Aggregate Modeling of Distribution System with Multiple Smart Inverters

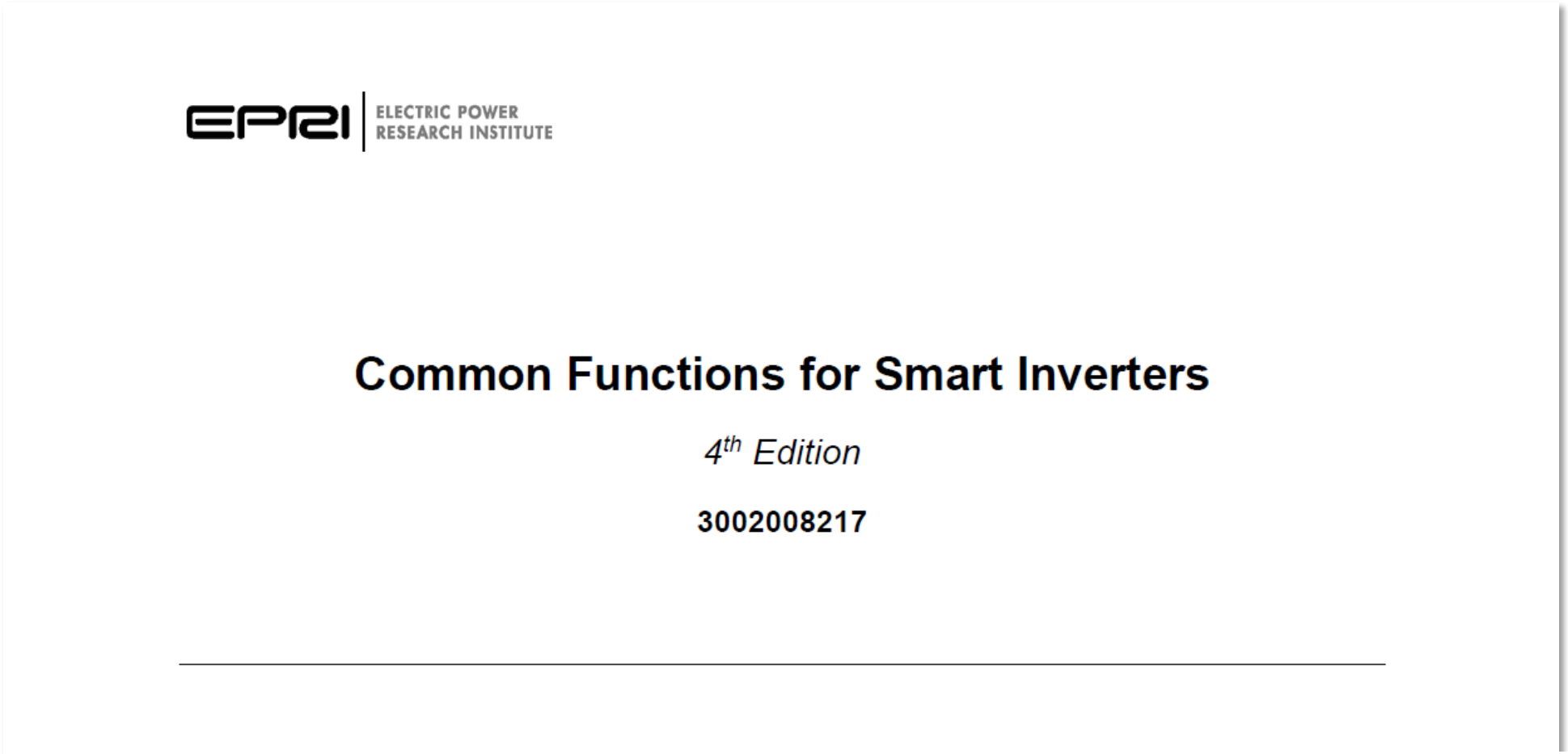
Hiroshi Kikusato, Taha Selim Ustun,
Jun Hashimoto, and Kenji Otani

Fukushima Renewable Energy Institute, AIST (FREA), Japan

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?


EPRI ELECTRIC POWER RESEARCH INSTITUTE

Common Functions for Smart Inverters

4th Edition

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

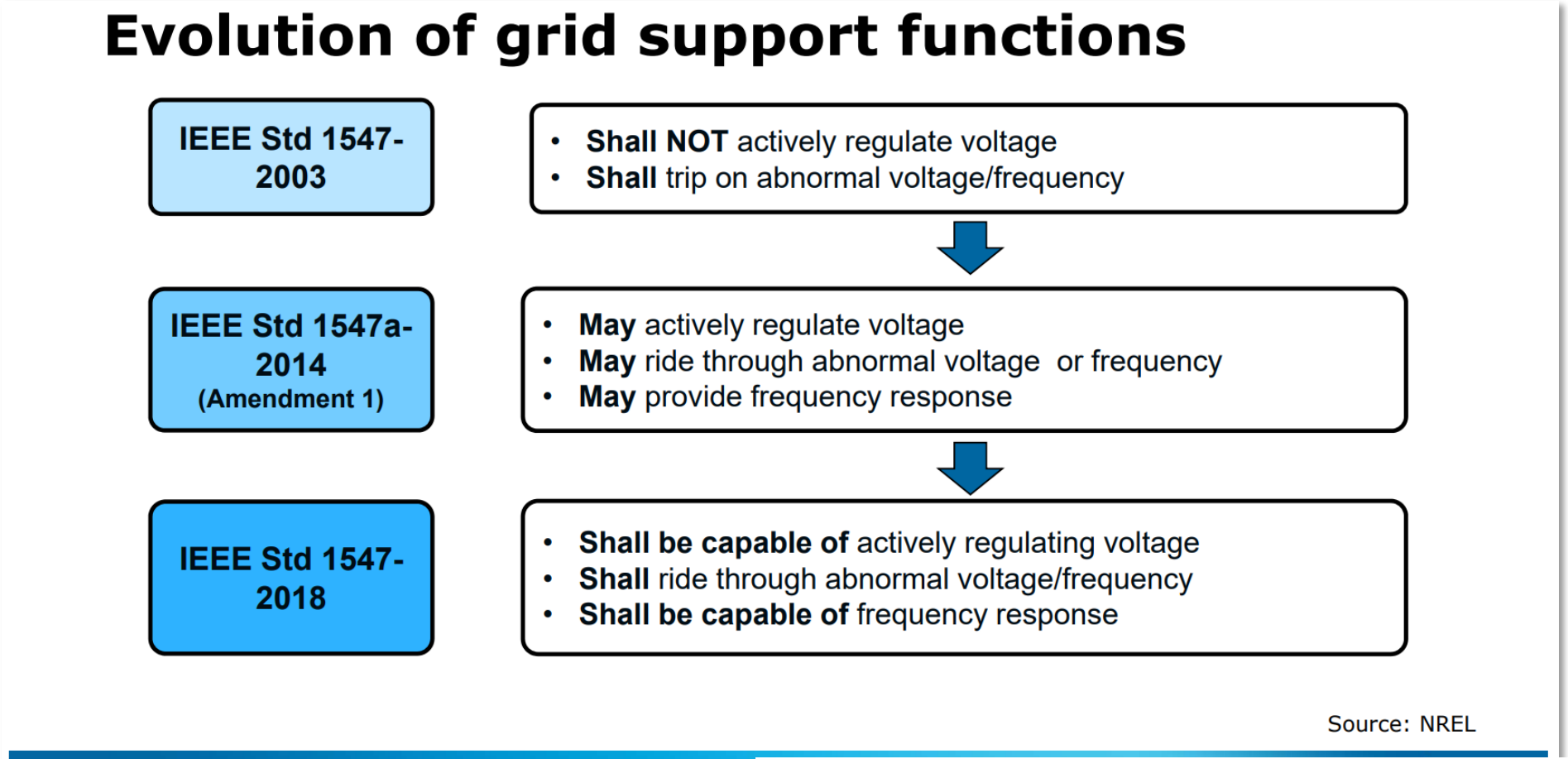
What is Smart Inverter?

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

CONTENTS

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

What is Smart Inverter?



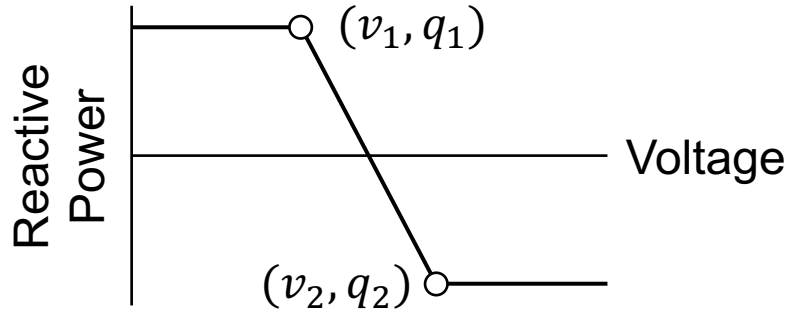
C. Stice, *et al*., "IEEE Std 1547-2018", NERC SPIDER WG Meeting, 2019
https://www.nerc.com/comm/PC/System%20Planning%20Impacts%20from%20Distributed%20Energy%20Re/IEEE%20SCC21_1547_Overview_NERC_SPIDERWG_01072019.pdf

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

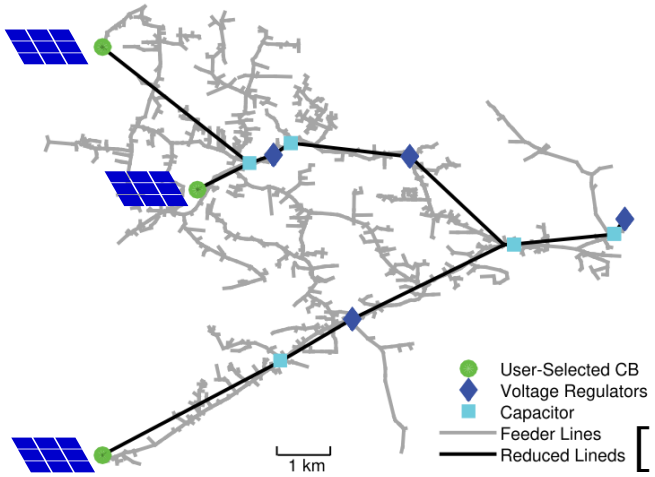
- Distribution system with smart inverters
  - Important to understand complicated power flow
  - Need various case studies
    → **Smaller computational burden is expected**

Volt-Var curve

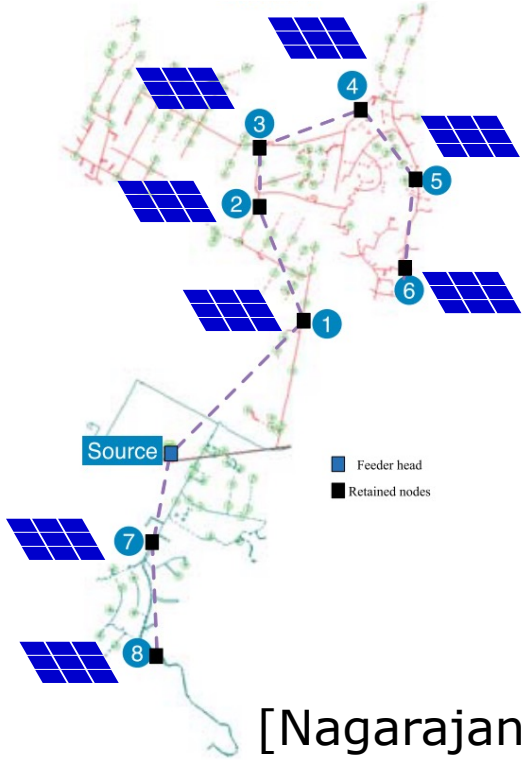


Method for Reducing Computational Burden

- 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



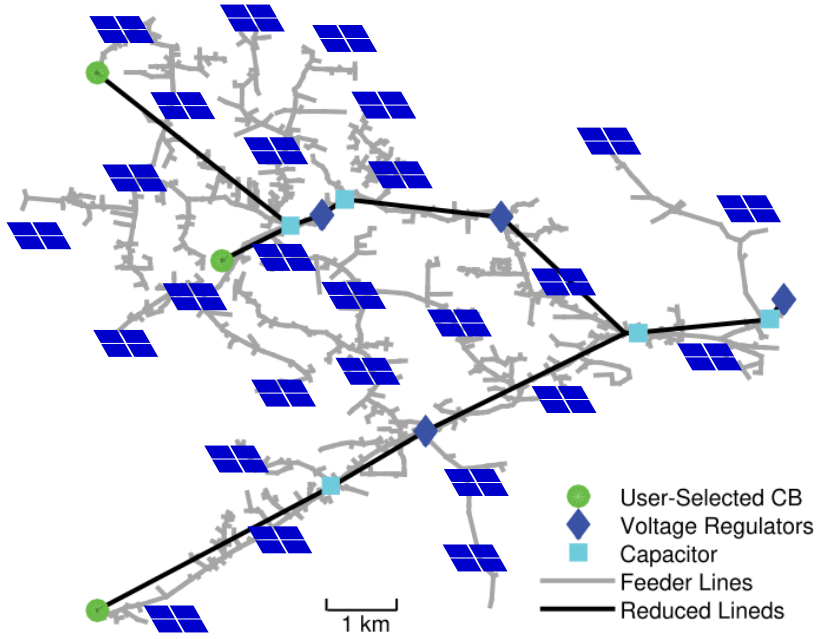
[Pecenak, *et al*., 2019]



[Nagarajan, *et al*., 2017]

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

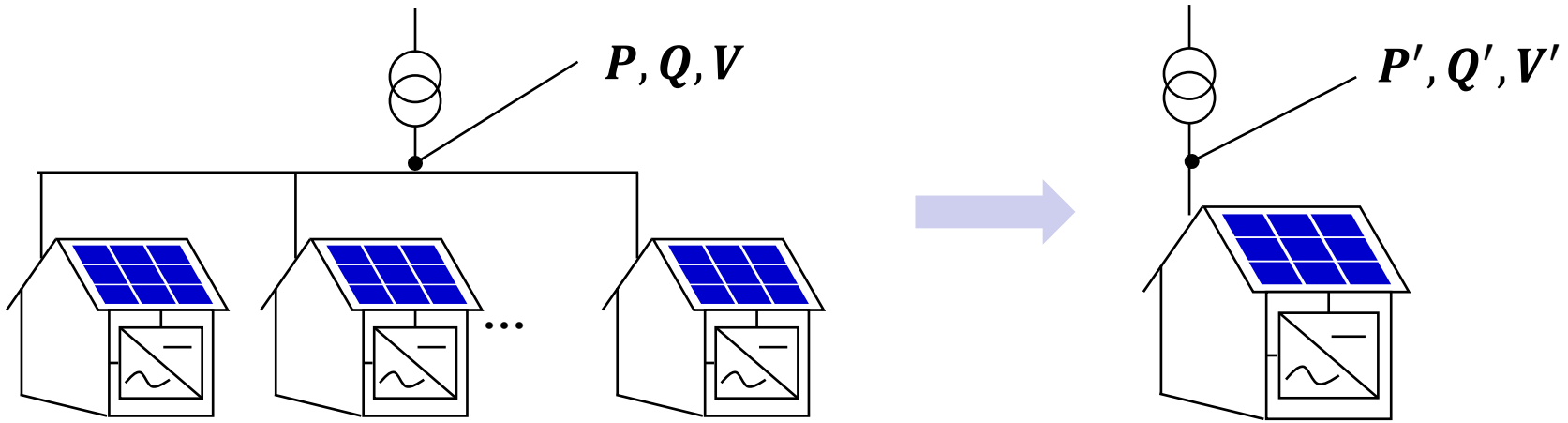
- LVDSs with Many smart inverters (SIs) with Volt-Var function
  - Each SI controls reactive power depending on its voltage
  - Timing of reactive power output is different
  - Node reduction method has not discussed well



[Pecenak, *et al*., 2019]

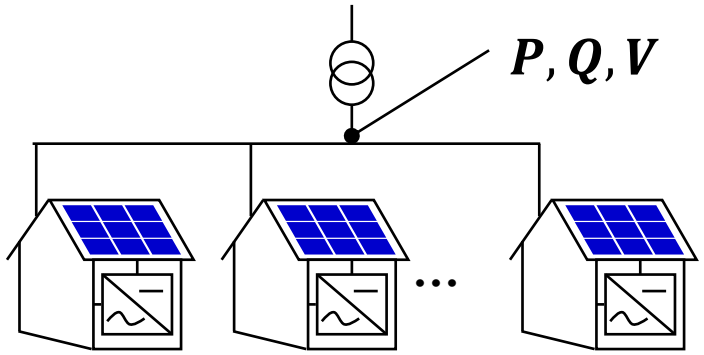
Node aggregation for Analysis of Distribution System with Volt-Var Function

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

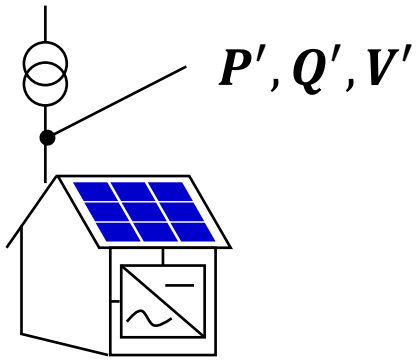


Proposed Method: Node Aggregation

- Original LVDS



- Aggregated LVDS



- PV capacity

$$\boldsymbol{c}^{\mathrm{pv}} = \{\ c_1^{\mathrm{pv}},\quad c_2^{\mathrm{pv}},\quad \ldots,\quad ,c_N^{\mathrm{pv}}\ \}$$

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

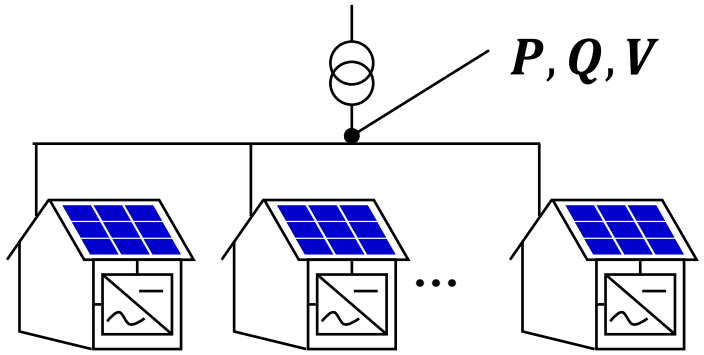
- Load capacity

$$\boldsymbol{c}^{\mathrm{ld}} = \{\ c_1^{\mathrm{ld}},\quad c_2^{\mathrm{ld}},\quad \ldots,\quad ,c_N^{\mathrm{ld}}\ \}$$

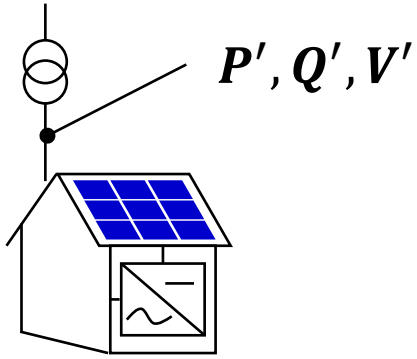
$$c^{\mathrm{ld}\prime} = \sum_{n=1}^{N} c_n^{\mathrm{ld}}$$

Proposed Method: Node Aggregation

- Original LVDS



- Aggregated LVDS



- PV profile

$$\boldsymbol{x}^{\mathrm{pv}} = \{\ \boldsymbol{x}_1^{\mathrm{pv}},\quad \boldsymbol{x}_2^{\mathrm{pv}},\quad \ldots,\quad ,\boldsymbol{x}_N^{\mathrm{pv}}\ \}$$

$$\boldsymbol{x}^{\mathrm{pv}\prime} = \frac{1}{N}\sum_{n=1}^{N} \boldsymbol{x}_n^{\mathrm{pv}}$$

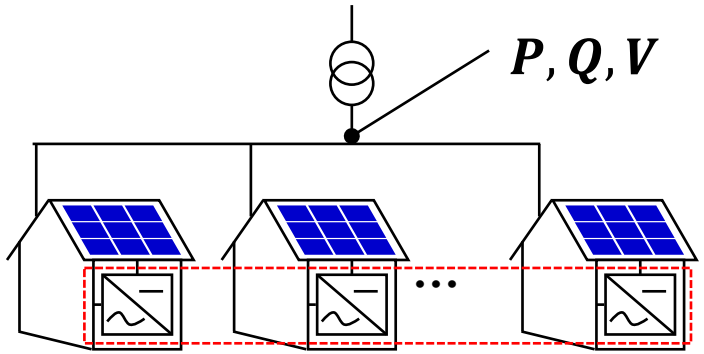
- Load profile

$$\boldsymbol{x}^{\mathrm{ld}} = \{\ \boldsymbol{x}_1^{\mathrm{ld}},\quad \boldsymbol{x}_2^{\mathrm{ld}},\quad \ldots,\quad ,\boldsymbol{x}_N^{\mathrm{ld}}\ \}$$

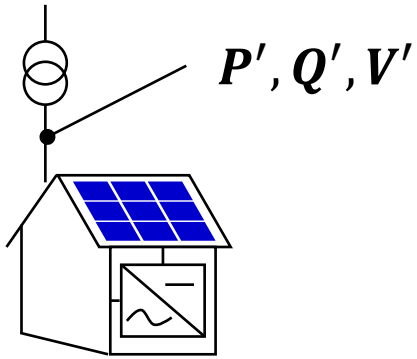
$$\boldsymbol{x}^{\mathrm{ld}\prime} = \frac{1}{N}\sum_{n=1}^{N} \boldsymbol{x}_n^{\mathrm{ld}}$$

Proposed Method: Determination of Volt-Var Curve

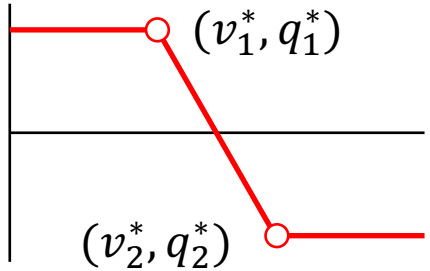
- Original LVDS

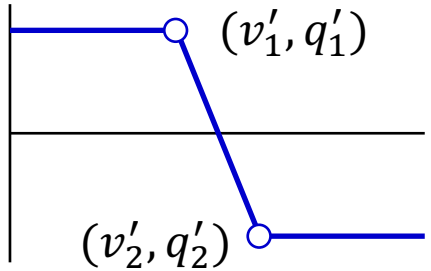


- Aggregated LVDS



- Volt-Var curve





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

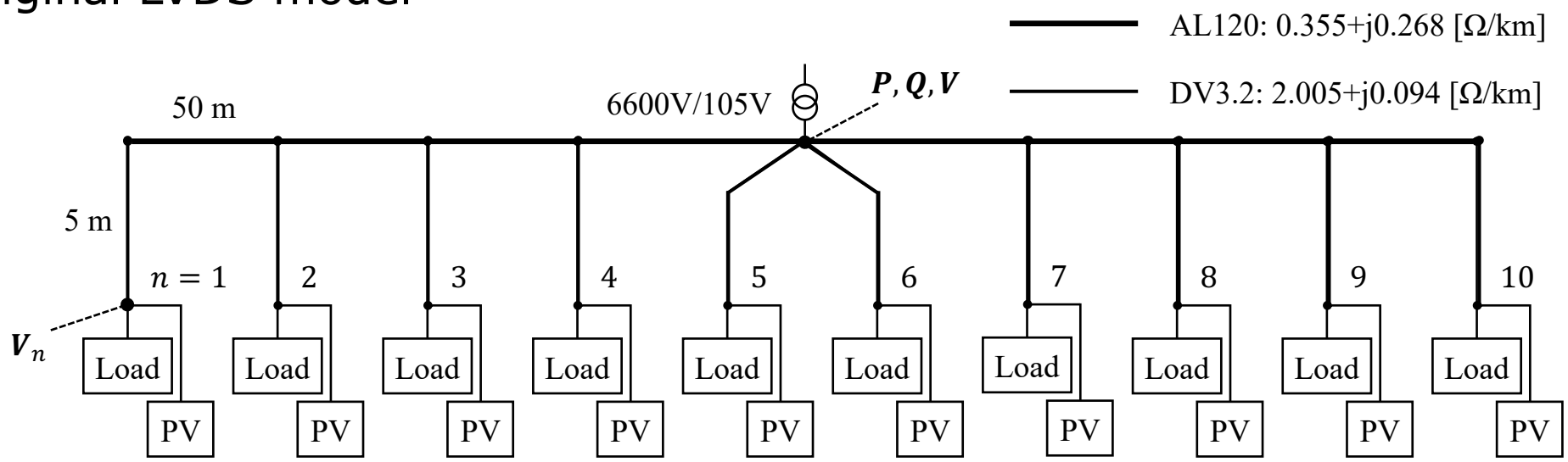
$$= \underset{\boldsymbol{VVC}}{\operatorname{argmin}} \sum_{n=1}^{N} \sum_{t=1}^{T} \{V_{n,t}(\boldsymbol{VVC}) - V^c\}$$

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

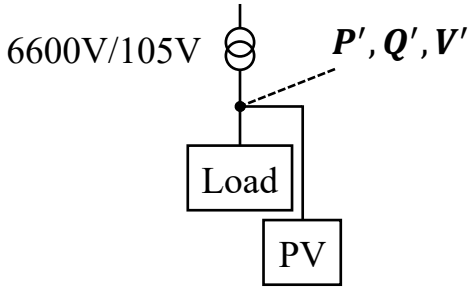
$$= \underset{\boldsymbol{VVC}}{\operatorname{argmin}} \frac{1}{T} \sum_{t=1}^{T} |V_t(\boldsymbol{X}, \boldsymbol{VVC}^*) - V_t'(\boldsymbol{X}', \boldsymbol{VVC})|$$

Simulation: Low-Voltage Distribution System Model

- Original LVDS model

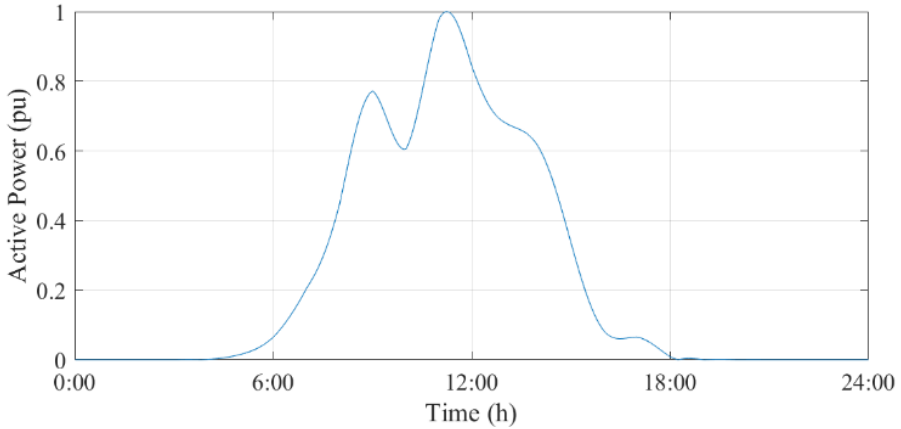


- Aggregated LVDS model

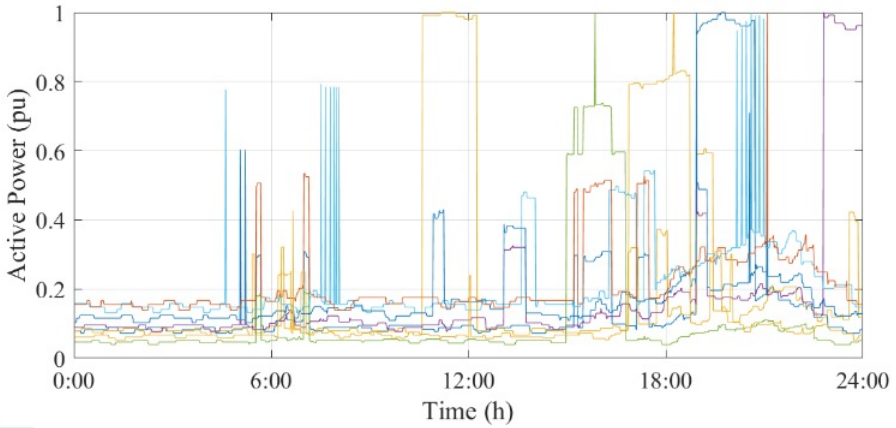


Simulation: PV and Load Profiles (1 min.)

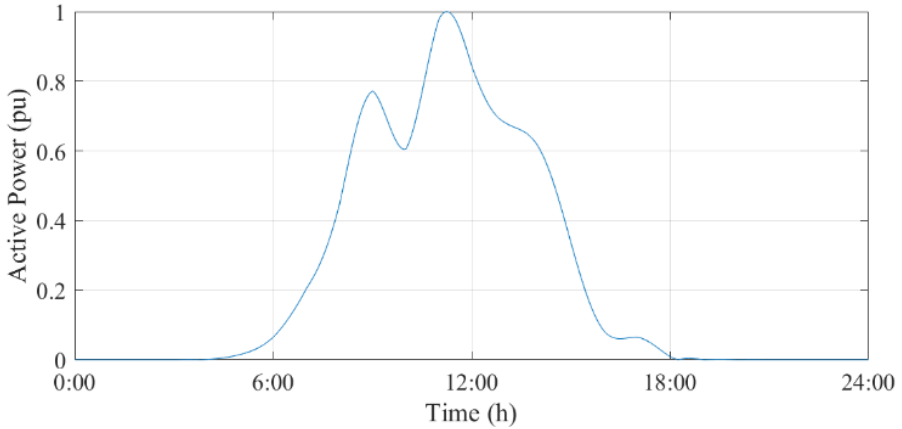
- Original LVDS
  - PV



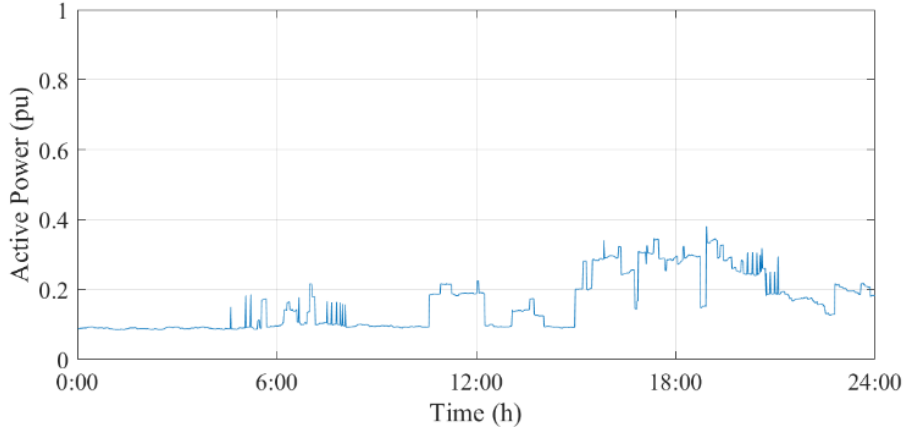
  - Load



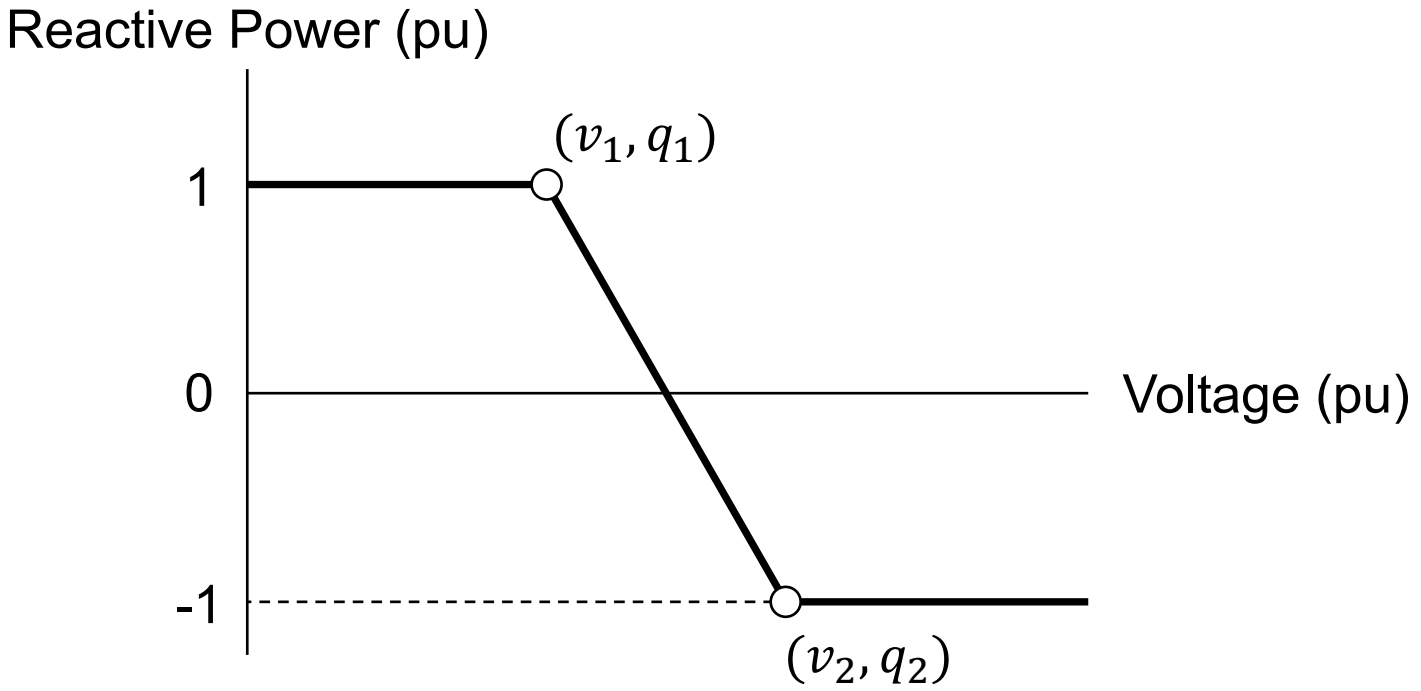
- Aggregated LVDS
  - PV



  - Load



Simulation: Volt-Var Curve



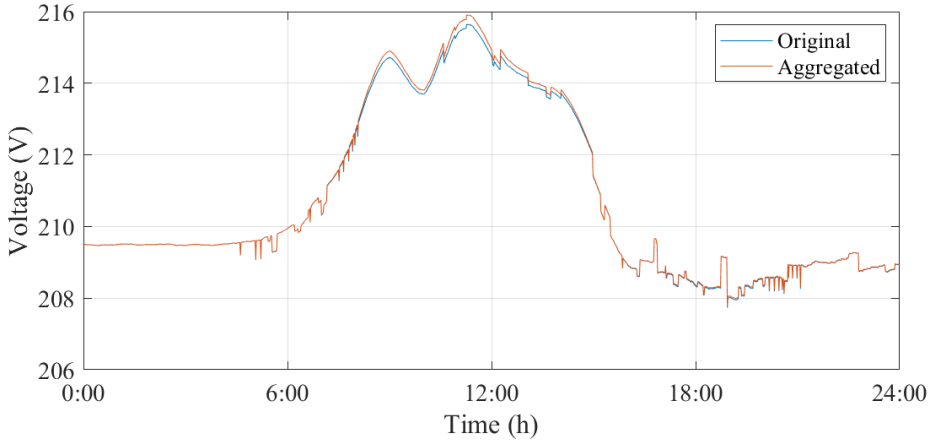
- Search combinations that satisfies $v_1 < v_2$

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

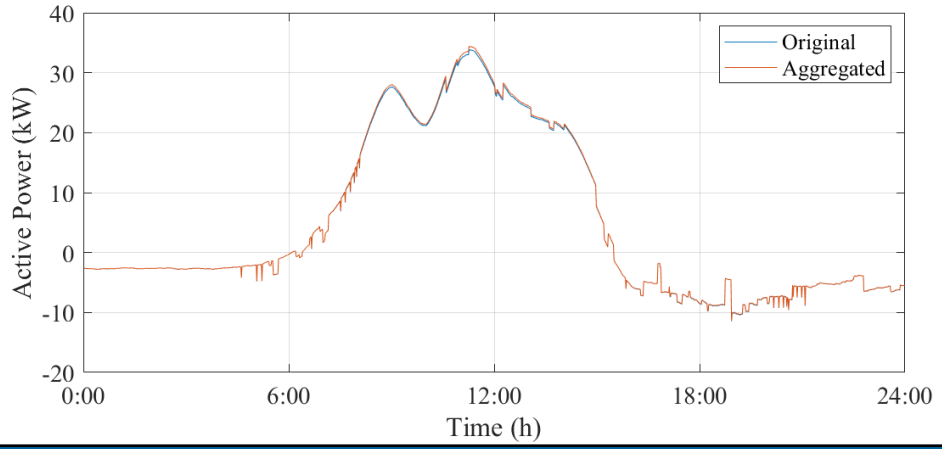
$$v_2: 0.955, 0.96, \ldots, 1.07$$

Simulation Result: w/o Volt-Var

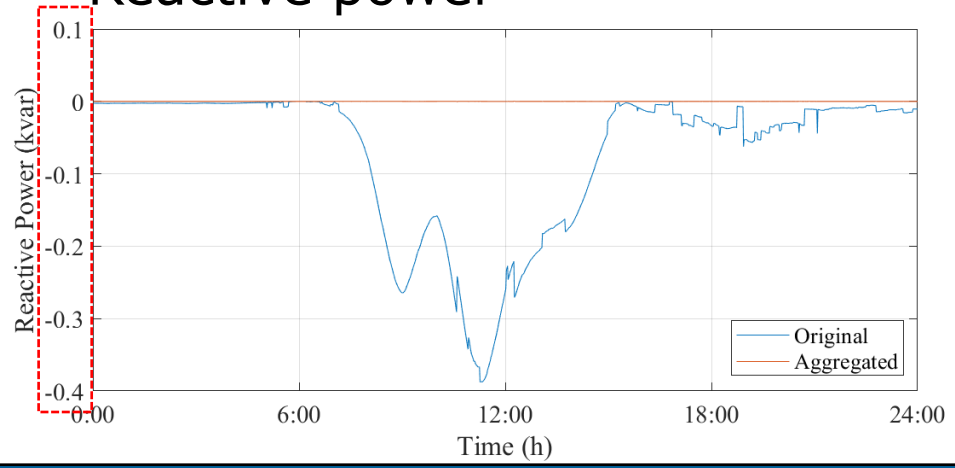
- Voltage



- Active power

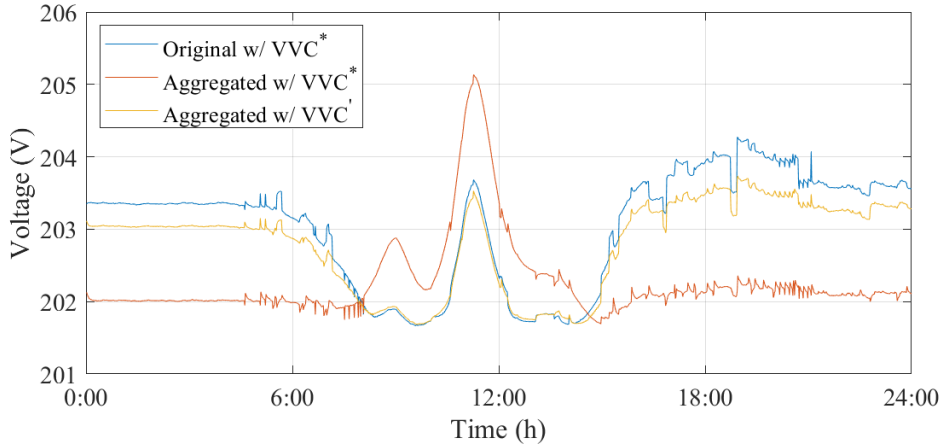


- Reactive power

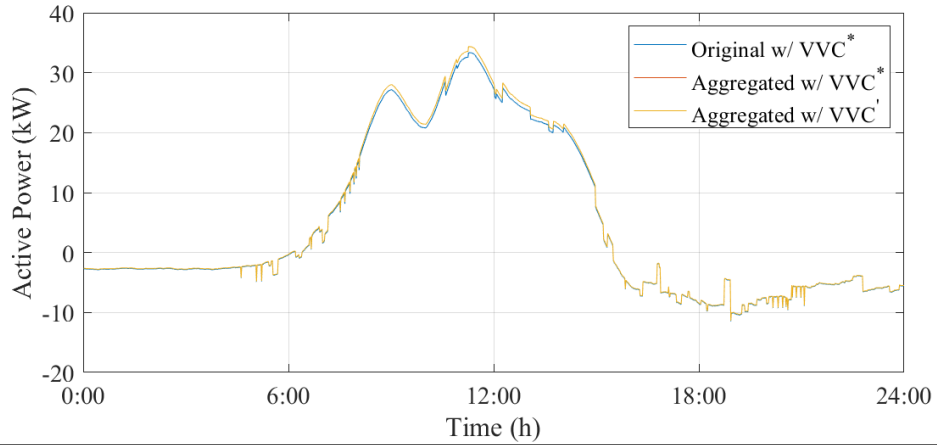


Simulation Result: w/ Volt-Var

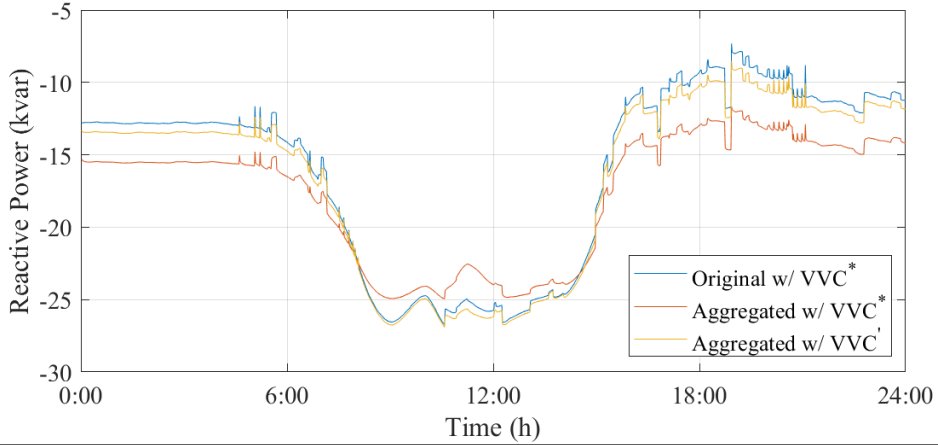
- Voltage



- Active power



- Reactive power

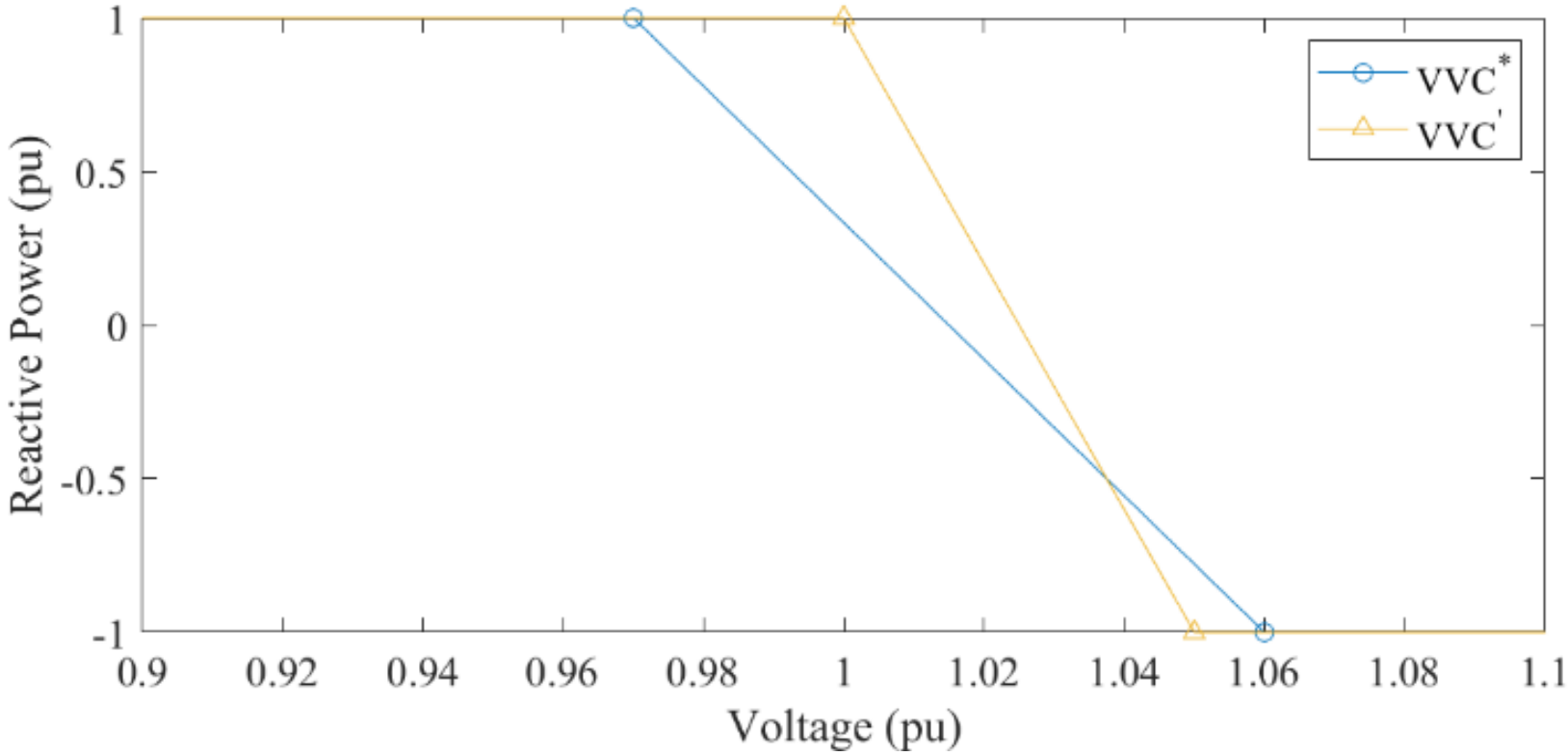


Simulation Result: MAE

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