

Aggregate Modeling of Distribution System with Multiple Smart Inverters

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Outline

- What is Smart Inverter (SI)?
- Issue of Distribution System Analysis with SIs
- Purpose of Our Research
- Proposed Method
- Simulation Result
- Summary

What is Smart Inverter?



Common Functions for Smart Inverters

4th Edition

3002008217

EPRI, "Common Functions for Smart Inverters: 4th Edition", 2016

What is Smart Inverter?

- PV/Battery inverter with grid support functions
(voltage/frequency control, ride-through, communication, etc.)

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EPRI, "Common Functions for Smart Inverters: 4th Edition", 2016

What is Smart Inverter?

Evolution of grid support functions

IEEE Std 1547-
2003

- **Shall NOT** actively regulate voltage
- **Shall** trip on abnormal voltage/frequency



IEEE Std 1547a-
2014
(Amendment 1)

- **May** actively regulate voltage
- **May** ride through abnormal voltage or frequency
- **May** provide frequency response



IEEE Std 1547-
2018

- **Shall be capable of** actively regulating voltage
- **Shall** ride through abnormal voltage/frequency
- **Shall be capable of** frequency response

Source: NREL

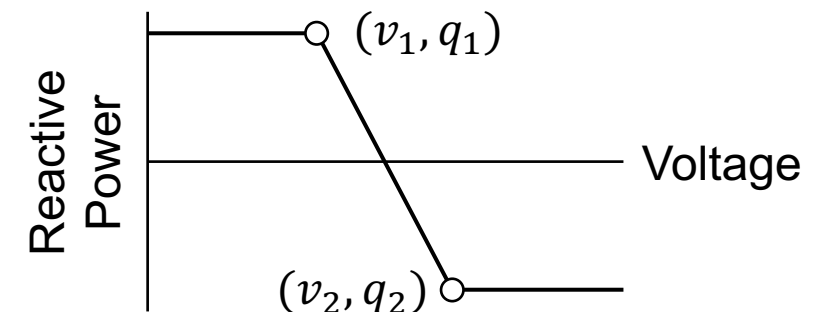
IEEE STANDARDS ASSOCIATION

C. Stice, *et al.*, "IEEE Std 1547-2018", NERC SPIDER WG Meeting, 2019
https://www.nerc.com/comm/PC/System%20Planning%20Impacts%20from%20Distributed%20Energy%20Re/IEEE%20SCC21_1547_Overview_NERC_SPIDERWG_01072019.pdf

Analysis of Distribution System with Smart Inverters

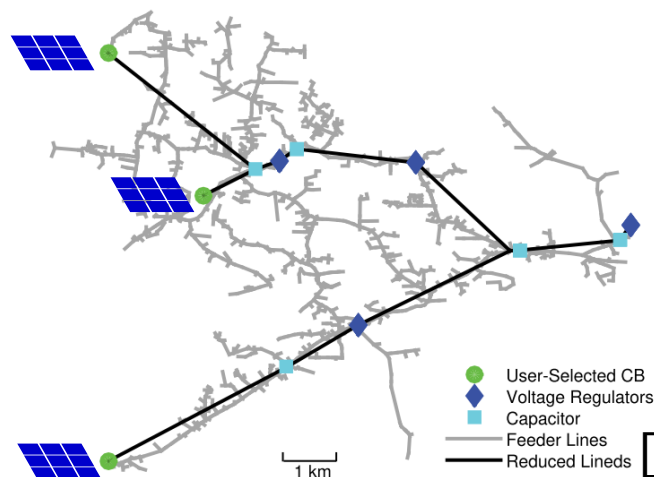
- Volt-Var function
 - Controls reactive power output depending on its voltage
 - Mainly used for voltage control in distribution system
- Distribution system with smart inverters
 - Important to understand complicated power flow
 - Need various case studies
 - **Smaller computational burden is expected**

Volt-Var curve

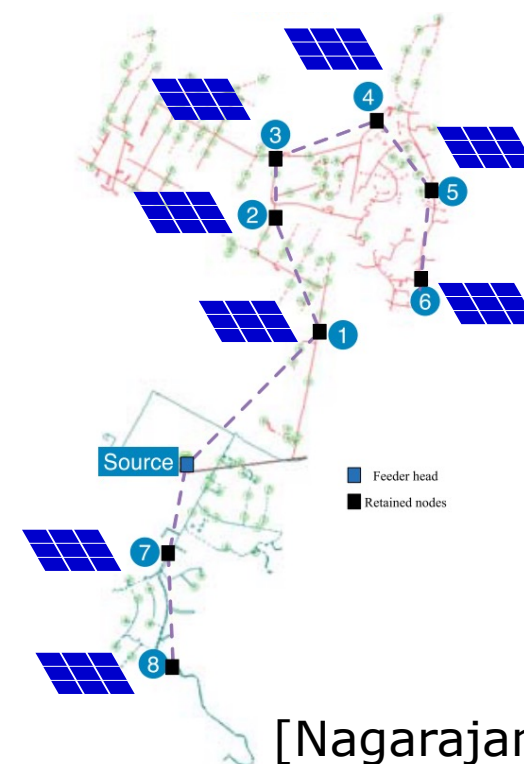


Method for Reducing Computational Burden

- Fast quasi-static time series simulation [Qureshi, *et al.*, 2018]
 - Difficult to apply to the commercial real-time simulators
- Distribution system node reduction [Nagarajan, *et al.*, 2017], [Pecenak, *et al.*, 2019]
 - Aggregate nodes with smaller error of voltage
 - PV is installed after node reduction



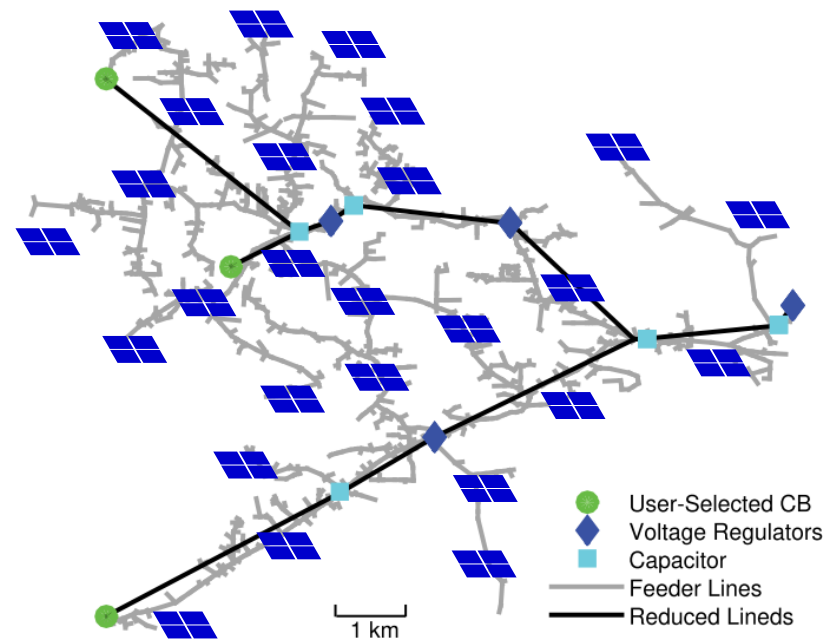
[Pecenak, *et al.*, 2019]



[Nagarajan, *et al.*, 2017]

Node aggregation for Analysis of Distribution System with Volt-Var Function

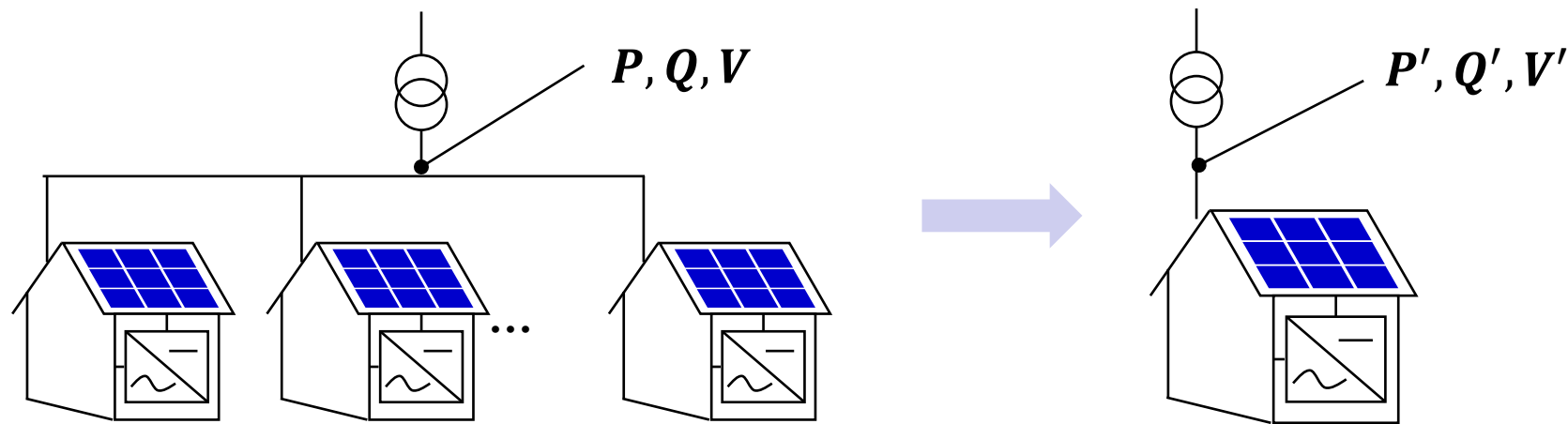
- LVDSs with Many smart inverters (SIs) with Volt-Var function
 - Each SI controls reactive power depending on its voltage
 - Timing of reactive power output is different
 - Node reduction method has not discussed well



[Pecenak, *et al.*, 2019]

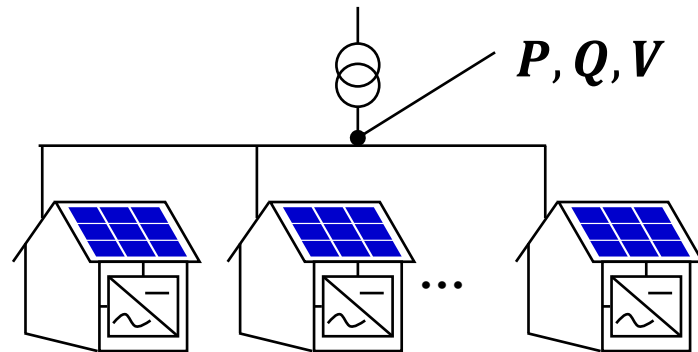
Node aggregation for Analysis of Distribution System with Volt-Var Function

- Purpose of our research
 - Propose node aggregation method in LVDS with multiple smart inverters with Volt-Var function

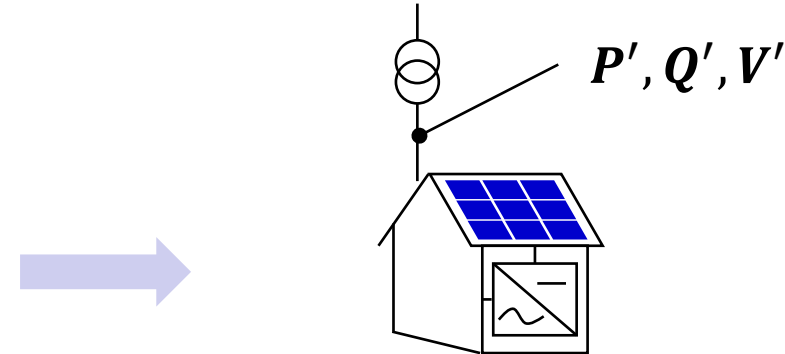


Proposed Method: Node Aggregation

- Original LVDS



- Aggregated LVDS



- PV capacity

$$c^{pv} = \{ c_1^{pv}, c_2^{pv}, \dots, c_N^{pv} \}$$

- Load capacity

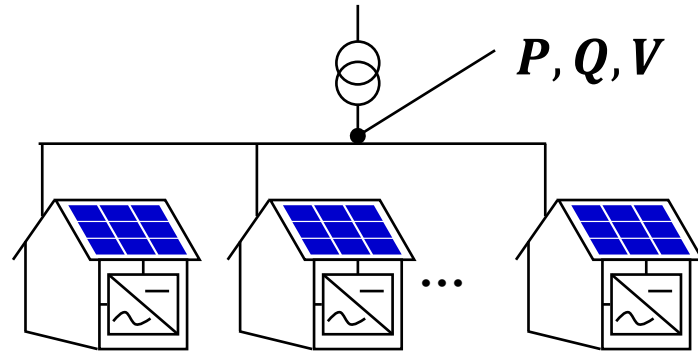
$$c^{ld} = \{ c_1^{ld}, c_2^{ld}, \dots, c_N^{ld} \}$$

$$c^{pv'} = \sum_{n=1}^N c_n^{pv}$$

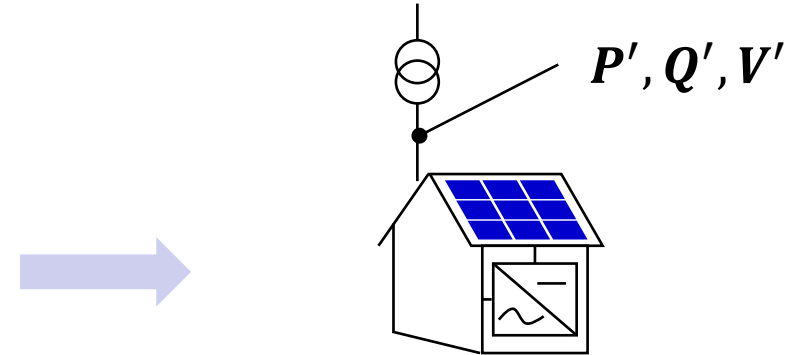
$$c^{ld'} = \sum_{n=1}^N c_n^{ld}$$

Proposed Method: Node Aggregation

- Original LVDS



- Aggregated LVDS



- PV profile

$$\mathbf{x}^{\text{pv}} = \{ \mathbf{x}_1^{\text{pv}}, \mathbf{x}_2^{\text{pv}}, \dots, \mathbf{x}_N^{\text{pv}} \}$$

- Load profile

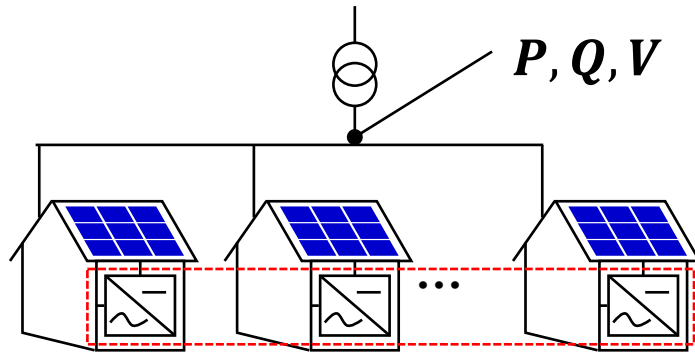
$$\mathbf{x}^{\text{ld}} = \{ \mathbf{x}_1^{\text{ld}}, \mathbf{x}_2^{\text{ld}}, \dots, \mathbf{x}_N^{\text{ld}} \}$$

$$\mathbf{x}^{\text{pv}'} = \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n^{\text{pv}}$$

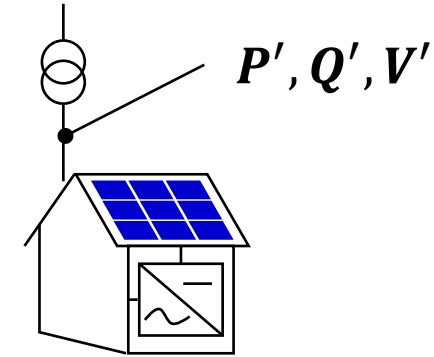
$$\mathbf{x}^{\text{ld}'} = \frac{1}{N} \sum_{n=1}^N \mathbf{x}_n^{\text{ld}}$$

Proposed Method: Determination of Volt-Var Curve

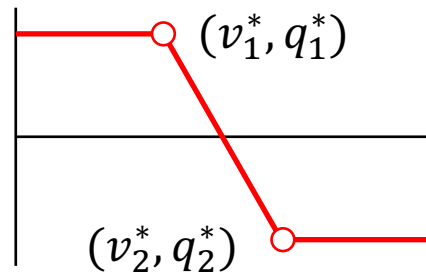
- Original LVDS



- Aggregated LVDS

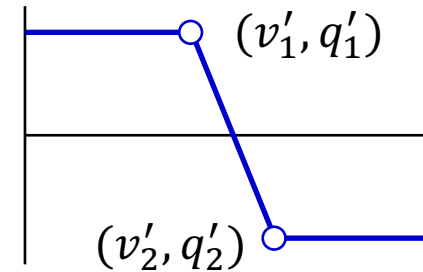


- Volt-Var curve



$$\mathbf{VVC}^* = \{(v_1^*, q_1^*), (v_2^*, q_2^*)\}$$

$$= \operatorname{argmin}_{\mathbf{VVC}} \sum_{n=1}^N \sum_{t=1}^T \{V_{n,t}(\mathbf{VVC}) - V^c\}$$

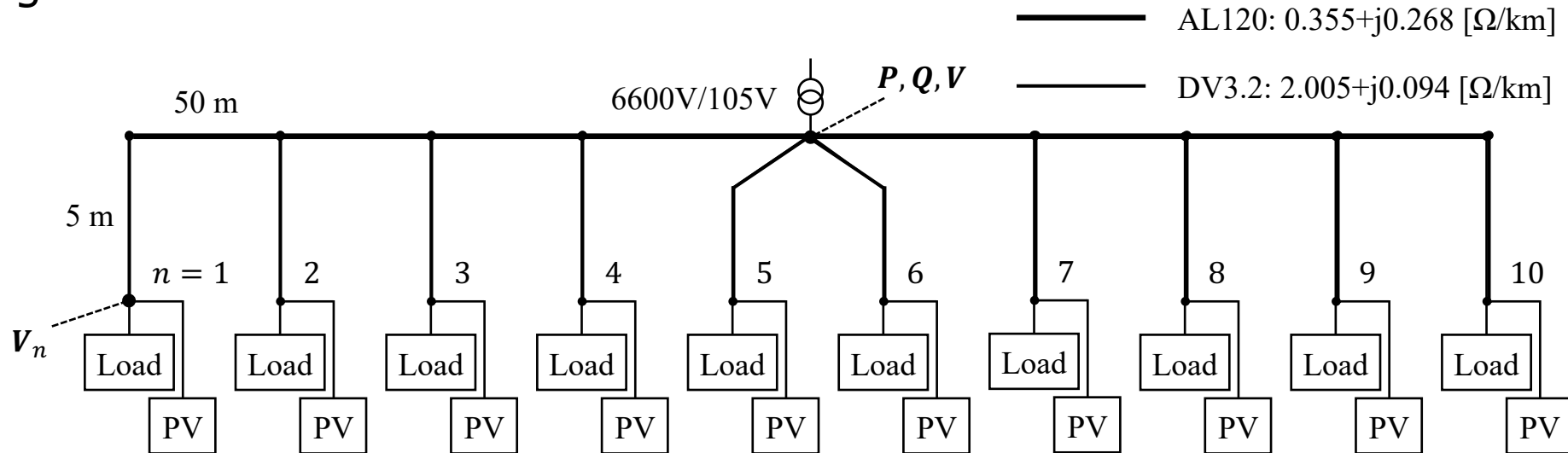


$$\mathbf{VVC}' = \{(v_1', q_1'), (v_2', q_2')\}$$

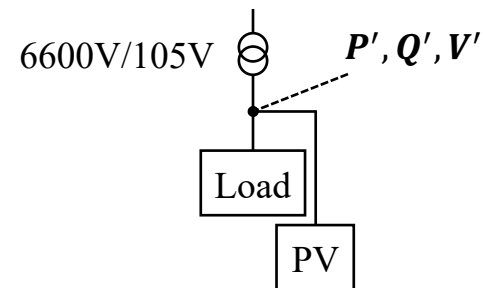
$$= \operatorname{argmin}_{\mathbf{VVC}} \frac{1}{T} \sum_{t=1}^T |V_t(\mathbf{X}, \mathbf{VVC}^*) - V'_t(\mathbf{X}', \mathbf{VVC})|$$

Simulation: Low-Voltage Distribution System Model

- Original LVDS model



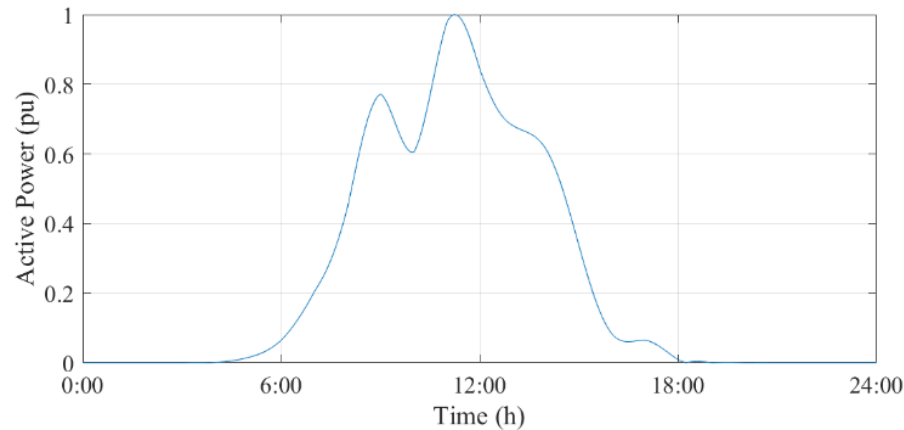
- Aggregated LVDS model



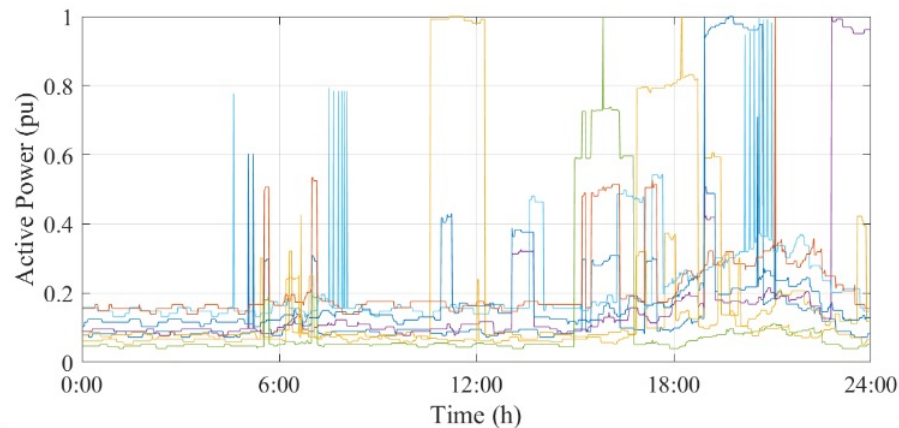
Simulation: PV and Load Profiles (1 min.)

- Original LVDS

- PV

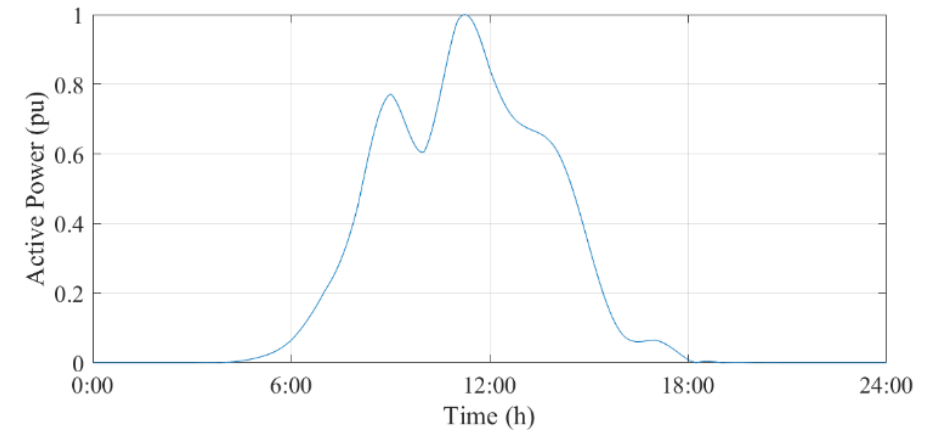


- Load

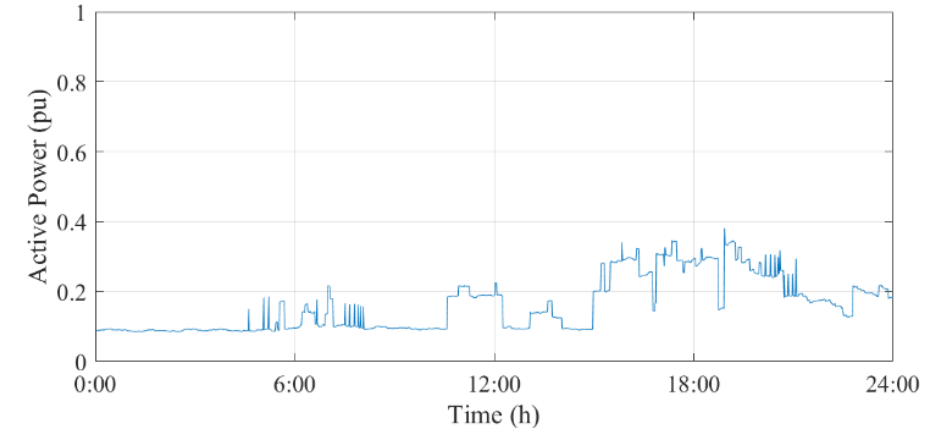


- Aggregated LVDS

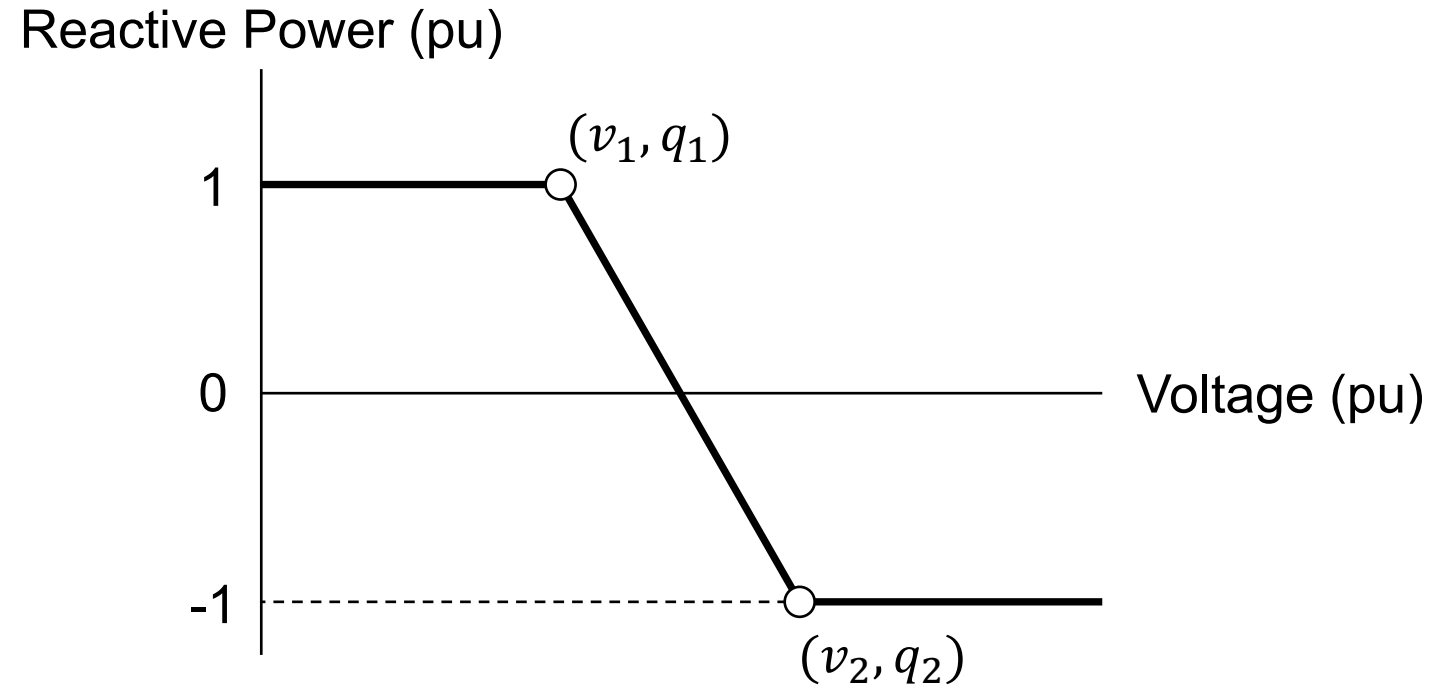
- PV



- Load



Simulation: Volt-Var Curve



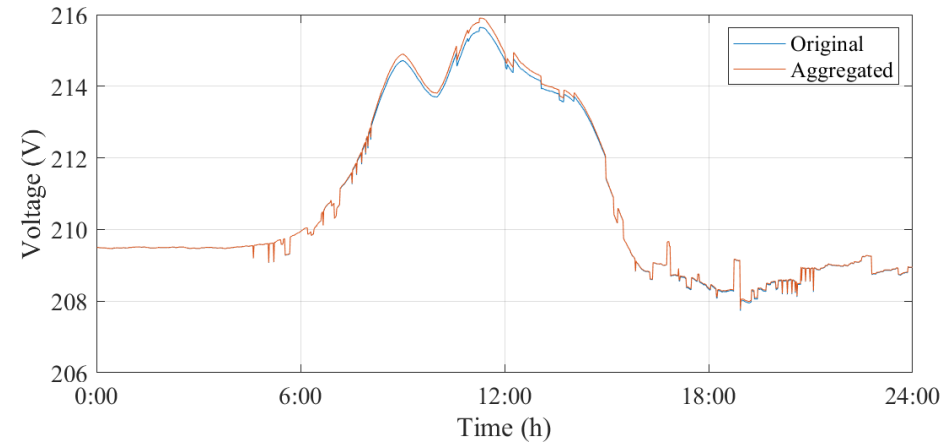
- Search combinations that satisfies $v_1 < v_2$

$v_1: 0.95, 0.955, \dots, 1.065$

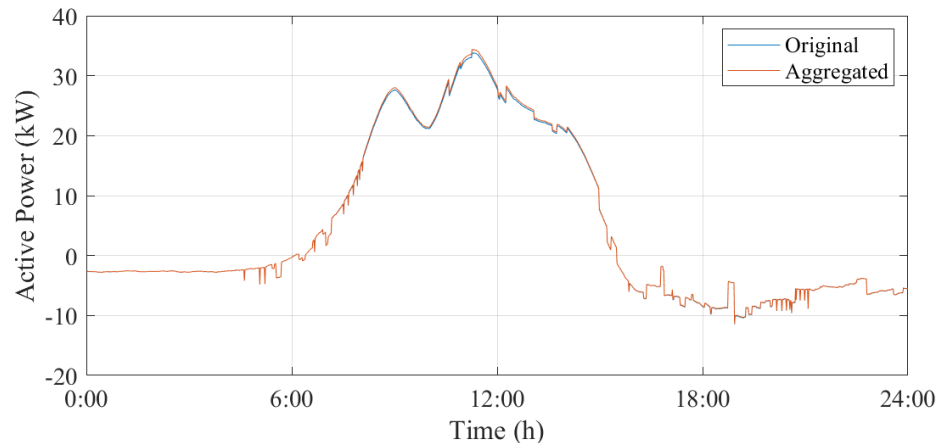
$v_2: 0.955, 0.96, \dots, 1.07$

Simulation Result: w/o Volt-Var

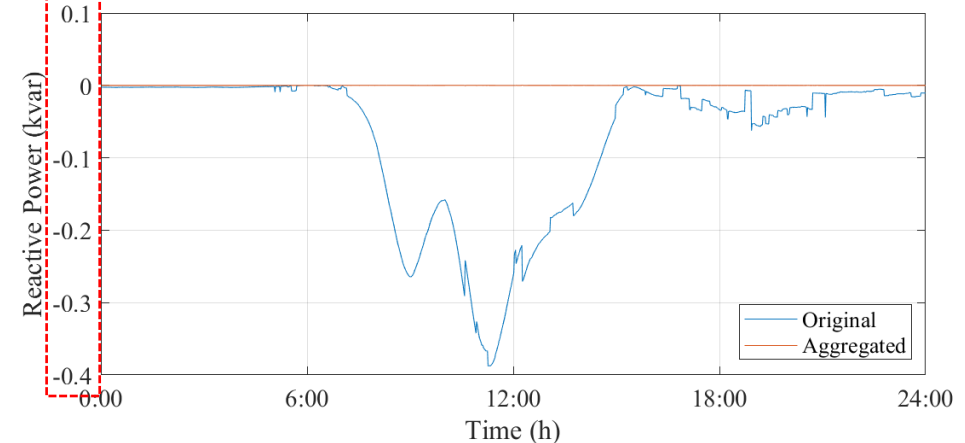
- Voltage



- Active power

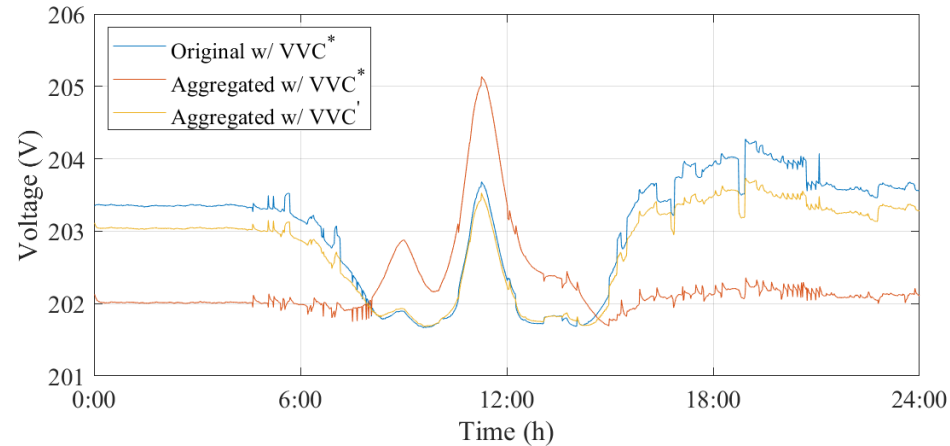


- Reactive power

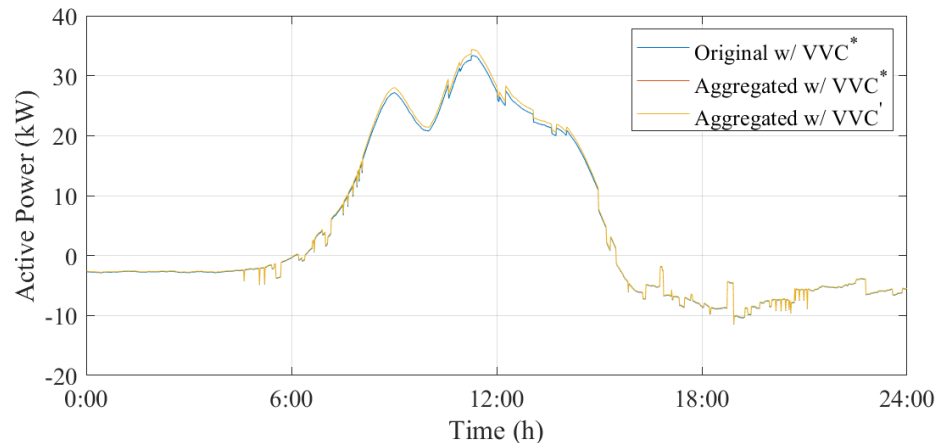


Simulation Result: w/ Volt-Var

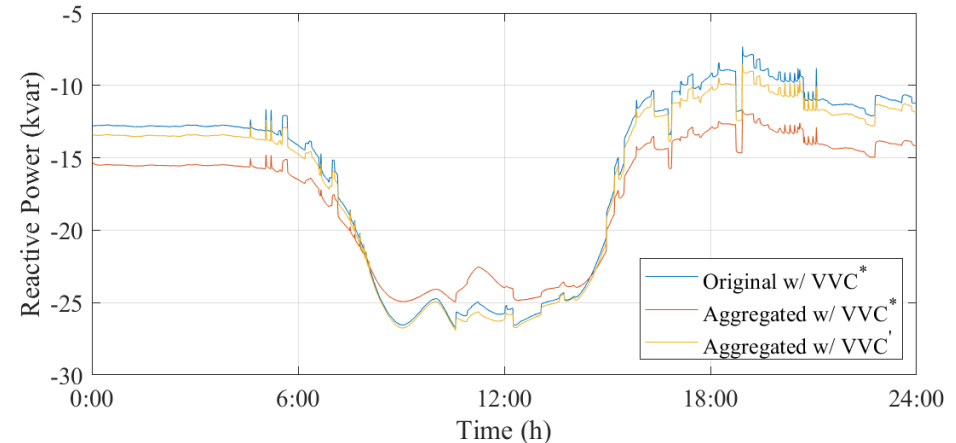
- Voltage



- Active power



- Reactive power

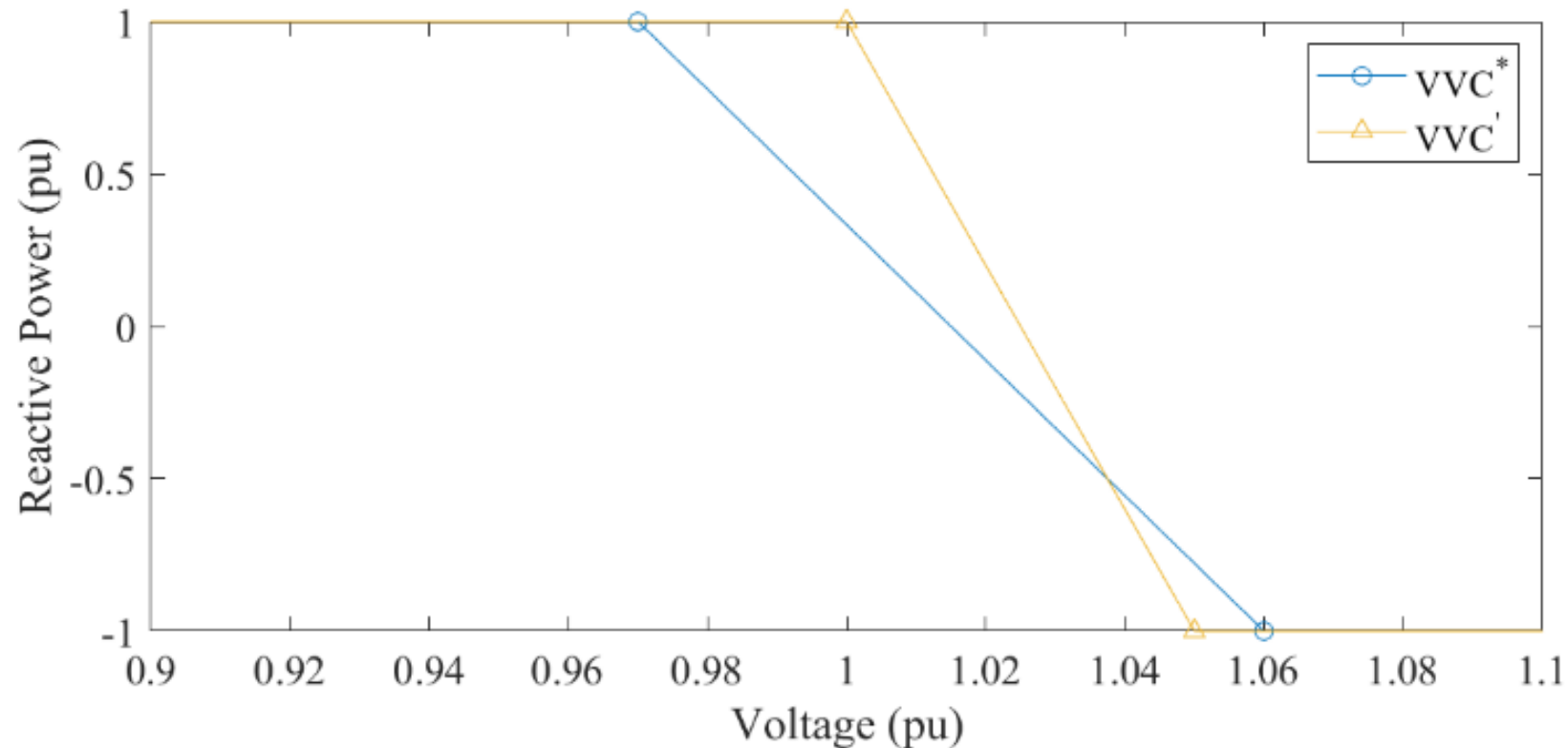


Simulation Result: MAE

	Active power (kW)	Reactive power (kvar)	Voltage (V)
w/o Volt-Var	0.1041	0.0717	0.0500
w/ Volt-Var <i>VVC*</i>	0.2689	2.3616	1.2002
w/ Volt-Var Proposed Method <i>VVC'</i>	0.2689	0.5726	0.2486

- Reactive power: **79.3%** reduction
- Voltage: **75.8%** reduction

Simulation Result: Volt-Var Curve



- Proposed VVC' is narrower than VVC*
- VVC' shows late output of reactive power and has a steep curve

Summary

- Proposed aggregate modeling of LVDS with multiple smart inverters with Volt-Var function
- Reduced MAE of reactive power 79.3% and voltage 75.8% at secondary side of distribution transformer
- Future work
 - Consider medium-voltage distribution system effect
 - Various PV and load profiles