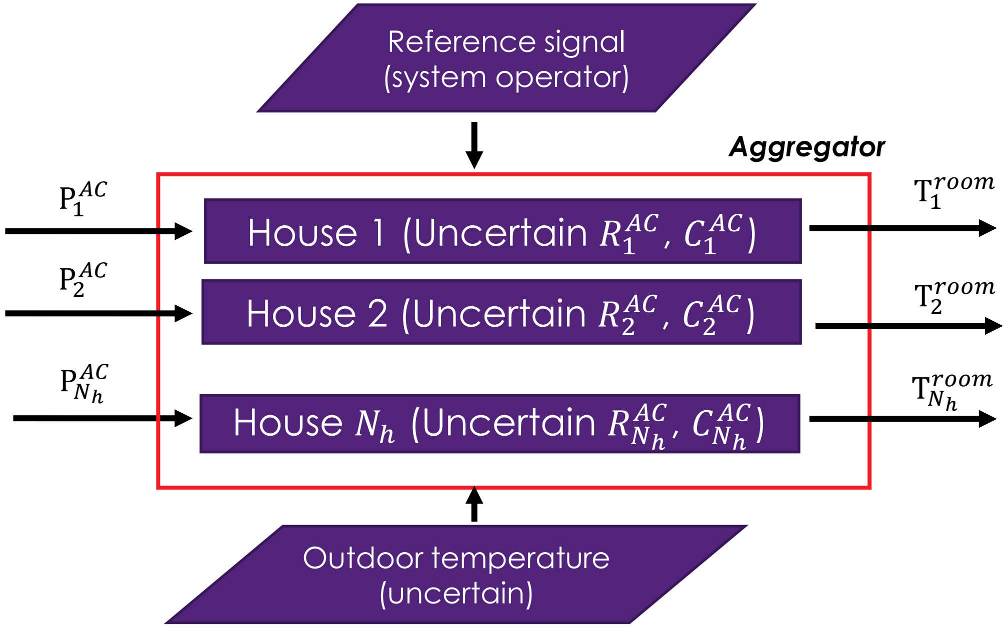
Indoor thermal comfort is maintained.

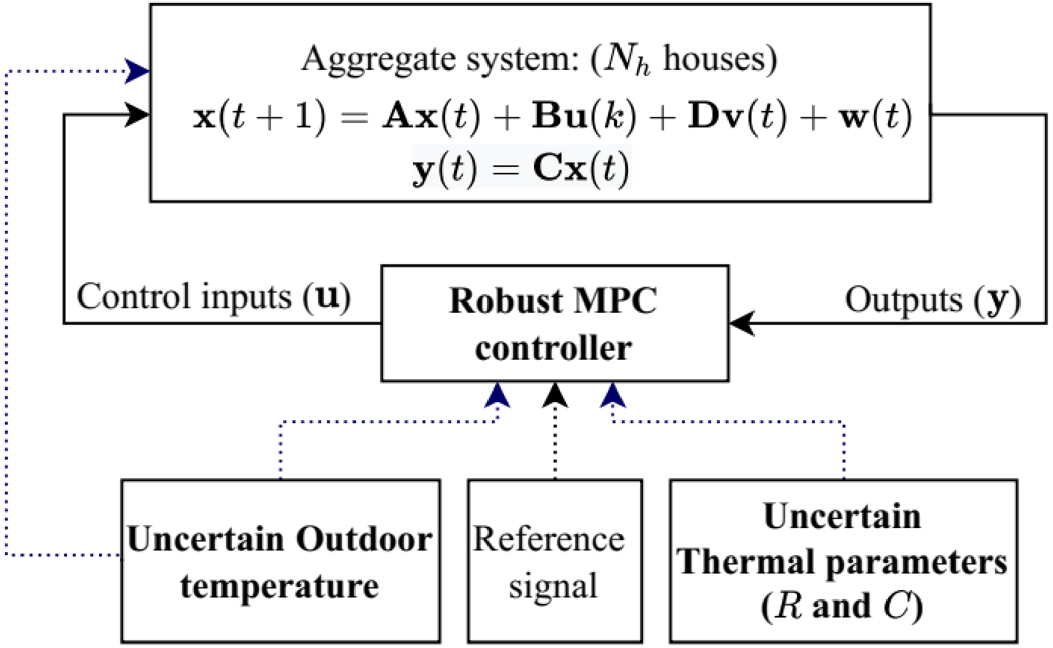
Set-point change (B)



The tracking performance increases as the population size increases.

Approach: Robust MPC scheme





Min. (aggregate tracking error + change in temperature from the set-point + control effort)

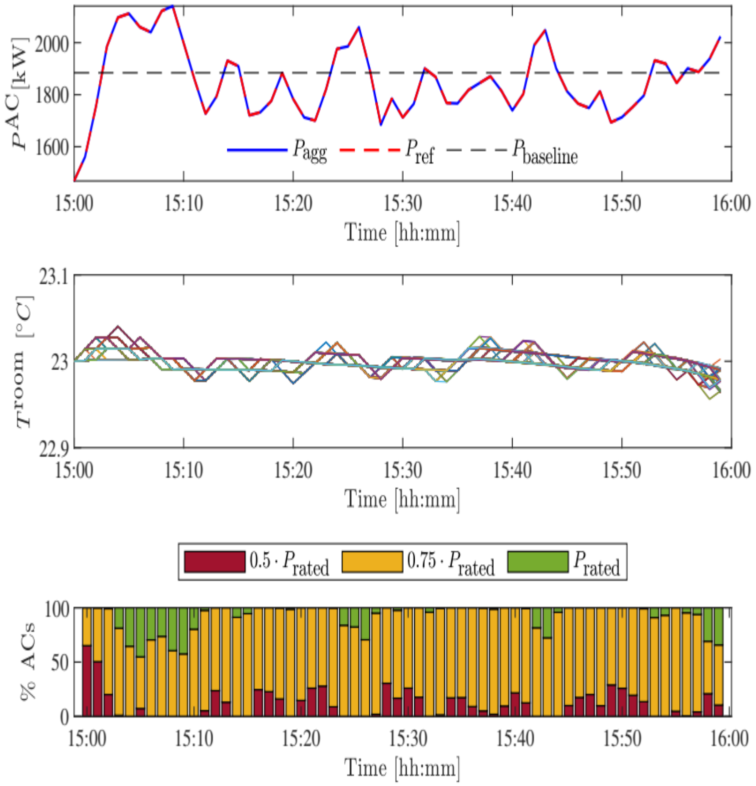
subject to:

Indoor temperature limits
DRM compliance
Worst-case uncertainties

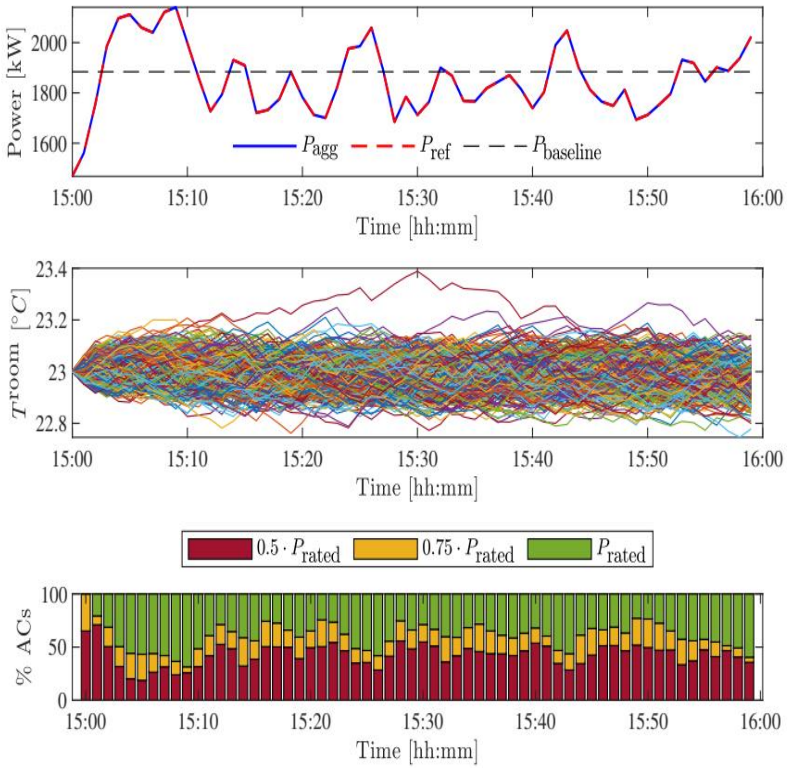
A term is derived to represent the uncertainty associated with:

- **thermal model parameters**
- **outdoor temperature forecasts**

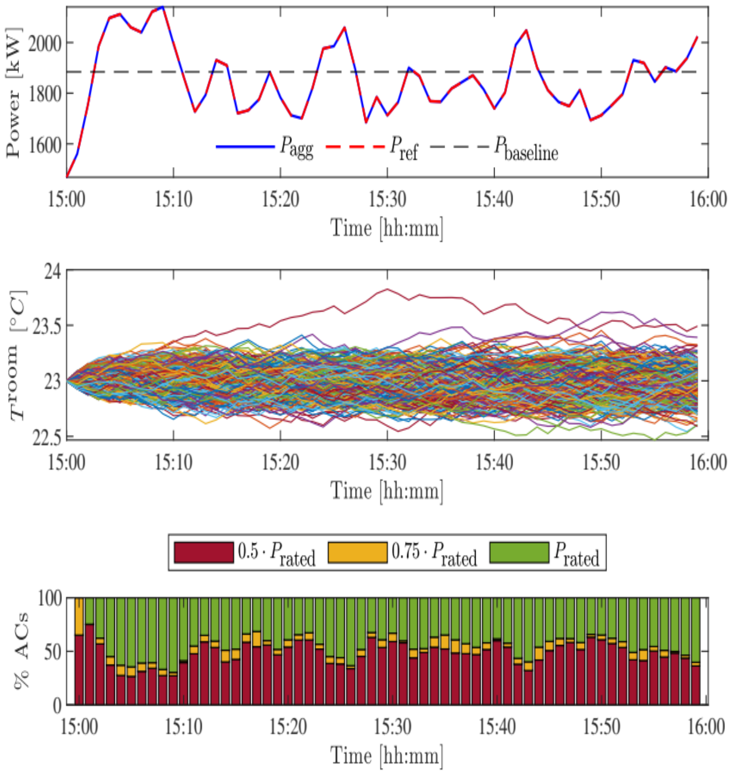
Results



Nominal scenario



with $w_0 = 0.05°C$

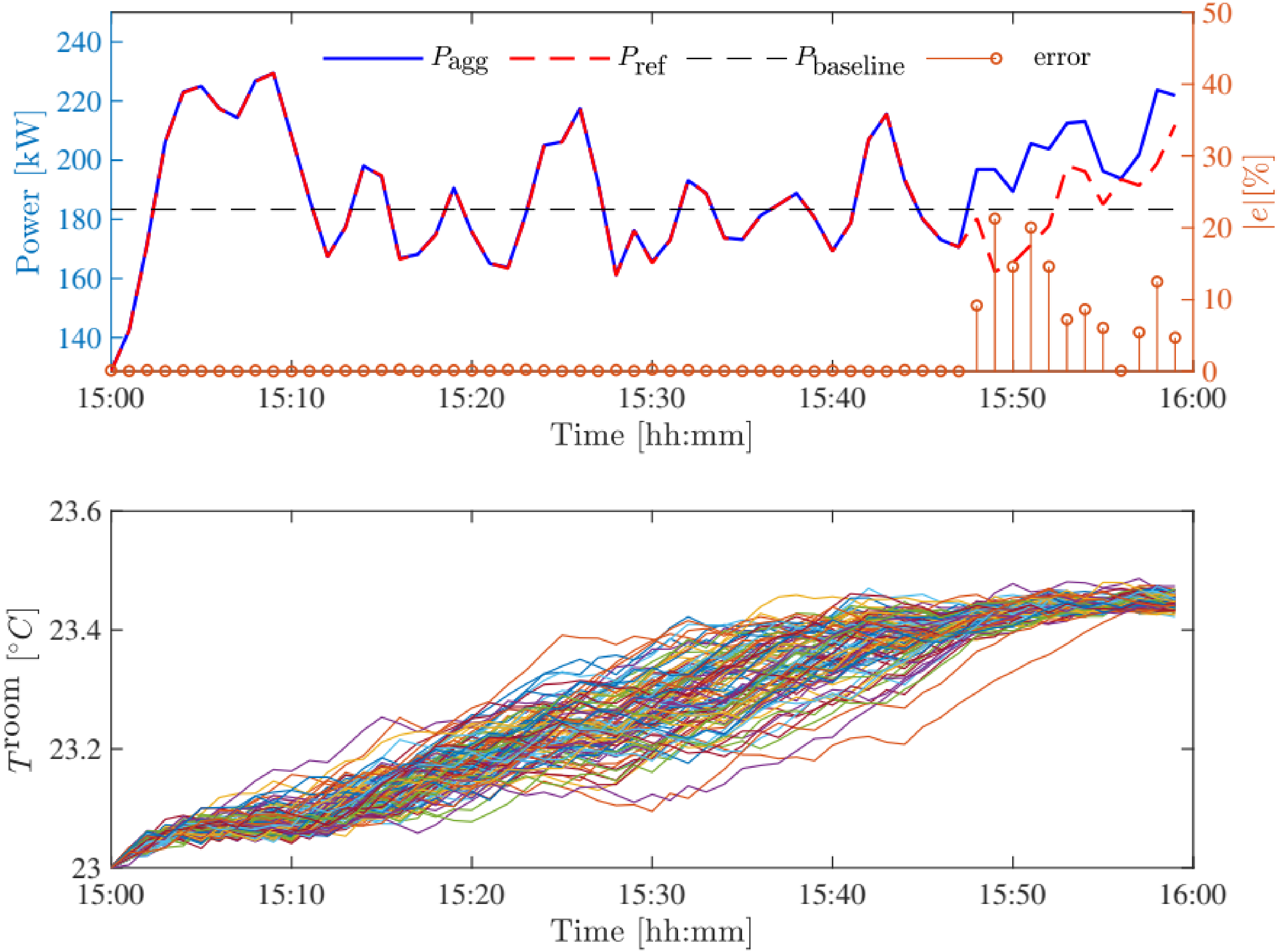


with $w_0 = 0.075°C$

Accurate tracking can be achieved in the presence of uncertainties while regulating the operation within thermal comfort limits.

Minimum control action on air-conditioners operating under AS 4755.3 DR standards.

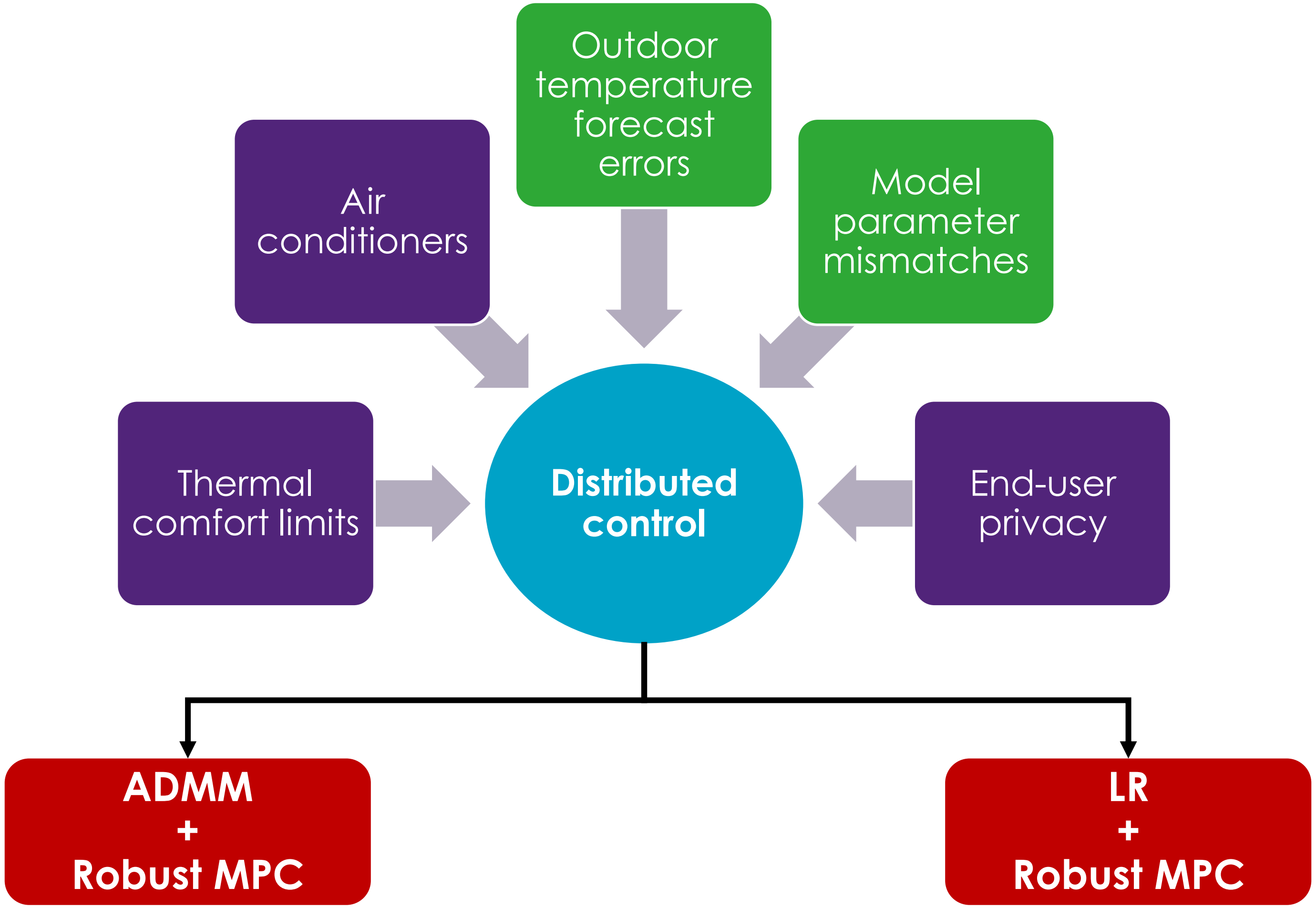
Tracking performance under tightened temperature limits



with $w_0 = 0.02°C$ under
$[22.5°C , 23.5° C]$
for $N_h = 100$

Tracking performance is compromised under tight temperature comfort limits in the presence of uncertainties.

Contribution 2: Distributed control frameworks for an aggregator to provide DR in real-time markets under uncertainties



Outdoor temperature forecast errors

Air conditioners

Model parameter mismatches

Thermal comfort limits

Distributed control

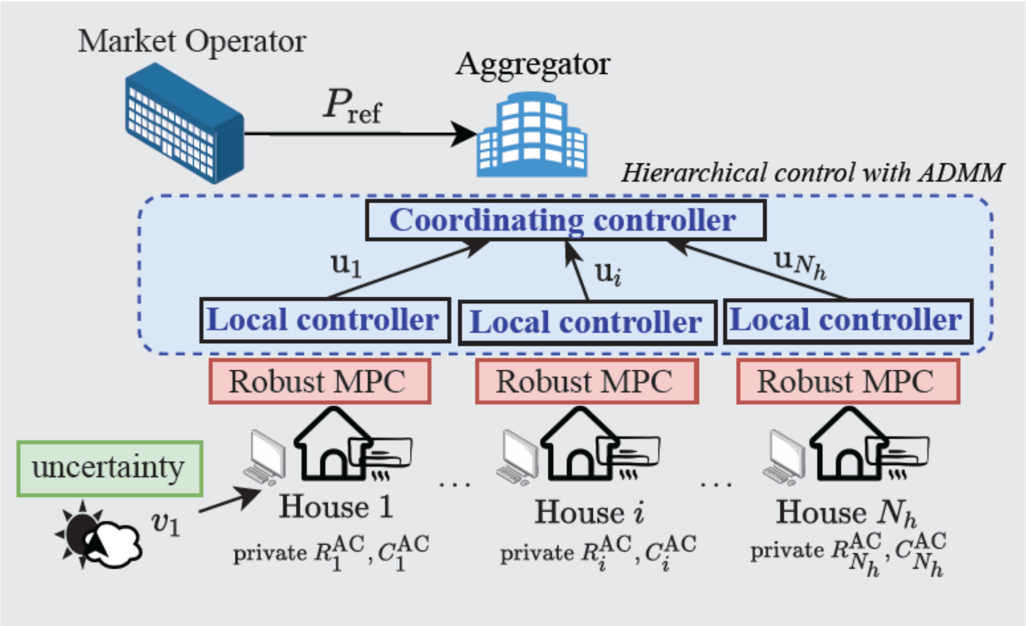
End-user privacy

ADMM
+
Robust MPC

LR
+
Robust MPC

- G. Lankeshwara, R. Sharma, R. Yan, and T. K. Saha, "A hierarchical control scheme for residential air-conditioning loads to provide real-time market services under uncertainties," Energy (Elsevier), vol. 250, p. 123796, 2022, doi: 10.1016/j.energy.2022.123796.
- G. Lankeshwara and R. Sharma, "Robust Provision of Demand Response from Thermostatically Controllable Loads using Lagrangian Relaxation," International Journal of Control (Taylor & Francis), (provisional acceptance)

Approach



Overall implementation

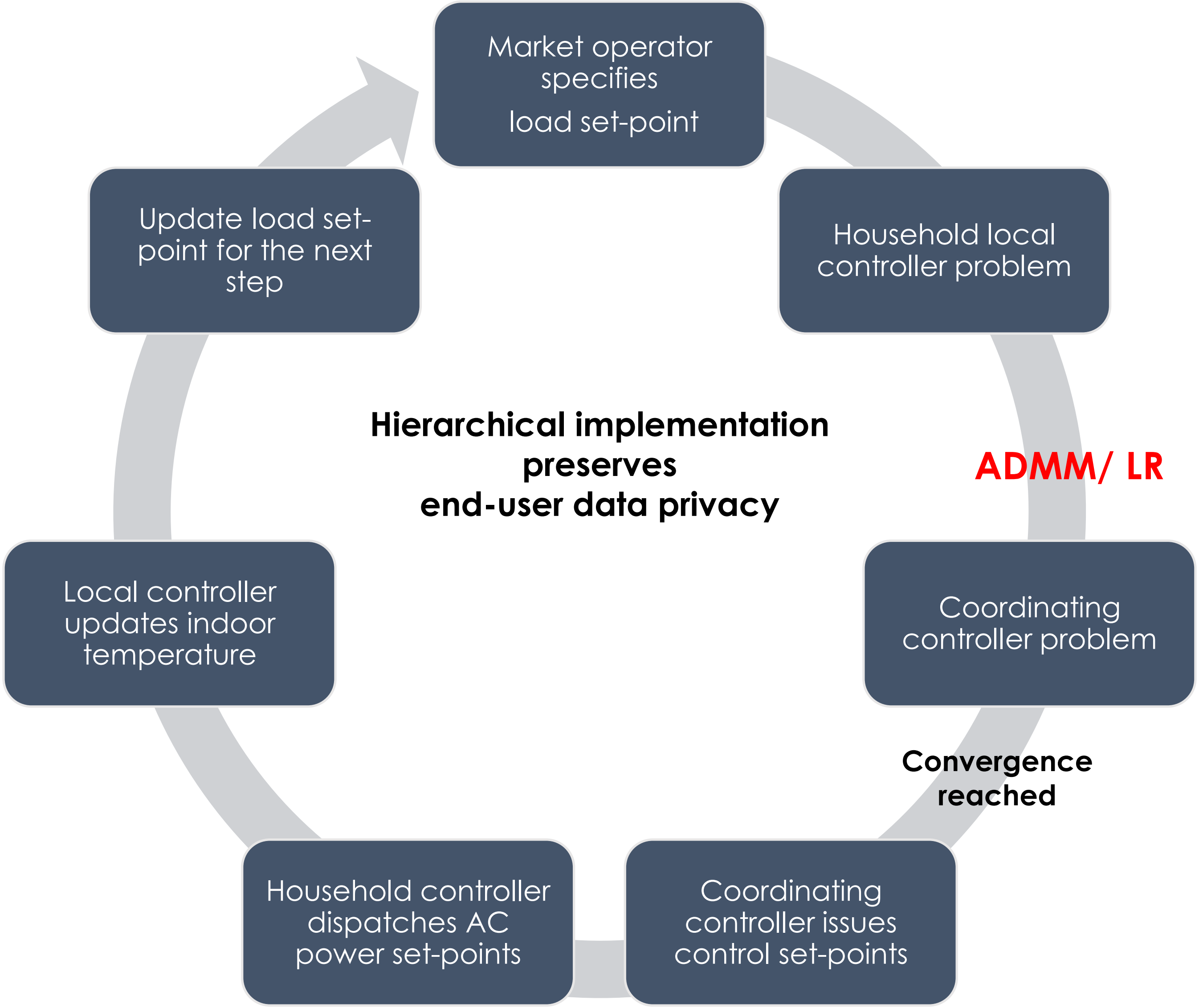
Household local controller (robust MPC)

- Minimise AC energy cost
- Address uncertainties

Coordinating controller at the Aggregator

Tracking the load set-point signal in real-time energy markets

At each time step,



Market operator specifies load set-point

Household local controller problem

ADMM/ LR

Coordinating controller problem

Convergence reached

Coordinating controller issues control set-points

Household controller dispatches AC power set-points

Local controller updates indoor temperature

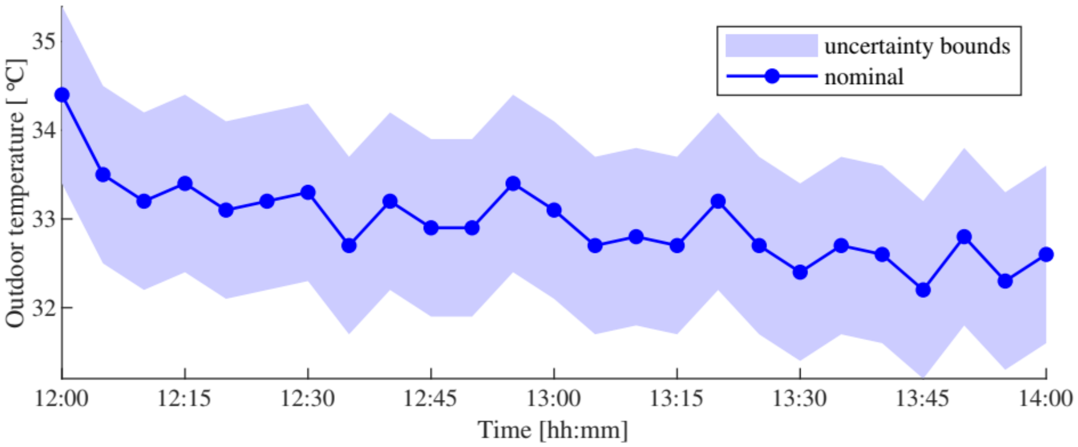
Update load set-point for the next step

Hierarchical implementation preserves end-user data privacy

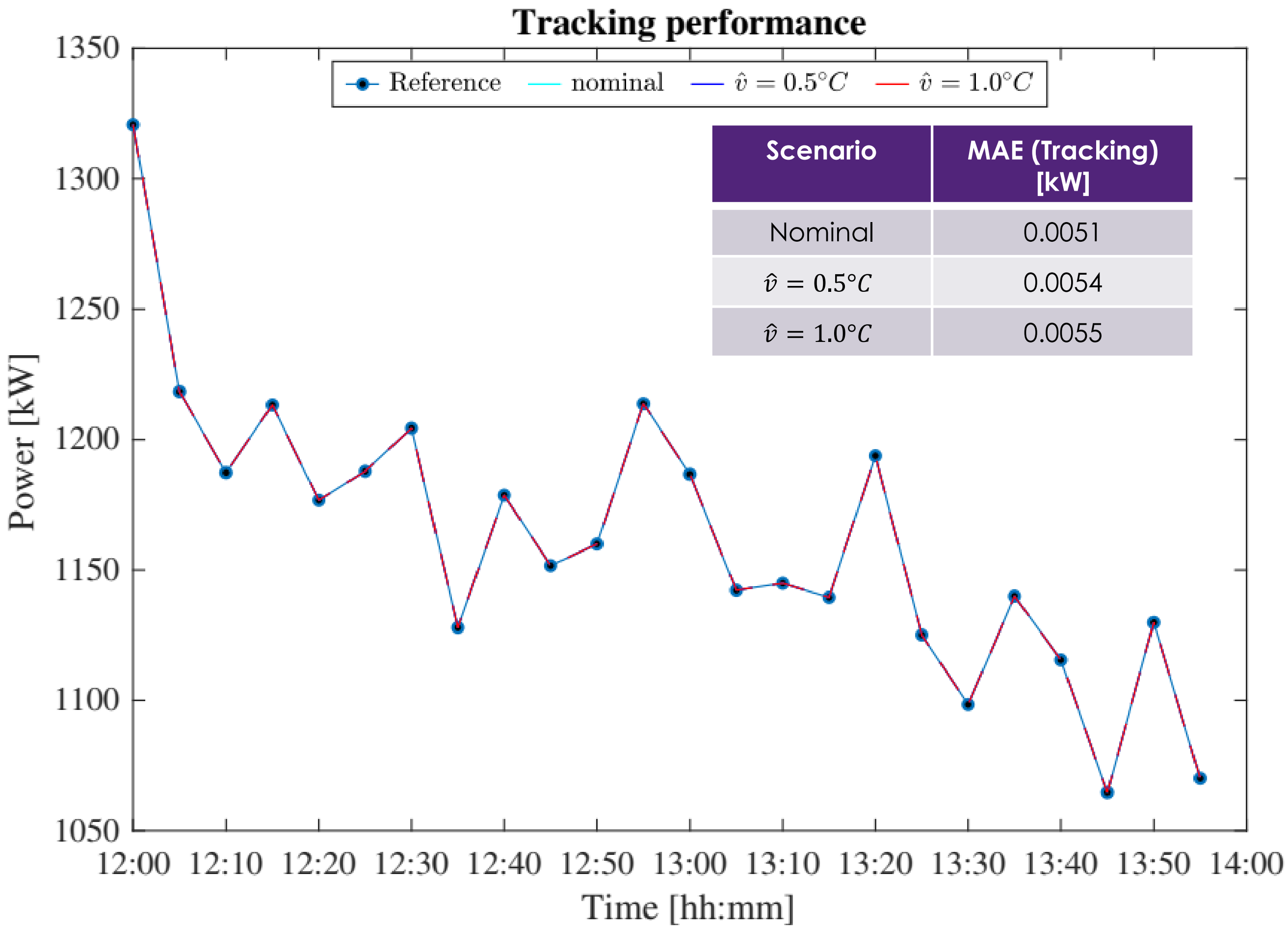
Results (ADMM+ robust MPC)

Three scenarios:

1. Nominal case – no uncertainties
2. With outdoor temperature bounds $(\hat{v}) = 0.5°C$
3. With outdoor temperature bounds $(\hat{v}) = 1.0°C$



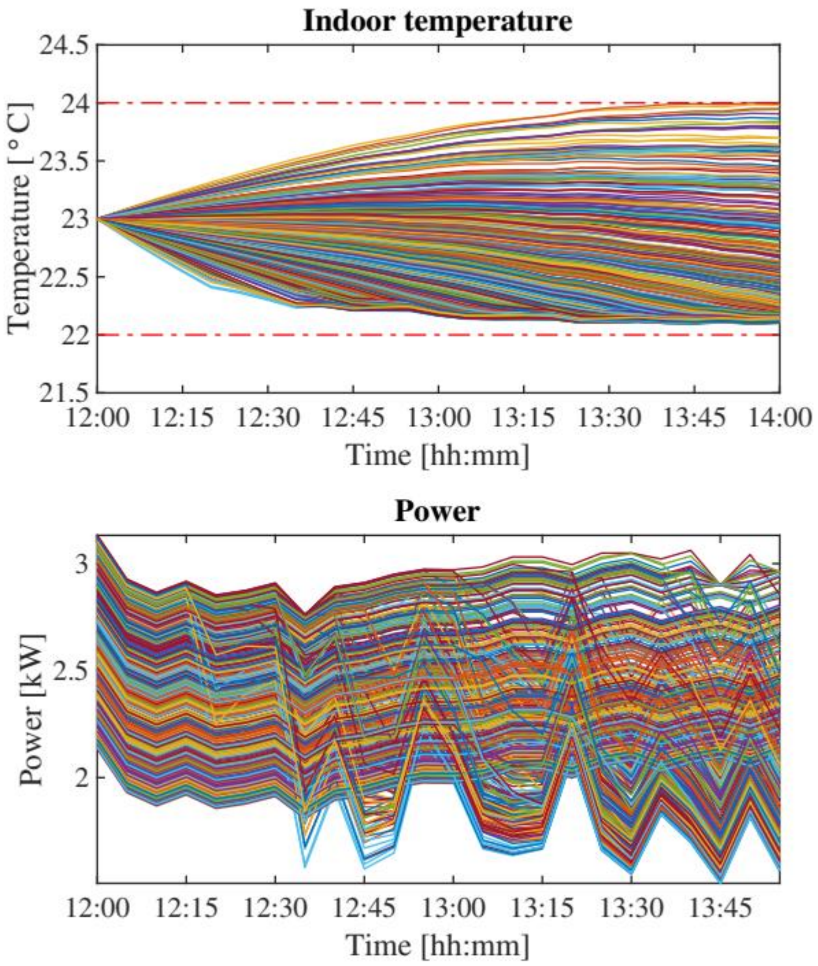
Uncertainty bounds for outdoor temperature



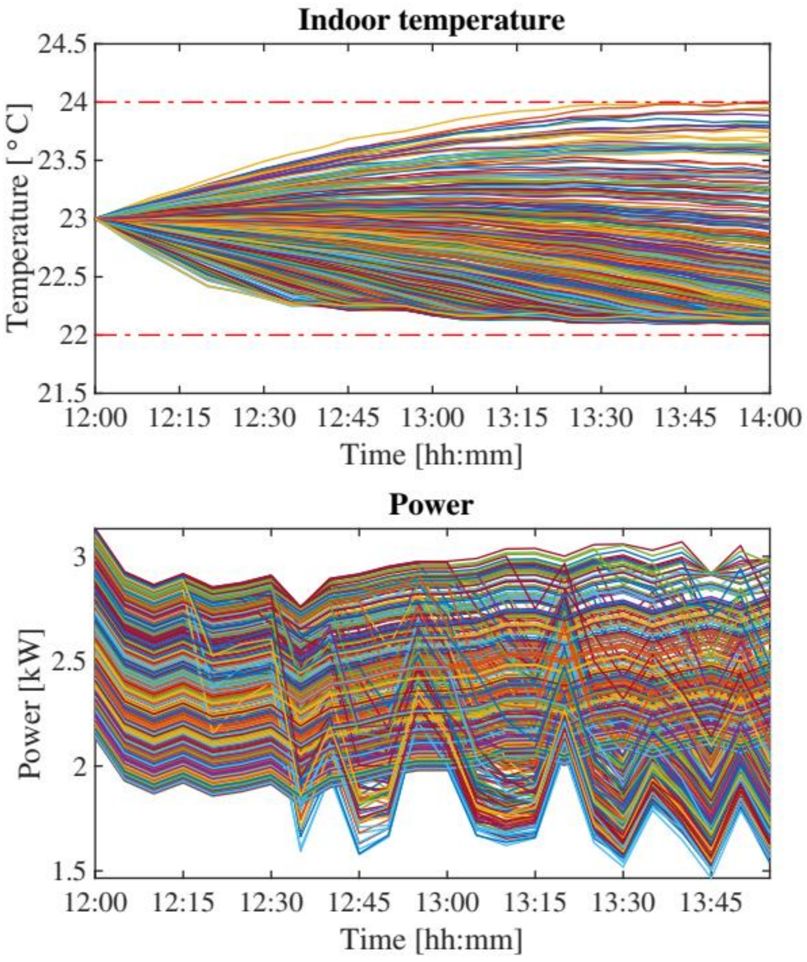
Scenario	MAE (Tracking) [kW]
Nominal	0.0051
$\hat{v} = 0.5°C$	0.0054
$\hat{v} = 1.0°C$	0.0055

Precise tracking of the load set-point signal up to $\pm 1.0°C$ variation of outdoor temperature from nominal value.

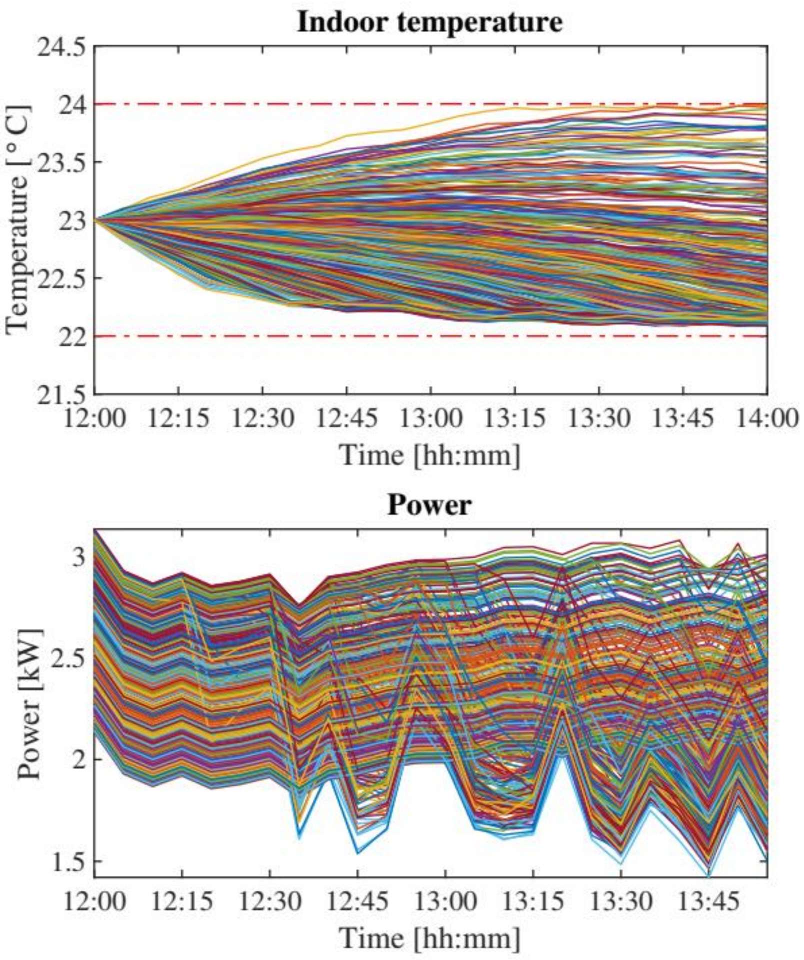
Contribution 2: Distributed control frameworks for an aggregator to provide DR in real-time markets under uncertainties



Nominal scenario



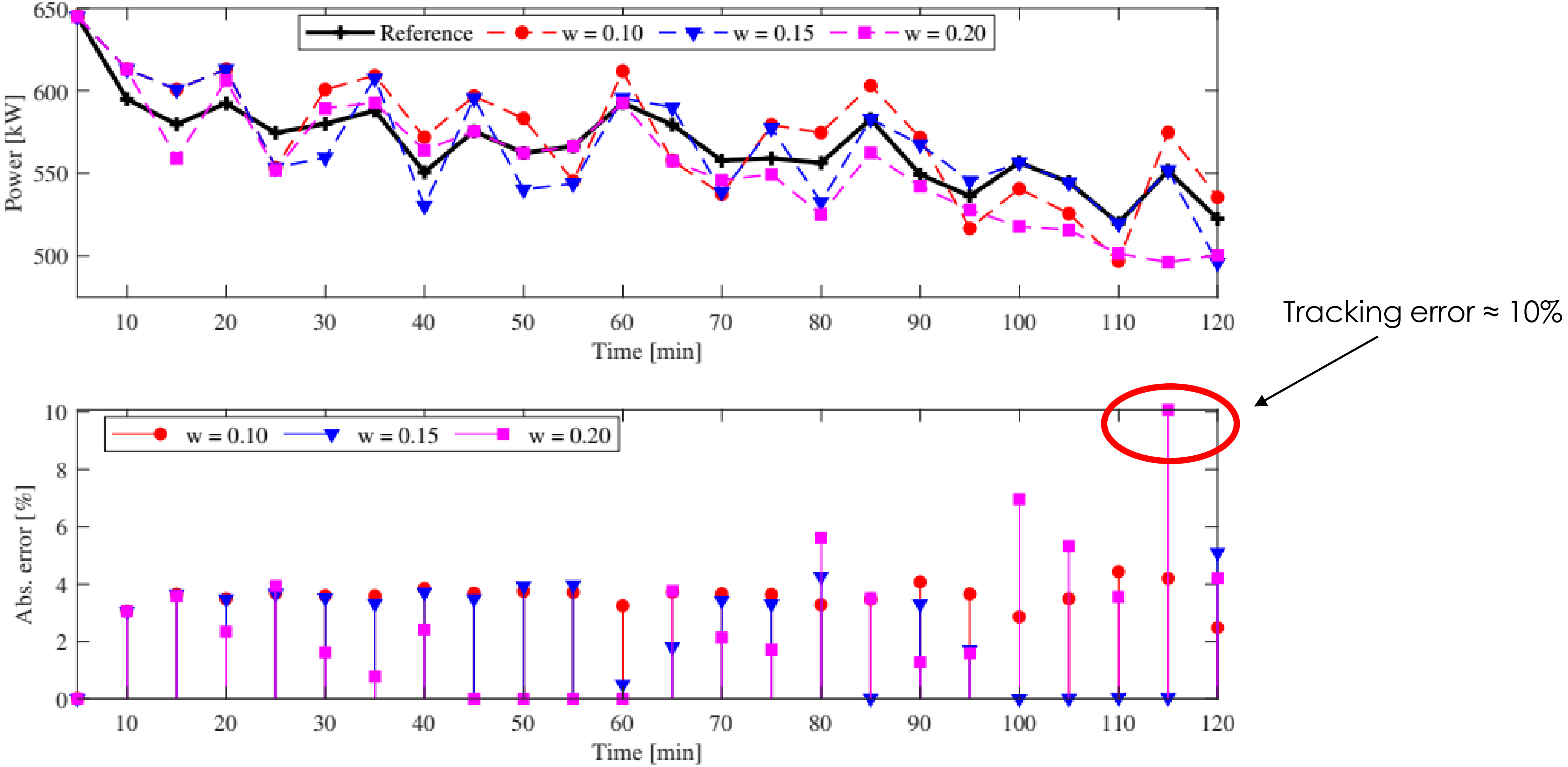
with $\hat{v} = 0.5°C$



with $\hat{v} = 1.0°C$

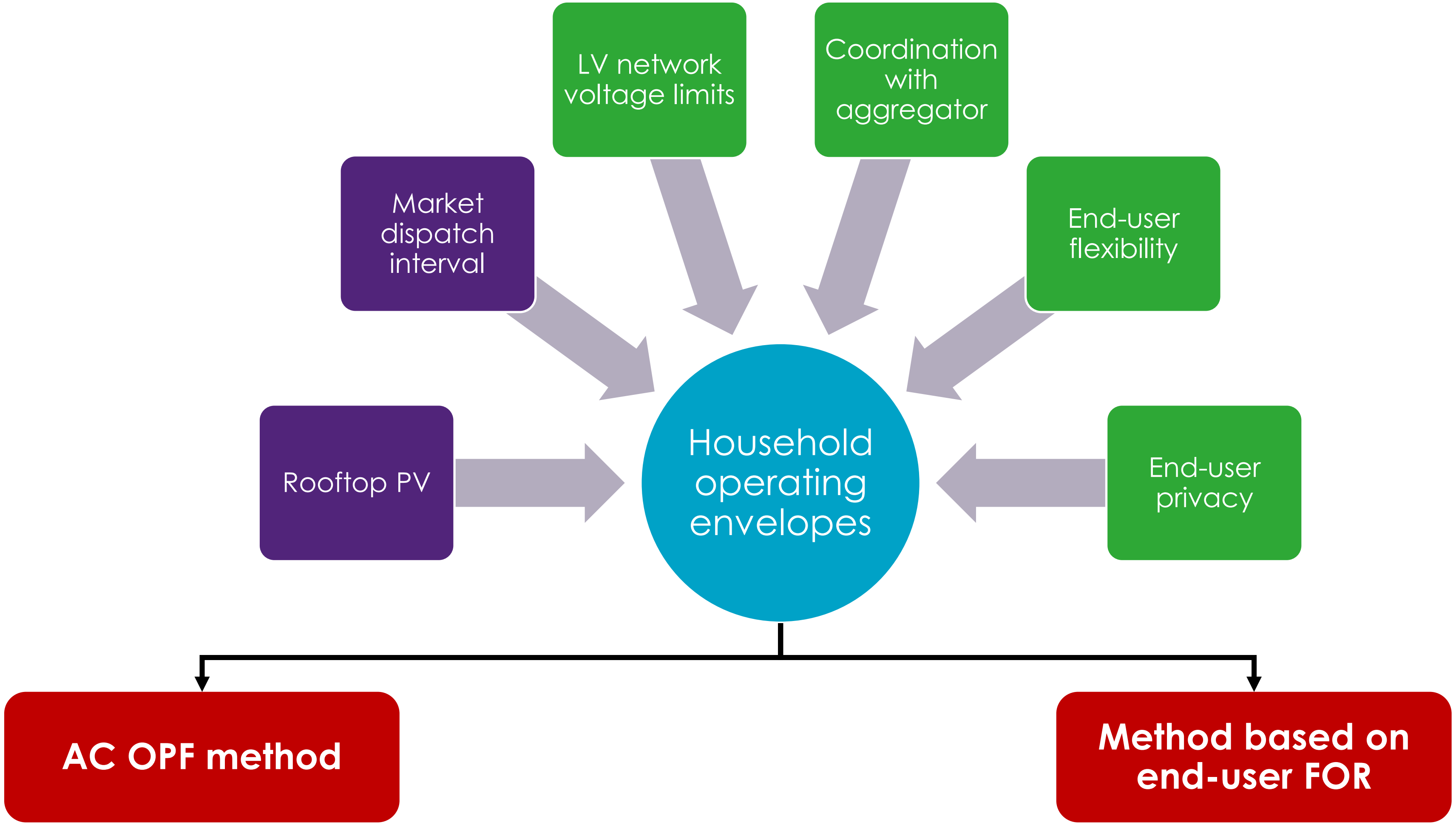
Indoor thermal comfort is preserved within $(22, 24)°C$ in the presence of outdoor temperature variations up to $\pm 1.0°C$ from its nominal value.

Results (LR+ robust MPC)



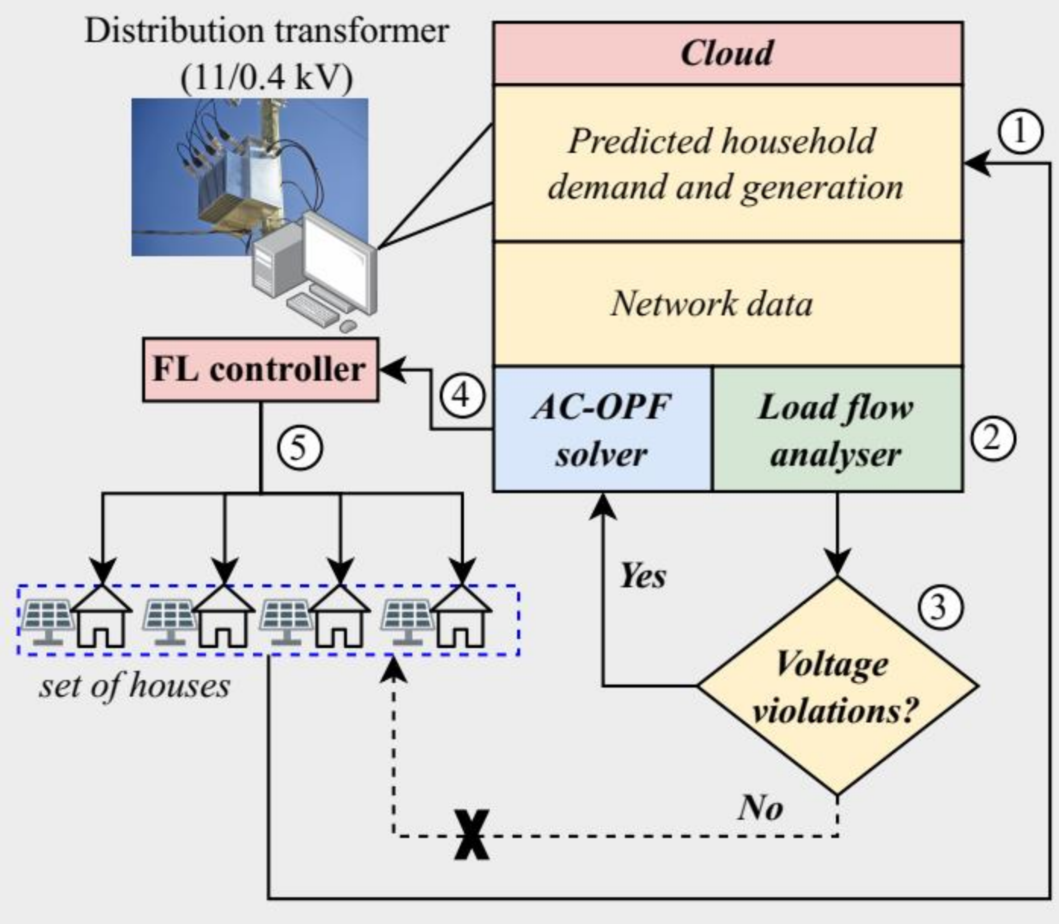
As the degree of uncertainty increases, the tracking performance degrades.

Contribution 3: Techniques to establish dynamic operating envelopes in low-voltage distribution networks



- G. Lankeshwara, “A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits,” in 2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), Dec. 2021, pp. 1–5, doi: 10.1109/ISGTAsia49270.2021.9715714.
- G. Lankeshwara, R. Sharma, R. Yan, T. K. Saha and J. Milanovic, “Operating Envelopes to Manage Low-voltage Distribution Networks,” (first revision submitted to IEEE Transactions on Power Systems)

AC-OPF Approach



A block diagram of the overall implementation

AC-OPF implementation

Min. (deviation of PV active power from the intended operation)

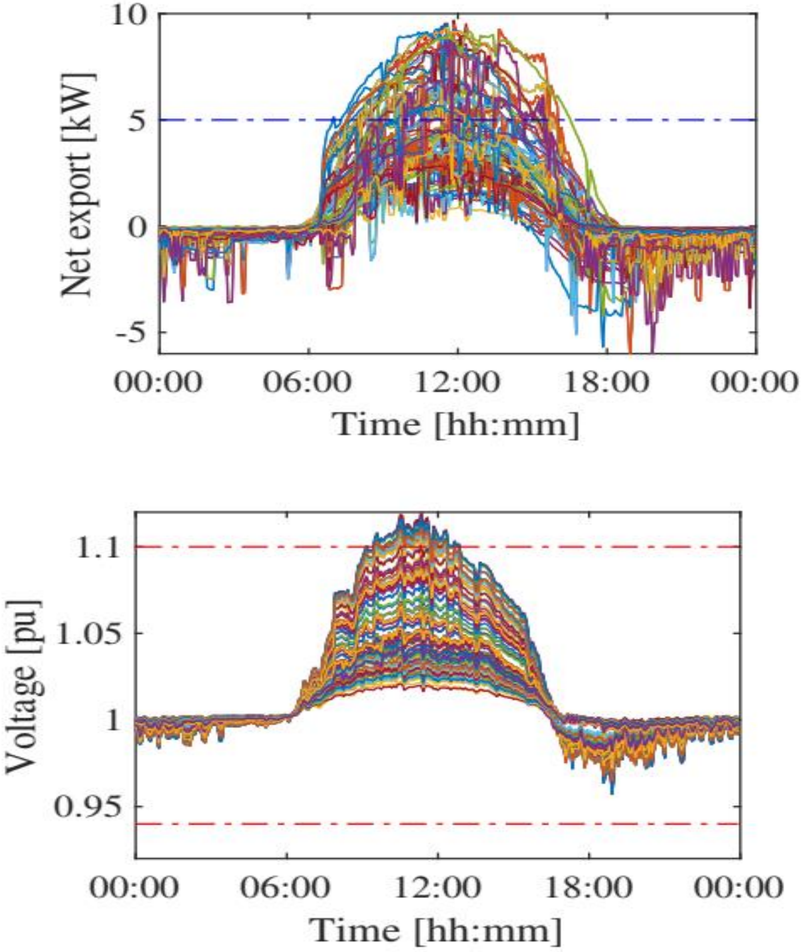
subject to:

Rooftop PV operational limits
Household load limits
Power balance (non-convex)
Voltage limits

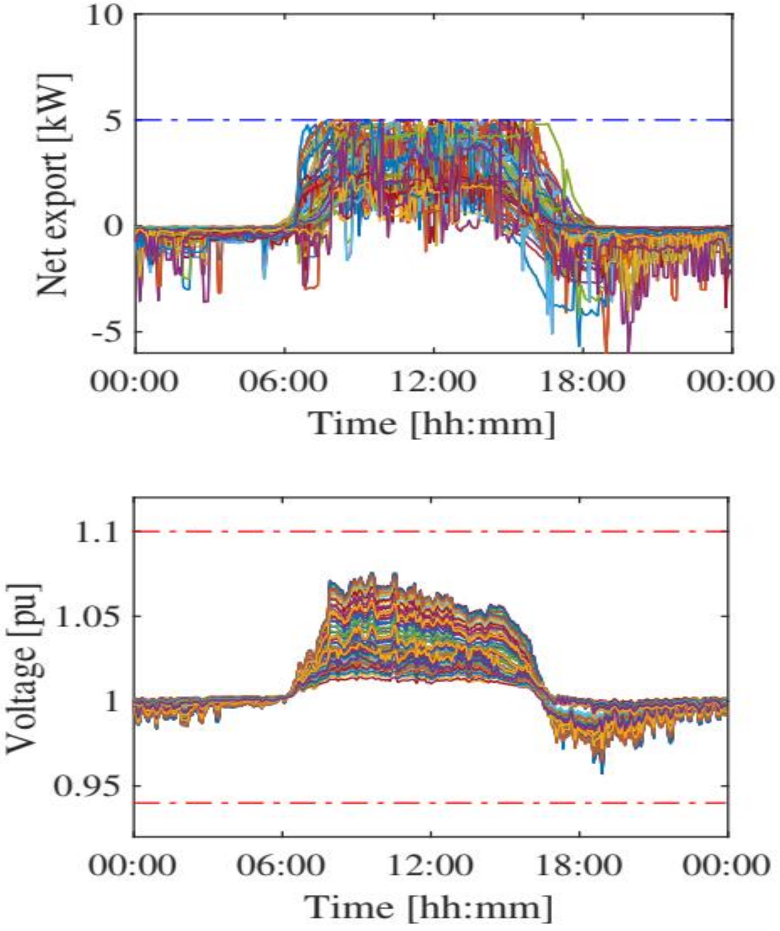
Controllable variable:
Household rooftop PV generation

Results (AC OPF approach)

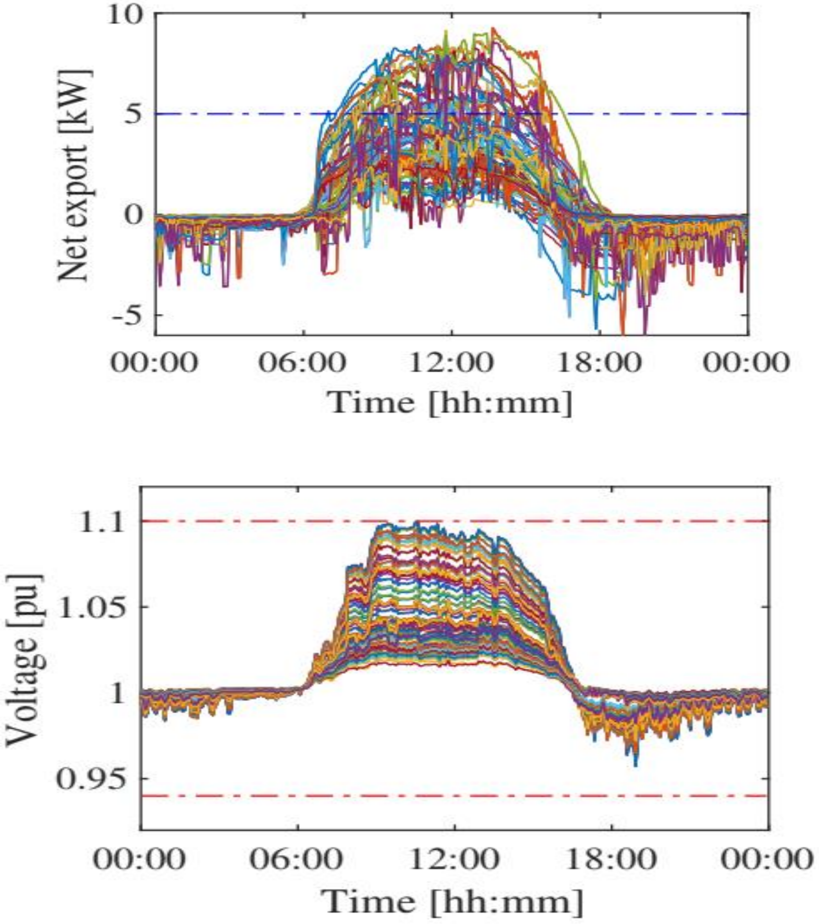
No export limits



Fixed export limits

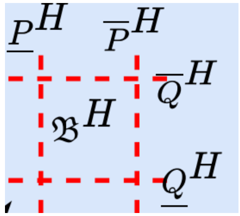


Dynamic export limits



Under the proposed dynamic envelopes framework, end-users can export more power to the grid without violating voltage limits.

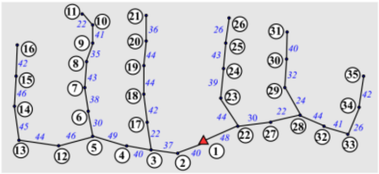
Approach based on FOR of end-users



Households determine limits of operation at POC
(P-Q space)

Privacy preserved

DNSP samples household operating region
- Latin Hypercube Sampling (LHS)



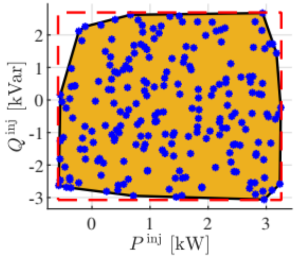
DNPS performs probabilistic load flows

Check for voltage violations
- If Yes, neglect the scenario
- If No, move to the next step

$0.95\,pu < v < 1.10\,pu$

Obtain the set of feasible P-Q pairs for households
- All cases without voltage violations

Accounts for network voltage limits



Convex hull estimation
- Operating envelopes for households

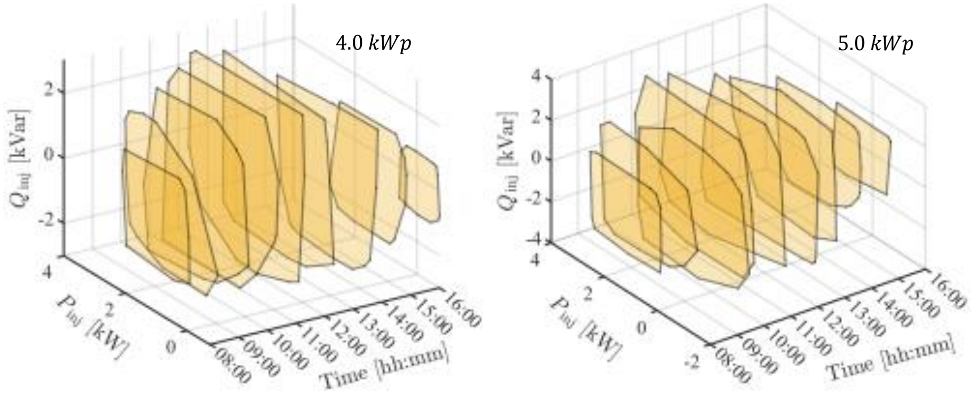
Aggregate envelope
- Head of feeder
- Using Minkowski sum ⊕

Send to aggregator

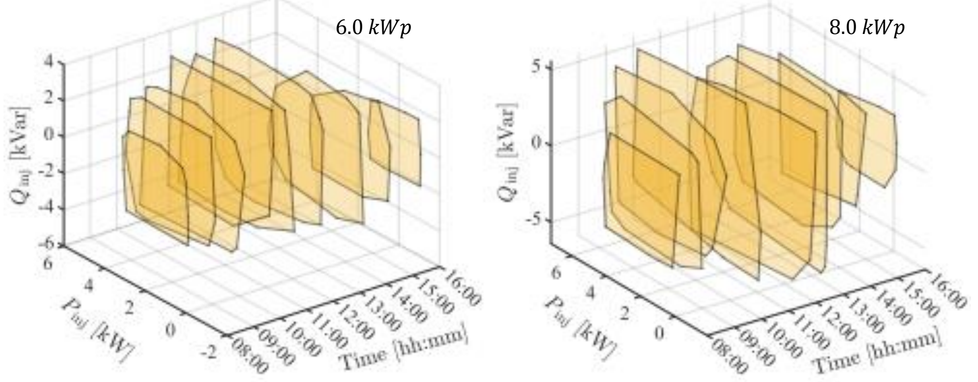
Privacy and separation between DNSP and aggregator

Results

Dynamic behaviour of envelopes



(a) H3 (b) H37

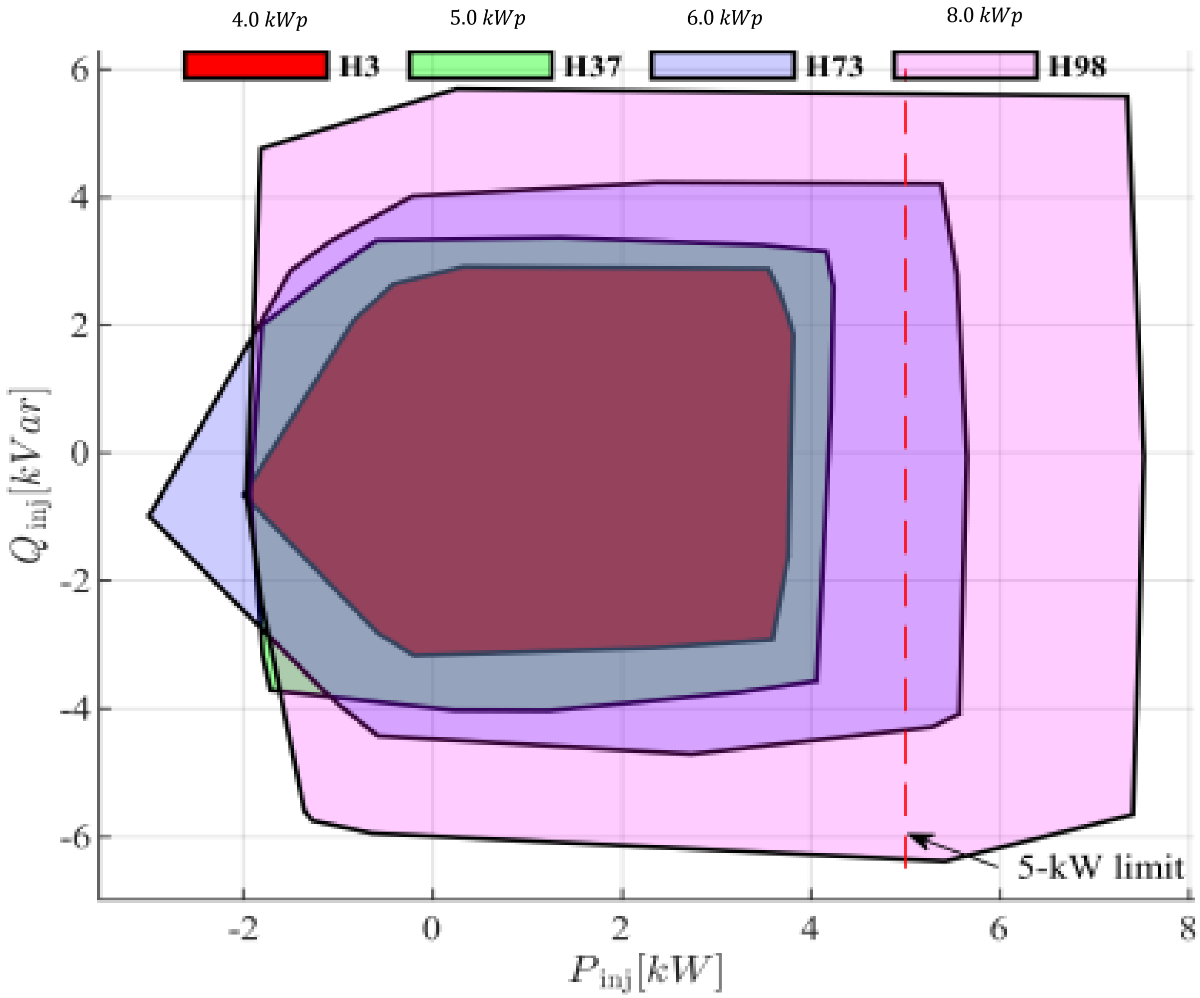


(c) H73 (d) H98

As PV generation ↑, the operating envelope widens.

Feasible operating region expands → Household flexibility ↑

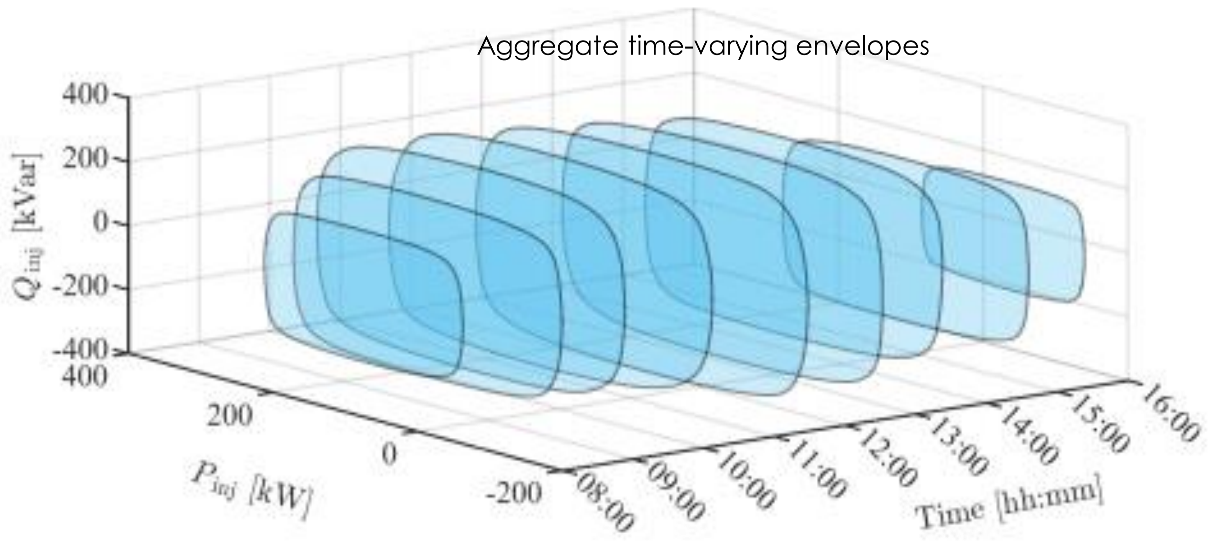
Overall feasible operating region for 24-hours

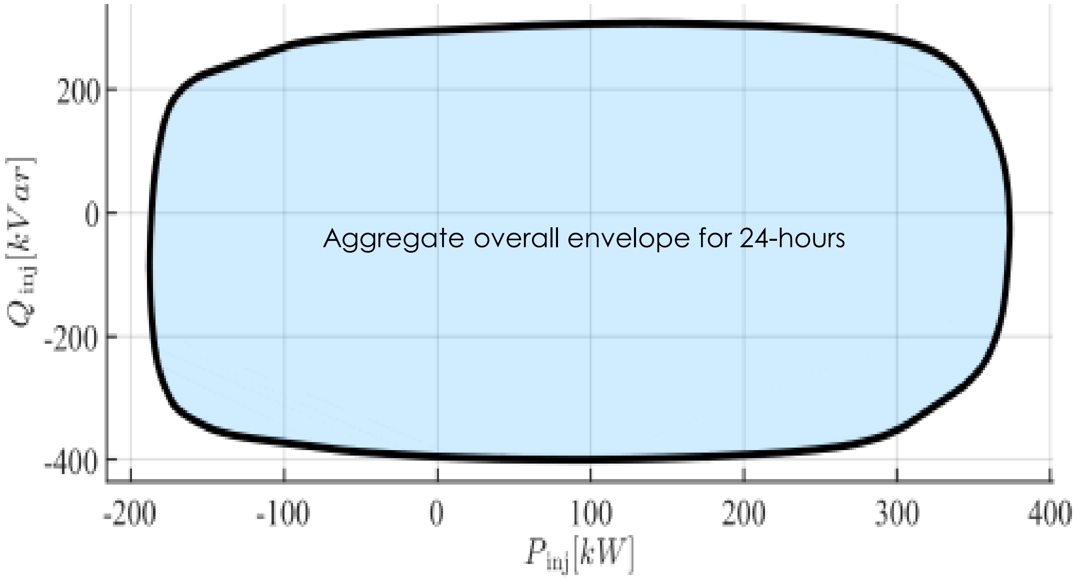


PV inverter rating ↑ envelopes shift towards $P_{inj} > 0$ $(export)$ region

Able to go beyond the fixed 5-kW export limit!

Behaviour of aggregate envelope





As PV generation ↑, aggregate envelope also expands

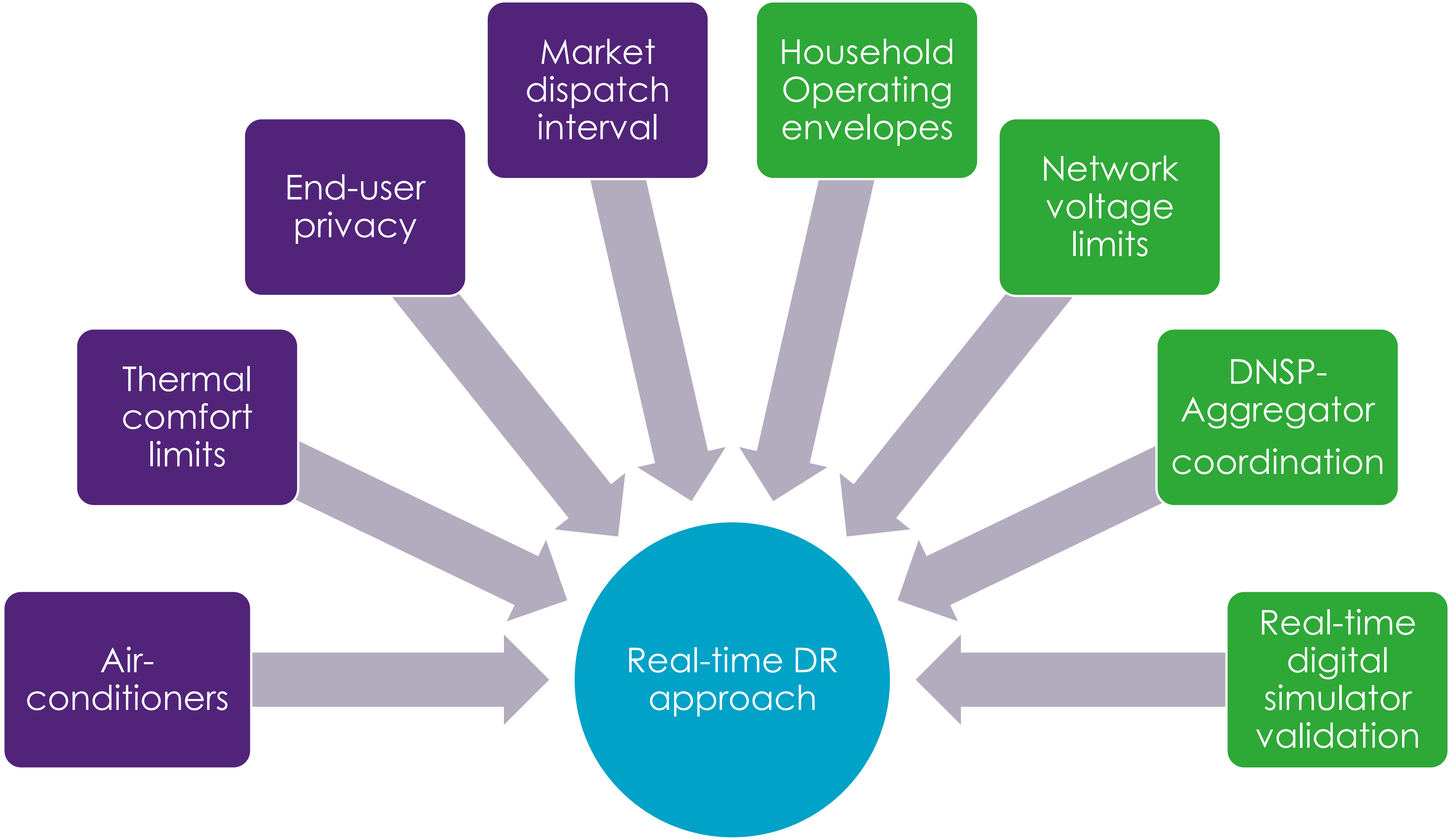
Smooth compared to household operating envelopes

Overall flexibility at the head of the feeder (approx.)

$$-200 < P_{inj} < 350\ kW$$
$$-400 < Q_{inj} < 250\ kVar$$

Aggregate envelopes are helpful for the aggregator in the network-aware market bidding process.

Contribution 4: A coordinated control scheme for dynamic operating envelopes-enabled demand response in low-voltage distribution networks



Market dispatch interval

Household Operating envelopes

End-user privacy

Network voltage limits

Thermal comfort limits

DNSP-Aggregator coordination

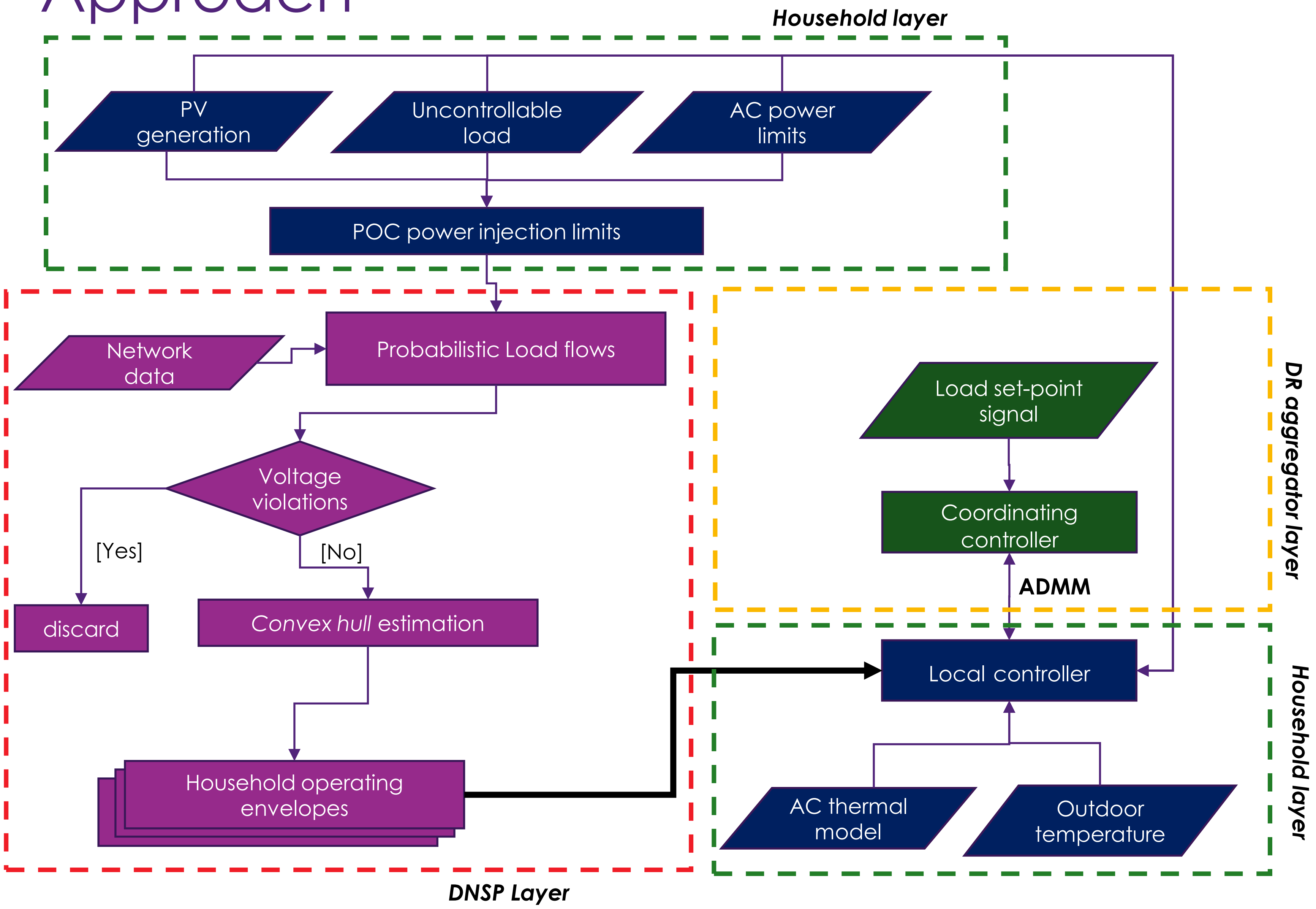
Air-conditioners

Real-time DR approach

Real-time digital simulator validation

- G. Lankeshwara and R. Sharma, "Dynamic Operating Envelopes-enabled Demand Response in Low-voltage Residential Networks," 2022 IEEE PES 14th Asia-Pacific Power and Energy Engineering Conference (APPEEC), Melbourne, Australia, 2022, pp. 1-7, doi: [10.1109/APPEEC53445.2022.10072108.](https://doi.org/10.1109/APPEEC53445.2022.10072108)

Approach



DNSP estimates envelopes and passes to the DR aggregator

Household local controller

Minimising household energy cost

subject to:

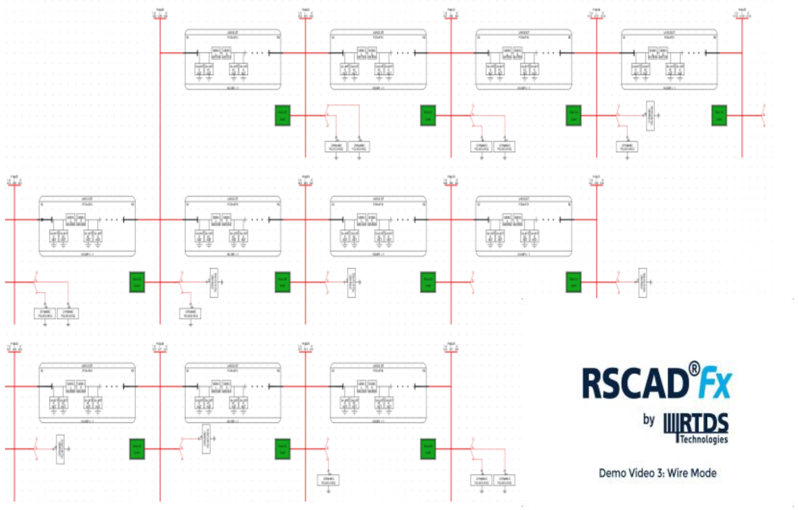
- AC thermal comfort limits
- **Voltage constraints (form of operating envelopes)**

Hierarchical implementation

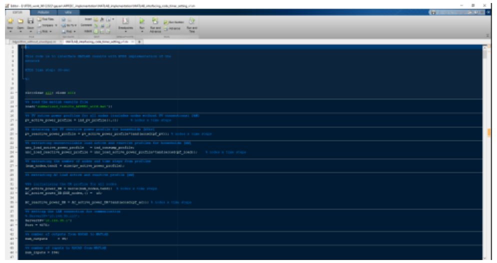
Coordinating controller (DR aggregator)

Minimising tracking error of the load set-point signal

Software-in-the-loop (SIL) setup

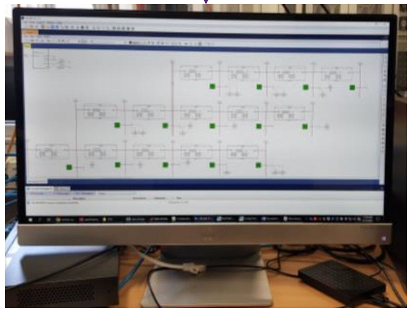


Network model in RSCAD FX 1.3.1



MATLAB script for communicating with RTDS

LAN switch



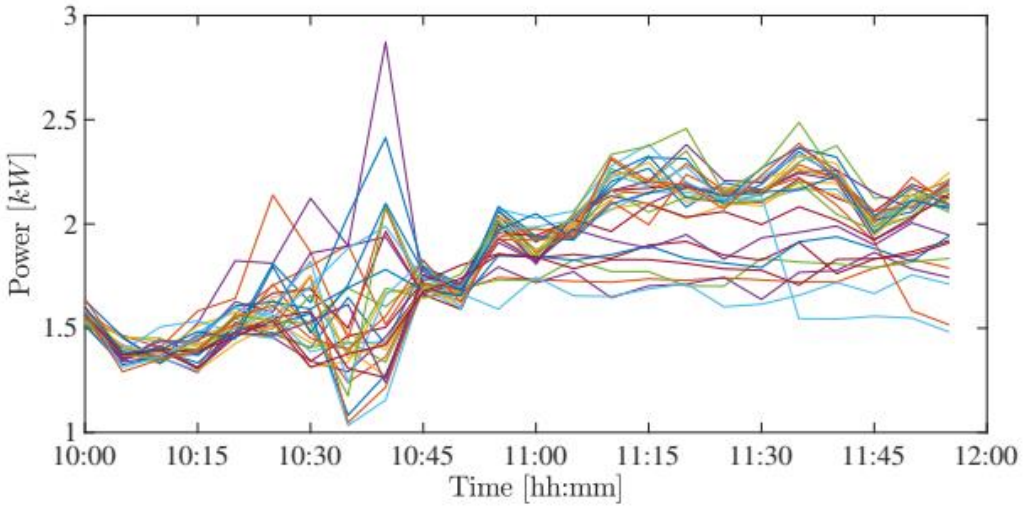
Workstation

RTDS chassis (NovaCor processor card + GTNETx2 card)

Results

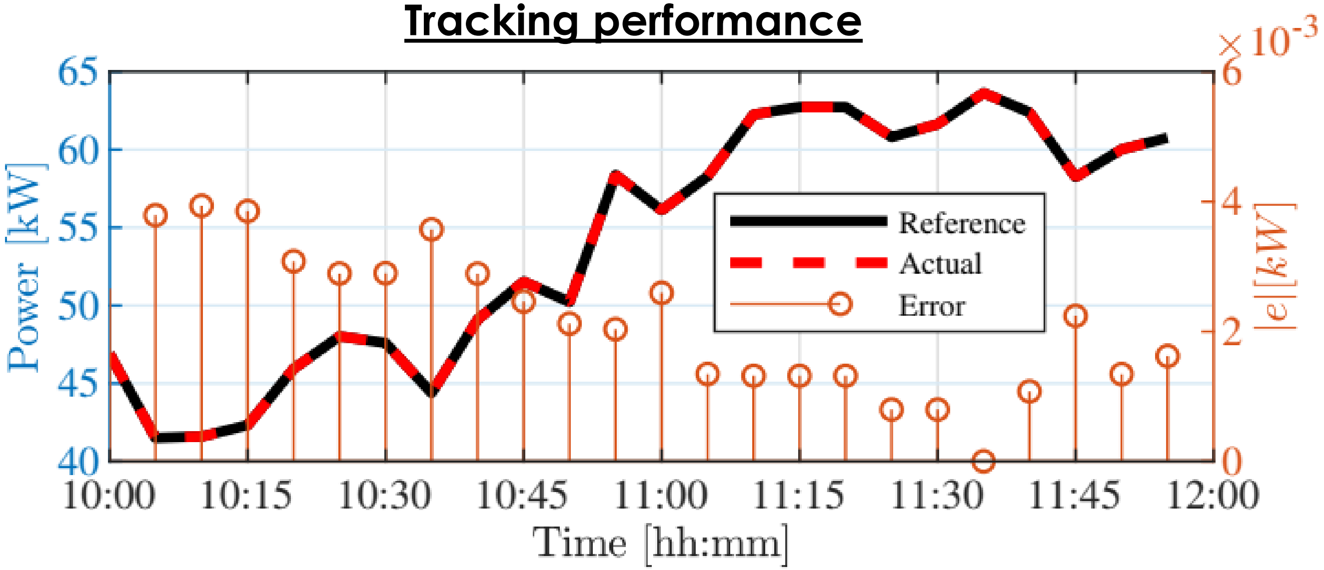
Three types of customers

- *Passive* - **56**
- *DOE* (only participate in DR) – **30**
- *Non-DOE* (5-kW export limits) – **16**

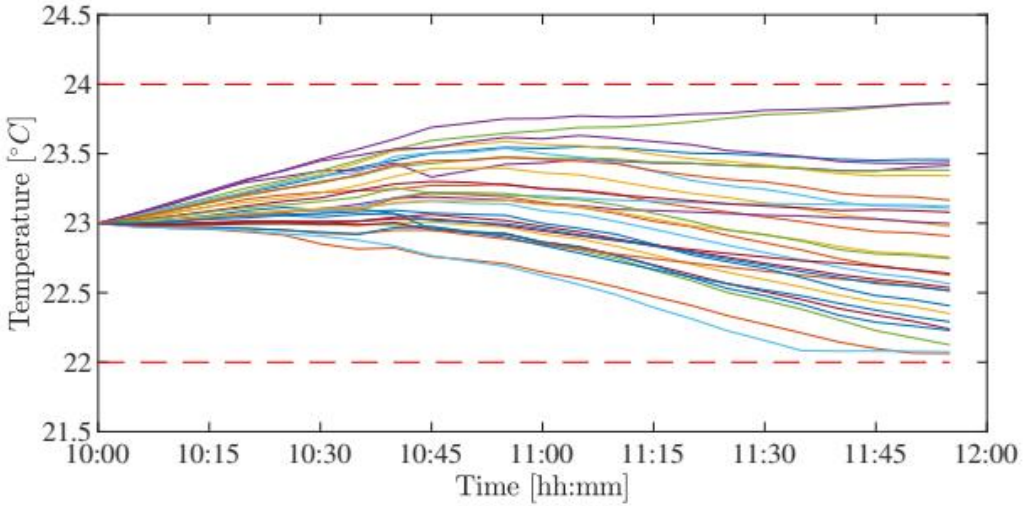


(b) The variation of air-conditioner power for *DOE customers*

Tracking performance



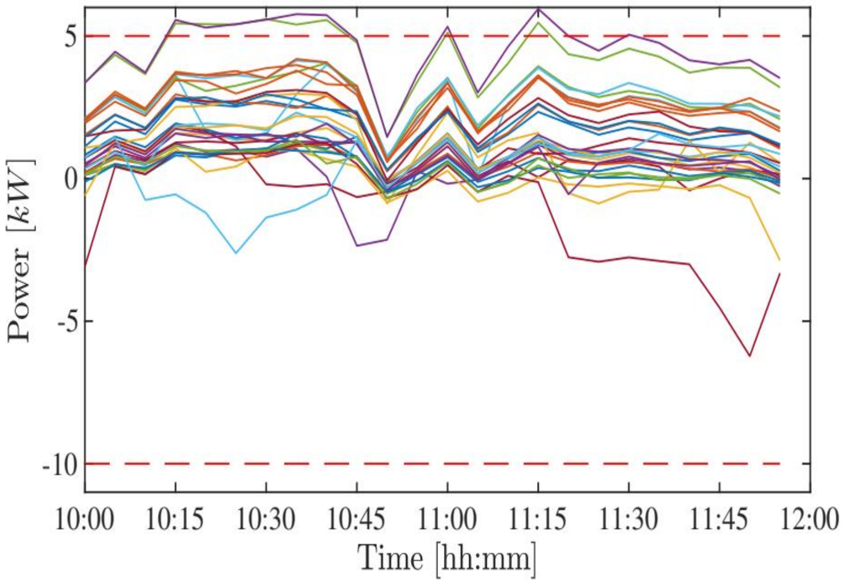
Precise tracking of the load set-point is achieved.



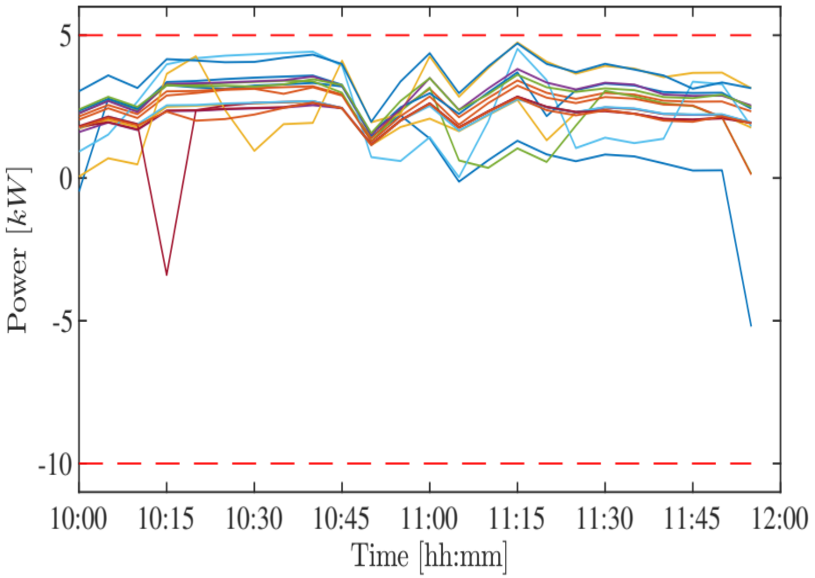
(c) The variation of indoor temperature for *DOE customers*

The overall approach preserves thermal comfort

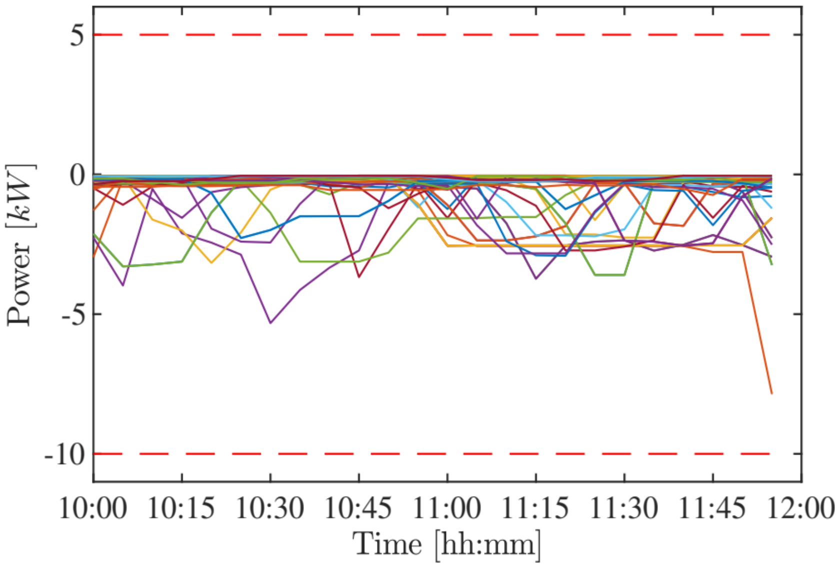
Active power injections at the POC



(a) *DOE customers*



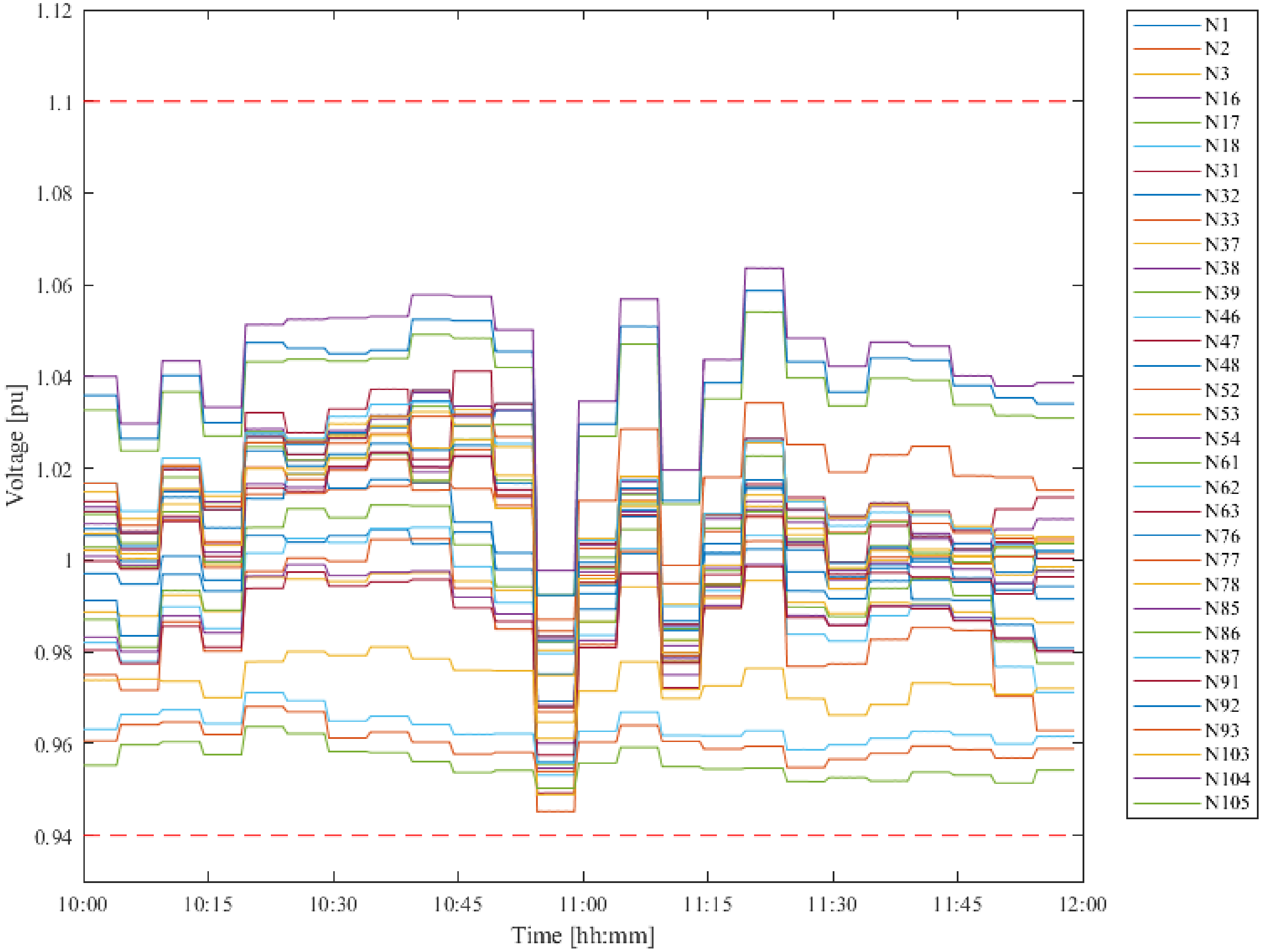
(b) *Non-DOE customers*



(c) *Passive customers*

**Active power exports beyond 5 kW (static limit) is possible for DOE customers.
Import power limit (-10 kW) is not reached.**

Voltage profile of selected nodes (software-in-the-loop simulation)



statutory limits

$$0.94\,pu < v < 1.10\,pu$$

The voltage profile is maintained within statutory limits for the DR period.

Outline

- Introduction
- Motivations
- Objectives
- Main Contributions
- Conclusions
- Publications

- Through effective **uncertainty mitigation techniques**, DR could provide accurate load set-point tracking in electricity markets.
- Factors such as **scalability**, **end-user data privacy** should also be paid attention in developing **centralised/distributed** control schemes for the aggregation of residential loads in DR services under uncertainties.
- The proposed techniques to establish DOEs **allow active power exports beyond 5 kW fixed limit** without breaching network technical limits.
- DOEs that specify **end-user feasible operating region** are beneficial for the aggregator to **assess household flexibility and the aggregate flexibility of distribution networks** and bid in electricity markets.
- With **adequate coordination between the aggregator and the DNSP**, DOEs could be utilised for providing DR services without breaching network technical limits.

Outline

- Introduction
- Motivations
- Objectives
- Main Contributions
- Conclusions
- Publications

Peer-reviewed Journals:

- **G. Lankeshwara**, R. Sharma, R. Yan, and T. K. Saha, "Control algorithms to mitigate the effect of uncertainties in residential demand management," *Applied Energy (Elsevier)*, vol. 306, p. 117971, 2022, doi: 10.1016/j.apenergy.2021.117971.
- **G. Lankeshwara**, R. Sharma, R. Yan, and T. K. Saha, "A hierarchical control scheme for residential air-conditioning loads to provide real-time market services under uncertainties," *Energy (Elsevier)*, vol. 250, p. 123796, 2022, doi: 10.1016/j.energy.2022.123796.
- **G. Lankeshwara** and R. Sharma, "Robust Provision of Demand Response from Thermostatically Controllable Loads using Lagrangian Relaxation," *International Journal of Control (Taylor & Francis)*, **(provisional acceptance)**
- **G. Lankeshwara**, R. Sharma, R. Yan, T. K. Saha and J. Milanovic "Time-varying Operating Regions of End-users and Feeders in Low-voltage Distribution Networks," (**first revision submitted to *IEEE Transactions on Power Systems*)**
- M. R. Alam, P. T. H. Nguyen, L. Naranpanawe, T. K. Saha and **G. Lankeshwara**, "Allocation of Dynamic Operating Envelopes in Distribution Networks: Technical and Equitable Perspectives," in IEEE Transactions on Sustainable Energy, doi: https://doi.org/10.1109/TSTE.2023.3275082.
- M. Imran Azim, **G. Lankeshwara**, Wayes Tushar, R. Sharma, T. K. Saha, Mohsen Khorasany and Reza Razzaghi, " A Dynamic Exchange-enabled P2P Trading Model to Maximise Financial Returns of Prosumers," **(first revision submitted to IEEE Transactions on Smart Grid)**

Peer-reviewed Conference Papers:

- **G. Lankeshwara**, R. Sharma, R. Yan, and T. K. Saha, "Control of Residential Air-conditioning Loads to Provide Regulation Services under Uncertainties," in *IEEE Power and Energy Society General Meeting*, 2021, vol. 2021-July, pp. 1–5, doi: 10.1109/PESGM46819.2021.9637890.
- **G. Lankeshwara**, "A Real-time Control Approach to Maximise the Utilisation of Rooftop PV Using Dynamic Export Limits," in *2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Dec. 2021, pp. 1–5, doi: 10.1109/ISGTAsia49270.2021.9715714.
- **G. Lankeshwara** and R. Sharma, "Dynamic Operating Envelopes-enabled Demand Response in Low-voltage Residential Networks," 2022 IEEE PES 14th Asia-Pacific Power and Energy Engineering Conference (APPEEC), Melbourne, Australia, 2022, pp. 1-7, doi: https://doi.org/10.1109/APPEEC53445.2022.10072108.

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Thank you

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Centre for Energy Data Innovation (CEDI)
The University of Queensland and Redback Technologies

Supplementary slides

Future Work

- Developing DR control schemes robust against **communication failures**
- Establishing household DOEs in LV distribution networks with **low visibility**
- Incorporating **battery storage** and **electric vehicles** in the overall DOE framework
- Establishing operating envelopes for household connections under **demand and generation uncertainties**
- Effect of **controllability** and **geographical distribution of loads** on the performance of DR under the DOE framework
- Effect of **demand composition** of household loads in the provision of DR in LV distribution networks

Gaps in the existing literature

- The effects of uncertainties
- End-user data privacy of DR schemes
- Scalability of DR approaches
- Compatibility of DR schemes with modern household appliances
- The effect of DR on the performance of the network
- Lack of information on end-user flexibility provided by dynamic operating envelopes
- Lack of coordination between stakeholders in the overall framework for DOEs

Contribution 1: Centralised control schemes for residential DR to participate in grid services under uncertainties

Computational performance

Number of houses (N_h)	Total execution time (sec)			
	customer override		*set-point change*	
	without-discrete	with-discrete	without-discrete	with-discrete
100	55.22	142.8	14.52	213.5
1000	188.6	2857	176.0	2823

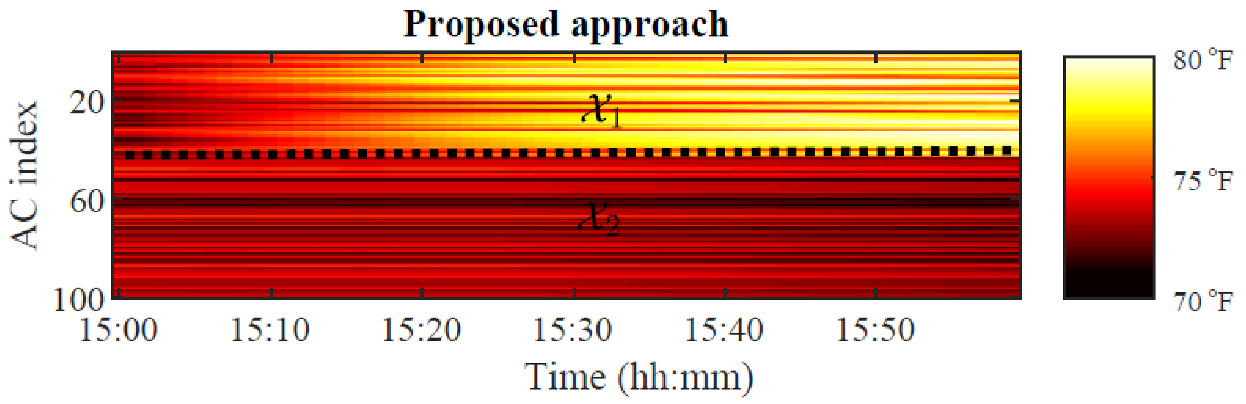
** Simulations are performed on a computing facility equipped with an Intel(R) Xeon(R) CPI E5-2680 v3 @ 2.5 GHz with 32 GB memory

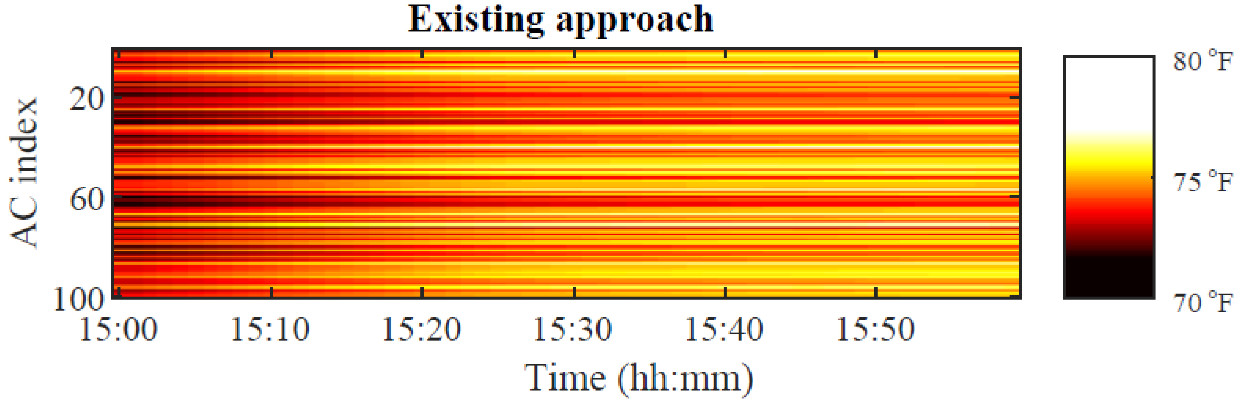
Sampling interval = 1-min

With $N_h = 1000$, total execution time < 3600 sec (1-hour)

Approach is scalable.

Comparison with *PeakSmart* (existing approach)



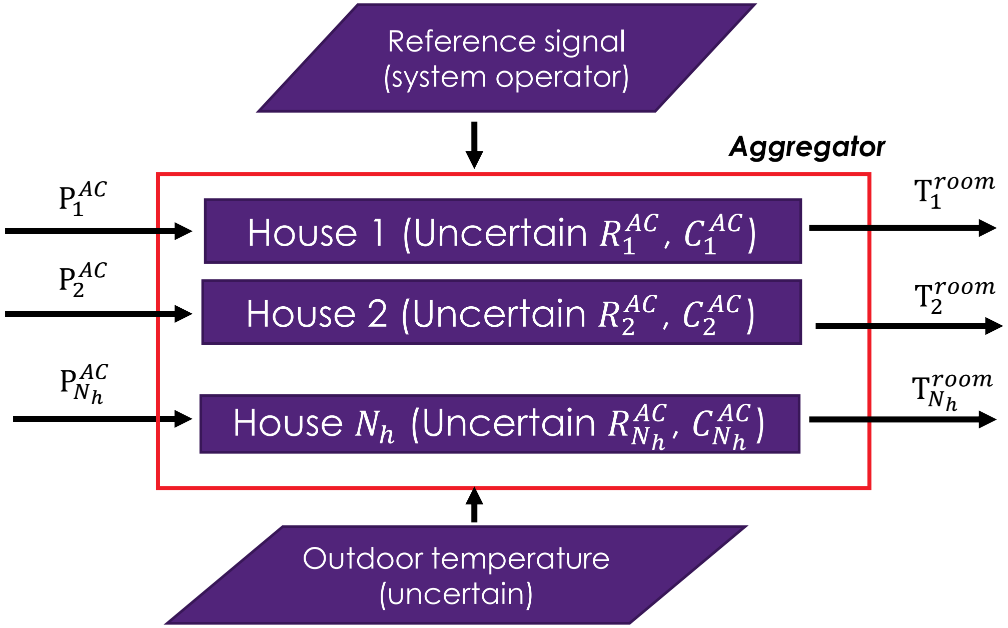


Proposed approach only controls a portion of ACs

Reduced control effort requirement

https://www.energex.com.au/home/control-your-energy/cashback-rewards-program/industry-information/peaksmart-installer-incentive-program

System model



Reference signal (system operator)

Aggregator

P_1^{AC} → House 1 (Uncertain R_1^{AC}, C_1^{AC}) → T_1^{room}

P_2^{AC} → House 2 (Uncertain R_2^{AC}, C_2^{AC}) → T_2^{room}

$P_{N_h}^{AC}$ → House N_h (Uncertain $R_{N_h}^{AC}$, $C_{N_h}^{AC}$) → $T_{N_h}^{room}$

Outdoor temperature (uncertain)

Aggregate system obtained by stacking individual state space models

$$\mathbf{x}(t+1) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\,\mathbf{u}(k) + \mathbf{D}\,\mathbf{v}(k) + \mathbf{w}(k)$$

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k)$$

$\mathbf{x}(t) = [x_1(t), x_2(t) \ldots, x_{N_h}(t)]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Indoor temperature
$\mathbf{u}(t) = [u_1(t), u_2(k), \ldots, u_{N_h}(t)]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Power consumption of ACs
$\mathbf{v}(t) = [v_1(t), v_2(k), \ldots, v_{N_h}(t)]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Nominal outdoor temperature
$\mathbf{w}(t) = [w_1(t), w_2(k), \ldots, w_{N_h}(t)]^{\mathrm{T}} \in \mathbb{R}^{N_h}$	Uncertainties

Derivation of the model with uncertainties

$$T_i^{\text{room}}(t+1) = a_i \cdot T_i^{\text{room}}(t) + (1-a_i) \cdot \left(T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t) \right)$$

$$\boxed{\begin{aligned} R_i^{\text{AC}} &= \tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}} \\ C_i^{\text{AC}} &= \tilde{C}_i^{\text{AC}} + \Delta C_i^{\text{AC}} \end{aligned}}$$

Bounds of uncertainty of thermal parameters known

$$a_i = \exp\left(\frac{-\Delta t}{R_i^{\text{AC}} \cdot C_i^{\text{AC}}} \right)$$

$$= \exp\left(\frac{-\Delta t}{(\tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}}) \cdot (\tilde{C}_i^{\text{AC}} + \Delta C_i^{\text{AC}})} \right)$$

$$a_i = \exp\left(\frac{-\Delta t}{\tilde{R}_i^{\text{AC}} \cdot \tilde{C}_i^{\text{AC}} + \tilde{R}_i^{\text{AC}} \cdot \Delta C_i^{\text{AC}} + \tilde{C}_i^{\text{AC}} \cdot \Delta R_i^{\text{AC}} + \Delta R_i^{\text{AC}} \cdot \Delta C_i^{\text{AC}}} \right)$$

$$a_i = \tilde{a}_i + \Delta a_i$$

$$T_i^{\text{room}}(t+1) = \tilde{a}_i \cdot T_i^{\text{room}}(t) + (1-\tilde{a}_i) \left(T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t) \right) + w_i(k)$$

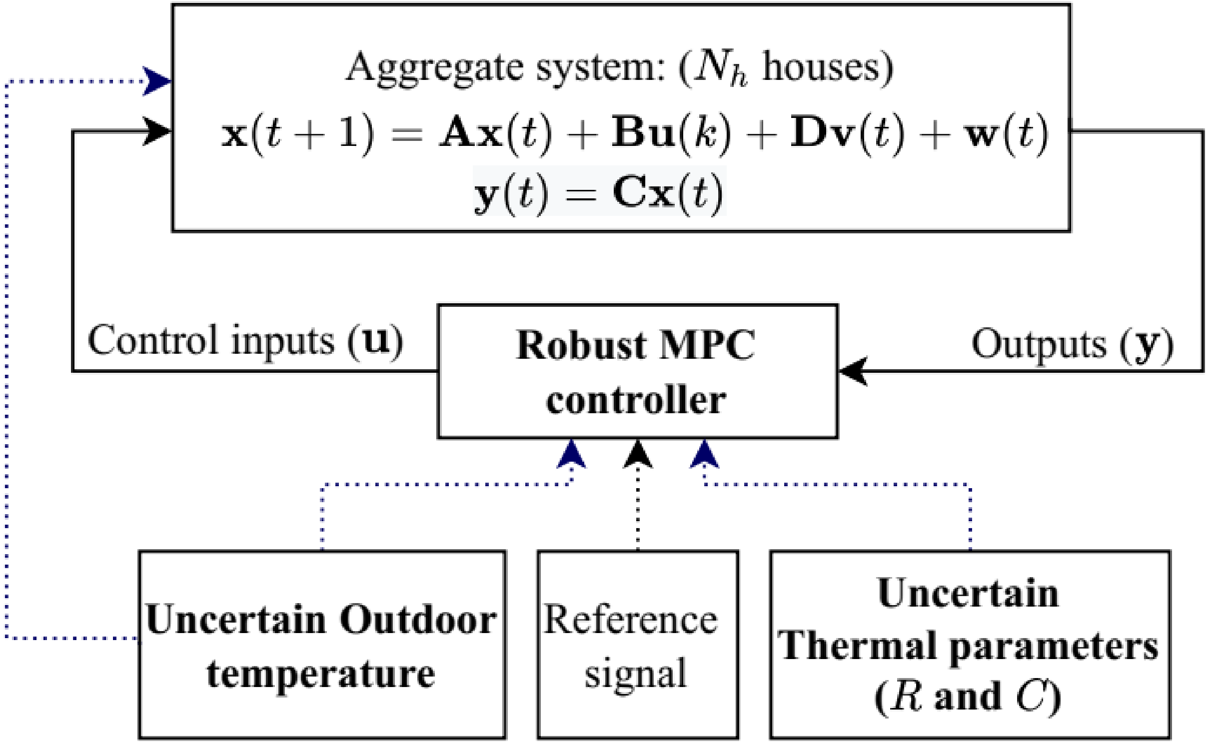
Embedding uncertainties in the model

$$\boxed{\begin{aligned} w_i(t) = {} & (1-\tilde{a}_i) \cdot \left(\Delta T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot \Delta R_i^{\text{AC}} \cdot P_i^{\text{AC}}(t) \right) \\ & - \Delta a_i \cdot \left(T_i^{\text{outdoor}}(t) - \Delta T_i^{\text{outdoor}}(t) - \eta_i^{\text{AC}} \cdot (\tilde{R}_i^{\text{AC}} + \Delta R_i^{\text{AC}}) \cdot P_i^{\text{AC}}(t) \right) \end{aligned}}$$

Individual state-space model with uncertainties

$$x_i(t+1) = A_i x_i(t) + B_i u_i(t) + D_i v_i(t) + w_i(t)$$

Centralised Robust MPC approach



Aggregate system: (N_h houses)

$$\mathbf{x}(t+1) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(k) + \mathbf{D}\mathbf{v}(t) + \mathbf{w}(t)$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t)$$

Control inputs ($\mathbf{u}$)

Robust MPC controller

Outputs ($\mathbf{y}$)

Uncertain Outdoor temperature

Reference signal

Uncertain Thermal parameters (R and C)

Centralised robust MPC implementation of the aggregate system

Population size $N_h = 1000$

Temperature comfort limits $(22{,}24)°C$

Robust MPC controller

- Minimising aggregate tracking error
- Minimising the change in temperature from the set-point
- Minimising the control effort

$$\min_{\mathbf{u}} \max_{\mathbf{w}} \sum_{k=0}^{N-1} \left[w_P \cdot \left| P_{\text{agg}}(t+k|t) - P_{\text{ref}}(t+k) \right| + w_x \cdot \left\| \mathbf{x}(t+k|t) - \mathbf{x}^{\text{set}} \right\|_1 + w_{\Delta u} \cdot \left\| \boldsymbol{\Delta u}(t+k|t) \right\|_1 \right]$$

$$\mathbf{x}(t+k+1|t) = A\,\mathbf{x}(t+k|t) + B\,\mathbf{u}(t+k|t) + D\,\mathbf{v}(t+k|t) + \mathbf{w}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$P_{\text{agg}}(t+k|t) = \mathbf{P}_{\text{rated}}^{\text{T}} \cdot \mathbf{u}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$\boxed{\underline{\mathbf{x}} \le \mathbf{x}(t+k|t) \le \overline{\mathbf{x}}, \quad \forall k \in \mathbb{Z}_{[0,N-1]}}$$ Indoor temperature limits

$$\boldsymbol{\Delta u}(t+k|t) = \mathbf{u}(t+k+1|t) - \mathbf{u}(t+k|t), \quad \forall k \in \mathbb{Z}_{[0,N-1]}$$

$$\boxed{u_i(t+k|t) = \begin{cases} 0.5 \cdot P_{i,\text{rated}}^{\text{AC}} & \\ 0.75 \cdot P_{i,\text{rated}}^{\text{AC}} & \forall i,\ \forall k \in \mathbb{Z}_{[0,N-1]} \\ P_{i,\text{rated}}^{\text{AC}} & \end{cases}}$$ DRM compliance

$$\boxed{\mathbf{w}(t+k|t) \subseteq \mathbb{W}, \quad \forall k \in \mathbb{Z}_{[0,N-1]}}$$ Uncertainties

$$\mathbb{W} = \{\mathbf{w} : \|\mathbf{w}\|_\infty \le \mathbf{w}_0\}$$

Computational performance (for a DR duration of 2-hours)

Population size	Nominal scenario [min]	Under uncertainties [min]	
		$\hat{v} = 0.5°C$	$\hat{v} = 1.0°C$
100	4.748	5.135	5.478
500	19.85	20.31	20.31
1000	**39.51**	**40.38**	**40.23**

** Simulations are performed on a computing facility equipped with an Intel(R) Xeon(R) CPI E5-2680 v3 @ 2.5 GHz with 64 GB memory (parallel execution of the local controller problem)

Sampling time = 5-mins

Total execution time < 2-hours (120-mins)

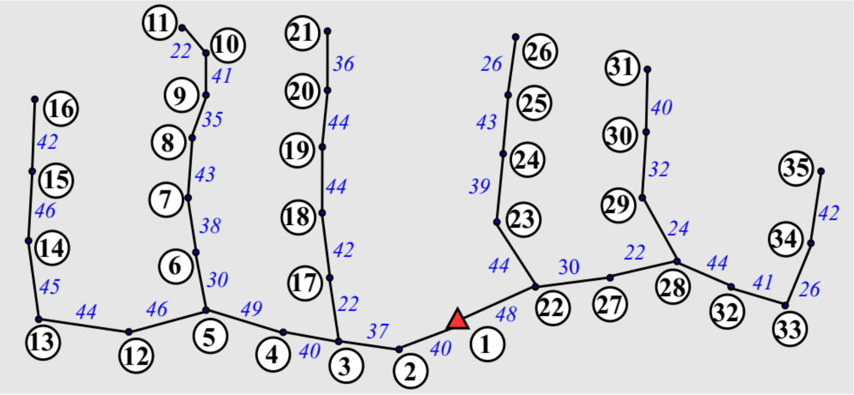
The overall hierarchical implementation is scalable in the presence of uncertainties.

Case study

- Sampling time = 5-mins

Three scenarios:

- No export limits
- With fixed export limits (5-kW)
- With dynamic export limits



Single Line Diagram of the LV network

Computational performance (24-hour period)

Scenario	Total execution time (sec)
No export limits	8.82
Fixed export limits	8.89
Dynamic export limits	110.56

** Simulations are performed on desktop computer equipped with an Intel(R) Core i7 3.20 GHz CPU and 16 GB RAM memory.

The proposed approach is scalable under 5-min dispatch intervals.

Software-in-the-loop validation

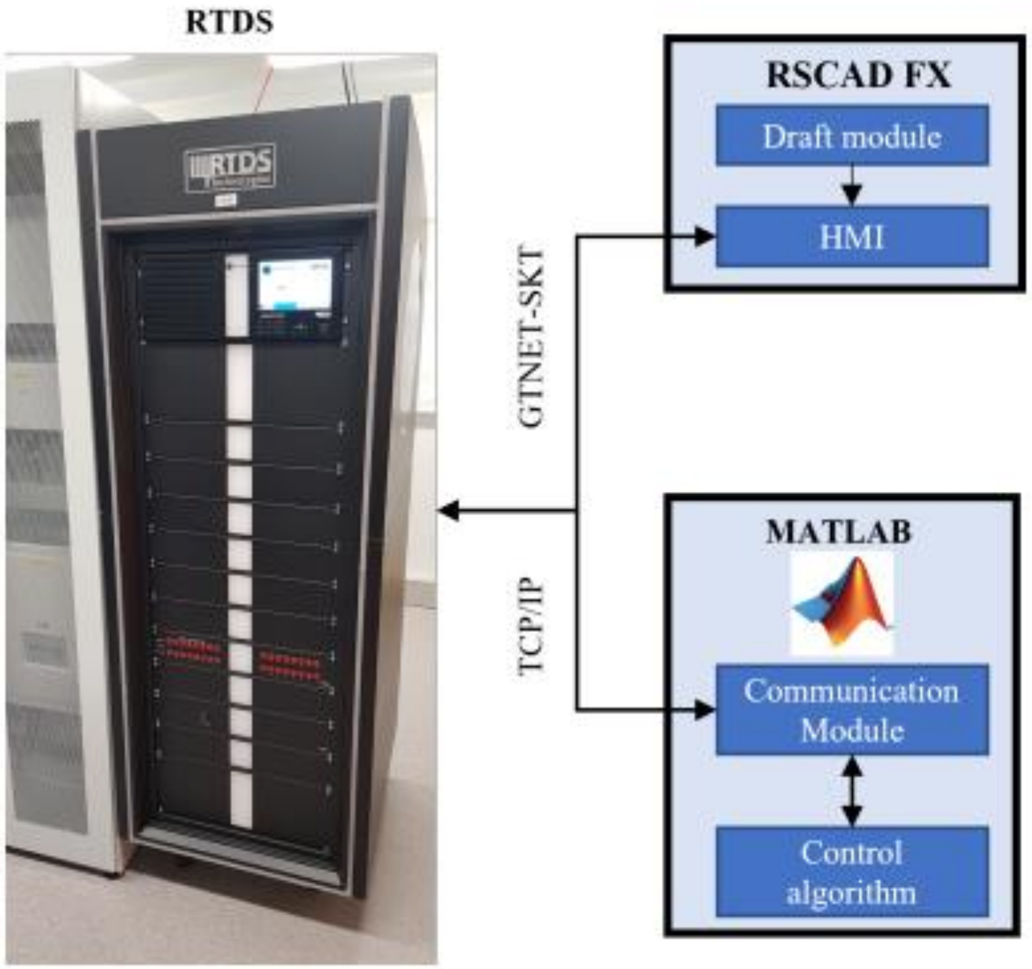


Figure 6.2: The overall SIL setup for RTDS

Software-in-the-loop validation (cnt.)

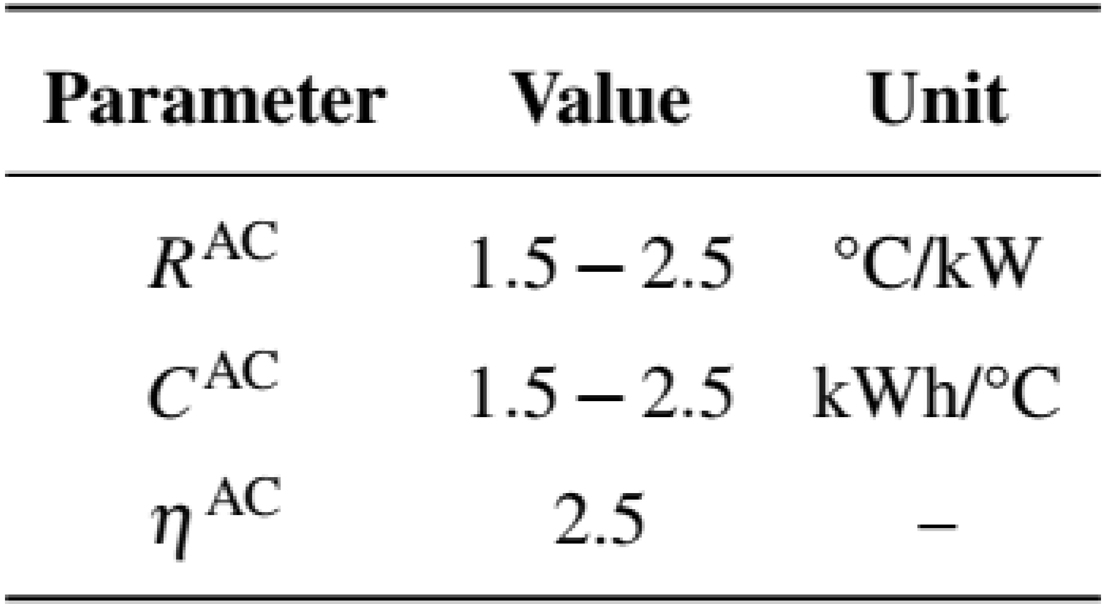
- *Distribution mode* in RSCAD FX used.
- Modelling household load → 1-ph dynamic PQ loads with P,Q controlled externally
- Modelling rooftop PV → 1-ph dynamic PQ sources with P/Q control type (externally controlled)
- Distribution lines → cascaded PI model (MATPI) with [R] and [L] lower-triangular matrices
- Measuring voltages → 1ph RMS meters
- Time step for simulation: 150 micro-seconds

- Inputs to the RTDS updated every 5-mins
- Outputs obtained every 30-sec

Q/A discussion slides

Modelling individual household thermal properties

- As the starting point, nominal thermal parameters can be used.



Parameter	Value	Unit
R^{AC}	1.5 – 2.5	°C/kW
C^{AC}	1.5 – 2.5	kWh/°C
η^{AC}	2.5	–

[1] Mathieu, J. L., Koch, S., & Callaway, D. S. (2013). State Estimation and Control of Electric Loads to Manage Real-Time Energy Imbalance. IEEE Transactions on Power Systems, 28(1), 430–440. https://doi.org/10.1109/TPWRS.2012.2204074

Modelling individual household thermal properties (cnt.)

- In the next stage, the following techniques can be utilised.
  - parameter estimation [1]
  - Data-driven techniques [2]

[1] Brastein, O. M., Perera, D. W. U., Pfeifer, C., & Skeie, N.-O. (2018). Parameter estimation for grey-box models of building thermal behaviour. Energy and Buildings, 169, 58–68. https://doi.org/https://doi.org/10.1016/j.enbuild.2018.03.057

[2] Lork, C., Li, W. T., Qin, Y., Zhou, Y., Yuen, C., Tushar, W., & Saha, T. K. (2020). An uncertainty-aware deep reinforcement learning framework for residential air conditioning energy management. Applied Energy, 276, 115426. https://doi.org/10.1016/j.apenergy.2020.115426

Other household parameters

In addition to thermal parameters, other household parameters can be obtained from [1].

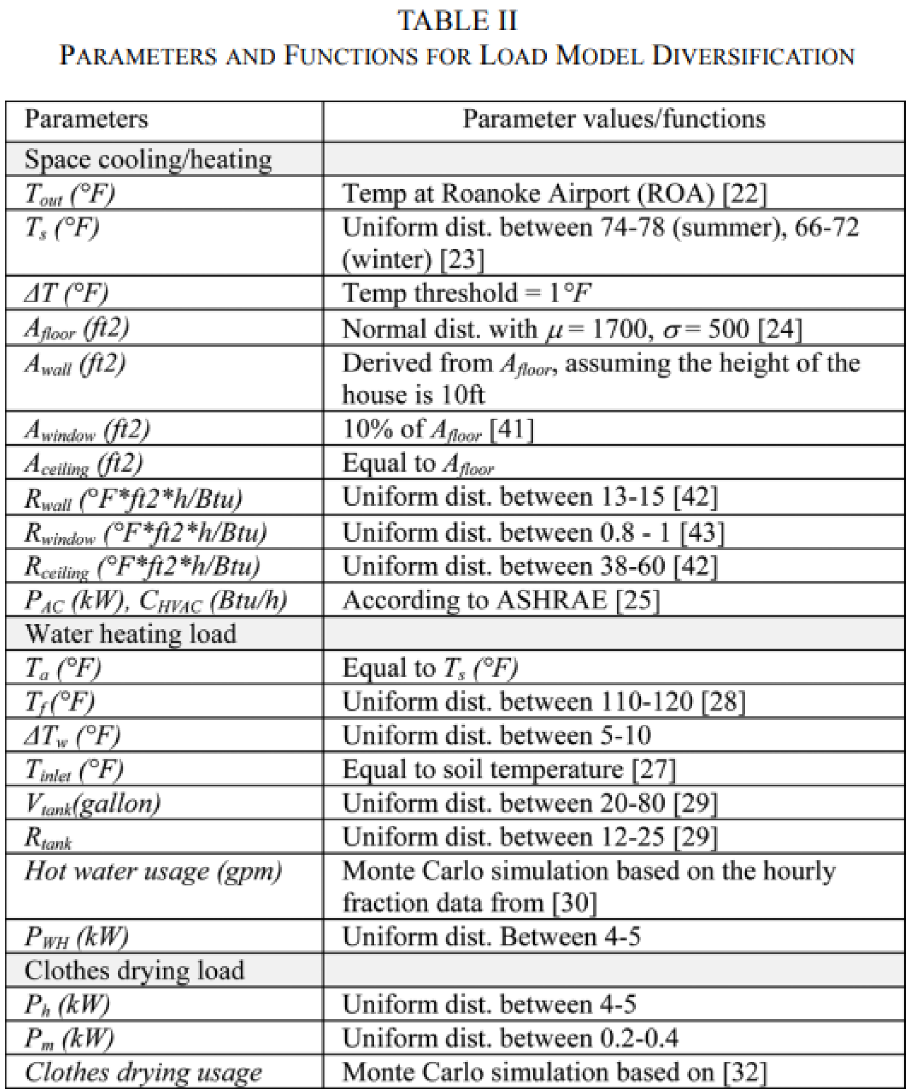
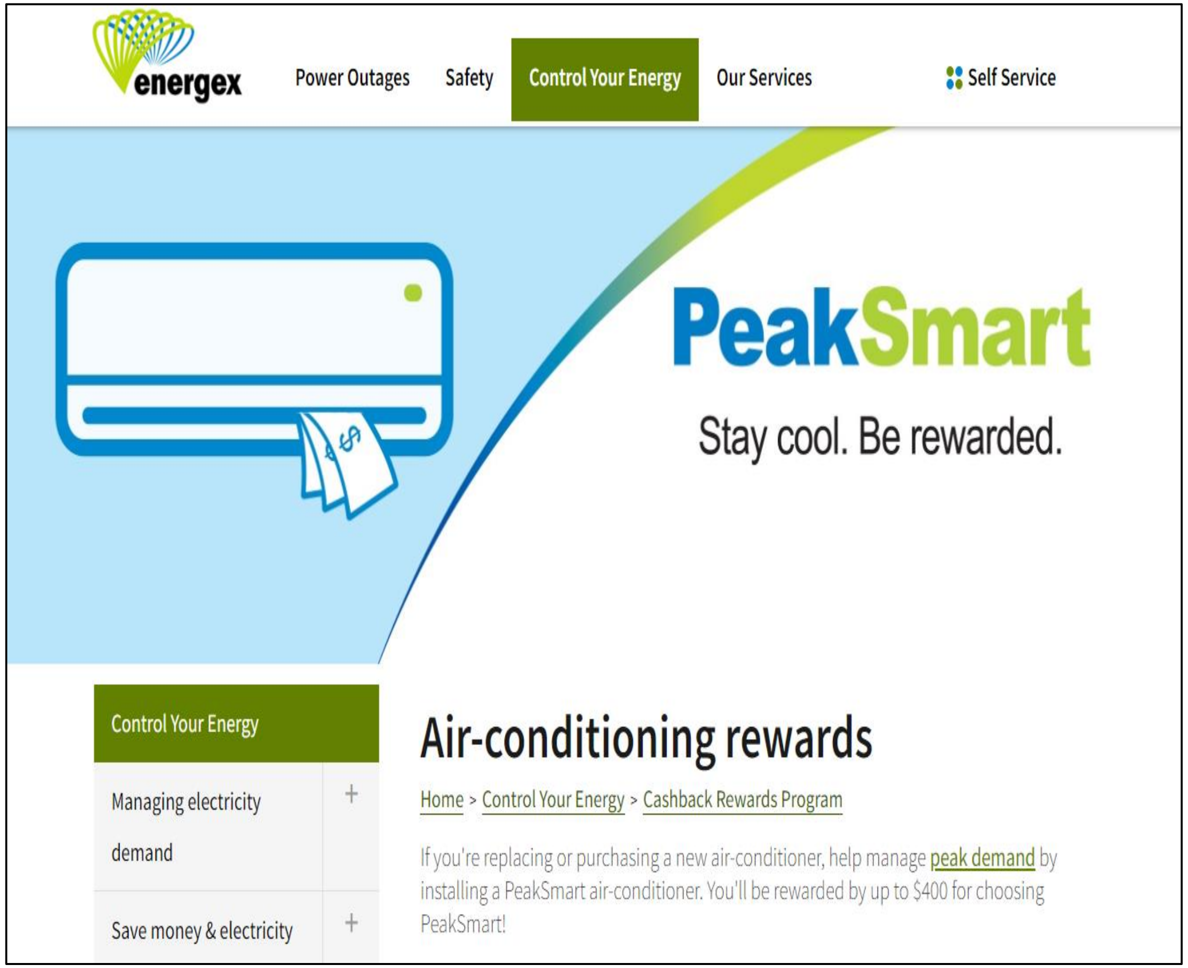


TABLE II
PARAMETERS AND FUNCTIONS FOR LOAD MODEL DIVERSIFICATION

Parameters	Parameter values/functions
Space cooling/heating	
T_{out} (°F)	Temp at Roanoke Airport (ROA) [22]
T_s (°F)	Uniform dist. between 74-78 (summer), 66-72 (winter) [23]
ΔT (°F)	Temp threshold = 1°F
A_{floor} (ft2)	Normal dist. with $\mu = 1700$, $\sigma = 500$ [24]
A_{wall} (ft2)	Derived from A_{floor}, assuming the height of the house is 10ft
A_{window} (ft2)	10% of A_{floor} [41]
$A_{ceiling}$ (ft2)	Equal to A_{floor}
R_{wall} (°F*ft2*h/Btu)	Uniform dist. between 13-15 [42]
R_{window} (°F*ft2*h/Btu)	Uniform dist. between 0.8 - 1 [43]
$R_{ceiling}$ (°F*ft2*h/Btu)	Uniform dist. between 38-60 [42]
P_{AC} (kW), C_{HVAC} (Btu/h)	According to ASHRAE [25]
Water heating load	
T_a (°F)	Equal to T_s (°F)
T_f (°F)	Uniform dist. between 110-120 [28]
ΔT_w (°F)	Uniform dist. between 5-10
T_{inlet} (°F)	Equal to soil temperature [27]
V_{tank}(gallon)	Uniform dist. between 20-80 [29]
R_{tank}	Uniform dist. between 12-25 [29]
Hot water usage (gpm)	Monte Carlo simulation based on the hourly fraction data from [30]
P_{WH} (kW)	Uniform dist. Between 4-5
Clothes drying load	
P_h (kW)	Uniform dist. between 4-5
P_m (kW)	Uniform dist. between 0.2-0.4
Clothes drying usage	Monte Carlo simulation based on [32]

[1] S. Shao, M. Pipattanasomporn, S. Rahman, Development of physical-based demand response enabled residential load models, IEEE Transactions on Power Systems 28 (2) (2013) 607–614. doi:10.1109/TPWRS.2012.2208232

Existing DR schemes for household air-conditioners



Air-conditioning rewards

If you're replacing or purchasing a new air-conditioner, help manage peak demand by installing a PeakSmart air-conditioner. You'll be rewarded by up to $400 for choosing PeakSmart!

PeakSmart events at a glance

PeakSmart events only occur a few times a year, but they have major benefits for the network.

Case Study

Sunday 12 February 2017: *5.30pm to 7.30pm*

Current demand reading: 4343 (MW) - Extreme
Demand Response Mode: 3 - capped to operate at 75%

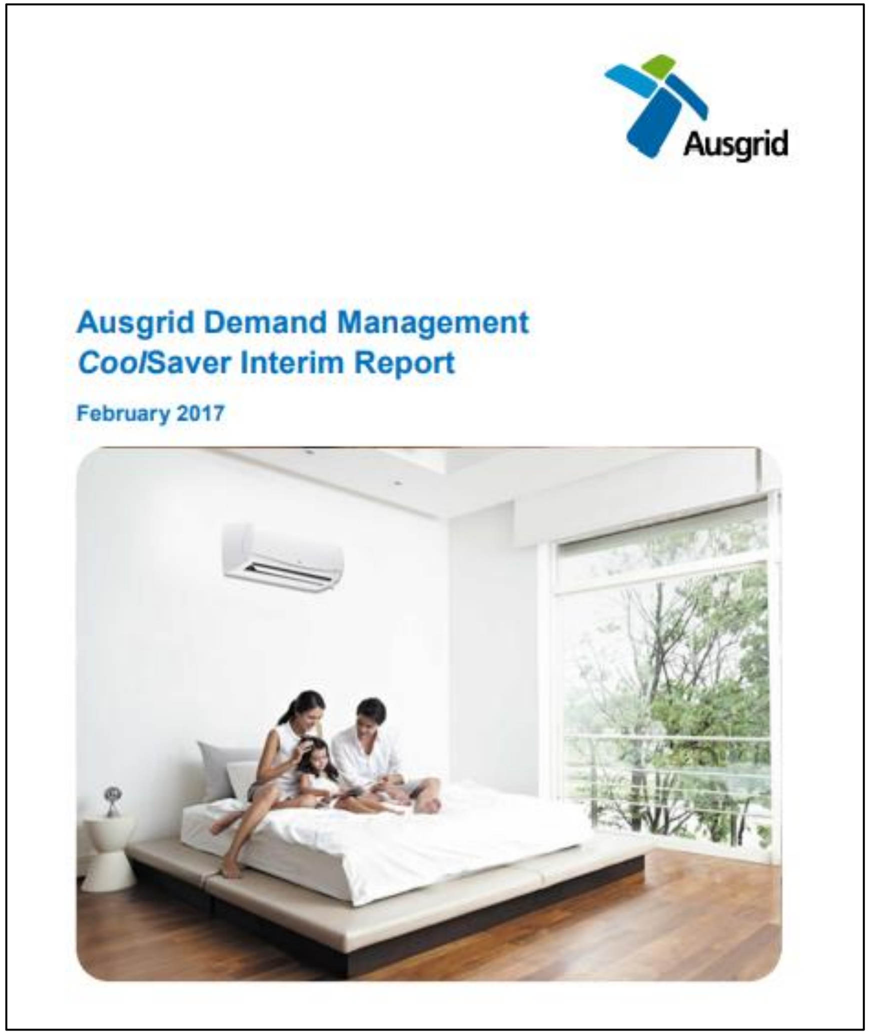
This means that on 12 February 2017, the Current Demand Meter registered an unusually high reading. We signalled our air-conditioners and capped their energy usage at 75% of normal capacity.

After the event, we surveyed our PeakSmart air-conditioning customers. They did not experience any discomfort; in fact, they were not even aware that a PeakSmart event had occurred.

PeakSmart technology means small changes to household or business air-conditioning usage can have big benefits for the community. By reducing demand on the network, we reduce the potential for power outages as well as the need for expensive power infrastructure.

[1] https://www.energex.com.au/home/control-your-energy/cashback-rewards-program/air-conditioning-rewards/peaksmart-events

Existing DR schemes for household air-conditioners (cnt.)



Ausgrid Demand Management
*Cool*Saver Interim Report

February 2017

[1] https://www.ausgrid.com.au/-/media/Documents/Demand-Mgmt/DMIA-research/Ausgrid-CoolSaver-Interim-Report-2017_Final.pdf

Existing DR schemes for household air-conditioners (cnt.)

- All these approaches follow **broadcast control**.

- All the air conditioners participating in the program will receive the **same dispatch set-point** from the utility (aligned with DRM levels) regardless of their operational state and thermal comfort experienced.

[1] https://www.ausgrid.com.au/-/media/Documents/Demand-Mgmt/DMIA-research/Ausgrid-CoolSaver-Interim-Report-2017_Final.pdf

AS 4755.3 DRM modes for inverter air-conditioners

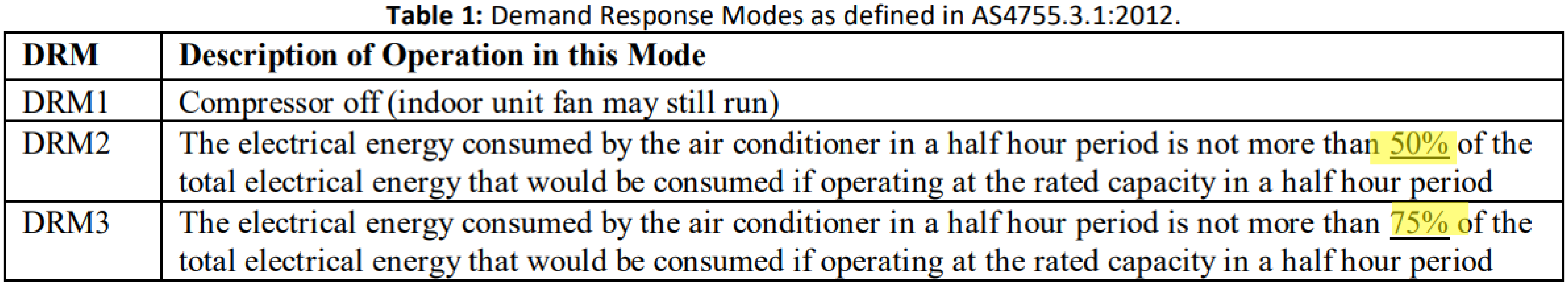


Table 1: Demand Response Modes as defined in AS4755.3.1:2012.

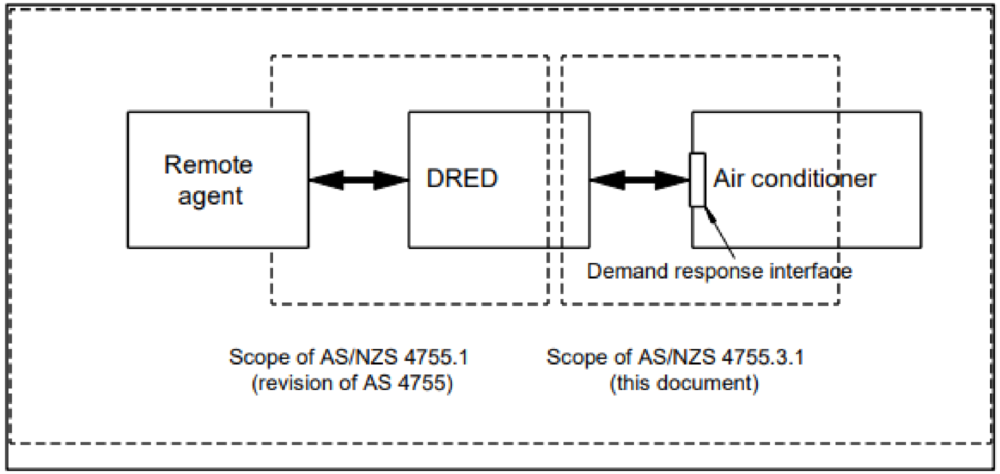
DRM	**Description of Operation in this Mode**
DRM1	Compressor off (indoor unit fan may still run)
DRM2	The electrical energy consumed by the air conditioner in a half hour period is not more than 50% of the total electrical energy that would be consumed if operating at the rated capacity in a half hour period
DRM3	The electrical energy consumed by the air conditioner in a half hour period is not more than 75% of the total electrical energy that would be consumed if operating at the rated capacity in a half hour period

- These DRM schemes are only compatible with inverter-type (variable speed) air-conditioners.
- Regular ON-OFF type air conditioners cannot adopt this control scheme.

[1] https://oia.pmc.gov.au/sites/default/files/posts/2019/08/smart_demand_response_capabilities_for_selected_appliances.pdf

Demand Response Enabling Device (DRED)

Figure 3. Relationship of Remote Agent and DRED to Air Conditioner



Source: AS/NZS 4755.3.1

Demand Response Device

ConnectGrid™ Smart Infrastructure Solution

Enable Intelligent Automatic Control

Applications

The Demand Response Device (DRED) provides a flexible IoT interface to allow remote control of supported network loads and distributed generation. Control output options include a dry contact relay output or AS4755/AS4777 compliant digital outputs, enabling control of equipment such as:

- Air conditioners
- Swimming pool pumps
- Battery storage
- Electric water heaters
- Electric vehicle chargers

As part of the Dynamic Ratings ConnectGrid™ Smart Infrastructure Solution, the DRED offers flexibility for demand response applications, and enables intelligent automatic control of connected distributed energy resources. This allows utilities to balance generation and load.

Features

The DRED has been designed to take advantage of the latest Low-Power Wide-Area Network (LPWAN) communication technologies. This includes the ability to leverage your existing AMI communications investment or take advantage of the latest Telecommunication Provider offerings including Cat M1 or NB IoT.

LPWAN technologies offers decreased power usage, increased range and lower capital and operational costs than traditional communication technologies that are being phased out (e.g. Dial-up / 3G etc.).

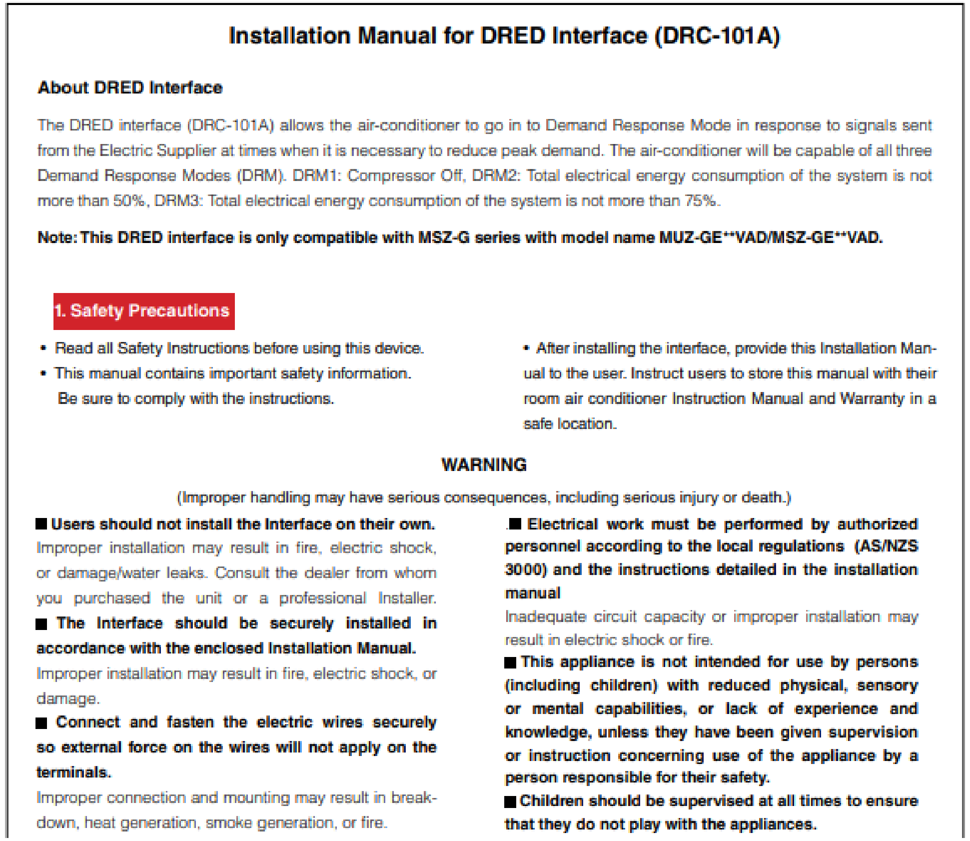
Unlike offerings that receive commands from a propriety central control, the DRED is centered on a secure, open standards enterprise architecture. The architecture supports cloud-based IoT platforms such as AWS or Azure, or on-premise servers.

[1] https://oia.pmc.gov.au/sites/default/files/posts/2019/08/smart_demand_response_capabilities_for_selected_appliances.pdf

[2] https://info.dynamicratings.com/dred

Demand Response Enabling Device (DRED) (cnt.)

MITSUBISHI ELECTRIC
AIR CONDITIONING SYSTEMS



Installation Manual for DRED Interface (DRC-101A)

About DRED Interface

The DRED interface (DRC-101A) allows the air-conditioner to go in to Demand Response Mode in response to signals sent from the Electric Supplier at times when it is necessary to reduce peak demand. The air-conditioner will be capable of all three Demand Response Modes (DRM). DRM1: Compressor Off, DRM2: Total electrical energy consumption of the system is not more than 50%, DRM3: Total electrical energy consumption of the system is not more than 75%.

Note: This DRED interface is only compatible with MSZ-G series with model name MUZ-GEVAD/MSZ-GE**VAD.**

1. Safety Precautions

- Read all Safety Instructions before using this device.
- This manual contains important safety information. Be sure to comply with the instructions.
- After installing the interface, provide this Installation Manual to the user. Instruct users to store this manual with their room air conditioner Instruction Manual and Warranty in a safe location.

WARNING

(Improper handling may have serious consequences, including serious injury or death.)

■ **Users should not install the Interface on their own.**
Improper installation may result in fire, electric shock, or damage/water leaks. Consult the dealer from whom you purchased the unit or a professional Installer.

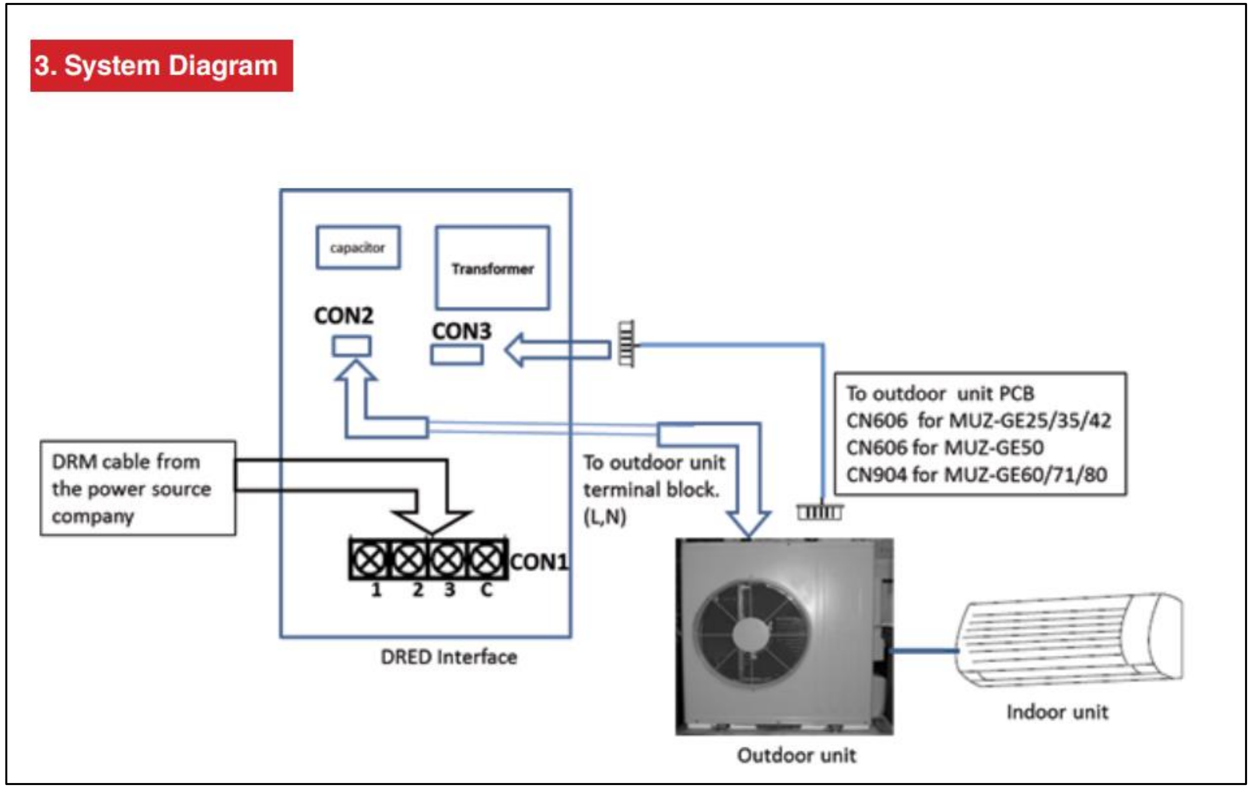
■ **The Interface should be securely installed in accordance with the enclosed Installation Manual.**
Improper installation may result in fire, electric shock, or damage.

■ **Connect and fasten the electric wires securely so external force on the wires will not apply on the terminals.**
Improper connection and mounting may result in break-down, heat generation, smoke generation, or fire.

■ **Electrical work must be performed by authorized personnel according to the local regulations (AS/NZS 3000) and the instructions detailed in the installation manual**
Inadequate circuit capacity or improper installation may result in electric shock or fire.

■ **This appliance is not intended for use by persons (including children) with reduced physical, sensory or mental capabilities, or lack of experience and knowledge, unless they have been given supervision or instruction concerning use of the appliance by a person responsible for their safety.**

■ **Children should be supervised at all times to ensure that they do not play with the appliances.**

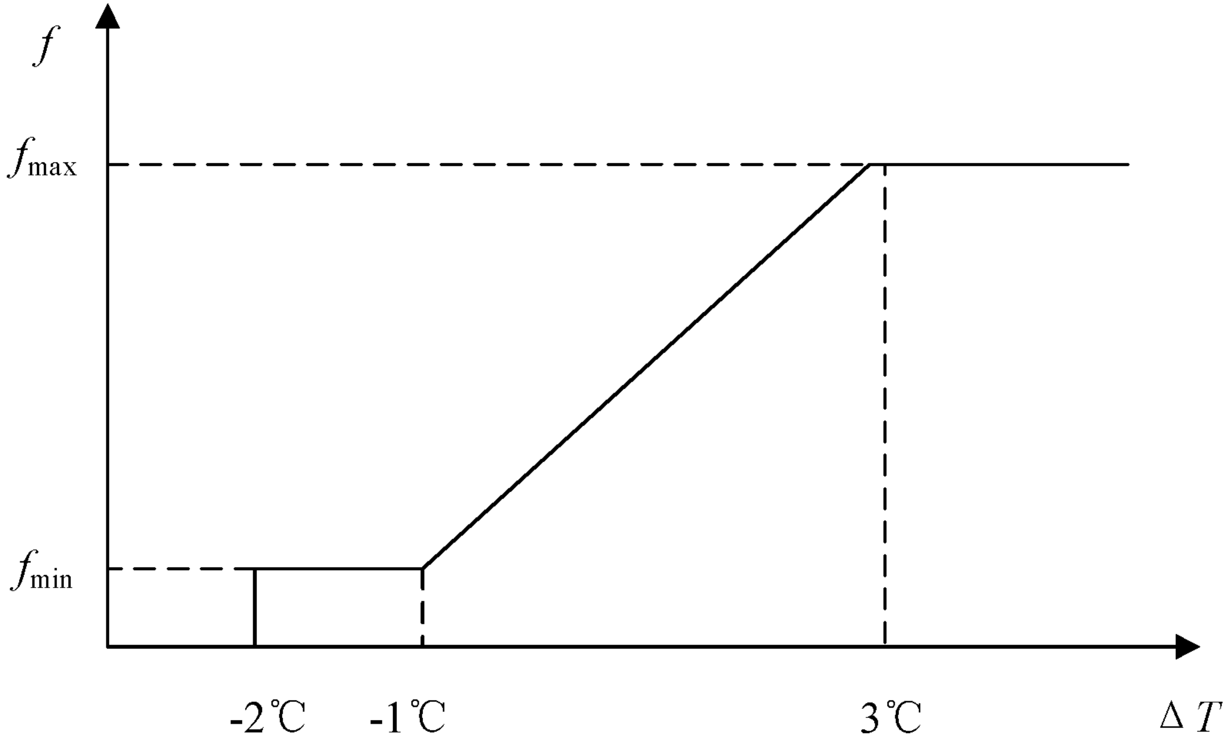


3. System Diagram

[1] https://www.ergon.com.au/__data/assets/pdf_file/0020/423344/Mitsubishi.pdf

Compressor frequency of inverter-type air conditioners

Compressor frequency operating range: 20 – 150 Hz [1]

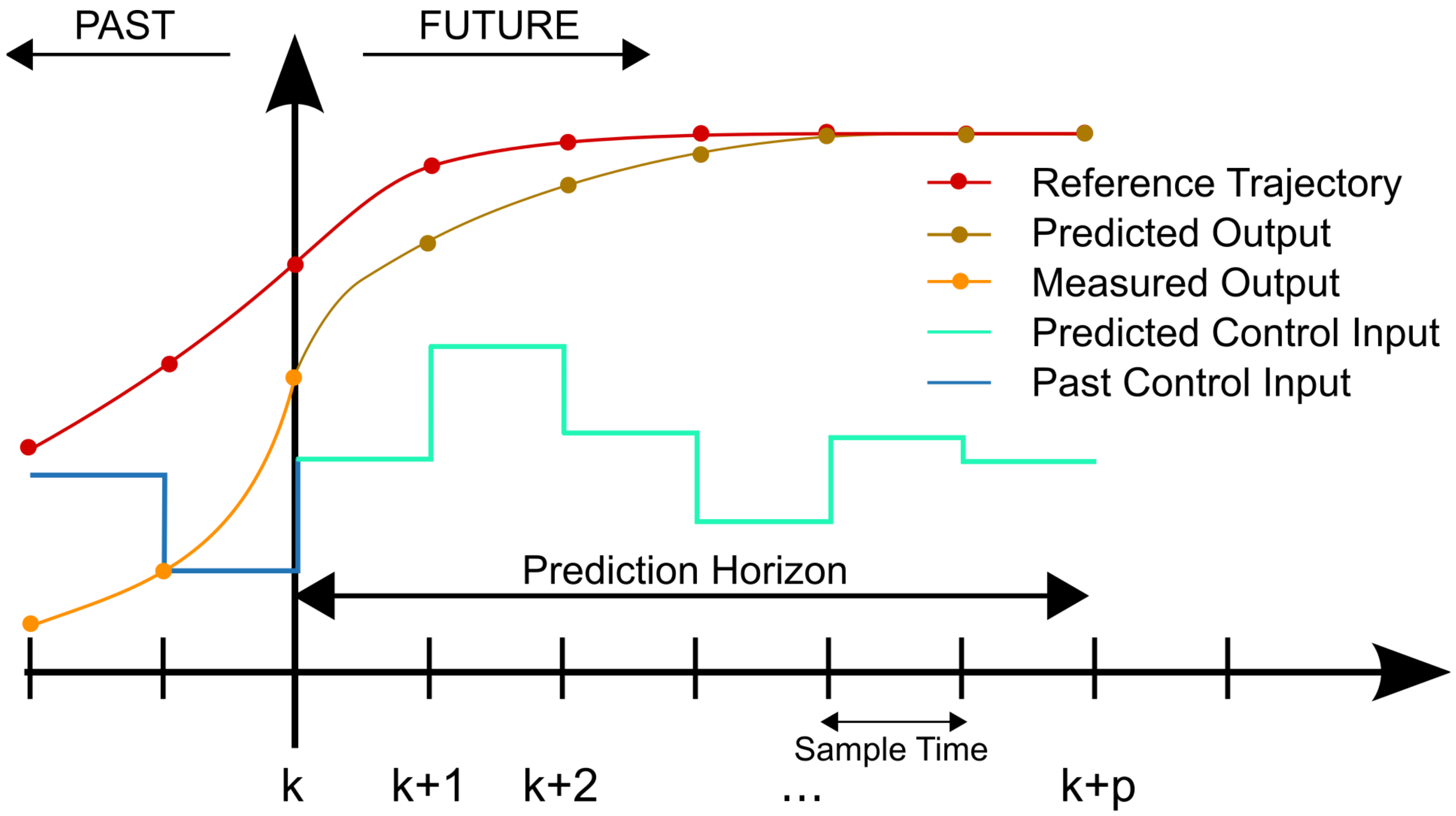


$$Q_i^{AC}(t) = \kappa_Q \cdot f_i(t) + \mu_Q$$
$$P_i^{AC}(t) = \kappa_P \cdot f_i(t) + \mu_P$$

[1] M. Song, C. Gao, H. Yan, J. Yang, Thermal battery modeling of inverter air conditioning for demand response, IEEE Transactions on Smart Grid 9 (6) (2018) 5522–5534. doi:10.1109/TSG.2017.2689820.

[2] Y. Che, J. Yang, Y. Zhao, and S. Xue, “Control Strategy for Inverter Air Conditioners under Demand Response,” Processes, vol. 7, no. 7, p. 407, Jul. 2019, doi: 10.3390/pr7070407.

MPC control strategy



By Martin Behrendt - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7963069

ADMM scheme: Information exchange

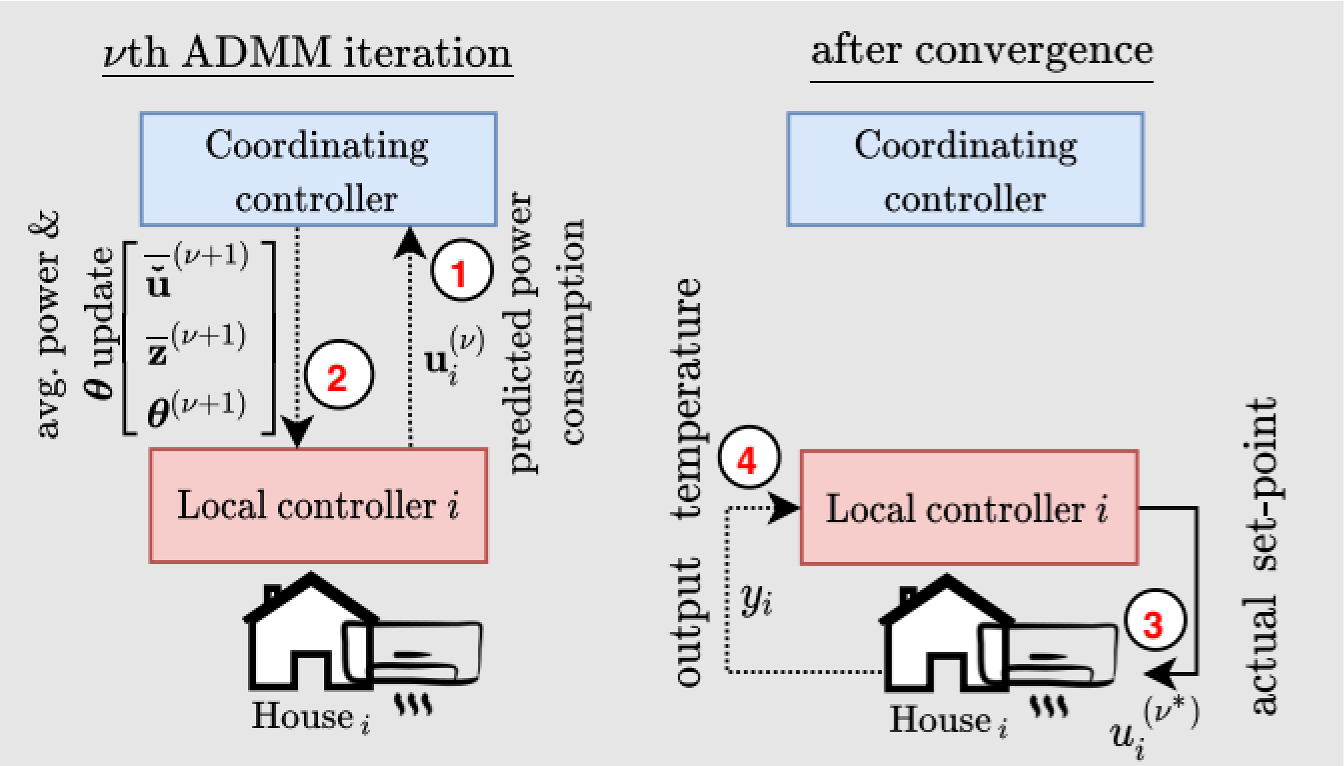


Figure 4.2: The hierarchical control scheme depicting the control and information flow between i-th local controller (LC_i) and the coordinating controller

Rooftop PV inverter control modes

- As per AS/NZS 4772:2:2020 standard, inverters should be capable of providing support to the grid by working outside the typical operating characteristics of an inverter.

- Available operating modes for the inverter
  - Volt-watt mode
  - Volt-var mode
  - Fixed power factor mode (reactive power mode)

- According to clause 2.6, all inverters will need to be able to absorb or supply reactive power in line with power quality response modes (e.g., volt-var, volt-watt)

Standards Australia, "AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements,"

Rooftop PV inverter control modes (cnt.)

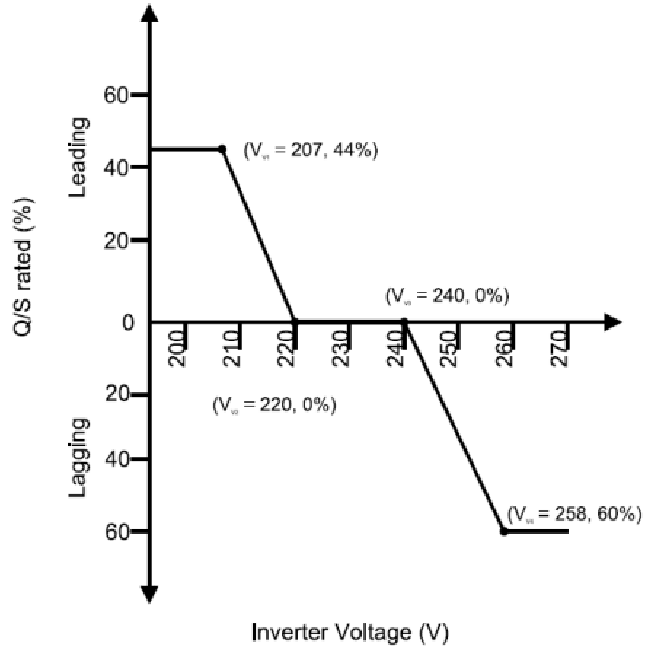


Figure 1: Volt-var response mode

Table 13 Volt–var response mode settings

Reference	Voltage	Inverter reactive power level (Q) % of S_{rated}
V_{V1}	207 V	44% supplying
V_{V2}	220 V	0%
V_{V3}	240 V	0%
V_{V4}	258 V	60% absorbing

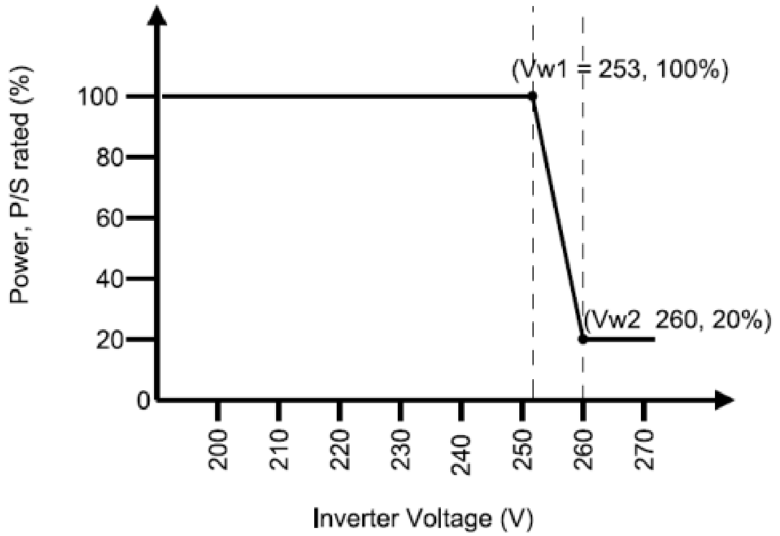


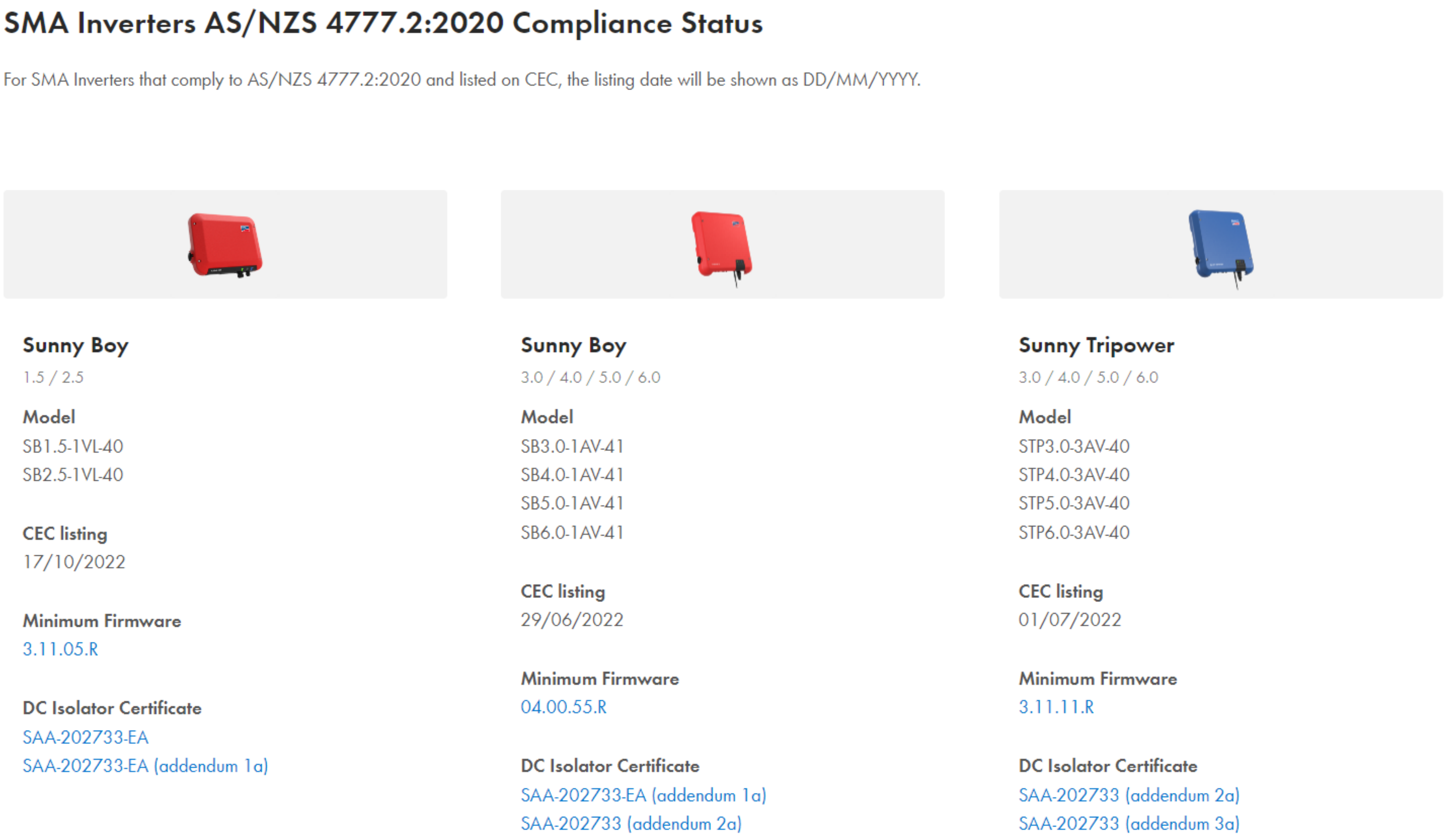
Figure 2: Volt-watt response mode

Table 14 Volt-watt response mode settings

Reference	Voltage	Inverter maximum active power output level (P) % of S_{rated}
V_{W1}	253 V	100%
V_{W4}	260 V	20%

STNW1174 Standard for Low Voltage Embedded Generating Connections, Energex, https://www.energex.com.au/__data/assets/pdf_file/0009/493515/STNW1174-Standard-for-Low-Voltage-EG-Connections.pdf

AS/NZS 4772:2:2020 compliant rooftop PV inverters



SMA Inverters AS/NZS 4777.2:2020 Compliance Status

For SMA Inverters that comply to AS/NZS 4777.2:2020 and listed on CEC, the listing date will be shown as DD/MM/YYYY.

Sunny Boy

1.5 / 2.5

Model

SB1.5-1VL-40

SB2.5-1VL-40

CEC listing

17/10/2022

Minimum Firmware

3.11.05.R

DC Isolator Certificate

SAA-202733-EA

SAA-202733-EA (addendum 1a)

Sunny Boy

3.0 / 4.0 / 5.0 / 6.0

Model

SB3.0-1AV-41

SB4.0-1AV-41

SB5.0-1AV-41

SB6.0-1AV-41

CEC listing

29/06/2022

Minimum Firmware

04.00.55.R

DC Isolator Certificate

SAA-202733-EA (addendum 1a)

SAA-202733 (addendum 2a)

Sunny Tripower

3.0 / 4.0 / 5.0 / 6.0

Model

STP3.0-3AV-40

STP4.0-3AV-40

STP5.0-3AV-40

STP6.0-3AV-40

CEC listing

01/07/2022

Minimum Firmware

3.11.11.R

DC Isolator Certificate

SAA-202733 (addendum 2a)

SAA-202733 (addendum 3a)

https://www.sma-australia.com.au/for-solar-professionals/as-nzs-4777-2020-inverter-standard

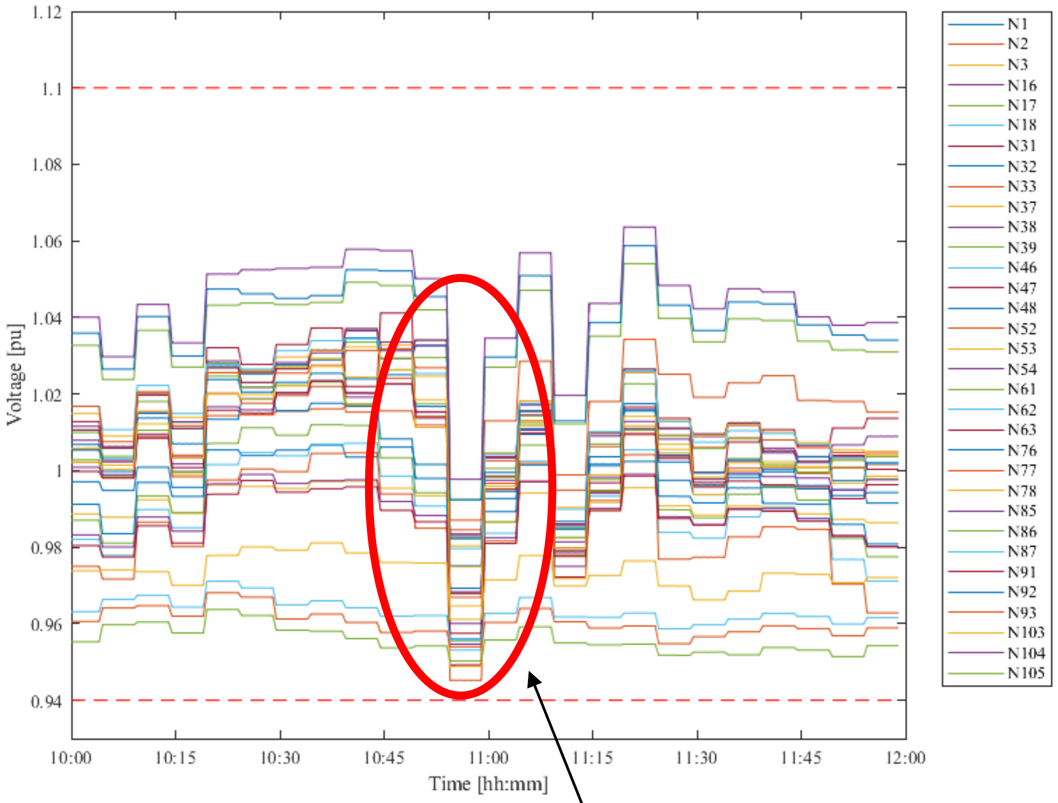
DNSP remotely switching off rooftop PV

- Aligned with AS:4777.2 standard for grid-connected inverters, export/generation limitations are enabled to maintain a minimum demand in the network.
- Under generation limit control and export limit control schemes, inverters are required to shut down within a specific period of time if pre-determined soft and hard limits are met.

Standards Australia, "AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements,"

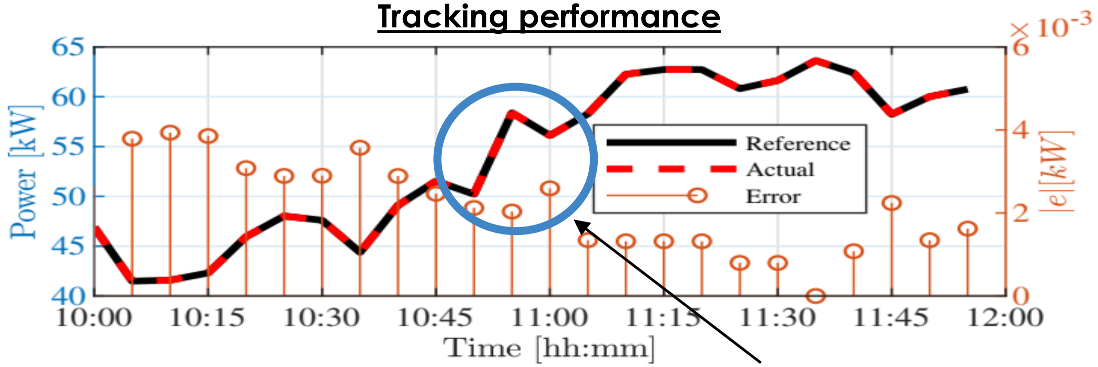
Clarification of the voltage profile in SIL validations

Voltage profile



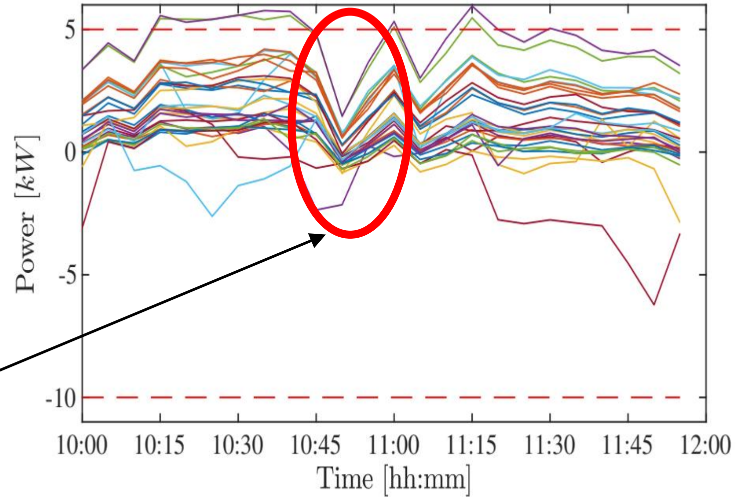
As airconditioner load increases, a dip occurs in the voltage profile between 10:45 and 11:00

Tracking performance



A sharp increase in the demand profile of air conditioners required to track the load set-point

Active power injections at the POC



(a) *DOE customers*

Active power **injection** at the POC decreases (as the airconditioner load increases)
[A reduction in power injection corresponds to an increment in demand]