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Using Building Thermal Energy Storage for Voltage Control Under high PV Penetration Condition

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ABSTRACT

The Photovoltaic (PV) hosting capacity of a low-voltage (LV) grid is generally limited by voltage swing issues, and the massive building thermal energy storage can be applied for relieving voltage fluctuations and increasing this capacity. Current voltage control methods (regulators and shunt capacitors) are originally design for conventional grid. New measures like battery storage still face economic controversies. This paper aims to empower air conditioning systems in residential houses for voltage regulation under high PV penetration.

First, two voltage stability issues under high PV penetration condition are revealed by simulation. Then, a temperature priority-based controller is designed for building air conditioning systems, which is categorized as passive thermal energy storage (TES), and a proactive schedule-based controller is designed for active TES - ice storage devices. Finally, A four-node test feeder populated with 360 single-phase PV-equipped residential houses was simulated to illustrate the effectiveness of the two control schemes for voltage regulation. We concluded that demand response (DR) is an effective way for LV grid voltage control. Air conditioning systems can be exploited for voltage control without sacrificing occupant comfort. Active thermal energy storage can effectively increase the DR potentials to regulate the voltage to acceptable levels.

Keywords: distribution network, voltage regulation, high PV penetration, thermal energy storage, priority-based control

NONMENCLATURE

Abbreviations	
DR	Demand response
HVAC	Heating, ventilation & air conditioning
LV	Low voltage
TES	Thermal energy storage
Symbols	
T_{air}	The house indoor air temperature
ΔT_{db}	The thermostat deadband
T_{set}	The indoor temperature setpoint
T_{lower}	The lower bound of the temperature comfort zone
$\widehat{\mathrm{T}}_{\mathrm{air}}$	The DR priority indicator of houses
$\mathrm{u}_{\mathrm{hvac}}$	The binary on/off indictor of HVACs
$\mathrm{U}_{\text{critical node}}$	The voltage of sensing critical node
$\Delta\mathrm{U}_{\mathrm{devi}}$	The voltage deviation to voltage boundary values

1. INTRODUCTION

High penetration of the PV system to distribution network may bring technical issues such as voltage fluctuation [1], frequency deviation, and circuit protection issues [2,3]. The frequency at the distribution level is maintained by the transmission system when grid-connected, while voltage levels are often locally controlled [4]. In a distribution network, PV power fluctuation is closely related to voltage fluctuation[5]. This study focuses on the impact of high-proportion distributed PV on grid voltage and aims to exploit the

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building thermal energy storage for distribution network voltage regulation.

Yan and Saha [5] demonstrated that the voltage stability issue with high PV penetration does exist in distribution networks and that PV inverter reactive power support and energy storage could relieve voltage instability. Demirok et. al. [2] proposed a novel reactive power control strategy for PV inverters considering location effects. However, PV inverters' reactive power support requires expensive oversized inverters and PV owners may prefer to output real power at its full capacity for revenues. The system power factor may deteriorate, and additional reactive power flow increases inverter and network losses. Electrical energy storage could be an alternative for local voltage control using dynamic (dis-)charging rates [6,7]. While the high initial cost of the battery significantly hinders the large-scale application of PV-battery systems [8,9].

Current voltage control measures were designed for the traditional grid without an extensive penetration of distributed generators (DGs). With the increasing of low-inertia renewable energies like PV, the regulator may face time delay problems [10] and the shunt capacitor bank may induce excessive power losses by the reactive power flow. DR is another way to regulate grid voltage by manipulating demand-side energy consumption. Seng and Taylor [11] validated the feasibility and effectiveness of DR for mitigating voltage rise problems by simulating a distribution network and two wind turbines. Vogt et. al. [12] conducted both simulation and field tests to verify that utilizing building mass thermal storage is able to increase the PV hosting capacity. Dong [13] also mentioned that building thermal load is useful to reduce voltage drops by predictive building load controls.

Prior DR papers dedicated to developing load control techniques [14] or focused on frequency regulations [15]. Less researches were using building thermal load for voltage regulation considering high PV penetrations. Recently, Jiang et al. [16] proposed a smoothing control that modules the HVAC power for voltage regulation in distribution networks with high PV penetration. They assumed commercial load characteristics by assigning each bus of IEEE-33 feeder a commercial load shape while this study suits for residential sector with 360 single-phase detailed house loads modeled.

This study is to develop an integrated simulation model, connecting building services, power distribution grid and communication network, to demonstrate the feasibility of using building thermal energy storage for LV network voltage regulation.

2. VOLTAGE STABILITY CONCERNS FOR HIGH PV PENETRATION

To investigate the voltage instability risks of high residential PV installations, a detailed four-node test feeder in the LV distribution network was simulated, as shown in Figure 1. Each phase on each load node is populated with 30 PV-equipped houses through a residential transformer. Physical load models like HVAC system and water heater are represented in the house models, as well as some schedule models of home appliances. Each PV system is connected to the grid directly and modeled as a negative load with a unity power factor.

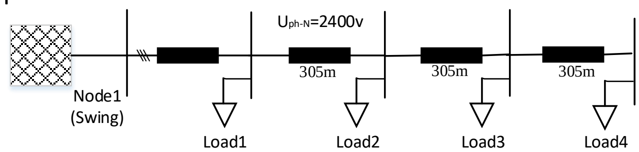
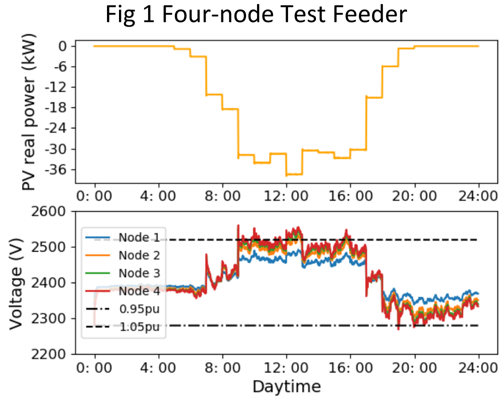
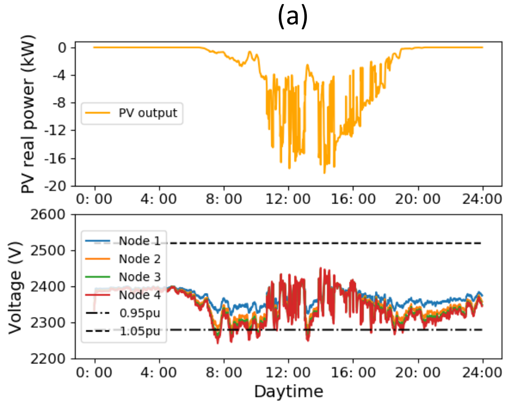


Fig 1 Four-node Test Feeder



(a)



(b)

Fig 2 Voltage instability risks under high PV penetration condition: (a) voltage rise during the clear sunny day; (b) voltage sudden drop during cloud passing moments;

The thermal dynamics of buildings and water heaters are modeled by ODE equations (1)(2). They are applied to simulate the thermal load of houses. For space concerns, the details are omitted here and the derivations can be obtained in [17,18]. Other occupant behavior-driven loads are modeled by home appliance schedules, including microwave, lights, dishwashers, sockets and so on.

$$\dot{T}_a(t) = \frac{1}{C_a}(U_a[T_o(t) - T_a(t)] + H_m[T_m(t) - T_a(t)] + Q_a(t))$$
$$\dot{T}_m(t) = \frac{1}{C_m}(H_m[T_a(t) - T_m(t)] + Q_m(t)) \quad (1)$$

$$\dot{T}_w(t) = \frac{1}{C_w}(\dot{m}C_p T_{inlet}(t) + UA * T_{amb}(t) + Q_{elec} - (UA + \dot{m}C_p) * T_w(t)) \quad (2)$$

Besides, in Figure 2, two voltage issues are demonstrated by simulations with high PV installations: 1) voltage rise due to high PV output and low demand; 2) voltage drop due to low PV output and high demand; In figure 2(a), the excessive power would flow reversely from PV panels to the grid at noontime. The voltage at the fourth node would exceed the upper voltage limit during the noontime. Figure 2(b) shows the passing cloud may reduce PV output power quickly and induce sudden voltage drops, which could exceed the lower voltage limit.

3. MITIGATION METHOD

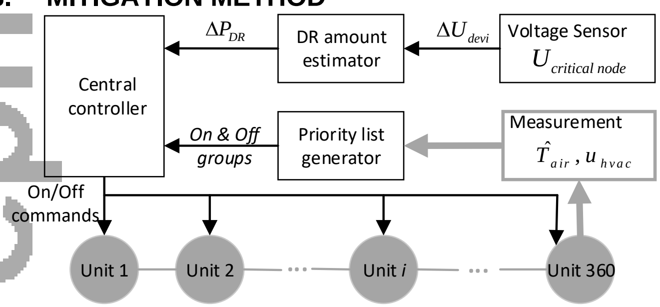


Fig 3 Temperature-priority based control for passive TES

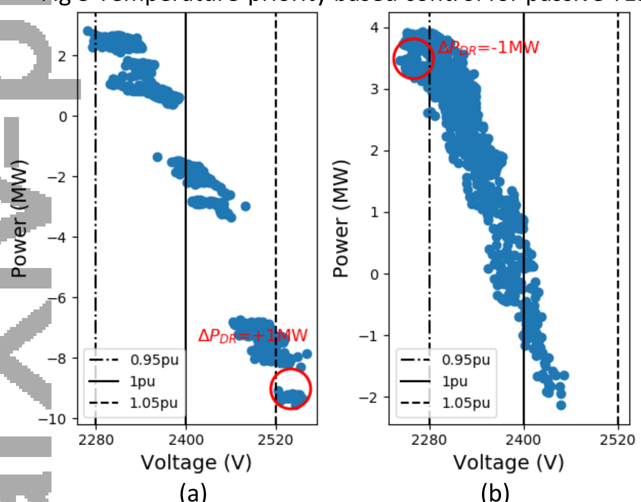


Fig 4 Estimation of DR amount for (a) overvoltage regulation; (b) voltage drop regulation

3.1 *Temperature priority-based control for passive TES*

This section employed the temperature priority-based central controller in [14] for voltage regulation, as shown in Figure 3. Instead of creasing priority list based on absolute temperatures, we defined a relative temperature factor $\hat{T}_{air}$ as (3) for indicating DR priorities.

$$\hat{T}_{air} = \frac{T_{air} - T_{lower}}{\Delta T_{db}}, T_{lower} = T_{set} - \frac{\Delta T_{db}}{2} \quad (3)$$

The controller works as follows. A voltage sensor is placed on one phase of critical node (load four). Once the voltage boundaries are exceeded, we estimated the DR amount needed for voltage regulation ΔP_{DR} (see Figure 4). Then, the number of HVAC units to be turned on or off is calculated as (4) by the average rate power of DR-engaged HVAC units. Meantime, the priority generator collects the temperatures $\hat{T}_{air}$ and on/off states (u_{hvac}) information from each HVAC unit and sends "on/off group" priority lists to the central controller when necessary. Since we considered a cooling mode for all HVAC units, the *ON-group* units are sorted ascendingly based on $\hat{T}_{air}$ and the *OFF-group* units are sorted in descending order. Finally, the top *N* HVAC units in the *ON-group* or *OFF-group* priority lists would be turned off or turned on depending on overvoltage or undervoltage degree.

$$N = \frac{\Delta P_{DR}}{P_{rated}} \quad (4)$$

3.2 *Schedule-based control for active TES*

Active thermal energy storage further increases the flexibility of building electric thermal loads and the DR potential. Thus, an ice storage was also modeled and controlled by a proactive schedule-based control in Figure 5.

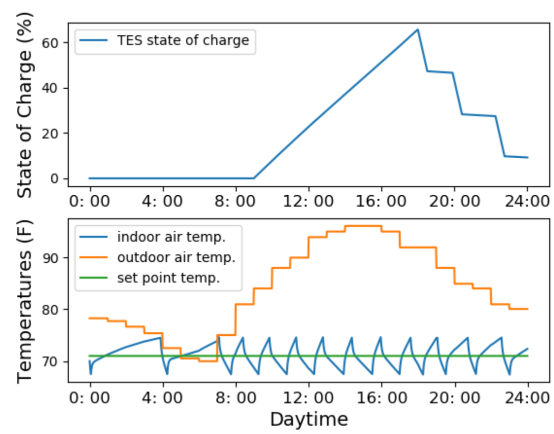


Fig 5 Schedule-based control for TES — (upper) state of charge and (lower) lossless thermal comfort

It is assumed that each house is equipped with a TES model. Each TES was (dis-)charged with a constant power of 10kW at recharging time between 9:00 - 17:00 or discharging time between 18:00 - 23:00. The discharging process consumes 0.3kW as the HVAC turned off the air conditioner and only fan consumed power to distribute cold air. The upper plot in Figure 5 shows the state of charge for the ice storage and the lower plot are the temperature profiles, indicating that the indoor thermal comfort was not deteriorated during (dis-)charging process.

4. SIMULATION AND RESULTS

An integrated simulation model was established for validation, combining LV network power flow analysis with detailed load modeling of residential houses. The virtual four-node distribution network model in Figure 1 was simulated in *Gridlab-d* engine, engaging *MATLAB* for temperature priority-based controls in Section 3. The weather file from Fort Worth, Texas was used and one summer day (2014/07/01) was simulated.

4.1 Results

Figure 6 shows that the sudden voltage drops were mitigated by using temperature priority-based control for the cluster of residential HVAC units. The original voltage curves in the upper plot exceeded the lower voltage boundary for several times due to the cloud passing effect. After manipulating the on/off states of HVAC units, these voltage drops were relieved, and the voltage profiles were held within the boundary. Figure 7 shows the indoor air temperature of 360 residential houses before and after temperature priority-based controlling. It is seen that the occupant comfort was hardly deteriorated.

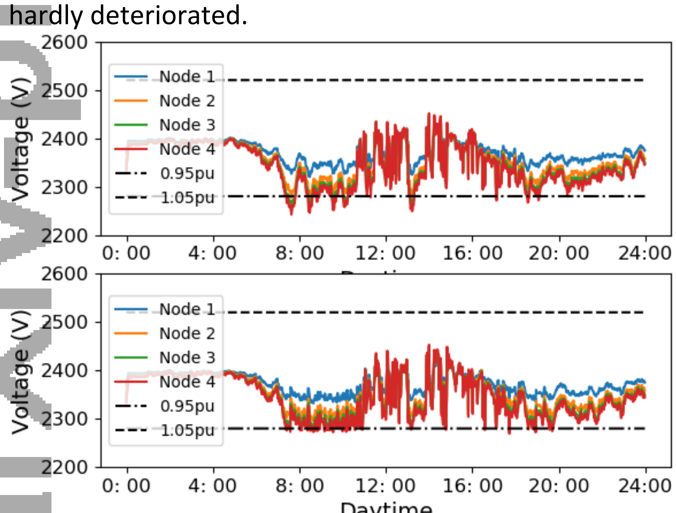


Fig 6 Voltage levels of the four-node system – (upper) before priority-based pass TES control and (lower) after priority-based passive TES control;

Figure 8 shows that the overvoltage issue can be mitigated by installing active TES in houses. It is observed that the voltage levels got reduced from 9:00 to 17:00 and got improved from 18:00 to 23:00. Because the aggregation of active TESs would bring less reverse power flows to the system during the daytime and supply part of the cooling demands in the evening. Similarly, the occupant temperature won't be sacrificed too much. For space concern, the temperature images are omitted here.

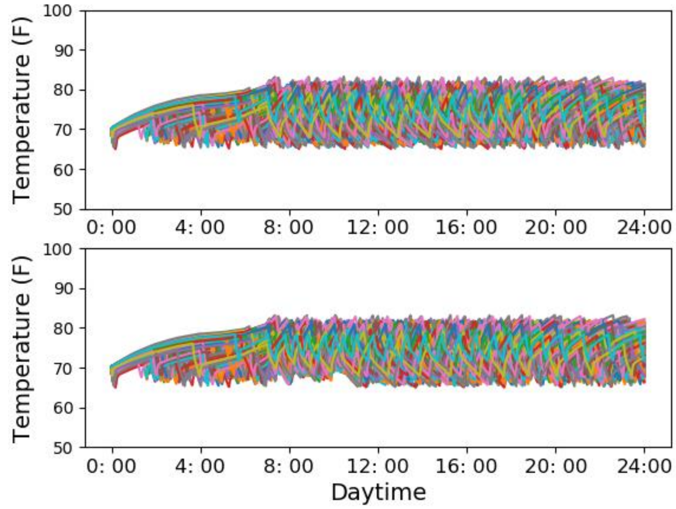


Fig 7 Indoor temperature profiles of 360 residential houses – (upper) before priority-based control and (lower) after priority-based control;

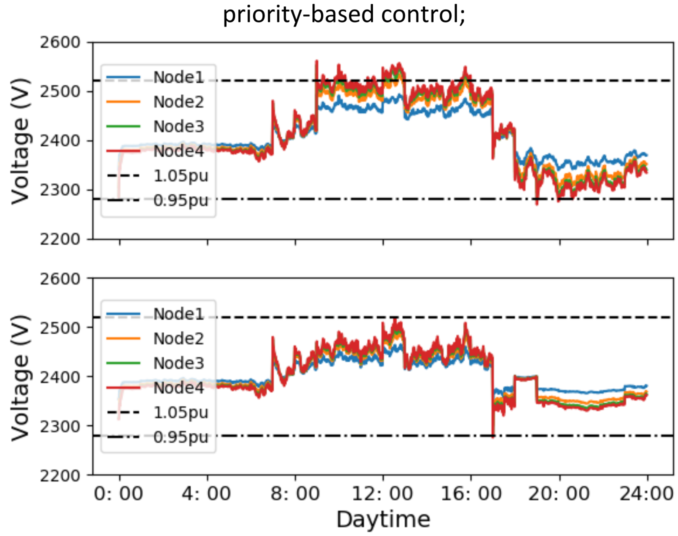


Fig 8 Voltage levels of the four-node system – (upper) before schedule-based active TES control and (lower) after schedule-based active TES control;

5. CONCLUSIONS

This study proposed two control schemes to exploit both passive and active building TESs for voltage regulation in LV distribution network. An integrated simulation model was modeled for demonstration, connecting building electrical loads, distribution power grid and communication network together. First, two voltage concerns under high PV penetration were analyzed through simulation. Then, the voltage fluctuations based on power flow analysis were simulated for a four-node test feeder with detailed house load modeling. Simulation results validated that the temperature priority-based controller could control multiple HVAC units in residential houses as critical flexible demand resources for voltage control without comprising occupant comfort too much. Active TES (ice storage) can effectively increase the DR capability of houses to regulate the voltage to acceptable levels.

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