Enhancing Grid Stability through Reactive Power Support from Inverter-Based Resources (IBRs)

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***Abstract*— The increasing integration of renewable energy sources into the electrical grid presents challenges to voltage stability. While inverter-based resources (IBRs) lack significant inertia, and their limited fault current capabilities affect the maintenance of voltage stability, these devices can still play a crucial role in enhancing overall grid stability.**

When utilized as reactive power support devices, IBRs function similarly to static synchronous compensators (STATCOMs). Recognizing the potential benefits of deploying small STATCOM-like devices throughout distribution circuits, Dominion Energy Virginia implemented a pilot project to examine the ability of a battery energy-storage system (BESS) to enhance system reliability and customer benefits.

During a six-month period, Dominion Energy Virginia utilized a substation-based BESS to provide reactive power support. We determined that, with the correct settings, this IBR quickly responded to changes in grid conditions by providing instantaneous voltage regulation. This reduced wear on the circulators, as the existing circuit regulator only operates when the BESS is offline, or when the state of charge is too low. For our test, we enabled the inverter's reactive power support function and observed the distribution transformer's low-side voltage to see if that function would stabilize the bus voltage. Results showed that the voltage profile stabilized after the activation of the reactive power support function provided by the BESS inverter.

This paper will describe the effects of the BESS voltage regulation on the substation distribution voltage and the life extension of circuit regulators. This feature of the BESS makes it a valuable tool for the existing circuit regulators and grid operators, helping to ensure a stable and reliable power system.

Keywords*— *BESS, grid stability, IBRs, reactive power, regulators, STATCOM, voltage stability

I. Introduction

IBRs have proliferated throughout electric utilities' Distribution systems over the past decade. The industry has discovered that some IBR systems can introduce voltage fluctuations that negatively affect equipment at the grid level [1]. However, inverters not only can minimize voltage issues at the point of interconnection, but they can also provide solutions to broader voltage problems at the Distribution level. This paper will demonstrate that enabling inverter reactive power support via Volt-VAR settings can minimize voltage fluctuations at the Distribution level as well as extend the life of circuit regulation equipment. Typically, the Volt-VAR functionality of IBRs is disabled due to concerns over wear-and-tear on the inverter. While it is too early to draw conclusions on the effect that enabling Volt-VAR functionality has on the life of inverters, this paper showcases the benefit of utilizing this functionality to stabilize grid voltage and reduce operations of existing voltage control devices.

For this study, to regulate voltage at the substation bus level we utilized a BESS connected to a 34.5kV distribution circuit that had a solar site connected to it. Once the reactive power function was programmed with the same per-unit voltage settings as the existing circuit regulators, the inverter operated for six months as the prioritized grid device to regulate voltage.

The paper will demonstrate how BESS usage of voltage regulation enhances grid stability by quickly responding to voltage fluctuations and reducing stress on the Distribution circuit. Section II highlights the importance of inertia and fault current capabilities. Section III introduces field results of the BESS implementing automatic voltage regulation (AVR) on the distribution circuit. Finally, Section IV covers the conclusion and proposes future work using electromagnetic transient (EMT) models to explore different voltage regulation methods.

II. Problem Formulation

A. Reasoning Behind Using IBRs for Voltage Support

Integrating renewable energy sources into the electrical grid creates significant challenges to operations. Traditionally, the grid has relied on synchronous generators, which inherently provide inertia for voltage regulation and the high-fault current capabilities essential for relay coordination. However, IBRs, such as those used in BESS applications, lack these characteristics, leading to potential grid instability [2]. Their lack of inertia and limited fault current capabilities pose a risk to the reliability and safety of the electrical system, especially on the Distribution grid. Voltage instability can cause equipment damage, power outages, flickering, and reduced efficiency in power delivery, which ultimately affect both utilities and consumers. With the growing number of Distributed Energy Resources (DERs) paired with IBRs and interconnected to the Distribution system, utilizing IBR voltage-control functionality will play a key role in ensuring grid reliability and stability.

B. Methodology of Testing Voltage Support

To test how an IBR could help stabilize grid voltage, the team paired a Dominion Energy Virginia-owned BESS with an inverter installed at a substation to provide reactive power support. By leveraging the fast response capabilities of the IBR, the team aimed to showcase the possibility of mitigating the wear on traditional circuit regulators and improving overall grid performance--with a particular emphasis on delivering constant voltage. The challenge lies in effectively integrating the BESS and IBR to function as a mini-STATCOM. This provided immediate voltage regulation in response to dynamic grid conditions by allowing the circuit regulator to operate only when the BESS was offline or when its state of charge was too low.

The results of this pilot project showed that utilizing a BESS for reactive power support can extend the life of circuit regulators and enhance overall voltage stability. This paper will present the effects of BESS-controlled voltage regulation on substation distribution voltage, supported by simulation data showing the before-and-after impacts on the reactive power function. These findings highlight the potential of IBRs as valuable tools for voltage regulation and grid stability.

III. FIELD RESULTS

In August 2024, the automatic voltage regulation (AVR) mode was activated on the BESS inverter. This mode allowed the inverter to adjust its reactive power output to reach a set voltage within a specified bandwidth. For the purposes of this application, the AC bus voltage was nominally at 480 V and the desire was to deliver 1.033 per unit voltage. Based on this, the inverter reference voltage was set to 496 V. The inverter was designed to function as a mini-STATCOM and take over regulation of the circuit, with the existing regulators working as a backup, the bandwidth was set to 0 to allow the inverter to instantaneously control voltage to the setpoint. Since it was connected directly to the distribution bus feeding a distribution circuit, the inverter also regulated the distribution voltage at the substation bus to 1.033 per unit. This created a voltage regulation setpoint of 124 V, derived from a 1.033 per unit ratio in a 120 V system.

During the six-month study period, the BESS AC bus voltage was much more stable with voltage control activated than without it (see Figs. 1 and 2).

A. AC Bus Voltage

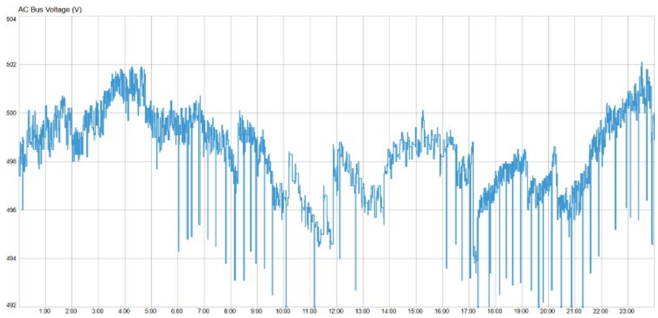

Fig. 1. BESS AC Bus Voltage on a Typical Day Pre-AVR Activation.

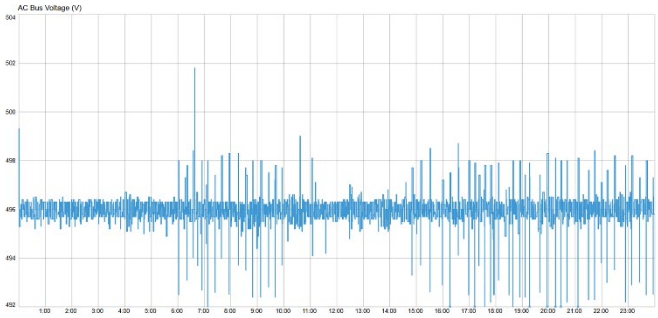

Fig. 2. BESS AC Bus Voltage on a Typical Day Post-AVR Activation.

When AVR is off, the voltage for a circuit is primarily controlled by its station circuit regulators, which have an inherent deadband. Therefore, the setpoint of 496 V was also achieved more consistently with the voltage control on.

To further demonstrate the stability of the bus voltage with active voltage control, the mean absolute error for 2024 was compared with and without AVR. For this calculation, the predicted value was the 496 V setpoint. All voltage datapoints when the inverter's voltage control mode was inactive over a six-month period were used to calculate the mean absolute error without AVR, which was 2.6%. The voltage datapoints for 2024 when the voltage control mode was active during the six-month study period provided a mean absolute error 0.5%. Results indicate that the DC bus voltage fluctuated approximately five times more when the voltage control mode was not enabled. Thus, a more stable voltage was delivered to the distribution customers when fed from the same circuit as the inverter.

B. Reactive Power Usage

It didn't require the full reactive power of the IBR to regulate the bus voltage to the 1.033 per unit setpoint. The inverter's maximum instant reactive power output over the year was +320 kVAR, while the minimum instant reactive power output was –650 kVAR. Since the BESS is capable of delivering up to 2 MVA, this means that only a fraction of the IBR's reactive capability was necessary to provide constant voltage at the 1.033 per unit setpoint. This provides promising results for future projects, illustrating that even smaller-sized inverters connected to DERs may be sufficient to regulate the circuit voltage to a specific level.

C. Circuit Regulator Usage

By having the BESS inverter operate with zero bandwidth, the inverter was able to act as the first regulating device for the distribution circuit. This has resulted in the existing circuit regulator requiring fewer operations to achieve 1.033 per unit voltage at the substation bus. Before voltage control was activated, each phase circuit regulator averaged 87 operations per month. After voltage control was activated, each phase circuit regulator dropped to an average of 52 operations per month, a 40% decrease. There were several BESS outages for maintenance purposes after activating AVR during the regulator operations measurement period, resulting in the circuit regulator operating as the primary voltage control device during the outages. This leads to the belief that a further reduction in regulator operations will be shown as the BESS is in service with AVR mode active. This will result in less wear-and-tear on the regulators as the inverter continues to function as the primary voltage support device for the circuit.

IV. Conclusion

Once the battery inverter's reactive power function was enabled in the field, the BESS's AC bus voltage at the substation became more stable. This increased consistency was achieved solely by the inverter applying zero deadband to its voltage control point. This allowed the inverter to respond instantly to voltage deviations and adjust its reactive power output prior to the operation of the station circuit regulators.

The established voltage setpoint was reached regularly when the voltage control function was active, illustrated by the mean absolute of 0.5%, compared to 2.6% when the function was disabled. This illustrates that the inverter was able to act as a de facto STATCOM by constantly adjusting its reactive power output to achieve a stable voltage setpoint. This also resulted in decreased operation of the circuit regulators, resulting in less wear and tear on them. Regulator operations decreased by 40% in the six-month period that voltage control was activated. A further reduction in operations is anticipated in future periods due to multiple maintenance-related BESS outages during the test period, which led to regulators becoming the primary voltage control device for the circuit. With fewer BESS outages expected, regulators operations should decrease.

Given the promising results of this research, the BESS inverter did not need to utilize its full reactive power capacity to maintain the desired voltage setpoint. The maximum and minimum reactive power outputs were well within the inverter's capabilities, indicating smaller inverters could also regulate circuit voltage effectively. Dominion Energy Virginia plans to take the following next steps:

- Gather more data when the battery inverter voltage regulation function is enabled, specifically on inverter wear-and-tear as well as circuit regulator operations.
- Enable and testing other IBR voltage regulation functions throughout the distribution system and monitor effects on customers.
- Conduct cost-benefit analyses to evaluate the economic advantages of deploying IBRs for voltage regulation across the grid.

These steps will help further validate the effectiveness of IBRs in enhancing grid stability and reliability. Future work involves detailed EMT modeling of the battery, inverter, and the distribution circuit using real field-load measurements to replicate the voltage fluctuations. This realistic representation of the distribution grid and battery site will enable further research on other voltage control methods. Advancing research and practical application of these technology solutions is promising for adapting to the growing demand of renewable energy integration.

References

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Biographies

Luis Rosa-Rivera earned a B.S. in Electrical Engineering, Power Systems, from University of Puerto Rico, Mayaguez (2017). He has worked at Dominion Energy since 2017. He spent four years as an EMS Modeling and Contingency Analysis subject mater expert in the Transmission System Operations Center. In 2021 he moved to Electric Distribution Grid Solutions. Currently, he is the supervisor of DER Integration and Engineering, overseeing Dominion Energy's Distribution-owned, regulated, BESS projects and Non-Wire-Alternatives (NWA) program. Member of the IEEE 1547 Standard Revision Committee. EPRI Advisor on P94.

Furkan Ilgin received his B.S. in Electrical Engineering from Old Dominion University, Norfolk, VA, USA in 2023 and his MBA from Western Governors University, Millcreek, UT. He is currently working toward an ME degree in Systems Engineering at the University of Virginia. He is an Engineer on the DER Integration and Engineering team. His research interests include machine learning, renewable energy, energy storage systems, microgrid design, engineering management, risk analysis and human technology interaction.

Alexander B Freeman received his B.S. (2017) in Electrical Engineering and his M.Eng. (2019) from Virginia Tech. He is a Senior Engineer on the DER Integration and Engineering team. He has worked for Dominion Energy for six years. His interests include power systems, DER controls, distribution grid planning, and reliability analysis. He is an advisor on EPRI P94.

Genesis B. Alverez earned a B.S. in Electrical Engineering from Florida Atlantic University, Boca Raton, FL, in 2017, followed by an M.S. in Electrical Engineering from Virginia Tech in 2019. After graduating, she joined Dominion Energy's Electric Transmission Operation Engineering team within the ET Strategic Initiatives group. In 2025, Genesis transitioned to Substation Standards as a Staff Engineer, focusing on developing and documenting engineering and design requirements for substation equipment. Genesis's research interests include grounding, system protection, and renewable energy integration within distribution systems.

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Gerald J. Warchol (Member, IEEE) received a B.S.E.E. degree from Northern Illinois University, DeKalb, IL, in 2006, and a Master of Engineering degree from Virginia Polytechnic Institute and State University, Blacksburg, VA, in 2014. Starting in 2006, he was a Power Electronics Engineer with Fermi National Accelerator Laboratory, Batavia, IL. In 2008, he started with Dominion Energy where he has held various positions in Power Generation, Electric Transmission, and Electric Distribution Engineering. He currently manages the Transmission System Operations Center. He is a Professional Engineer with the Commonwealth of Virginia