

EMT-Based Study on Temporary Overvoltages and System Stability in a Practical Grid-Connected DER Implementation

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Abstract—The rapid integration of medium-voltage inverter-based resources requires robust methodologies to ensure reliable microgrid operation. This paper presents one such methodology: electromagnetic transient (EMT) assessment of temporary overvoltages (TOVs) and dynamic stability for a 34.5 kV distribution-connected microgrid with 1.1 MW solar generation and a 1.5 MW Battery Energy Storage System (BESS). This study addresses the critical challenge of maintaining feeder ground protection sensitivity during grid-connected operation while ensuring effective grounding in islanded mode through a controller-coordinated switching scheme using a 0.9 MVA Yg/Δ grounding transformer. EMT simulations using original equipment manufacturer (OEM) black-box inverter models confirmed acceptable performance. Perturbation-based EMT testing was used to evaluate stability across a wide operating range, with results demonstrating bounded and well-damped system response to disturbances, coordinated grounding control actions, and transitions between grid-connected and islanded operating modes. The proposed framework provides practical guidance for EMT analysis of DER-based microgrids with protection sensitivity constraints.

Keywords—Battery Energy Storage System (BESS), Black-Box Inverter Modeling, Distributed Energy Resource (DER), Electromagnetic Transient (EMT) Analysis

I. INTRODUCTION

The increasing adoption of inverter-based resources (IBRs), including battery energy storage systems (BESSs) and solar photovoltaics (PVs), introduces new challenges for distribution-connected microgrids due to their fast, control-driven dynamics [1]. Two critical assessments for systems with islanding capability are temporary overvoltages (TOVs) and electromagnetic transient (EMT)-based dynamic stability. TOVs resulting from islanded ground faults can rapidly damage equipment and compromise protection [2] [3], while improper control during grid-following (GFL) to grid-forming (GFM) transitions can cause instability and service disruptions [4].

These risks necessitate EMT-based validation since rms tools cannot capture fast transients, phase-locked loop (PLL) dynamics, or converter limits [5] [6].

A central design challenge is maintaining feeder protection sensitivity during grid-connected operation while ensuring effective grounding when islanded. Utility restrictions on zero-sequence injection eliminate continuous grounding solutions, and grounding loss can drive voltages toward 1.73 pu during faults [2] [7], requiring a controlled grounding-switching strategy that is validated through EMT simulation. This paper addresses this dual constraint, presents a perturbation-based EMT methodology using black-box original equipment manufacturer (OEM) inverter models [5] [8], and validates coordinated microgrid control, including grounding transformer switching and GFM transitions. This approach provides a practical framework for analyzing distributed energy resource (DER) microgrids under real-world constraints.

A. DER System Architecture and Operation

The system studied is a distribution-connected nonexport DER microgrid connected to a 34.5 kV utility distribution feeder at a point-of-interconnect (POI) recloser, as shown in Figure 1. Generation is sized to serve local loads with no intentional export to the utility.

The DER facility generation mix consists of a BESS capable of operating in both GFL and GFM modes and PV arrays distributed across multiple building areas operating exclusively in GFL mode. The BESS is the sole GFM-capable resource during islanded operation. This single-GFM, multi-GFL architecture places critical requirements on black-start capability, dynamic response, and mode-transition coordination. A backup generator is available for extended islanded operation, primarily to support BESS charging during low state-of-charge conditions.

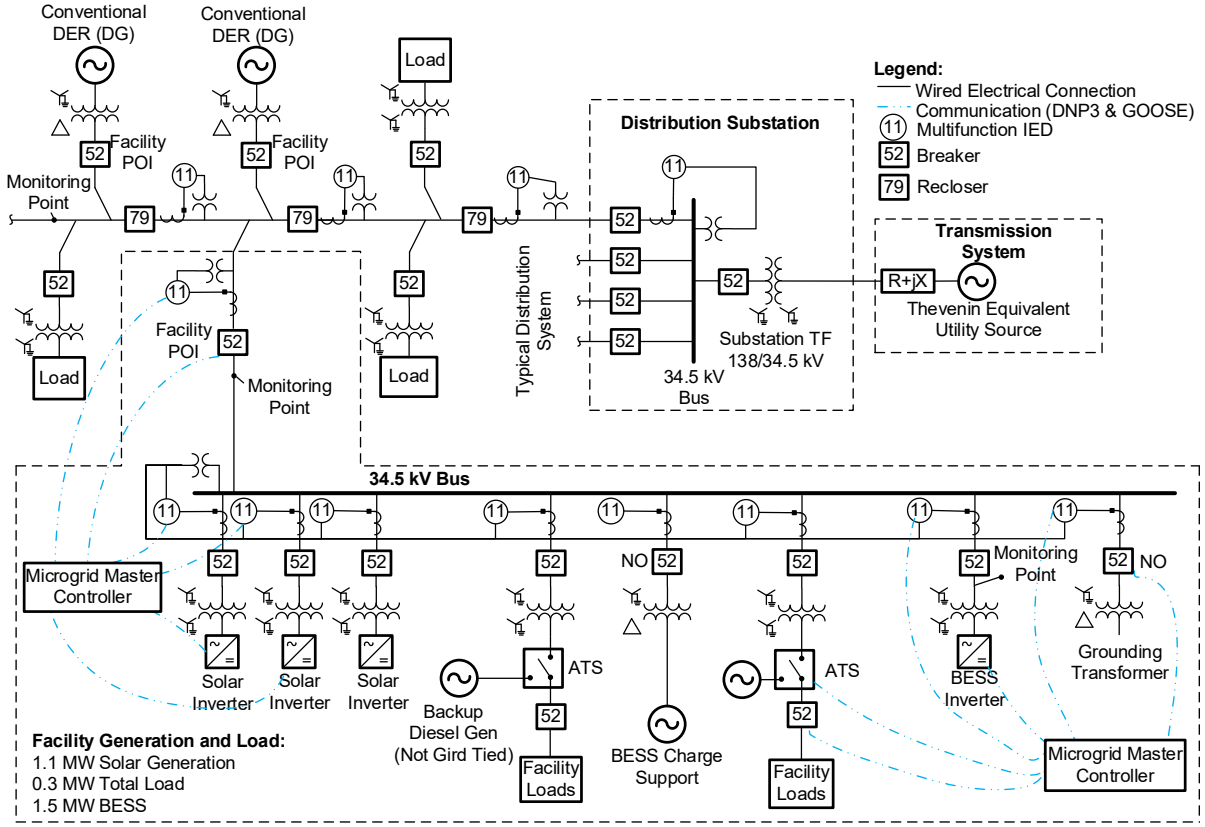


Figure 1 – Single-line diagram of a distribution-connected DER

B. Grounding Constraint and Switching Strategy

The medium-voltage system lacks a local zero-sequence grounding source under islanded conditions, as the utility substation provides this reference during grid-connected operation; upon POI isolation, this reference is fully removed, leaving the system ungrounded. A key utility requirement prohibits any DER-side from injecting zero-sequence current during grid-connected operation to preserve feeder protection sensitivity, thereby eliminating conventional continuously connected grounding solutions, including both solid and impedance-grounded configurations [3]. To address this constraint, a switched grounding approach using a dedicated Yg/Δ transformer was implemented, remaining disconnected during grid-connected operation and automatically inserted upon confirmed POI isolation to restore effective grounding without impacting feeder protection, and subsequently disconnected during grid reconnection. Operationally, the master controller confirms islanding following POI opening, closes the grounding transformer breaker, and enables BESS grid-forming control to establish voltage and frequency, while during reconnection the system synchronizes with the grid, recloses the POI, and then opens the grounding transformer to restore normal operation.

II. EMT MODELING FRAMEWORK

The reliability of EMT results depends critically on model fidelity. Unlike phasor-domain simulations, which assume balanced steady-state conditions and simplified dynamics, EMT simulations capture subcycle electromagnetic dynamics

and control interactions with high resolution, enabling accurate representation of fast inverter-driven phenomena.

The following requirements, aligned with NERC EMT guidelines [5] and recent IBR modeling literature [8], were utilized for the DER facility assessment:

- OEM inverter delay-locked loop (DLL) models with site-specific parameters (including BESS controls): generic models are insufficient. OEM-provided DLL models replicate inverter control behavior—including PLLs, current limiting, ride-through, and mode transitions—with site-specific settings. For the BESS, accurate representation of control functions, such as active/reactive power control modes and GFM/GFL operation, is critical, as these functions strongly influence system response during disturbances and mode transitions. This study used OEM-validated models with site-aligned parameters.
- Complete sequence network data: both positive- and zero-sequence parameters for all system elements are required. Zero-sequence impedance, which is the primary driver of TOV magnitude, is often overlooked.
- Utility short-circuit variability: maximum and minimum grid-strength conditions must be represented to bind TOV severity and stability margins.
- Synchronous generator representation: where present, generator models must include exciter and governor dynamics, which influence islanded frequency response.

- Representation of upstream networks beyond the POI: accurate modeling of the external grid should extend beyond a simple equivalent source at the POI to include relevant upstream buses and distribution or subtransmission lines. This information is necessary to capture the effective system strength, zero-sequence impedance, and fault current pathways seen by the DER interface. NERC EMT guidelines emphasize appropriate study area selection and representation of the external system [5], as insufficient upstream detail can lead to inaccurate DER dynamic response predictions. For this DER study, the EMT model was created up to the nearest distribution substation.
- Nonlinear transformer behavior, including saturation and winding configuration, must be represented.

III. TOV ASSESSMENT AND GROUNDING PERFORMANCE

A. TOV Scenario Framework and Acceptance Criteria

The TOV acceptance criterion is defined by limiting unfaulted phase voltages to 1.38 pu, which is consistent with the coefficient of grounding ($\text{COG} \leq 80$ percent) requirement per IEEE 1547-2018 [2] and IEEE C62.92.1 [7]. This threshold is assessed using a fundamental-frequency rms window and should be interpreted as a steady-state overvoltage limit. Compliance is further verified against the manufacturer's TOV capability curve of the installed surge arresters to ensure that simulated overvoltages remain within their thermal withstand limits. This verification is critical, as surge arresters are designed to dissipate transient energy; however, sustained TOVs can lead to excessive energy absorption and thermal stress, making them one of the most critical limiting components under such conditions.

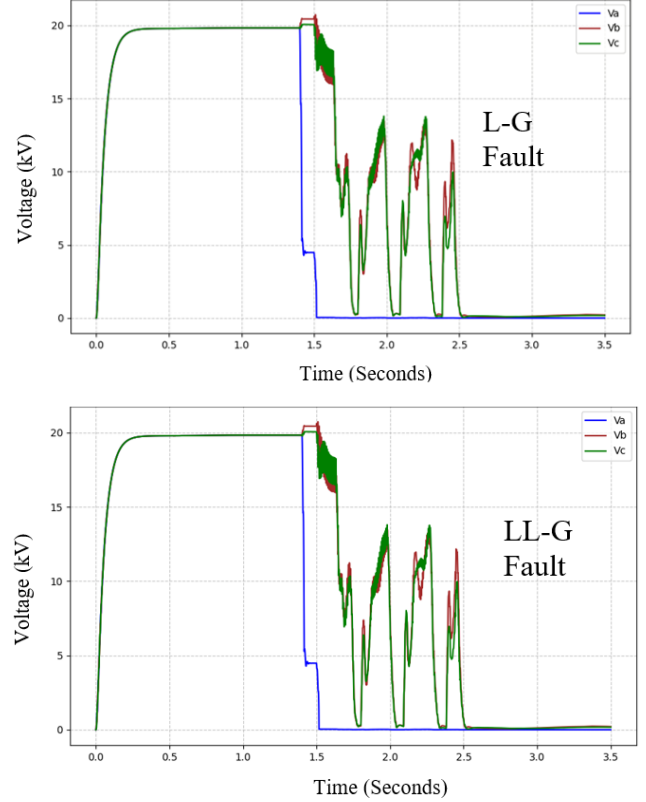
For assessment, voltages are monitored at three locations: the utility substation feeder terminal, the end of the distribution line, and the DER medium-voltage bus (the primary location of interest). Within the DER system, measurement points are selected at electrically weak (high-impedance) nodes, where the highest overvoltages are expected to occur during ground fault conditions. This approach ensures that the worst-case TOV scenario is captured and provides a conservative basis for compliance evaluation, as shown in Table 1.

TABLE 1 – SUMMARY OF TOV ASSESSMENT SCENARIOS

Category	Operating Mode	Event Type	Fault Type
Load rejection	Grid-connected	POI opening Load feeder opening	NA
Load rejection	Islanded	Local load tripping	NA
Fault grid	Grid-connected	Fault	SLG, LLG-2 Ω
Fault-islanded	Ungrounded	Fault	SLG, LLG-2 Ω
Fault-islanded	Grounded with GND TX	Fault	SLG, LLG-2 Ω

B. Grid-Connected TOV Results

Grid-connected load rejection and fault scenarios did not produce sustained TOV exceeding 1.38 pu at the DER bus, as shown in Figure 2. This result is attributed to the utility substation transformer maintaining a zero-sequence grounding reference, limiting neutral shifts as the grounding transformer remains disconnected, preventing zero-sequence current injection into the feeder, and thereby preserving relay sensitivity. Load rejection events in this study did not result in significant overvoltage due to the relatively small load at the DER facility.



C. Islanded TOV Results and Grounding Effectiveness

Islanded fault scenarios produce the most severe TOV conditions and therefore govern the grounding design. Figure 3 illustrates the DER bus voltage during an SLG fault in islanded operation without the grounding transformer. Unfaulted phase voltages rise rapidly to approximately 1.65 pu and remain above the 1.38 pu threshold until the inverter trips on overvoltage protection. Figure 3 also shows the same fault with the grounding transformer connected within the worst-case GND TX connection control timing. The grounded Yg winding establishes an immediate zero-sequence path, suppressing neutral shift and maintaining unfaulted phase voltages below 1.38 pu. The resulting improvement is clear: TOV is reduced from approximately 1.65 pu to within the effective grounding limit.

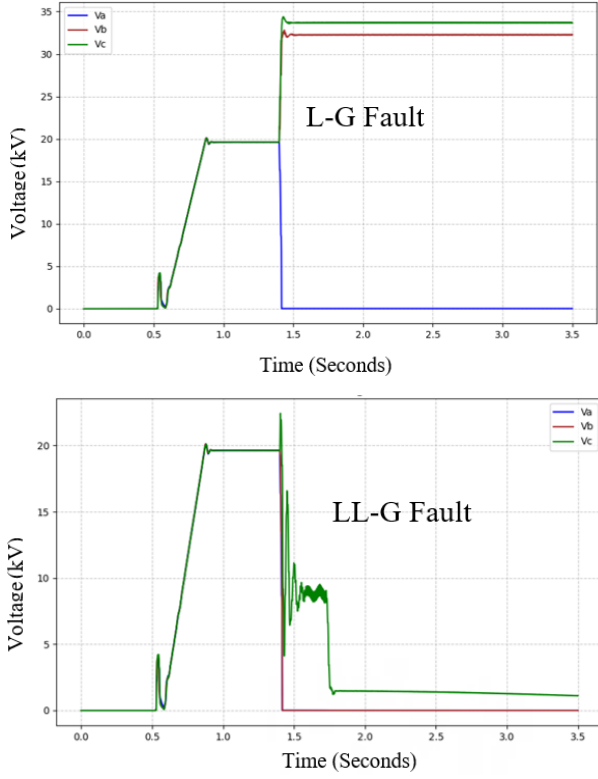
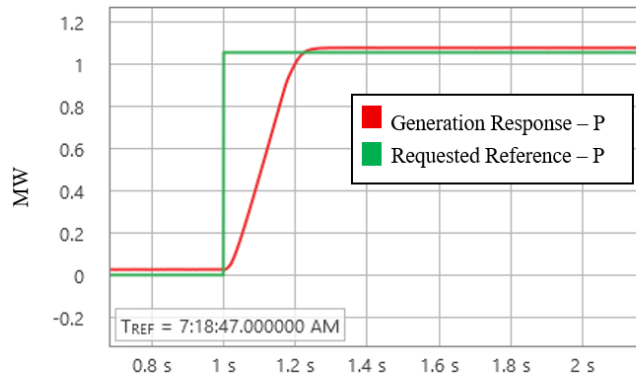


Figure 3 – Islanded SLG fault response at DER bus with and without grounding transformer

IV. DYNAMIC STABILITY ASSESSMENT

A. Perturbation-Based EMT Methodology for Black-Box Inverter Validation

The perturbation-based methodology enables system-level validation of networks with OEM black-box inverter models, where internal control parameters are inaccessible and analytical stability methods are impractical. Stability is assessed by applying disturbances across the operating envelope and verifying that observable quantities (e.g., POI voltage, frequency, power, dc-link) remain bounded and converge, as any instability would manifest sustained oscillations. The test framework in this section provides a practical method for demonstrating stability using black-box EMT models, as shown in Table 2.

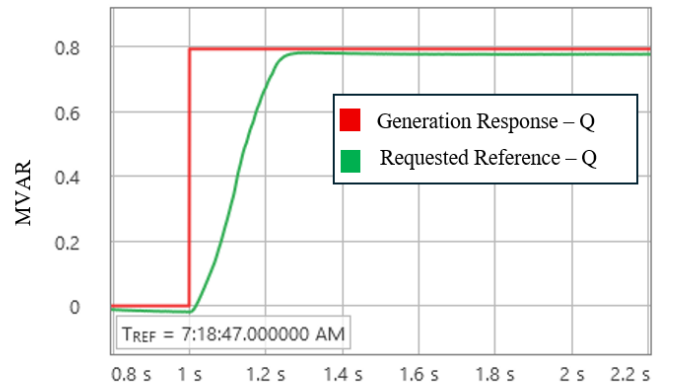


Generation Variation—Real-Power Step Change

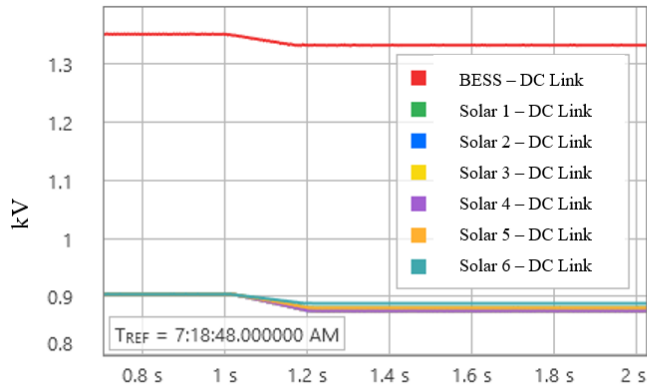
Category	Operating Mode	Disturbance Type		Key Evaluation for DER
Generation variation	Grid-Connected	Active-power step/ramp	Full and partial dispatch changes	Control response, damping
Load variation	Grid-connected	Load rejection and disconnection	Feeder and local load changes	Current response, power tracking, grid interaction
Voltage disturbance	Grid-connected	POI voltage step ($\pm 10\%$)	Heavy and light loading	Voltage tracking, grid interaction
Grid-strength variation	Grid-connected	Source-impedance change	Reduced system strength	Weak grid-stability margin
Frequency disturbance	Grid-connected	Frequency step (± 1.5 Hz)	Short-duration excursions	Frequency tracking, PLL stability
Phase disturbance	Grid-connected	Phase angle step (10° – 25°)	Sudden phase shifts	PLL-locking stability
Planned islanding	Transition	Controlled POI opening	Transition test	Transition stability
Unplanned islanding	Transition	Sudden POI trip	Worst-case transition	Black start with transition stability
Return-to-grid	Transition	Synchronization and reconnection	GFM > GFL transition	Resynchronization performance

B. Grid-Connected Stability Results

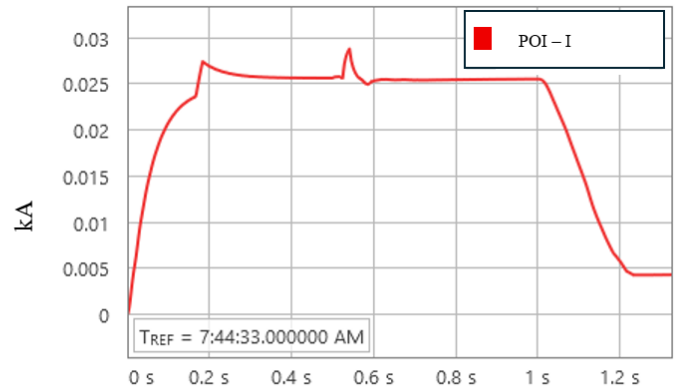
Generation ramp tests demonstrated well-damped responses across all operating points, as shown in Figure 4, with dc-link voltages remaining within OEM limits and normal load cases remaining stable, confirming adequate gain margin in GFL PLL and voltage control loops. Phase shift tests at 10, 19, and 25 degrees further quantified PLL stability, with oscillations damping out, thus confirming stability. No observable resonance or sustained oscillation was observed following grid-impedance increase, demonstrating robustness across expected grid-strength variations. It is important to note that this system is connected to a strong grid.



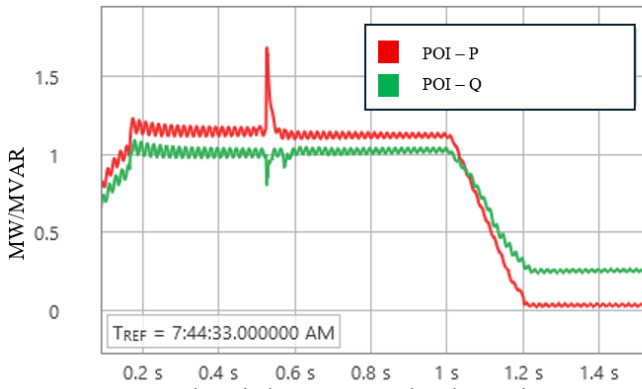
Generation Variation—Reactive-Power Step Change



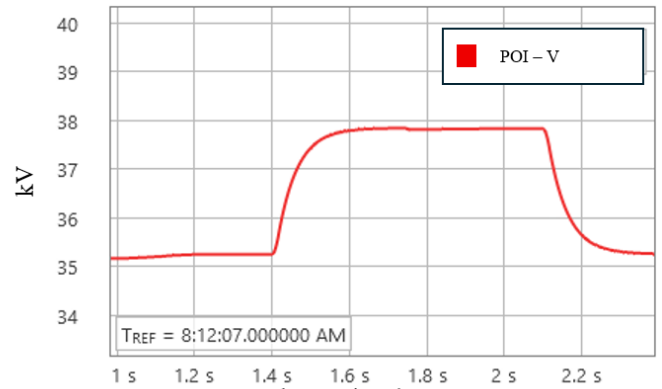
Generation Variation—DC-Link Voltage



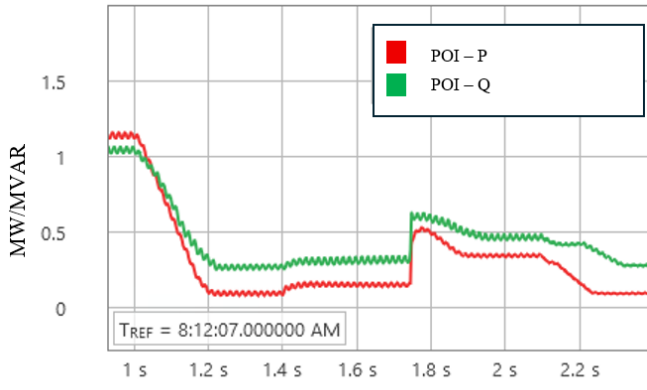
Load Variation—POI I Rms



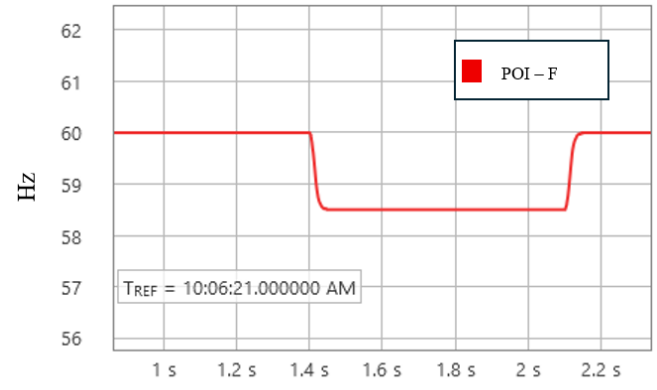
Load Variation—POI Real and Reactive Power



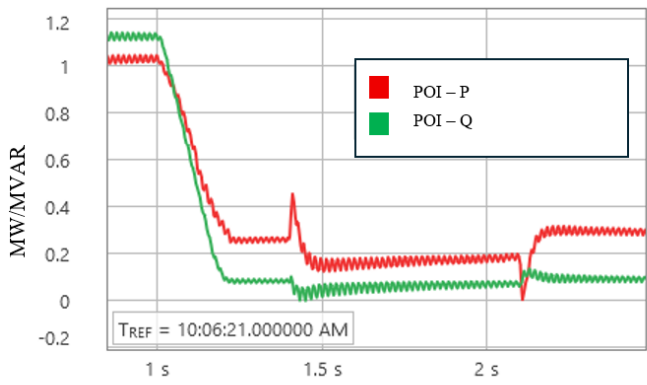
Voltage Disturbance—POI



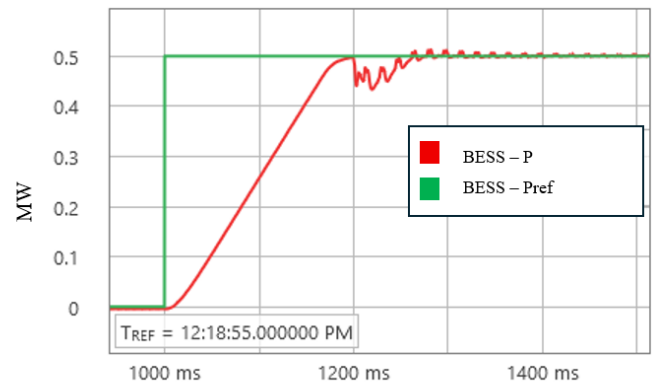
Voltage Disturbance—POI



Frequency Disturbance—POI



Frequency Disturbance—POI



Phase Disturbance 25°—BESS P

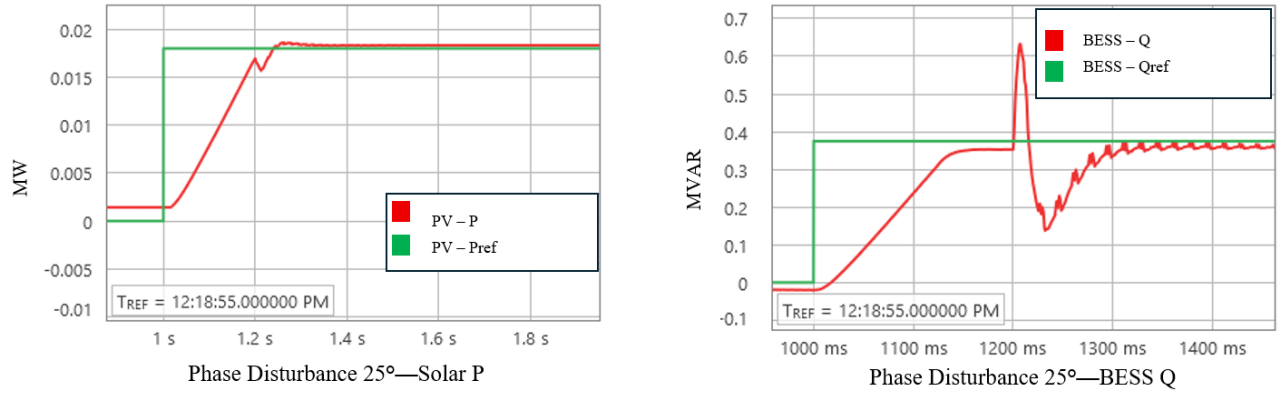


Figure 4 – Grid-connected stability assessment results

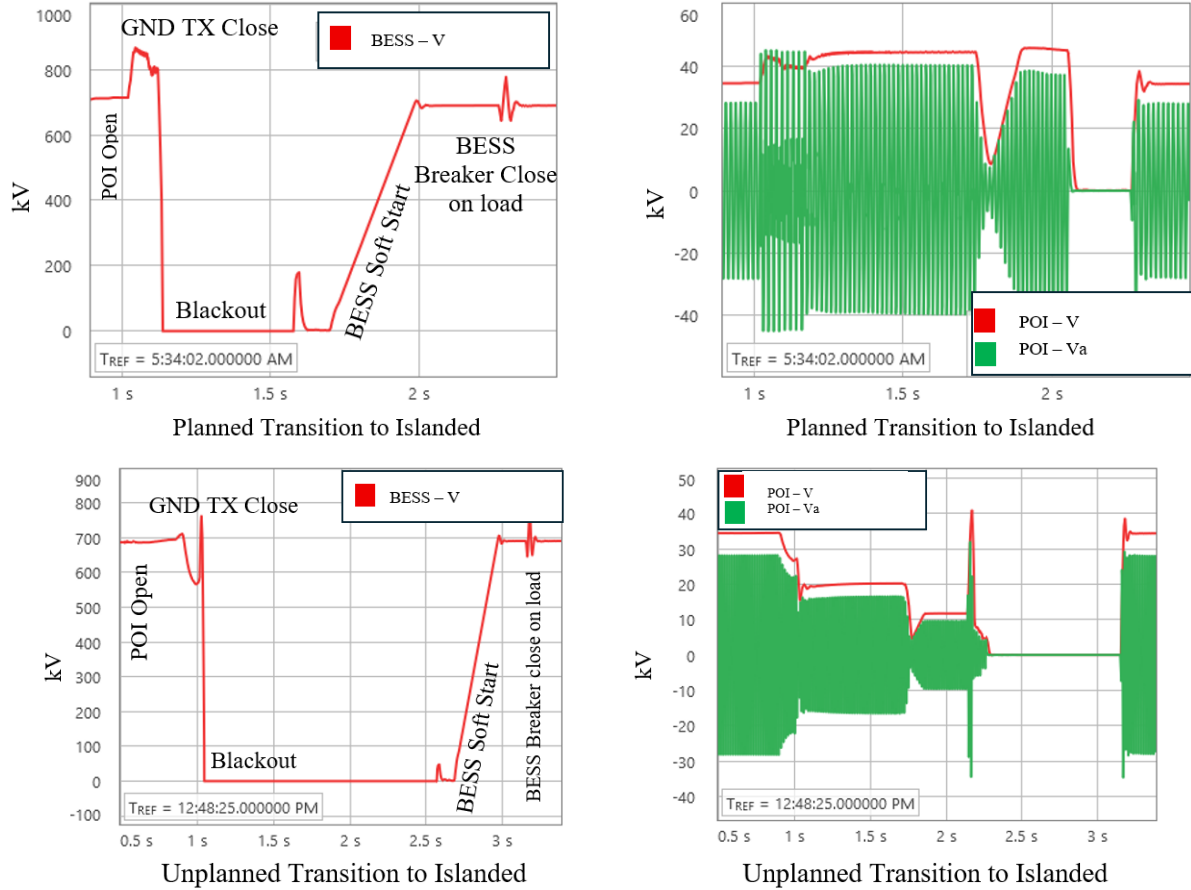


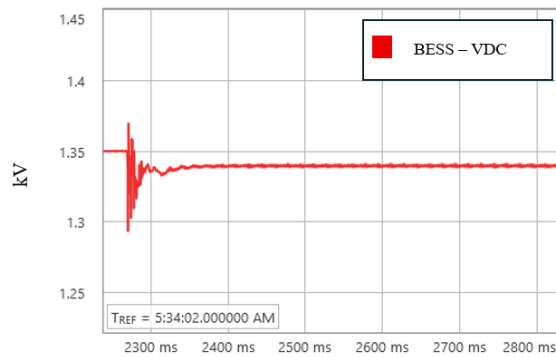
Figure 5 – Transition results

C. Mode-Transition Stability Results

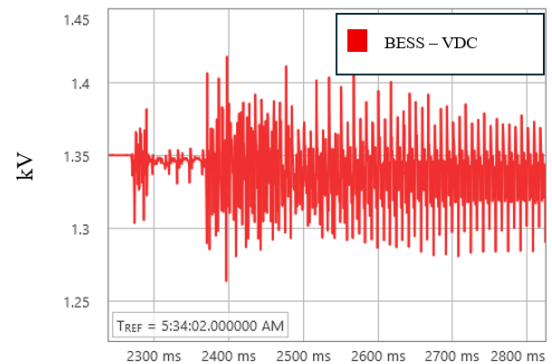
Mode-transition validation, as shown in Figure 5, confirmed the end-to-end microgrid controller sequence—including grounding transformer switching, BESS GFM activation, PV coordination, and return-to-grid synchronization—executed correctly and maintained stable operation. The planned islanding case verified proper sequencing, with grounding established prior to GFM activation, followed by a controlled voltage ramp and stable current and frequency response. Power profiles demonstrated that the BESS reliably established and sustained island load balance in GFM mode. A key insight was the impact of the black-start energization strategy; simultaneous load energization yielded well-damped

performance due to the strong BESS-to-load capacity ratio, whereas staggered energization with very short delays ($\ll 100$ ms) for the same loads introduced higher oscillations on BESS output. For stable operation, staggered restoration must employ interstep delays of at least 3–5 s, highlighting sequencing and timing as critical design parameters for GFM-based microgrids.

While all tested scenarios demonstrated stable system behavior, additional analysis identified conditions where the system took more time to stabilize. Specifically, rapid control actions, such as closely spaced load restoration, resulted in the oscillatory responses shown in Figure 6. These observations highlight the importance of sequencing, timing, and control tuning in maintaining stable operation of GFM-based microgrids.



Time-Delayed Staggered Load Restoration



Fast Staggered Load Restoration

Figure 6 – Increased switching oscillations

V. CONCLUSION

This paper has presented a comprehensive and rigorously validated EMT-based framework for assessing TOVs and dynamic stability in distribution-connected DER microgrids, demonstrating how practical engineering constraints can be resolved through a coordinated control strategy. By combining high-fidelity EMT simulation with OEM-validated black-box inverter models and the simulated control system controller actions, this study has established a robust methodology for capturing complex inverter control interactions inaccessible through conventional analysis. The proposed switched grounding architecture, governed by a microgrid controller, simultaneously eliminates zero-sequence injection during grid-connected operation and restores effective grounding under islanded conditions, with quantitatively-verified suppression of TOV, from unacceptable levels to within safe limits. The perturbation-based stability framework further demonstrates that system stability can be confidently validated without access to proprietary inverter internals, while the explicit simulation of mode transitions highlights the critical role of sequencing logic in ensuring reliable operation. Collectively, these results provide not only a validated solution for this real-world deployment, but also a transferable and practically implementable methodology for industrial application, advancing the state of practice in EMT-based analysis of modern inverter-dominated distribution systems.

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