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Evaluation of Adaptive Volt-VAR to Mitigate PV Impacts

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***Abstract*—Distributed generation (DG) sources like photovoltaic (PV) systems with advanced inverters are able to perform grid-support functions, like autonomous Volt-VAR that attempts to mitigate voltage issues by injecting or consuming reactive power. However, the Volt-VAR function operates with VAR priority, meaning real power may be curtailed to provide additional reactive power support. Since some locations on the grid may be more prone to higher voltages than others, PV systems installed at those locations may be forced to curtail more power, adversely impacting the value of that PV system. Adaptive Volt-VAR (AVV) could be implemented as an alternative, whereby the Volt-VAR reference voltage changes over time, but this functionality has not been well-explored in the literature. In this work, the potential benefits and grid impacts of AVV were investigated using yearlong quasi-static time-series (QSTS) simulations. After testing a variety of allowable AVV settings, we found that even with aggressive settings AVV resulted in <0.01% real power curtailment and significantly reduced the reactive power support required from the PV inverter compared to conventional Volt-VAR but did not provide much mitigation for extreme voltage conditions. The reactive power support provided by AVV was injected to oppose large deviations in voltage (in either direction), indicating that it could be useful for other applications like reducing voltage flicker or minimizing interactions with other voltage regulating devices.**

***Keywords*—adaptive voltage reference, autonomous Volt-VAR, distributed generation (DG), high penetration photovoltaics (PV), grid-support functions**

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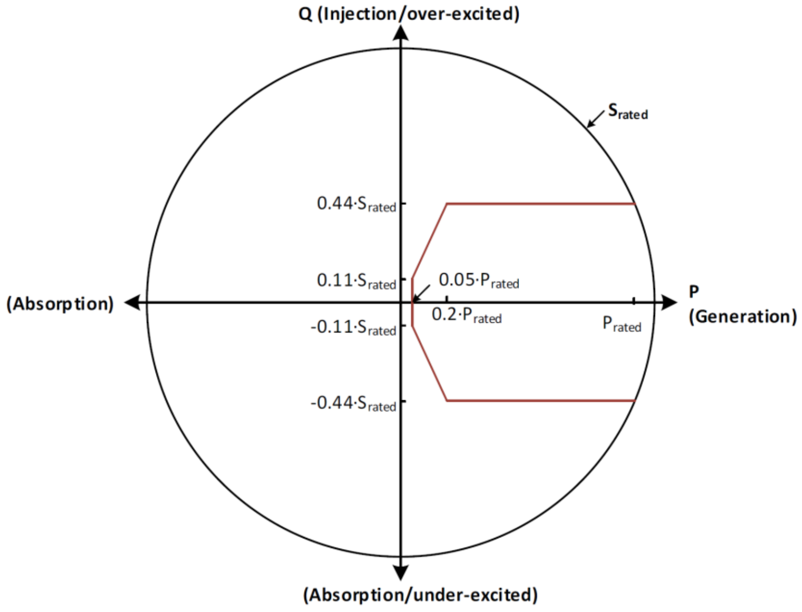
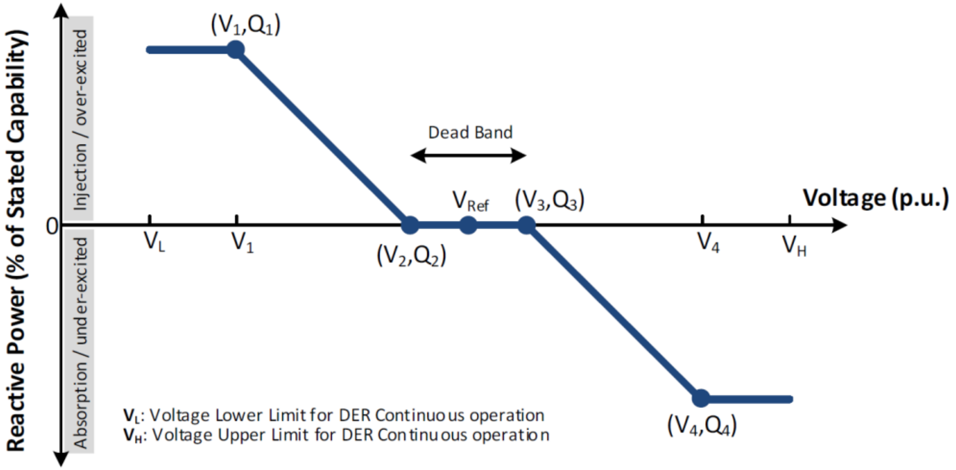
Contents

Introduction

- Per the IEEE 1547 Standard [1], all new PV inverters must be able to operate in a variety of grid-support modes, including Volt-VAR (VV) mode
  - In VV mode, inverter will inject reactive power to boost low voltages and consume reactive power to reduce high voltages, curtailing real power if necessary (VAR-priority)
- When inverters are set to operate in autonomous Volt-VAR mode, the amount of reactive power support and curtailment depends in part on the installation location on the feeder
- Inverters connected near the substation or voltage regulators often experience higher voltages, even without the effects of PV voltage rise, meaning curtailment risk is higher for those inverters



Category B



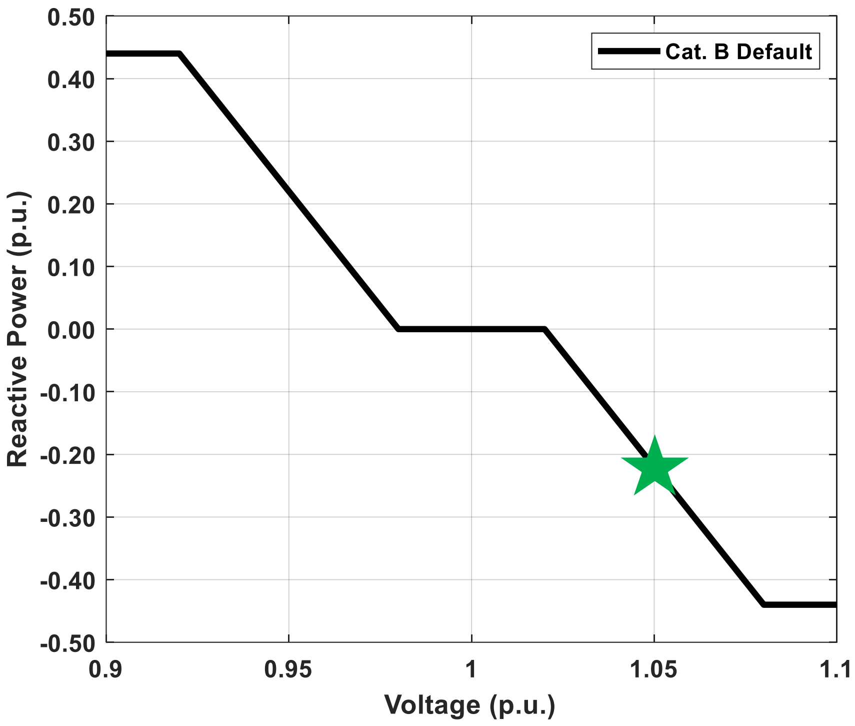
Background

- IEEE 1547 also requires that PV inverters are capable of autonomously adjusting their reference voltage setting for VV mode
  - This feature is referred to here as *Volt-VAR with Adaptive* V_{ref}, or simply Adaptive Volt-VAR (AVV), as opposed to conventional "Static" Volt-VAR
- For AVV mode, V_{ref} is autonomously set to the low-pass filtered measured voltage using a time constant at least in the range of [300, 5000] seconds
  - In this work, AVV was implemented in OpenDSS by autonomously adjusting V_{ref} based on a moving average of the terminal voltage using a window size in the same range [300, 5000] seconds

> The DER shall be capable of autonomously adjusting reference voltage (V_{Ref}) with V_{Ref} being equal to the low pass filtered measured voltage. The time constant shall be adjustable at least over the range of 300 s to 5000 s. The voltage-reactive power Volt-Var curve characteristic shall be adjusted autonomously as V_{Ref} changes. The approval of the Area EPS operator shall be required for the DER to autonomously adjust the reference voltage. Implementation of the autonomous V_{Ref} adjustability and the associated time constant shall be specified by the Area EPS operator.

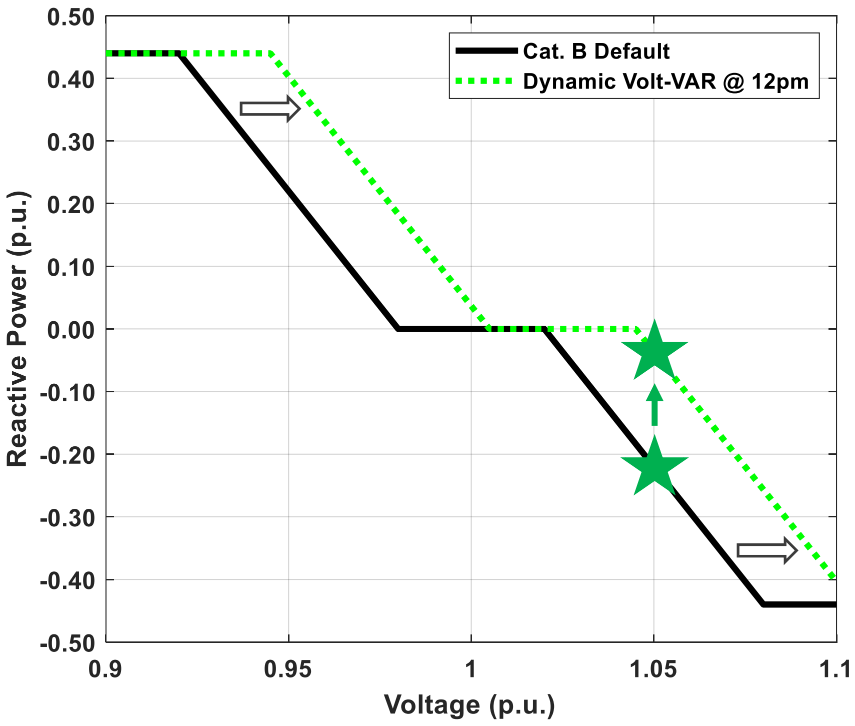
Background

- For Static Volt-VAR with Category B default settings, reference voltage V_{ref} never changes (typically Vref = 1 p.u.)
- For example, consider an inverter InvA:
  - InvA is just outside the substation
  - At 12:00 pm, V_{InvA} =1.05 pu
  - InvA must consume 0.22 kVARpu
  - *High curtailment risk*
- To reduce curtailment risk when using “static” Volt-VAR, V_{ref} would have to be manually adjusted (perhaps more than once as grid conditions evolve)



Background

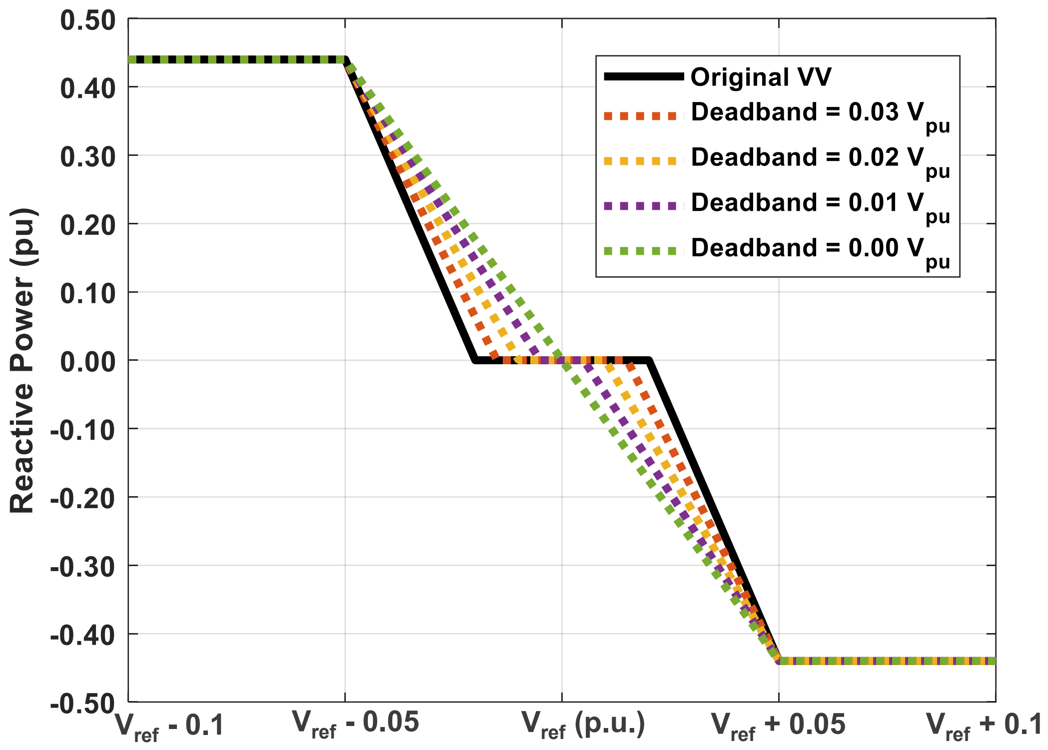
- In this scenario, AVV could be implemented allowing for V_{ref} to adjust itself autonomously
- Revisiting the previous example, but with AVV and an 1800s averaging window:
  - At 12:00 pm, V_{ref} =1.00 p.u., V_{InvA} =1.05 p.u.
    - InvA must consume 0.22 kVARpu
  - By 12:30 pm (1800s later), V_{InvA} = 1.05 p.u., but V_{ref} =1.025 p.u.
    - InvA Q consumption reduced to 0.0367 kVARpu
- At 12:30, AVV required (0.22 - 0.0367) = 0.1833 kVARpu less consumption than Static VV



Background

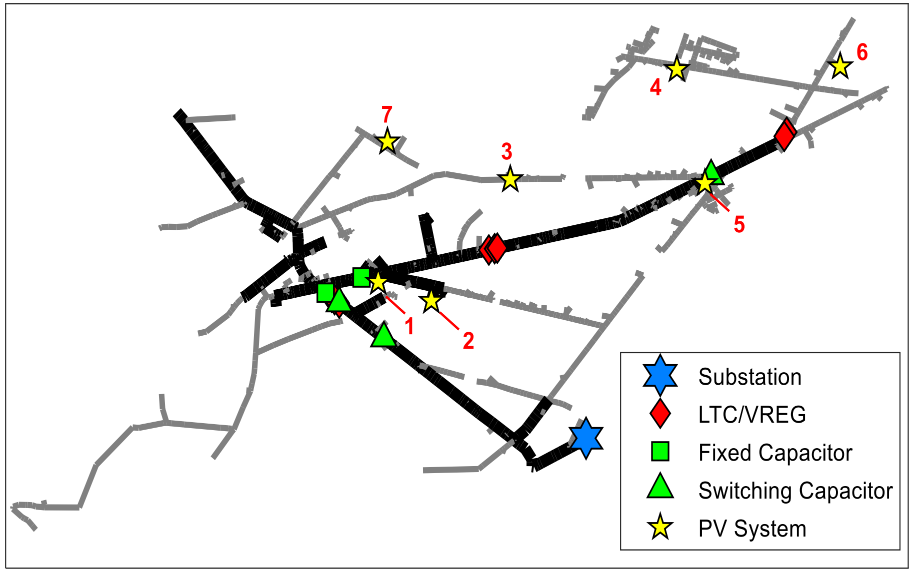
Impact of VV Curve Deadband

- The deadband settings for the Cat. B Volt-VAR curve reduce the VAR support required when voltages are near nominal values
- AVV inherently provides a similar feature, so the including a deadband may be partially redundant
    - Therefore, a variety of VV curves (shown on the right) were investigated, starting with default deadband of 0.04 Vpu (1.02 – 0.98 Vpu) and stepping down to 0 in steps of 0.01 Vpu



Methods

- All simulations conducted in OpenDSS on **Modified EPRI J1** test circuit:
  - Based on an actual 12kV feeder w/ 3433 buses
  - 1,354 residential customers, 30 commercial, w/ peak load of 6.3 MW
  - 7 PV systems (1.8 MW total, 28% of peak load)
- Yearlong quasi-static time-series (QSTS) simulations performed with 1-minute time steps

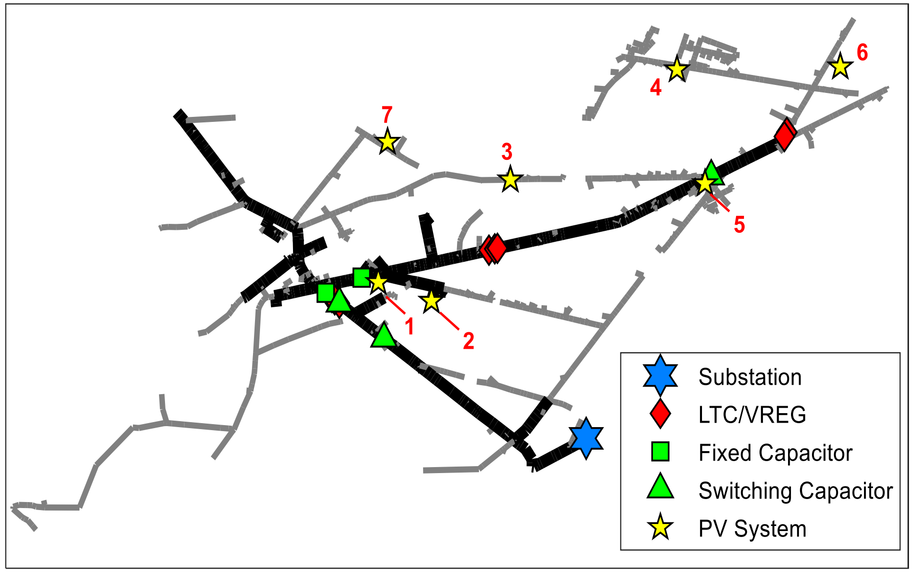


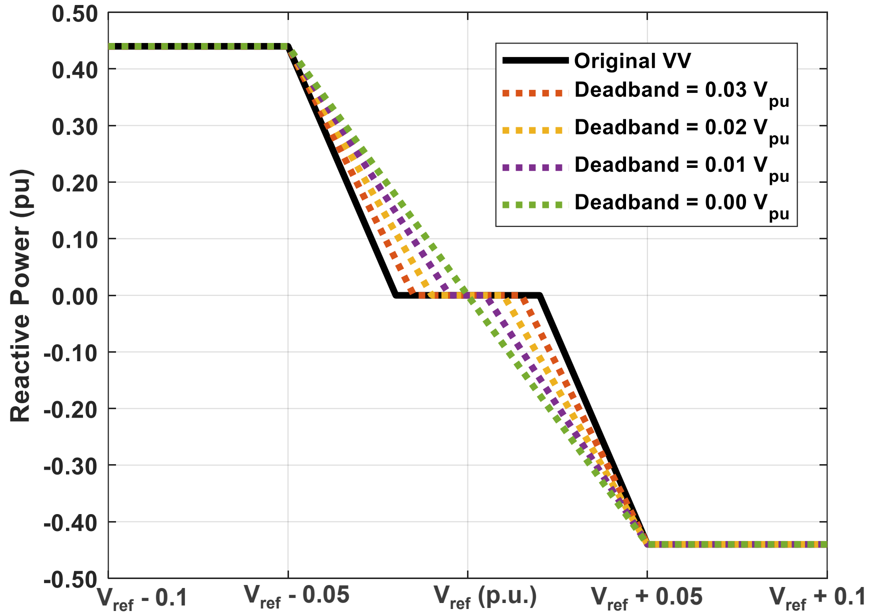
PV #	Name (Phase)	kW (DC)	kVA (AC)	DC/AC Ratio
1	3p_existingsite1 (ABC)	600.60	475.0	1.2644
2	3p_existingsite3 (ABC)	1562.00	1235.0	1.2648
3	c_existing2 (C)	14.08	11.10	1.2685
4	b_existing3 (B)	12.65	10.00	1.2650
5	c_existing5 (C)	25.30	20.00	1.2650
6	a_existing9 (A)	12.65	10.00	1.2650
7	c_existing13 (C)	18.37	14.50	1.2669

**Settings common to all PV systems: tilt angle=40°, azimuth angle=180°, VV Curve=Category B*

Methods

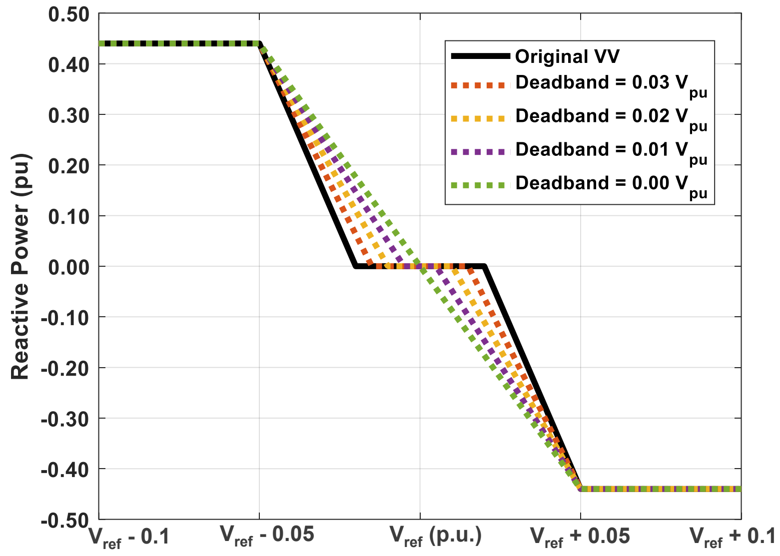
- In this work, we evaluated the impact of Adaptive VV on curtailment risk, VAR support, and voltage regulation
  - Adaptive VV results compared to Static VV with the same VV curves
- The simulations were then repeated for each combination of the settings below:
  - **Avg. window lengths** = [300, 600, 900, 1800, 3600, 5000, 10000] seconds (AVV only)
  - **VV curve deadband** = [0.04, 0.03, 0.02, 0.01, 0.00] Vpu

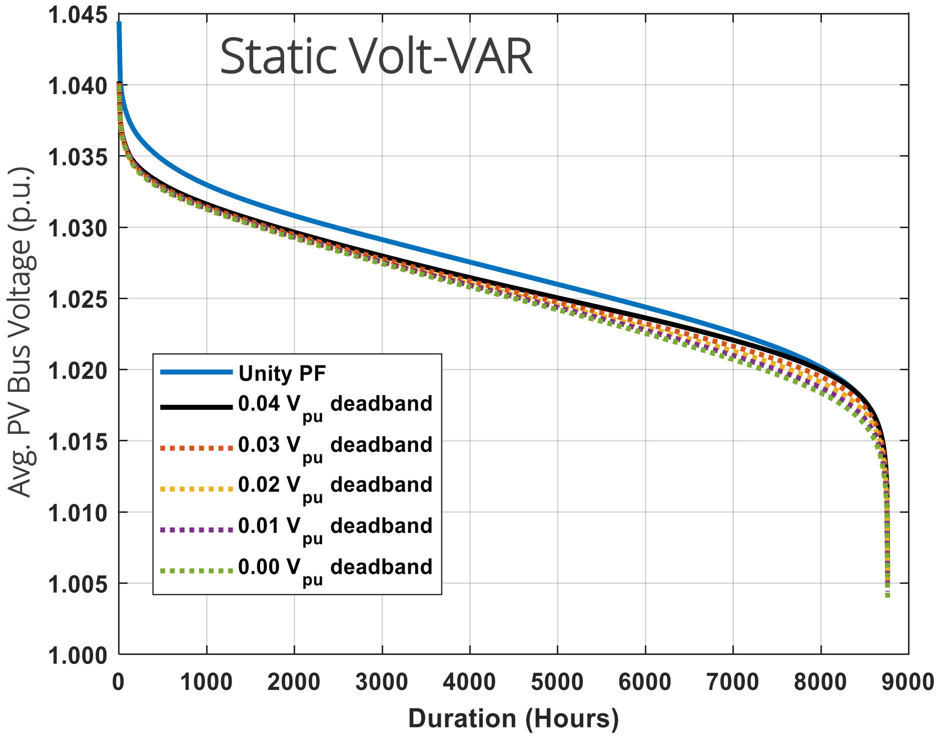


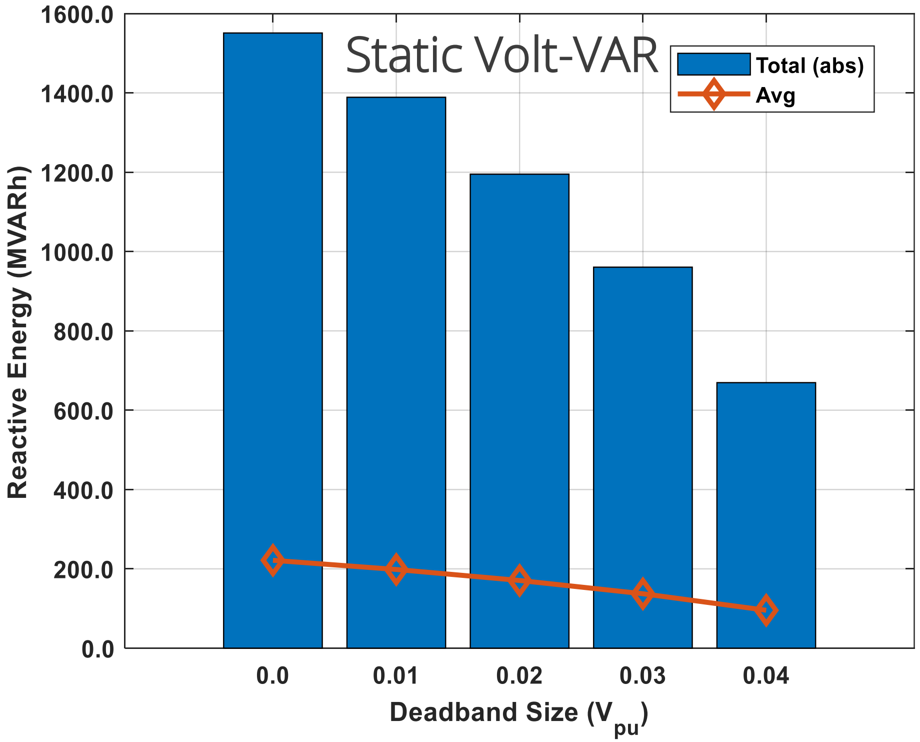


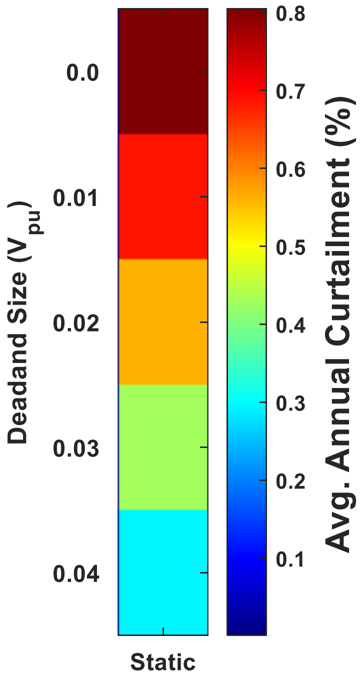
Results – Static Volt-VAR

- As deadband increases, the same voltages require less VARs from the inverters, so total reactive energy and voltage regulation decreases
- Curtailment was low (0.30%), but increased up to nearly 0.80% as deadband decreased



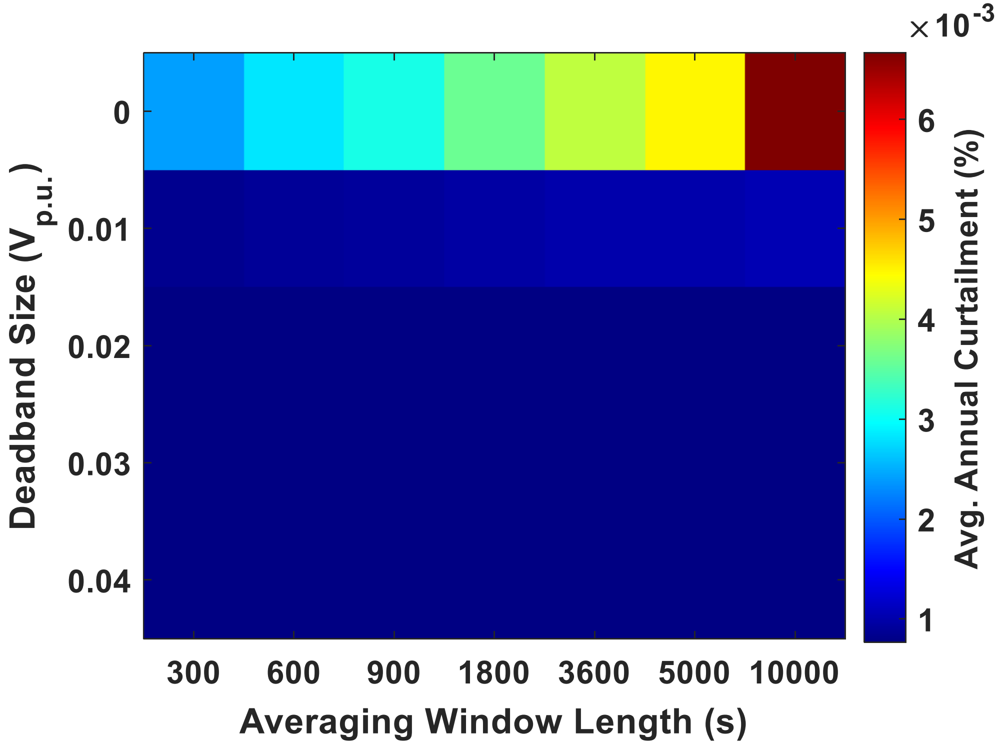


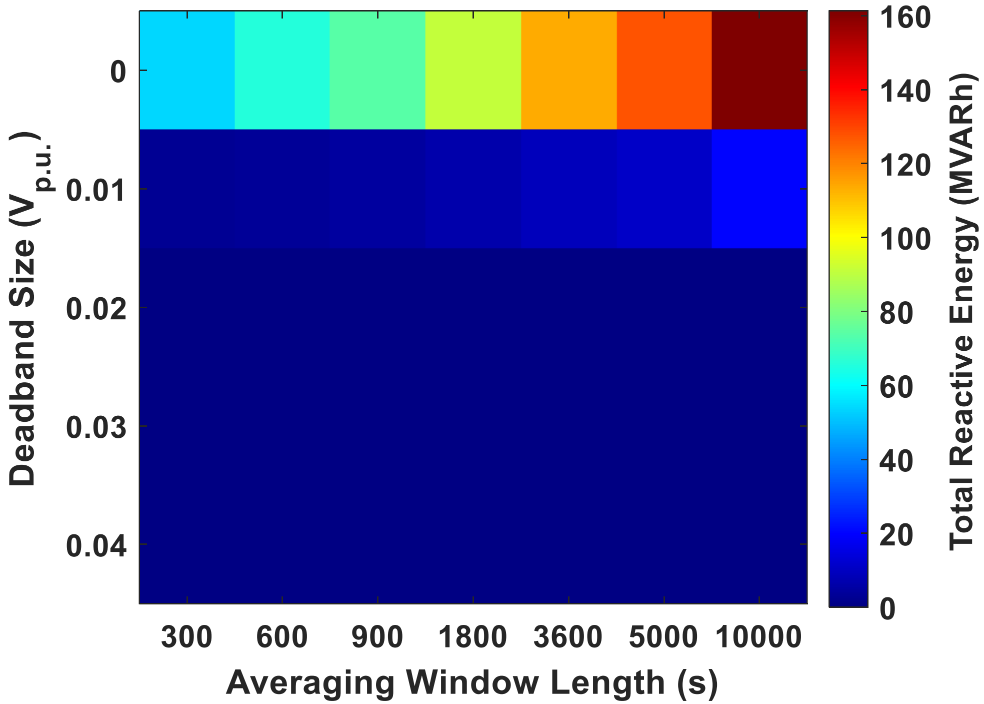




Results – Adaptive Volt-VAR

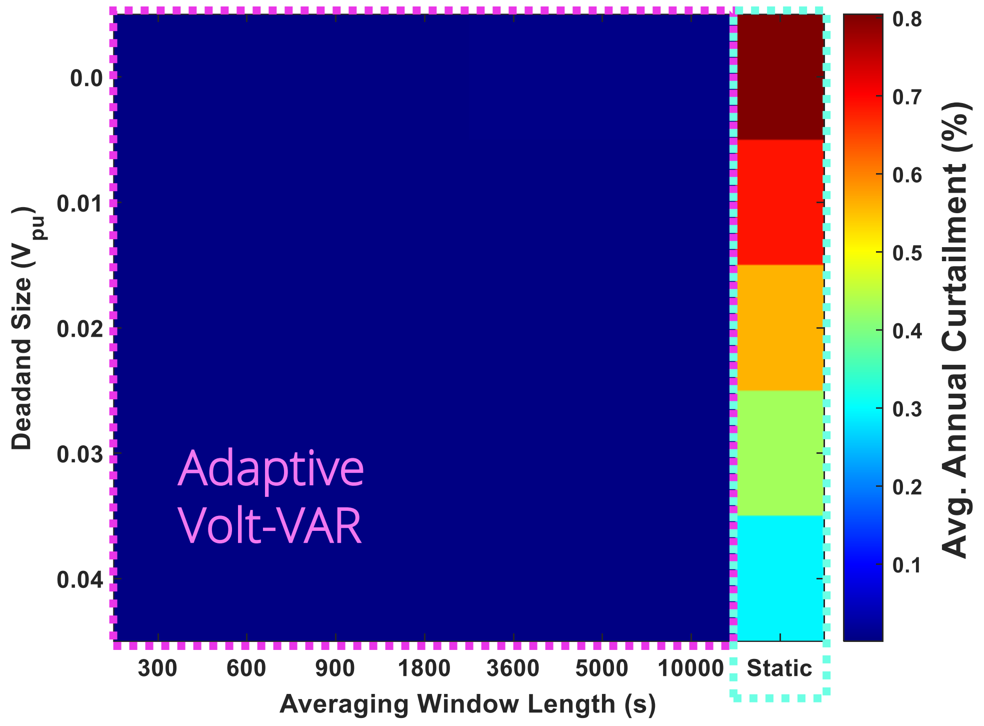
- Curtailment was not a factor (<0.01% of annual energy) even with worst case settings
- Increasing the averaging window increases VARh
  - Shorter windows meant that V_{ref} and deadband tracked more closely with real-time voltages
- Reducing deadband dramatically increases VARh

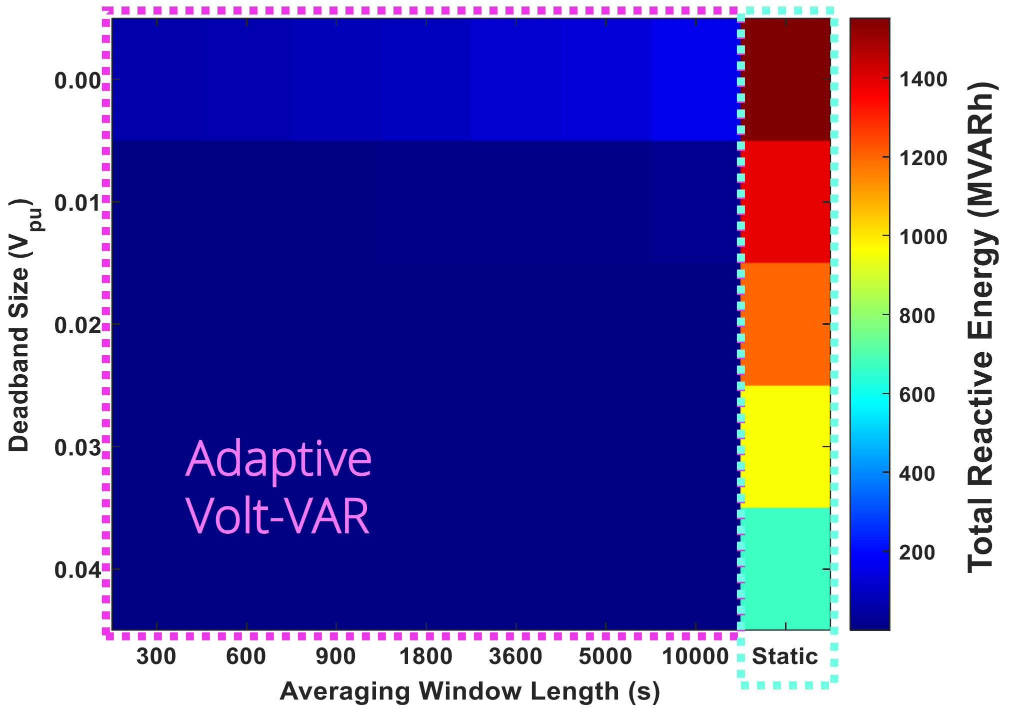




Results: Static vs. Adaptive Volt-VAR

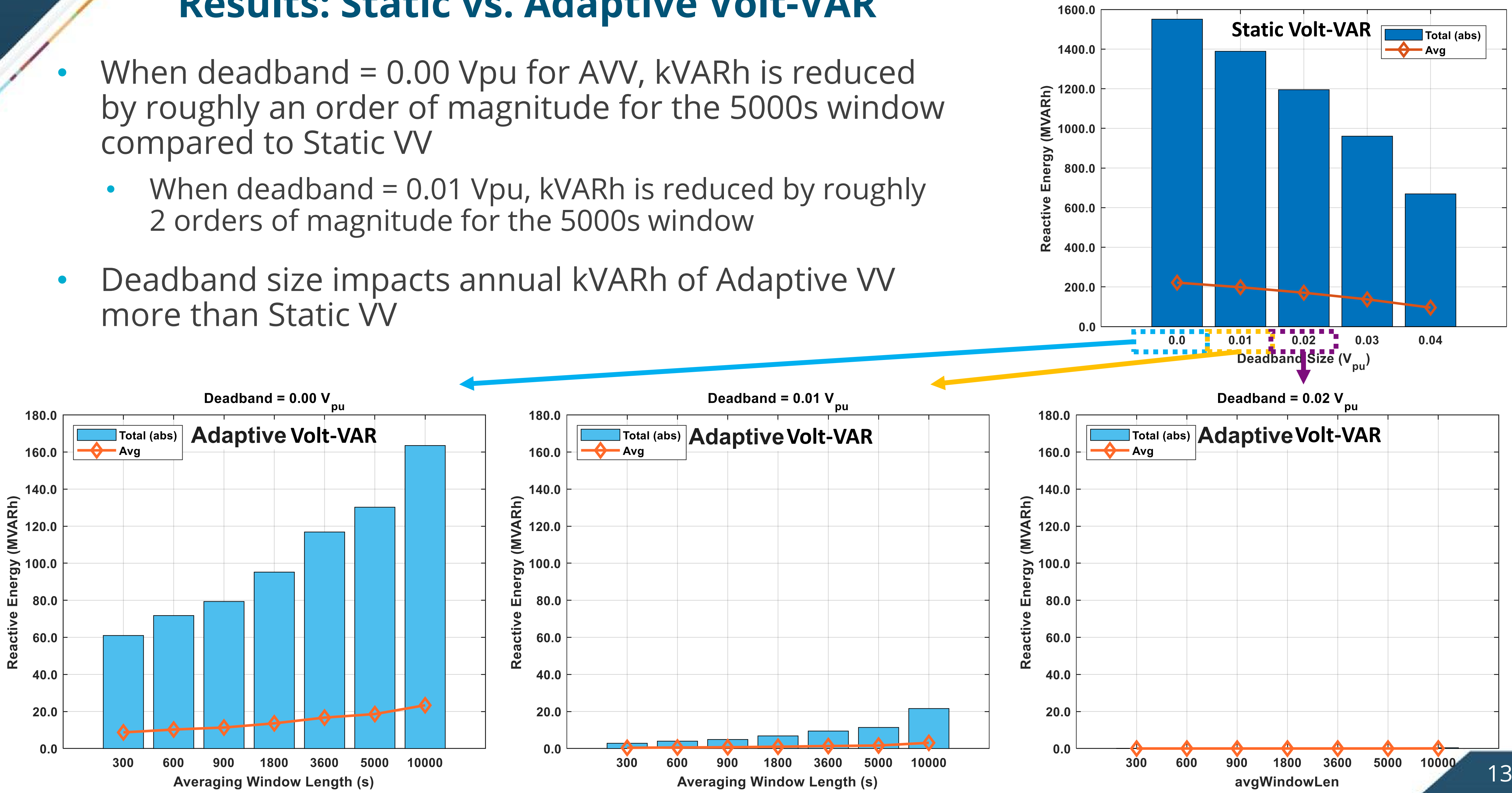
- Compared to Static VV, essentially zero curtailment was observed for Adaptive VV
- Adaptive VV also requires significantly less reactive power support from the inverter





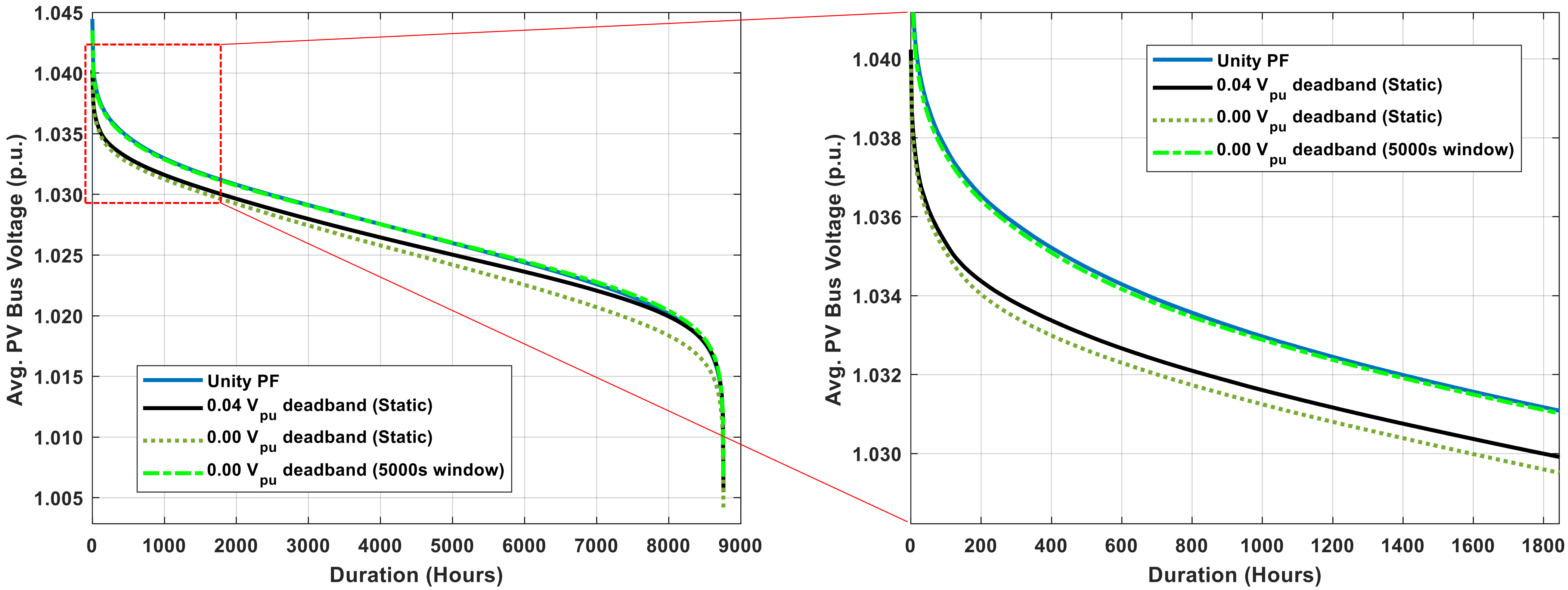
Results: Static vs. Adaptive Volt-VAR

- When deadband = 0.00 Vpu for AVV, kVARh is reduced by roughly an order of magnitude for the 5000s window compared to Static VV
  - When deadband = 0.01 Vpu, kVARh is reduced by roughly 2 orders of magnitude for the 5000s window
- Deadband size impacts annual kVARh of Adaptive VV more than Static VV



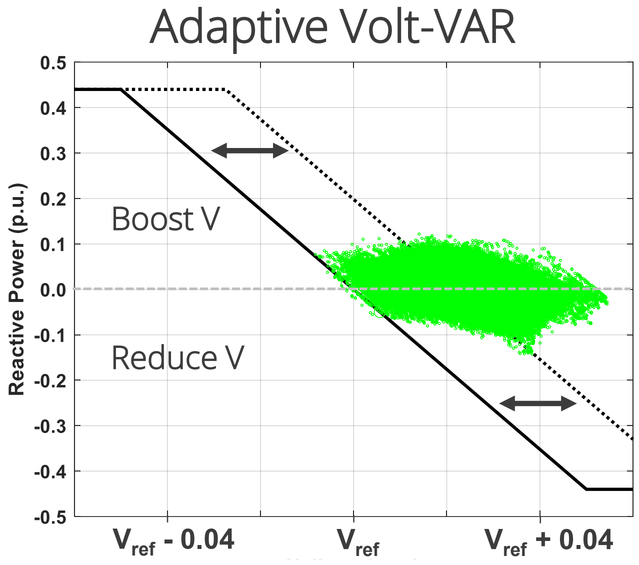
Results: Static vs. Adaptive Volt-VAR

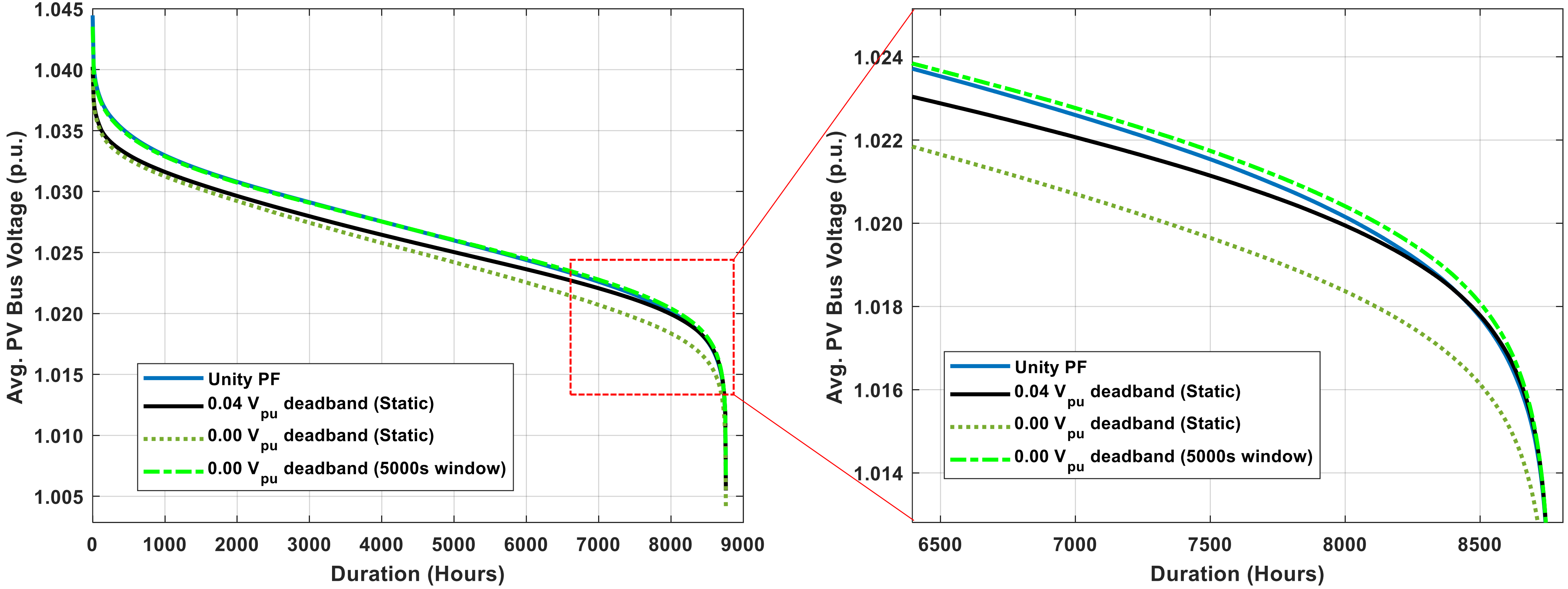
- Consider Adaptive VV results with no deadband and 5000s window, which represents the most aggressive settings
  - Some regulation of high voltages compared to unity PF case, but much less than Static VV (even when deadband was 0.04 Vpu for Static VV)



Results: Static vs. Adaptive Volt-VAR

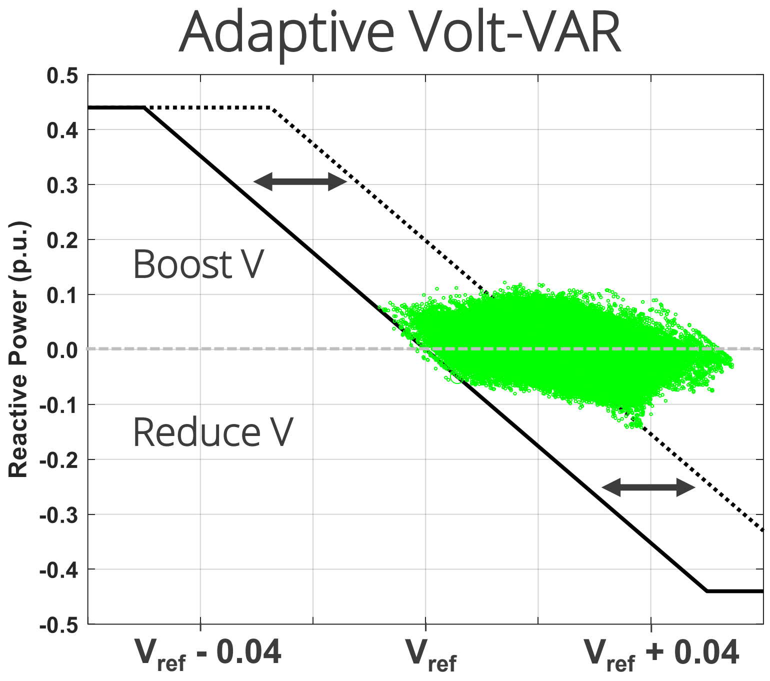
- Since V_{ref} is changing with Adaptive VV, some voltages are **boosted** compared to unity PF
  - Static VV only *reduced* voltages compared to unity PF





Discussion

- Since the V_{ref} for Adaptive VV changes with the terminal voltage, reactive power is only required when there is a *sudden voltage change* in either direction
  - Therefore, Adaptive VV is not as effective as Static VV in reducing the presence or duration of extreme voltages
- Adaptive VV has very little curtailment risk and may be useful for other applications, such as reducing voltage flicker, dampening interactions between PV and voltage regulation devices, or minimizing PV impacts during conservation voltage reduction (CVR) events [2-4]
  - A similar approach to AVV has been used to reduce voltage flicker from inverter-interfaced wind generators [5]



*Each green dot represents a unique point in time

Conclusion

- Adaptive VV requires much less reactive power support than Static VV, and curtailment risk was shown to be negligible
  - Reactive power support from Adaptive VV was mainly dependent on the deadband setting of the VV curve, but also increased as the averaging window increased
- Static VV was significantly better at regulating extreme voltages
  - However, Adaptive VV resisted sudden voltage changes in either direction, so it may be more useful in applications that benefit from smaller/smoother voltage deviations

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