NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Technical Report

Beyond Positive Sequence RMS Simulations for High DER Penetration Conditions

October 2022

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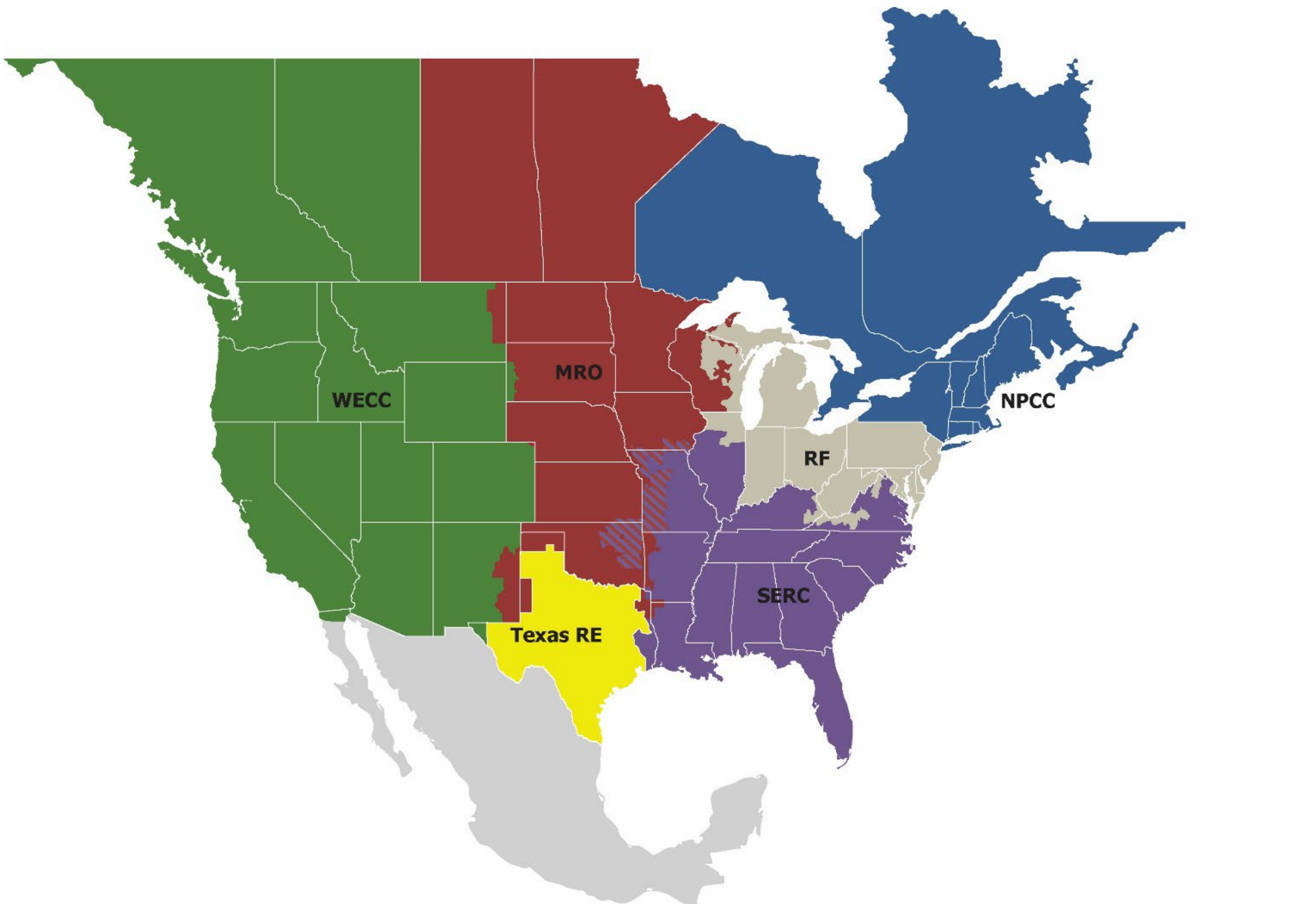
Preface

Electricity is a key component of the fabric of modern society and the Electric Reliability Organization (ERO) Enterprise serves to strengthen that fabric. The vision for the ERO Enterprise, which is comprised of NERC and the six Regional Entities, is a highly reliable, resilient, and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

Reliability | Resilience | Security
Because nearly 400 million citizens in North America are counting on us

The North American BPS is made up of six Regional Entity boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Regional Entity while associated Transmission Owners/Operators participate in another.



MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Executive Summary

The NERC SPIDERWG studied various limitations of the current set of positive sequence tools to determine which, if any, boundary cases can be identified to switch from a positive sequence tool into a "beyond positive sequence" framework. The capabilities of current transmission and distribution (T&D) co-simulation tools were determined to be capable of modeling the complexities of both systems. Simulations were performed on a set of reduced cases rather than the current Interconnection-wide base cases in order to provide a technical baseline for further investigation. This report is intended to help Transmission Planners (TPs) and other relevant engineers understand the benefits and limitations of current and beyond positive sequence frameworks with respect to analyzing the impact of DERs on the BPS and the response of distributed energy resources (DER) to BPS events in high DER penetration scenarios. To do so, SPIDERWG listed the current limitations in positive sequence tools and explored two use cases to highlight areas where beyond positive sequence tools can assist the TP in their studies. This work would also create awareness and helpful information on DER unique characteristics as it relates to how planning engineers use them in their operational day-ahead, near-term planning horizon, and long-term planning horizon studies.

TPs and Planning Coordinators (PCs) are able to take this document, read the various use cases for beyond positive sequence tools, and incorporate any changes to their planning criteria to explore when to utilize tools to assess the reliability of the BPS outside of the typical positive sequence root mean square (RMS) framework. However, it should be noted that, while this document provides investigations into DERs specifically, other factors like load may be applicable for a TP or PC to begin developing a model in a beyond positive sequence tool.

The report finds that buses electrically distant from the site of studied disturbance show very similar behavior during and post-disturbance, indicating that the typical positive sequence tools capture the impact of aggregate DERs well. Close to the site of studied disturbance, however, there are instances of adequate difference between a positive sequence tool and beyond positive sequence tool that warrant further investigation. While this difference can be attributed to modeling differences between T-only and T&D co-simulation, implementation of the class and type of numerical methods used and other implemented model details (such as the composite load model) that impact numerical convergence all require support of a beyond positive sequence tool to determine the impact of DER on the BPS. Furthermore, the studies conducted compared a framework of aggregated modeling in a positive sequence tool versus the more detailed modeling of an explicit distribution system (where the DER is located) and found that under tested conditions, the DER_A model and previous SPIDERWG guidance was adequate.[1] While engineering judgement is a viable tool, leveraging approaches (e.g., T&D co-simulation to understand aggregate model usage, representation, parameterization) will increase understanding of the system behavior; this can then inform TP and PCs in a way that allows them to update their practices to more accurately capture their system's behavior.

It is worth pointing out that the results provided here for the mixed vintages of DER scenarios does not rule out the possibility of a set of parameters that will result in appropriate response of single DER_A model used to represent mixed vintages. The rationale to explore alternative means of modeling stems from the following:

- There is a potential challenge in deriving generic and universal parameter values, especially the parameters associated with voltage and/or frequency zones and associated timers in simulation of scenarios where there could be more than two interconnection standards in mixed vintages of DERs.
- Here, while engineering judgement could be used with the use of a single DER_A model to provide a TP with the trend of the response, the need for increased accuracy in simulation results can warrant use of multiple DER_A models.

[1] The studies here are not intended to be used to achieve "perfect" simulation results. Rather, these are used to assist in planning analysis and scenario development for use in a utility's planning practices.

Introduction

In the past, DER penetration levels have been insignificant, and transmission planning studies either did not include DERs in the simulations or used Positive Sequence RMS (Root Mean Square)) tools to model DERs. This methodology has been sufficient in the past to represent the impacts of these resources on the BPS. However, as DER penetration levels increase, TPs need to use a more detailed model to represent DER behavior and study the impact of these resources[2] in order to understand their impacts on the reliability of the grid.

Today, the industry is becoming familiar with the DER_A dynamic model,[3] which is an aggregate positive sequence model for inverter based DERs. This model[4] captures the behavior and features of DERs and is used to help understand the impact of DERs on BPS reliability. However, aggregation masks the individual behaviors of DERs on the distribution system and the positive sequence simulation tools currently used cannot accurately represent the impact of unbalanced faults on DERs. With the proliferation of DERs these limitations of existing simulations tools and methods (despite improvements) has given rise to questions of whether TPs should explore other simulation options that go beyond positive sequence and use beyond positive sequence tools to assess whether the existing tools adequately capture the effect of DERs. The goal is not to find a "perfect" simulation result but rather to define the parameters by which a planning department can develop scenarios or parameter sets to study the stability of the bulk grid in various scenarios with engineering judgement.

In order to define the scope of this technical report, the report first defines "beyond positive sequence" (See **Definition of Beyond Positive Sequence**) in the context of positive sequence modeling software. In addition to the formal definition, the report categorizes positive sequence modeling software as software used for transmission-only analysis. The goal is not to discuss the theoretical differences that exist in positive sequence versus three-phase models, but rather to dissect the modeling practices that are naturally followed in positive sequence tools, namely the aggregated representation of loads and DERs. Once the modeling philosophies behind positive sequence modeling of DERs are explained, the report then transitions to dissect the benefits and limitations of aggregate DER modeling. Beyond positive sequence in this context includes dynamic simulation of the detailed distribution system along the transmission system (T&D co-simulation). However, it must be noted that advancement in detailed co-simulation modeling techniques is not guaranteed to provide the relevant answers due to a possible lack of adequate modeling data for distribution system as well as convergence issues that could arise as a result of controller feedback.

As existing transmission simulation practice does not include capturing detailed representation of the distribution system, the potential occurrence of DER control instability within the distribution system and any resulting impact on the BPS is not captured. This could be of concern to a TP. Hence, there may be a potential need for "Beyond Positive Sequence" tools that can help to model, represent, and capture the detailed behavior of DER in the distribution system in order to ascertain their impact on the BPS. However, before going down this path, it is prudent to take a look at existing distribution planning practices on this topic. Unlike transmission planning, the majority of present day distribution planning practices do not include dynamic simulation studies. Since many DER control interactions and instabilities would potentially arise within the distribution system before they translate up to the transmission system, it should be asked as to whether incorporation of dynamics studies within distribution planning is a first step to be taken before a transmission planning engineer makes an attempt to co-simulate both T&D systems.

The focus of this document is on answering questions about situations wherein present positive sequence simulation analysis may be insufficient to enable a transmission planning engineer to make a decision regarding the impact of DERs on the BPS. As part of this technical report, the deficiencies in the current process for analyzing DER impacts on the BPS will also be highlighted while simultaneously providing some insights into the capabilities and features that

[2] SPIDERWG is currently working on a reliability guideline to provide guidance on bulk system studies while including DER.
[3] This is referred to in some software as the "Distributed Energy Resource Aggregate model." It is a model that can be attached to a
[4] SPIDERWG has developed guidance on the DER_A model, available here: https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_DER_A_Parameterization.pdf

future tools would need to have in order to adequately model and represent the impact of DERs on the BPS, especially under high penetration scenarios. This document would help TPs and other relevant engineers to understand the benefits and limitations of current and "Beyond Positive Sequence" frameworks with respect to analyzing the impact of DERs on the BPS and the response of DERs to BPS events in high DER penetration scenarios. This work would also create awareness and helpful information on DER unique characteristics as it relates to how planning engineers use them in their operational day-ahead, near-term planning horizon, and long-term planning horizon studies.

Definition of Beyond Positive Sequence

The term "positive sequence" is used in this white paper to refer to positive sequence (i.e., does not include negative or zero sequence impedances, voltages, or currents), phasor domain, power flow and dynamic transmission planning practices and simulation methodologies. Positive sequence modeling assumes three main conditions: the three phases are balanced (i.e., the magnitudes of voltage/current phasors of each phase are respectively equal and the phases are spaced 120 degrees apart), the impedances of the network are represented algebraically at the fundamental frequency, and any electromagnetic transients from the network components is sufficiently damped and thus not represented. Transmission system studies have historically considered a balanced transmission system.

When the term "Beyond Positive Sequence" is used in this document, it is used to refer to simulation methods that can account for unbalanced conditions on the transmission system, the distribution system, or both. These unbalanced conditions may be represented either in phasor time domain or in electromagnetic transient (EMT) time domain. Sometimes these tools can be labeled as "T&D co-simulation" as they take present T&D simulation tools to simulate them together. Unbalanced conditions are more common in the distribution system and distribution planning tools are able to solve unbalanced load flows. It should be noted that T&D co-simulation can also interface positive sequence transmission simulator with a three-phase distribution simulator. Under such a setup, the T&D co-simulation will help capture the spatial characteristics of the DERs that positive sequence model cannot capture; however, such a setup cannot help answer questions related to unbalanced faults onto the transmission system.[5]

When investigating the impact of distribution system on the transmission network, there could be limitation of considering only phasor time domain even if the unbalance has been considered. Here, use of the EMT domain can be considered. However, the need for EMT planning tools in relation to increasing DER penetrations and the impact on transmission planning has not yet been identified across the industry. In this white paper, the use of EMT planning tools has been considered to showcase the impact of DERs on the BPS; however, the use of the results is from the perspective of developing sufficient parameters for an aggregated composite load model. To be clear, the use of EMT tools for DER impact studies do require a specific modeling of the distribution circuit parameters in a system. Should transmission planning pursue an EMT study relating to DER impacts, this document contains a preliminary checklist to assist in making sure a study is ready for EMT analysis.

[5] As with all tools, a clear understanding of the benefits and limitations is required. Here, the interface described is limited to reflecting unbalanced conditions on the transmission system due to the transmission system solver requiring positive sequence assumptions. Different tools or tool improvements, such as using a solver that can handle unbalanced phases for the transmission system in this case, can enhance the applicability and usability of any tool discussed in this paper. Note this is not a limitation of T&D co-simulation but of a solver that cannot handle the unbalanced fault conditions.

Chapter 1: Limitation of Positive Sequence Tools and Aggregated Modeling

One of the major concerns related to the present transmission planning simulation tools is their use of aggregated models to represent the entire distribution system with connected DERs and composite load models at a substation. As the entire distribution system is represented through a single model, the parameterization of the model becomes even more important[6] to adequately capture the voltage diversity throughout the distribution system. Although this process requires extensive simulation on the back end (which does not necessarily have to be carried out by the TP) to adequately parametrize the model, generic parameters that can be applied over a wide geographical area can be easily applied for the purpose of transmission planning. However, as with any aggregated model, it is likely that the actual system behavior may not be perfectly captured due to the assumptions made during the parametrization process itself under certain scenarios. For example, if induction motor loads are present in the distribution system, the voltage at the load ends can be well below the voltage at the substation level due to stalling of the motors. Also, the voltage recovery at these loads can be substantially slower than at the substation bus, a phenomenon known as fault induced delayed voltage recovery (FIDVR). This phenomenon may result in more DER tripping in reality than shown by the aggregated models if the models do not properly capture the stalling characteristics of motor load on the T–D interface. Similarly, electrically close DER installations to stalling motor load may also experience return-to-service voltages separate from the majority of the aggregation that is also not reflected well when modeled in aggregate at the T–D interface. Another issue with existing positive sequence tools is the inability to demonstrate the impact of coordination of multiple DERs on the BPS operational stability.

Identification of Issues that need "Beyond Positive Sequence" Tools

The specific limitations with using only positive sequence tools to study the increasing DER penetrations and its impact on transmission planning are identified in this section. Each of the limitations are illustrated with an example using a test system.

DERs Tripping on Individual Phase Voltage

For unbalanced faults, positive sequence tools only provide a positive sequence equivalent voltage of the unbalanced set of voltages that tend to be a value higher than the lowest individual phase voltages. **Table 1.1** illustrates this point well as each positive sequence voltage value was higher than the lowest individual phase for the fault. Due to the positive sequence voltages being higher than the lowest individual phase during unbalanced faults, positive sequence tools tend to underestimate the amount of DER tripping in simulation. In contrast, beyond positive sequence tools that take into account the individual phase voltages can be parameterized to account for single-phase DER tripping on individual voltages.

Transformer Configurations Impact the Voltage Profile across the T&D Interface

The T&D transformer winding configuration affects the phase voltages on either side of the T&D transformer. This is apparent during an unbalanced fault on either side of the T&D transformer. In **Figure 1.1,** represented in an EMT simulation platform, the nominal voltage of Bus 1 is 230 kV, Bus 2/Bus 3 is 115 kV, and Bus 4/Bus 5 is 12.47 kV. Transformer T1 is between Bus 1 and Bus 2 while transformer T2 is between Bus 3 and Bus 4. A variety of unbalanced faults were applied on Bus 1 and the voltage on Bus 5 (both the individual phase voltages and the positive sequence equivalent) was noted and tabulated as shown in **Table 1.1**. In the table, the coloration of red indicated DER on that phase (or phases) experience terminal voltage below the trip threshold, yellow indicated a likelihood that some DER on the phase(s) experience terminal voltage below the trip threshold, and green indicating all DER terminals on the phase(s) experiencing a voltage above the trip thresholds Buses 1, 2, and 3 represent a simplistic representation of the transmission side of the T–D interface while Buses 4 and 5 represent the distribution side. In addition, the voltages are tabulated for different values of fault impedances.

[6] It should be noted that parameterization of any simulation model is very important for accurate simulation results

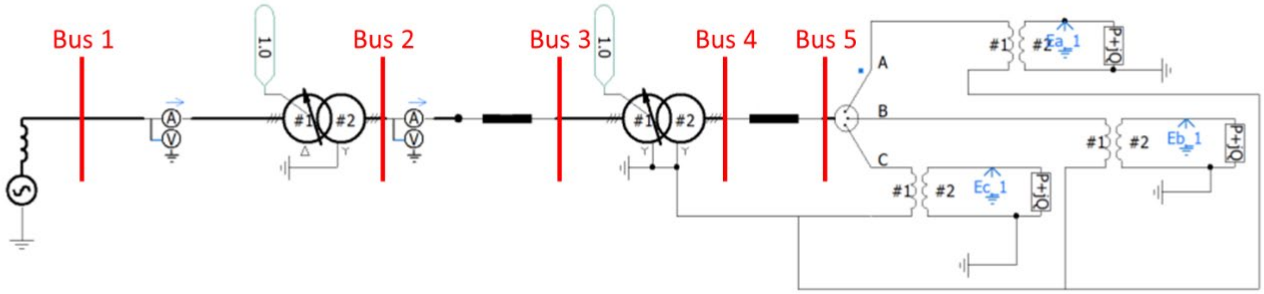


Figure 1.1: One-line diagram of System

Table 1.1: Voltages at Bus 5 for Different Scenarios of Unbalanced Faults and Transformer Winding Connections

Fault Impedance	Fault Type	Quantity	Voltage (p.u.)	Voltage (p.u.)	Voltage (p.u.)
		T1/T2 Configuration	Y-Y/Y-Y	Y-Y/Δ(30)-Y	Δ(30)-Y/Y-Y
Zf = 0	L-G at Bus 1	V_a	0.05	0.57	0.58
		V_b	0.95	0.56	0.56
		V_c	0.97	0.96	0.96
		V_+	0.656667	0.6966667	0.7
	L-L at Bus 1	V_a	0.55	0.85	0.85
		V_b	0.55		
		V_c	0.97	0.85	0.85
		V_+	0.69	0.68	0.6766667
	L-L-G at Bus 1	V_a	0.29	0.58	0.58
		V_b	0.29	0.34	0.34
		V_c	0.96	0.58	0.57
		V_+	0.513333	0.5	0.4966667
Zf = 0.1 pu (52.9Ω)	L-G at Bus 1	V_a	0.6	0.91	0.91
		V_b	0.96	0.54	0.54
		V_c	0.96	0.96	0.96
		V_+	0.84	0.8033333	0.8033333
	L-L at Bus 1	V_a	0.8	1.01	1
		V_b	0.28	0.37	0.37
		V_c	0.96	0.67	0.67
		V_+	0.68	0.6833333	0.68
	L-L-G at Bus 1	V_a	0.6	0.91	0.91
		V_b	0.6	0.61	0.61
		V_c	0.96	0.55	0.54
		V_+	0.72	0.69	0.6866667
Zf = 0.2 pu (105.8Ω)	L-G at Bus 1	V_a	0.8	1	1
		V_b	0.96	0.72	0.72
		V_c	0.96	0.96	0.96
		V_+	0.906667	0.8933333	0.8933333
	L-L at Bus 1	V_a	0.95	1.09	1.09

Table 1.1: Voltages at Bus 5 for Different Scenarios of Unbalanced Faults and Transformer Winding Connections

Fault Impedance	Fault Type	Quantity	Voltage (p.u.)	Voltage (p.u.)	Voltage (p.u.)
		T1/T2 Configuration	Y-Y/Y-Y	Y-Y/Δ(30)-Y	Δ(30)-Y/Y-Y
		V_b	0.34	0.6	0.6
		V_c	0.96	0.6	0.6
		V_+	0.75	0.7633333	0.7633333
	L-L-G at Bus 1	V_a	0.84	1	1
		V_b	0.83	0.82	0.82
		V_c	0.96	0.75	0.75
		V_+	0.876667	0.8566667	0.8566667

As an example, for a solid L-L-G fault (Zf = 0) at Bus 1, when T1 winding is Delta-Wye[7] (also known as a Δ(30)-Y) configured and T2 winding is Y-Y configured, the simulated voltage level under fault conditions on Phase A at Bus 5 is 0.58 pu, on Phase B is 0.34 pu, and on phase C is 0.57 pu. Now, if all DERs on the feeder have a trip threshold of 0.5 pu at their terminals, then we can safely assume that all single-phase DERs connected on Phase B would trip (hence the pink color in the table). On Phases A and C, some amount of single-phase DER trips would occur, especially if the DER are located towards the middle or tail end of the feeder.[8] Due to this uncertainty, the cells are highlighted in mild yellow color, indicating that there will some amount of DER trips, but it would be difficult to generalize and quantify the exact amount. Finally, three-phase DERs would also trip as the least voltage phase voltage (Phase B) is below the trip threshold. Overall, when viewed from the substation (either at Bus 3 or Bus 5) for this fault, it can be assumed that more than 50% of the DERs on the feeder would trip.

Now, if this fault was approximated in a positive sequence simulation platform, the positive sequence voltage observed at Bus 5 would be 0.497 pu. If the DER_A model's voltage trip characteristic is parameterized to reflect tripping behavior due to unbalanced faults as detailed in Reference 1 in **Appendix B** with the characteristic lying between 0.8 pu and 0.6 pu, then for this same unbalanced fault, DER_A model would reflect that all DERs at the substation would trip (as indicated by the red color in **Table 1.1**). This is of course a conservative representation because as reasoned previously, possibly only 50% of DERs may trip. However, in such a scenario, a conservative representation may be alright for transmission system planning.

Another example scenario is for a line-to-line (L-L) fault at Bus 1 with a fault impedance (Zf) equal to 0.2 pu. If both T1 and T2 are assumed to have windings with Y-Y configuration, then the individual phase voltages at Bus 5 are 0.95 pu, 0.34 pu, and 0.96 pu, respectively, on Phases A, B, and C. Here, all single-phase DER connected on Phase B will trip. However, single-phase DERs connected on Phases A and C would ride through the fault (denoted by the green color in **Table 1.1**). All three-phase DERs would also trip because of the low Phase B voltage. Thus, it can be assumed that 30–50% of DER MWs would trip. This scenario can be assumed to be a mild DER trip.

When represented in a positive sequence platform, the positive sequence voltage at Bus 5 would be 0.75 pu. Here, the DER_A model (if the voltage trip characteristic is parameterized as before to lie between 0.8 pu and 0.6 pu) would show a possible 20–30% DER trip based on the 0.75 pu positive sequence voltage. Again, for this unbalanced fault, the DER_A could possibly adequately reflect the trip of DERs from the requirement of transmission planning. However, specific instances may need further investigation in beyond positive sequence tools by TPs as highlighted

[7] Note that the Delta-Wye configuration has a 30-degree phase shift from the primary to the secondary phases.
[8] This assumes the voltage profile follows historic norms where it decreases from the head to the tail of the feeder.

in this example; the positive sequence representation is not a conservative estimation of tripping under specific parameterizations of the DER_A model.[9]

While this method and approximation may be adequate in most scenarios, it is not 100% precise or accurate. As an example, consider a line-to-ground (L-G) fault at Bus 1 with Zf = 0.1 pu. In this scenario, irrespective of the transformer winding configuration, two phases never see the chance of DERs tripping, but one phase could possibly see DER tripping based upon the voltage profile across the feeder. Thus, there is a chance of about 10–30% of DER tripping. However, the equivalent positive sequence voltage is marginally above 0.8 pu at the substation head. Here, if the DER_A model is placed right at the substation bus, then it possible that the DER_A model would suggest that all DERs would be able to ride through the event. However, if the DER_A model is placed at the low end of an equivalent feeder, then the model may be able to represented a small percentage of DER tripping as the equivalent positive sequence voltage at the low end of the equivalent feeder would be lower than the equivalent positive sequence voltage at the high end of the equivalent feeder.

Limitations to the Variation of the Voltage as Seen in the Distribution Circuit's Voltage Profile

Historically in radial distribution circuits, the farther the electrical distance from the substation of the circuit indicates a greater voltage drop unless a voltage regulating device boosts the voltage. DERs connected at different distances down the distribution feeder experience different per unit voltages, and DERs may not be uniformly distributed across the length of the feeder. Furthermore, as DERs are sources of electrical power, they can also boost the voltage on the distribution feeder as a voltage regulating device. The following examples are provided to illustrate to TPs how voltage varies across the distribution feeder with multiple DERs in the distribution system. Due to this variation in the voltage profile, it is possible that different percentages of DERs may trip at different instances of time for the same transmission event. In a traditional positive sequence representation, it is not easy to capture this entire variation in voltage profile in the distribution network. As a result, it is worth mentioning that this limitation,[10] if deemed to be significant by the TP, can be overcome by using T&D co-simulation, a beyond positive sequence simulation process that is discussed in detailed in the next section. However, not every scenario or transmission network requires the representation of the entire voltage profile in the distribution feeders. Furthermore, the DER_A model, a model that represents aggregate equipment, has a voltage trip characteristic that can be parameterized to approximate the variation in voltage and the unequal tripping that can result to some level. Hence, identification of the use cases of when and where to expand beyond positive sequence tools[11] is critical in order to bring about an efficient planning process. The next sections illustrate distribution feeder changes that may be of value for a TP.

Circuit 5

The SPIDERWG took a simulation tool from EPRI's Public Test Circuits[12] to provide TPs and Planning Coordinators (PCs) with descriptions of how the addition of 10 MW of DERs can influence the voltage profile on a distribution feeder. The SPIDERWG chose Circuit 5 in the tool to begin their analysis. **Figure 1.2** displays the one-line diagram of Circuit 5, and **Figure 1.3**, **Figure 1.4**, and **Figure 1.5** demonstrate the voltage profiles variations with different connection of the 10 MW of DERs for this circuit. As seen from the figures, the distribution circuit voltage profile does not decrease as sharply when DERs are on the circuit (**Figure 1.4** and **Figure 1.5**) as opposed to the original voltage profile (**Figure 1.3**)

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[9] It must be kept in mind that the parameterization of the DER_A model's voltage trip characteristic to lie between 0.8 pu to 0.6 pu is to be used only to observe the performance under unbalanced faults. For three-phase faults, the trip characteristic should lie between 0.55 pu and 0.45 pu as the trip threshold of an individual DER is assumed to be 0.5 pu.

[10] That is, the inability to represent voltage profile variation of a distribution feeder to individual DER terminals in the aggregated positive sequence model.

[11] In this example, this would mean moving to a T&D co-simulation tool to model the voltage variations past the T&D Interface.

[12] These are available here: https://smartgrid.epri.com/SimulationTool.aspx).

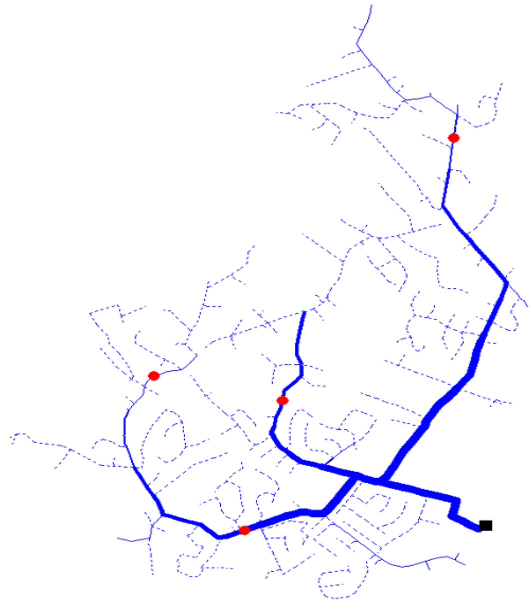

Figure 1.2: One-line of Circuit 5 [Source: EPRI]

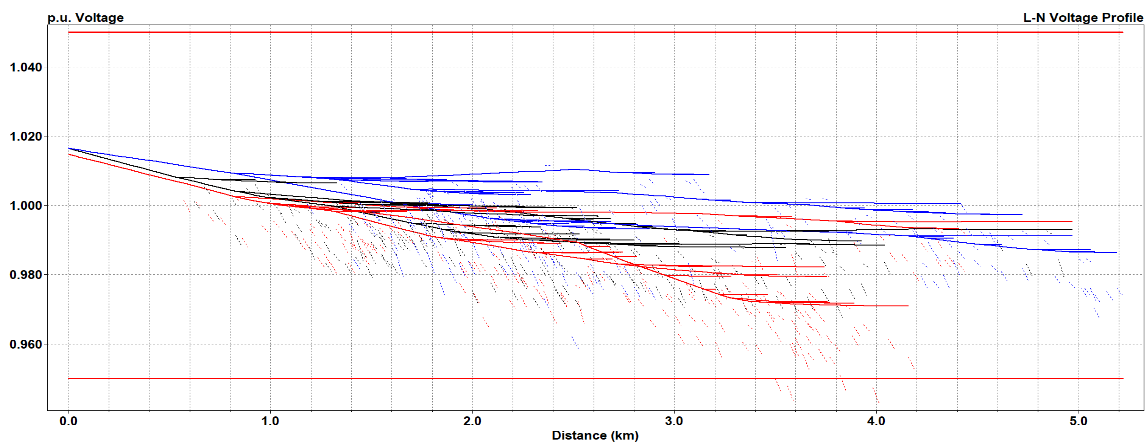

Figure 1.3: Circuit 5 Voltage Profile without DER Penetration

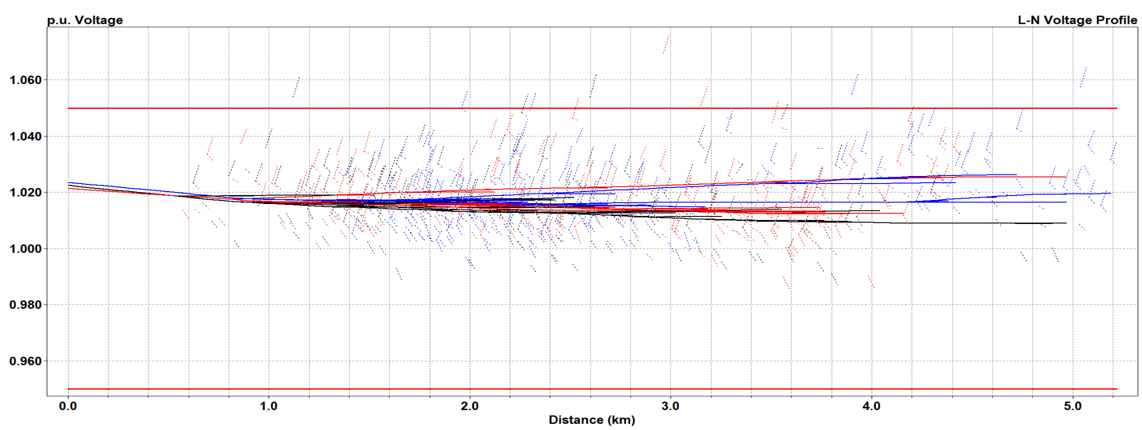

Figure 1.4: Circuit 5 Voltage Profile with 10 MW of Single-Phase DERs

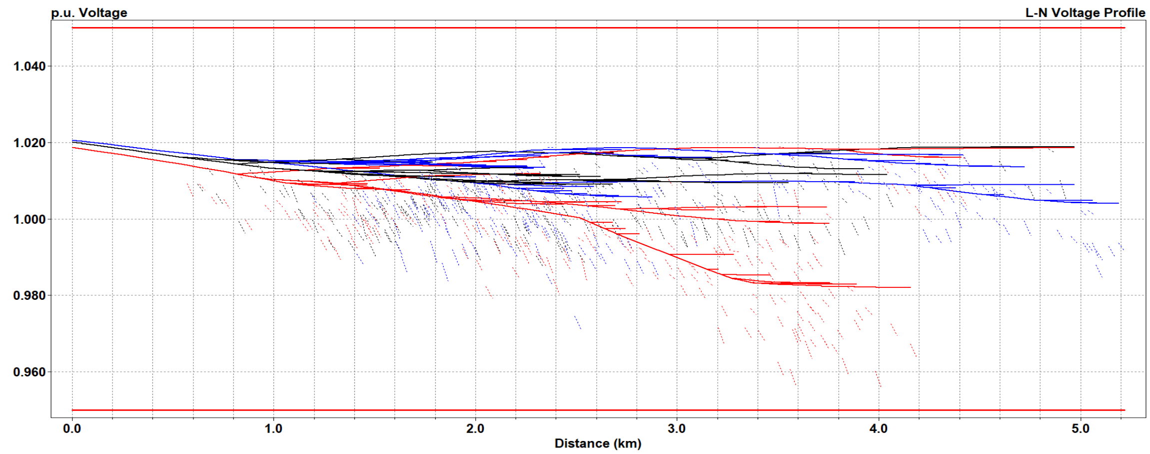

Figure 1.5: Distribution Feeder Voltage Profile with 10 MW of Three-Phase DERs.

Circuit 24

Further expanding on these example feeders, SPIDERWG took Circuit 24 from the ERPI tool above and performed the same addition of 10 MW of DERs (both if all single-phase or three-phase connections). **Figure 1.6** demonstrates the one-line diagram of this circuit, and **Figure 1.7**, **Figure 1.8**, and **Figure 1.9** demonstrate the voltage profiles variations with different connection of the 10 MW of DER. In this particular circuit, the voltage profile shifted enough to increase with electrical distance from the feeder head rather than decrease with the addition of DERs on the feeder. Such changes indicate that TPs and PCs may need to use beyond positive sequence tools to represent the various voltage profile changes in simulation.

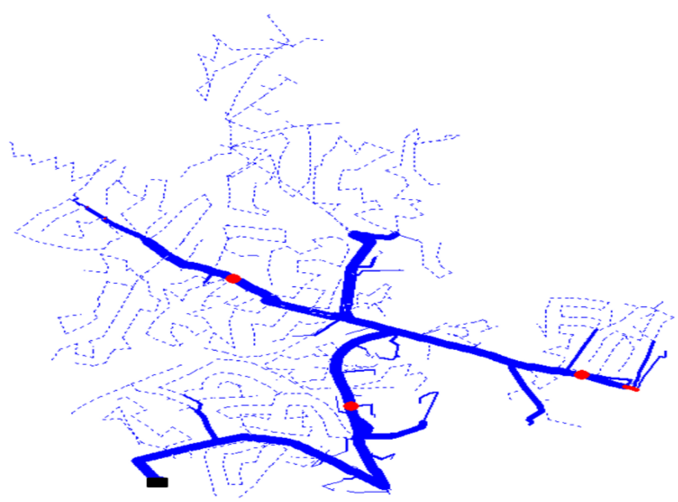

Figure 1.6: One-line of Circuit 24 [Source: EPRI]

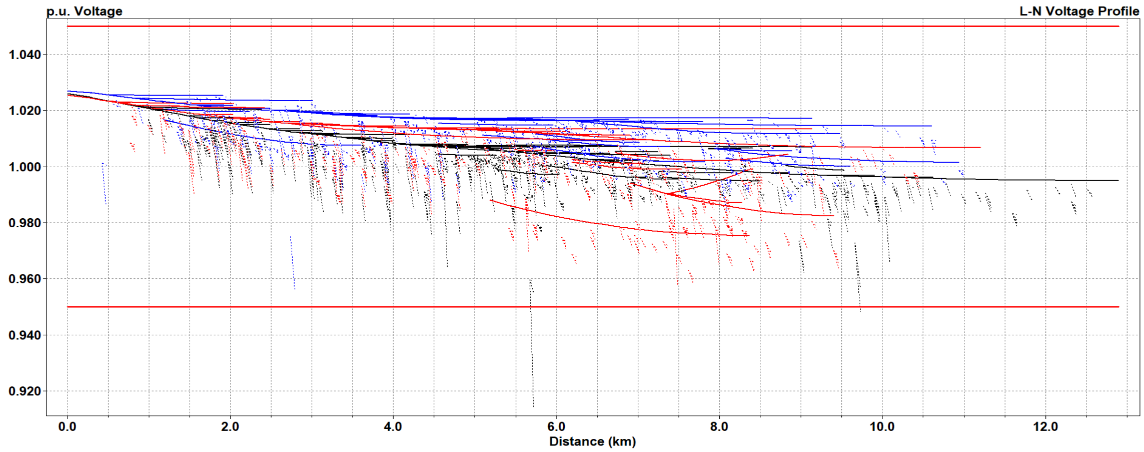

Figure 1.7: Circuit 24 Voltage Profile without DER Penetration

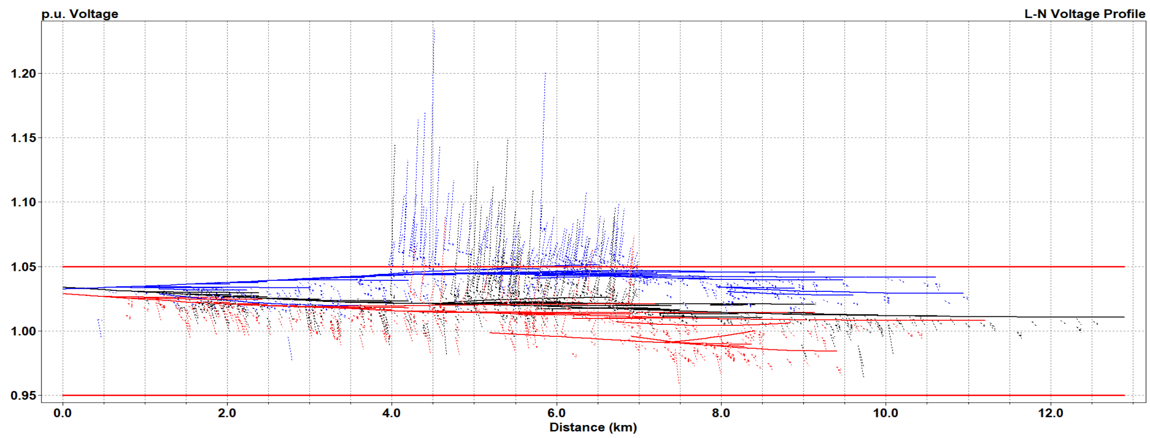

Figure 1.8: Circuit 24 Voltage Profile with 10 MW of Single-Phase DERs

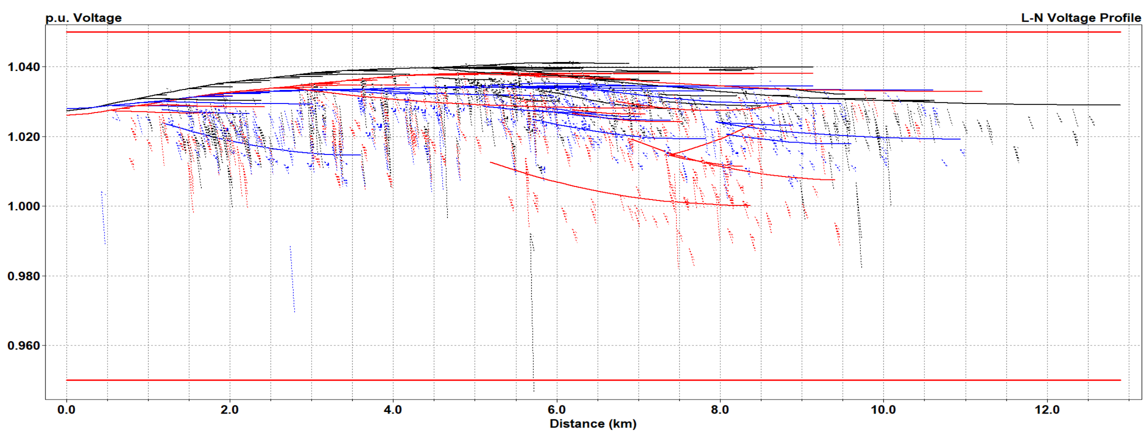

Figure 1.9: Circuit 24 Voltage Profile with 10 MW of Three-Phase DERs

A Feeder in Arizona

Outside of the EPRI tool, the SPIDERWG wished to confirm real feeders exist such that the voltage profile across the feeder no longer decreases the farther away from the feeder head, but rather increases. Such was the case from this feeder from a utility operating in Arizona. **Figure 1.10** demonstrates the circuit diagram of this distribution feeder and **Figure 1.11**, **Figure 1.12**, and **Figure 1.13** show the voltage profiles under various load and DER output conditions. As seen from the figures, under the minimum load and high DER output conditions, the voltage profile across the feeder increased as distance from the feeder head increased in opposition to the historical norm described in the sections above.

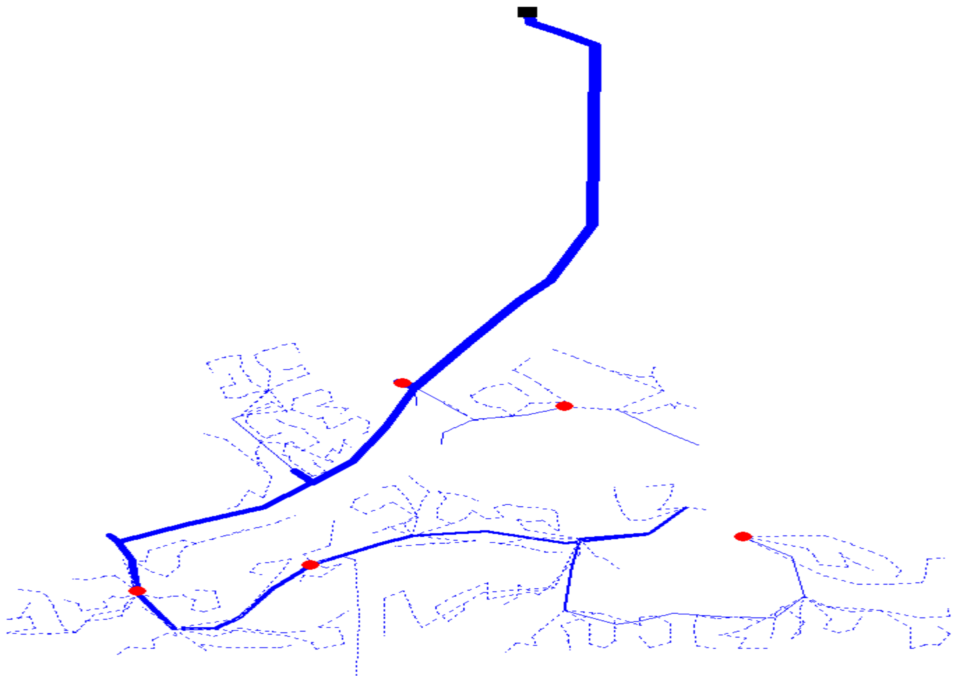

Figure 1.10: One-line of Arizona Feeder

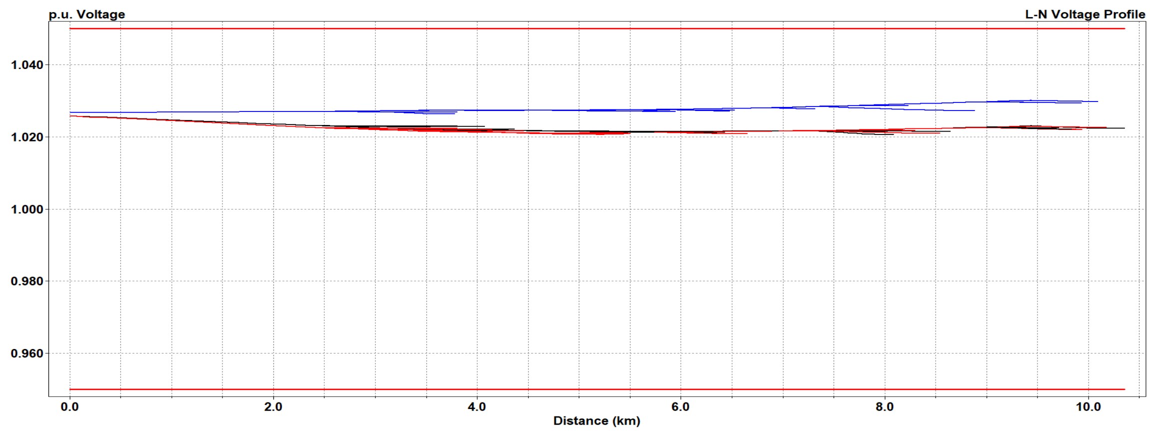

Figure 1.11: Arizona Feeder Voltage Profile at Minimum Load with No DER Output

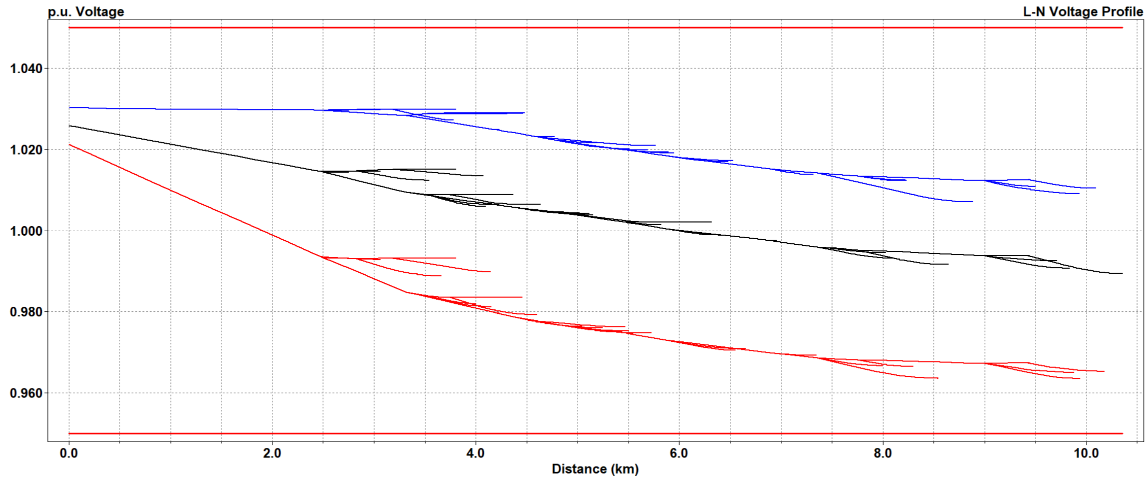

Figure 1.12: Arizona Feeder Voltage Profile at Peak Load with No DER Output

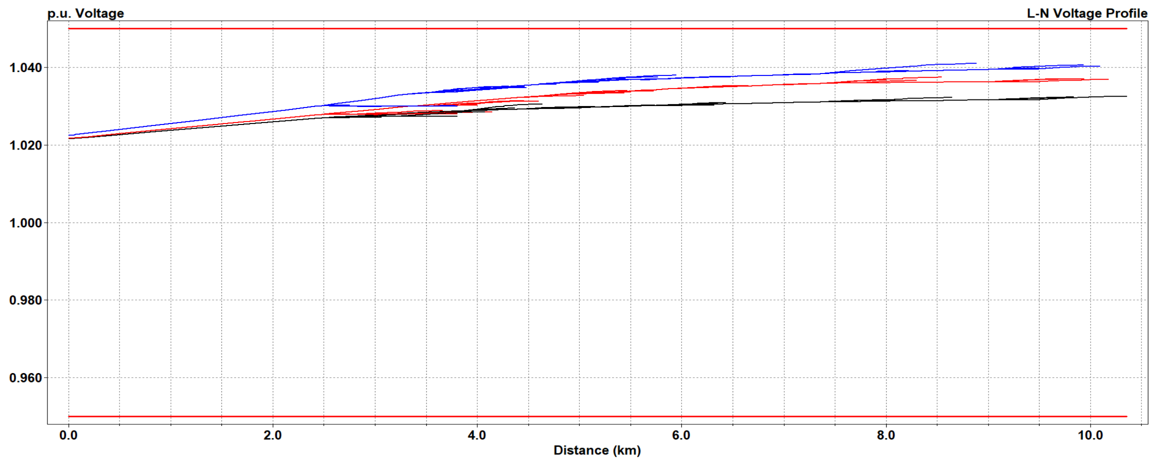

Figure 1.13: Arizona Feeder Voltage Profile at Minimum Load with High DER Output

Summary

From the figures that show the voltage variation across different distribution circuits, it is demonstrated that DERs may have a wide variety of voltages as seen from their terminals. Beyond positive sequence tools are needed to represent this variation as the inability to represent the variations in feeder voltage profiles is a current limitation of positive sequence tools. SPIDERWG notes that modeling the variations at individual components along a distribution feeder is different from the current positive sequence modeling guidance it provides in its other reliability guidelines. The guidance holds for the positive sequence tools; however, the positive sequence limitation on modeling the phase by phase voltage variations demonstrates cases where TPs may need to go beyond the positive sequence tools (and thus, beyond the positive sequence modeling guidance from other SPIDERWG documents) to adequately plan their system for DER.

Chapter 2: Potential Use Cases for Transmission and Distribution Co-simulation

This chapter explores the various use cases for T&D co-simulation tools as explored by the NERC SPIDERWG members. These are included here to describe to TPs and PCs instances where the typical positive sequence modeling software would be lacking, and a T&D co-simulation tool would be more appropriate for the study. While NERC SPIDERWG did not explore EMT tool use cases in the same detail, a general checklist is provided for when to move to such tools.

Use Case 1: Motor Stalling and Load Recovery

An increasingly active distribution network with the presence of a variety of smart inverter control methods coupled with induction motor interactions raises the question of accuracy of the composite load models[13] for use in BPS planning studies with positive sequence simulation tools. Additionally, there is a need to ascertain whether simulation tools that go beyond positive sequence simulation environments are required from a BPS planning perspective. Using few example case studies, the impact of DERs on the stalling and recovery of single-phase induction motor loads is documented. The entire transmission system and the distribution system is represented in detail in an electromagnetic (EMT) simulation platform. The ability of DERs to mitigate the stalling of induction motor loads is also investigated. Additionally, these case studies aim to identify scenarios that would need the use of detailed representation of the distribution system for BPS planning studies. Here, co-simulation is considered to be the combined simulation of both T&D network with both networks represented in detail within the same simulation software.

A modified New England 39 bus system was used to represent the transmission network as shown in **Figure 2.1**. The transmission network in this figure also has transmission-connected IBRs. In addition to reducing the size of the network, the impedance of few transmission paths was increased, enabling the creation of a load pocket following clearance of a fault. The load pocket results in a depressed transmission voltage when the low impedance path is opened with the fault. All load on the transmission network was represented as constant current for active power and constant impedance for reactive power. To represent a distribution network, a feeder was connected at three individual buses (Bus 3, 4, and 18) of the transmission network. This feeder is representative of a distribution feeder in Hawaii and has previously been used to study the impact of DER on stalling of induction motors.[14]

[13] This includes the current parameterization of the composite load model without generation components, i.e., DER.

[14] As in the following two references:

P. Mitra, A. Gaikwad, and J. C. Boemer, "Impact of Distributed Energy Resources (DER) Voltage Regulation and Ride Through Settings on Distribution Feeder Voltage Recovery," in *CIGRÉ U.S. National Committee, Grid of the Future Symposium*, Cleveland, OH, Oct. 2017

Impact of DER Voltage Regulation and Voltage Ride Through Settings on Fault Induced Delayed Voltage Recovery (FIDVR), EPRI, Palo Alto, CA., Tech. Rep. 3002009363, 2017.

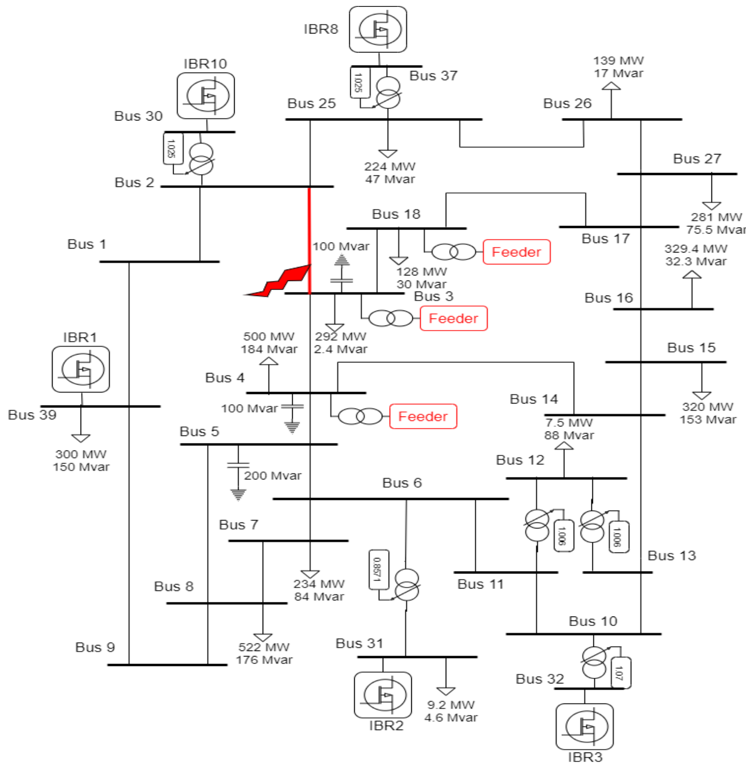

Figure 2.1: Modified IEEE 39 Bus system Used in the Study

The addition of DERs to these feeders was arbitrarily done as one of the aims of this study was to ascertain the need of representing the transmission network to a level of detail greater than just an equivalent source. DERs were added only to the feeders connected to Bus 3 and Bus 4 and were not added to the feeder at Bus 18 in order to observe whether the impact of DERs from the adjacent feeders. Each DER was controlled to inject a constant value of active power while having the capability to provide dynamic voltage support during abnormal voltage conditions and allow for adjustable momentary cessation voltage thresholds. DER tripping was not considered.

Within the feeder, single-phase induction motors were modeled with the previously developed model in Reference 5 in **Appendix B**. Each feeder contained a total of 14 single-phase induction motors with each motor being a combination of numerous 5.278 kW motors. The motor has a speed dependent load torque of 6 N-m and a triangular load torque with an average value of 8 N-m. There is a small degree of imbalance in the loading of the feeder across the three phases.

To observe the impact of various operational features of DERs on induction motors, a variety of DER scenarios were studied. A few relevant scenarios are tabulated in **Table 2.1**. A more detailed discussion of all scenarios studied is available at Reference 6 in **Appendix B**. All DERs were also assumed to be reactive current priority mode. Additionally, all DERs were assumed to be three phase and connected at 12.47 kV buses within the feeder. In each case, an 80ms fault was applied on the line between Bus 2 and Bus 3 at a distance of 0.1% from Bus 3. Upon clearing the fault, the line between Bus 2 and Bus 3 was opened 10 ms later.

Table 2.1: DER Scenarios Studied

Case	DERs	DER %	DVS	Scenarios
0	OFF	0%	N/A	LLL-G fault, L-G fault
2	ON	200%	OFF	LLL-G fault
9	ON	300%	ON	LLL-G fault, L-G fault

The results from the detailed EMT simulations were compared with results obtained from a positive sequence simulation tool to ascertain the sufficiency of positive sequence tools under a scenario with high DER percentage in the distribution network, along with presence of FIDVR. With the proliferation of BPS-connected inverter based resources and distribution-system-connected, power electronic interfaced DERs, there is a concern that conventional positive sequence simulation tools would not be able to capture all aspects of the dynamic behavior associated with these fast power electronic devices. While there certainly can be technical justification behind this concern, and there is no doubt that positive sequence simulation environments would not be able to capture the dynamic behavior to a high degree of detail,[15] TPs have to also consider the practical factors associated with electric utilities moving to simulation environments beyond positive sequence. The following are a few crucial questions that should be asked that could aid in making a decision regarding this transition for the use case of studying impact to motor load stalling:

- Is the behavior obtained from a positive sequence aggregated composite load model insufficient for TPs to make an informed decision about the impact of DERs and load on the BPS?
- If the behavior is sufficient, will it be sufficient even under future DER percentage levels?
- Would there be particular scenarios under which the behavior obtained from a positive sequence aggregated composite load model will not be sufficient?

In positive sequence tools, the dynamic behavior of loads and DERs connected at the substation are represented with a composite load model with distributed generation. Parameterization of the components of the composite load model have been widely discussed previously.[16,17,18] This aggregated model can be described as follows:

- Electrical representation of aggregated behavior of three-phase induction motors driving loads with different speed-torque characteristics
- Performance based model representing the aggregated behavior of single induction motors
- Representation of static and power electronic load
- Representation of the aggregated behavior of power electronic based DERs using the DER_A model

Although the values of the parameters of the *cmpldwg* model did not change in the DER scenario being studied, few of the parameters of the performance based model representing the aggregated behavior of single-phase induction motors had to be different across the three buses (Bus 3, Bus 4, and Bus 18) where the model was placed due to initialization and imbalance issues found in the simulation. The primary reason for this difference was due to the difference in steady state voltage at these buses along with the single-phase induction motor model being a performance based aggregated model.

Load Recovery Simulations

Case 0: For the base case without any DERs (denoted as Case 0 in **Table 2.1**), the comparison of the dynamic behavior between a full, detailed EMT simulation and the aggregated behavior from a positive sequence model observed at Buses 3 and 18 is shown in **Figure 2.2** for an LLL-G fault with creation of a load pocket. It can be seen that the aggregated load model in the positive sequence tool is able to provide a fair representation of the active and reactive power drawn by each of the three feeders while also providing a reasonable representation of the voltage magnitude both on the 230 kV side and the 12.47 kV side.

[15] This is especially true for frequencies away from nominal frequency, during unbalanced network conditions, and with regard to sub-cycle transient behavior

[16] NERC Reliability Guideline: *Developing Load Model Composition Data*, March 2017

[17] NERC Reliability Guideline: *Parameterization of the DER_A Model*, Sept. 2019

[18] NERC Reliability Guideline: *Modeling Distributed Energy Resources in Dynamic Load Models*, Dec. 2016

The large and sustained increase in reactive power consumption (in comparison to the pre-fault loading level) is characterized by the stalling of single-phase induction motors that trip 2 seconds later. The stalled motor trip is noted by the reduction of reactive power consumption across the T&D interface and also by the reduction in active consumption. However, due to the formation of the load pocket, the voltages remain at a value of approximately 0.8 pu. Additionally, the feeders at Bus 3 and Bus 18 are impacted to an equal and larger extent when compared to the feeder at Bus 4. Of the 14 single-phase induction motors on each feeder, only one single-phase induction motor was able to successfully ride through the fault on each feeder at Bus 3 and Bus 18. On the feeder at Bus 4, 11 out of the 14 motors were able to successfully ride through the fault.

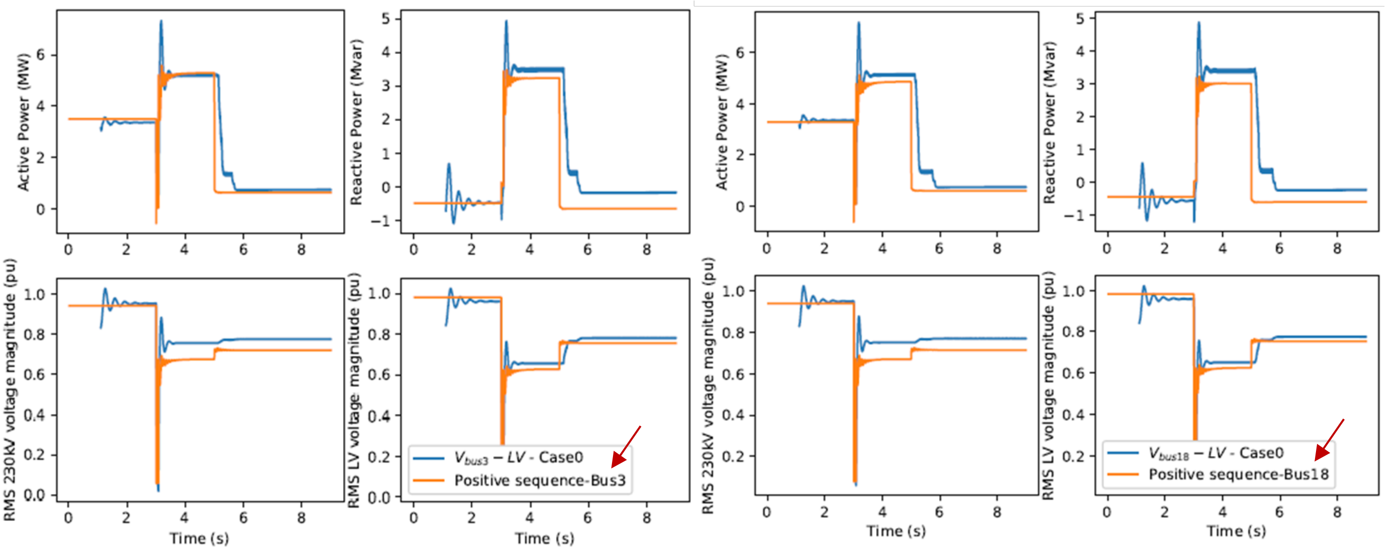

Figure 2.2: Case 0—Bus 3 and Bus 18

Case 2: Upon adding close to 200% of DERs with a momentary cessation threshold to 0.50 pu (denoted as Case 2 in **Table 2.1**), comparison of the dynamic behavior at Bus 3 and Bus 4 is shown in **Figure 2.3**. Here, although the response at Bus 3 shows the same trend between positive sequence and EMT domain, the response observed at Bus 4 shows a more conservative behavior in the positive sequence simulation model. In the detailed EMT simulation at Bus 4 with a DER momentary cessation threshold of 0.50 pu, all single-phase induction motors were able to successfully ride through the fault as opposed to the motors at Bus 3. The response from the positive sequence model shows a conservative behavior of more single-phase induction motor stall and trip, which is primarily driven by the stall and restart voltage thresholds of the single-phase induction motors in the performance based positive sequence model. However, although there is a difference in output, the trend of the response observed from the positive sequence model could be sufficient to make informed transmission planning decisions.

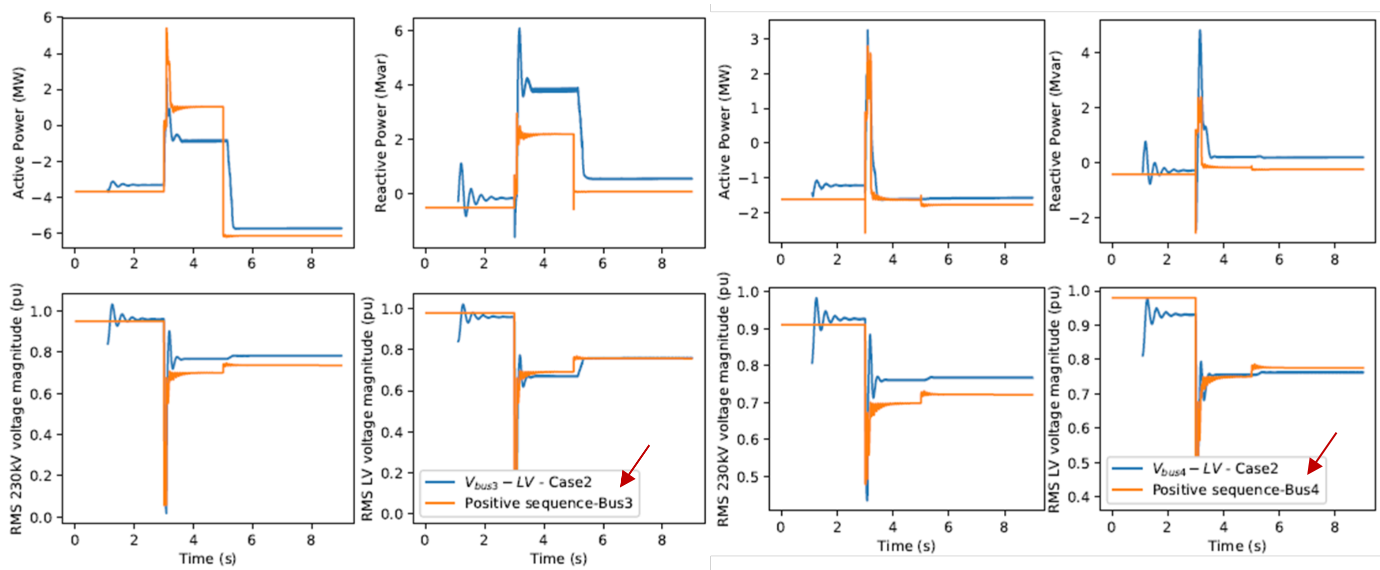

Figure 2.3: Case 2—Bus 3 and Bus 4

Case 9: With additional DERs located at the feeder head along with provision of dynamic voltage support from DER (denoted as Case 9 in **Table 2.1**), comparison of the dynamic response is shown in **Figure 2.4** for Bus 3 and Bus 4. It can be seen that there is still further work that can be done to improve the derivation of the composite load model parameter values although there is a good match between the responses. The parameters that play a crucial role in the response of the positive sequence aggregated composite model are the value of voltage at which the performance based model of single-phase induction motors is allowed to restart (*Vrst*) and the upper value of the under voltage trip threshold (*vtr1*). In the detailed EMT model, the trip of the single-phase induction motors occurs based on its measured speed. However, since the performance model in the composite load model does not have this attribute, motor tripping is initiated with the under voltage trip settings. While the values for voltage threshold can be parameterized adequately, further continued research work is to be carried out.

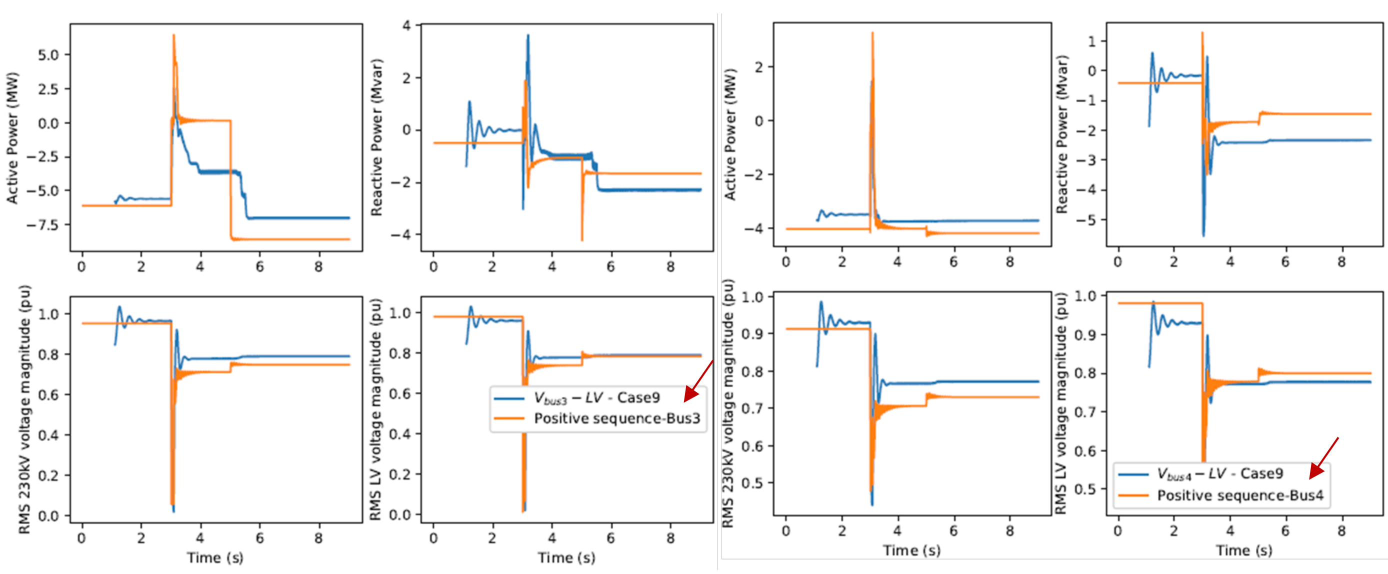

Figure 2.2: Case 9—Bus 3 and Bus 4

Due to the inherent conceptual limitation of positive sequence simulations, capturing the behavior of load and DERs for unbalanced faults on the transmission system can be a challenge (See **Chapter 1** discussion on this particular limitation). Furthermore, as the dynamic behavior of DERs and load is represented in an aggregated manner in positive sequence simulations, the parameterization of the aggregated model must be carefully considered. In Reference 4 of **Appendix B**, a method to parameterize the positive sequence DER_A model to enable representation of tripping of DERs for unbalanced transmission faults was presented. This concept has been used to investigate the validity of the dynamic response observed from the aggregated model.

Motor Stalling Simulations

Case 0: As before, prior to adding DERs, the dynamic behavior of Case 0 is first compared to verify the dynamic response shown by the performance based single-phase induction motor against the EMT representation. The response observed at various buses for an L-G fault is shown in **Figure 2.5**. The values of the parameters of the composite load model were assumed to be the same as previously used for the LLL-G fault. However it can be seen in the figure that there is a drastic difference in the behavior observed in the positive sequence simulation. In the EMT case, there are very few single-phase induction motors at Bus 3 that are impacted by the fault. But after observing the dynamic behavior in the positive sequence simulation, one may infer that an L-G fault can cause stalling of single-phase induction motors to the same extent as an LLL-G fault. A similar behavior is also observed at Bus 18. In contrast, at Bus 4, both the positive sequence model and the detailed EMT model show a similar response.

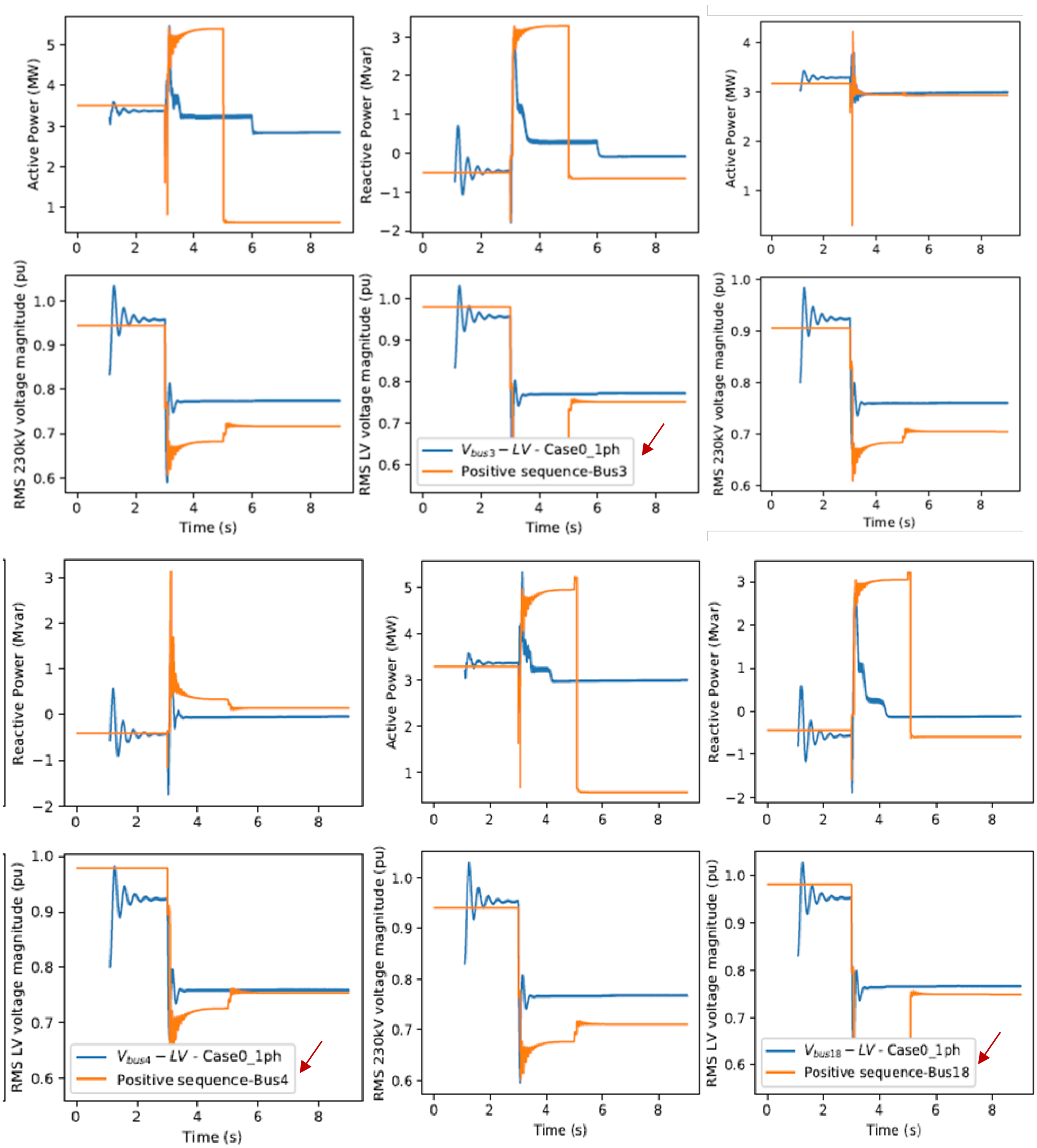

Figure 2.3: Case 0—Bus 3, Bus 4, and Bus 18

This behavior points towards a necessary discussion regarding parameterization of the performance based single-phase induction motor model in positive sequence. As an example, rather than using the in-built stall curves in the positive sequence software, the stall voltage and time thresholds were set to *Vstall = 0.45 pu* and *Tstall = 0.05s*. In contrast to the in-built stall curves that have been derived from laboratory test data, here the parameterization of the values have been carried out based on observing the response in the detailed EMT simulation. Additionally, at Bus 3, the value of *vtr1* was set to 0.6 pu rather than 0.8 pu. With these changes, the dynamic behavior at Bus 3, Bus 4, and Bus 18 is compared in **Figure 2.6**.

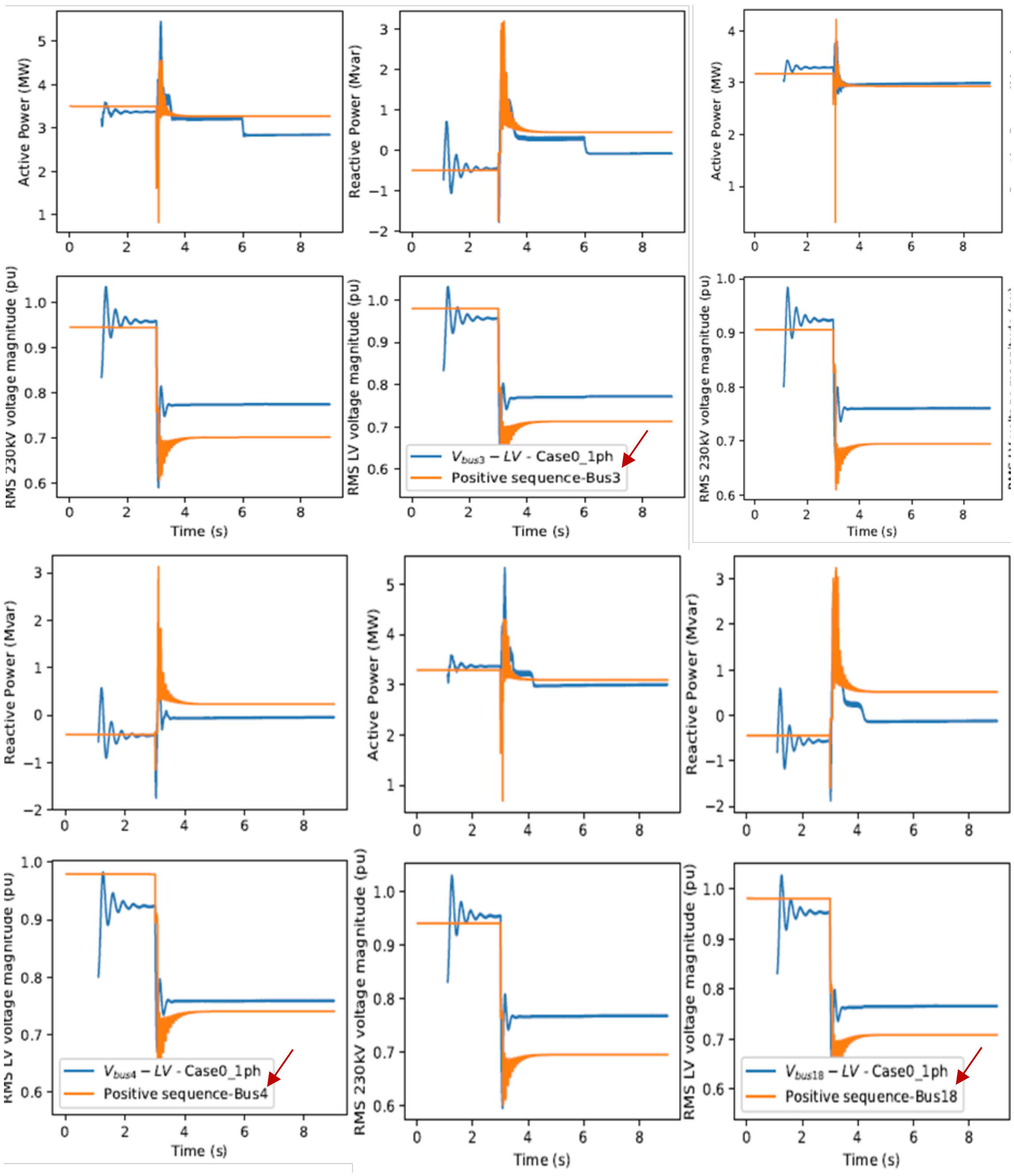

Figure 2.4: Case 0—Bus 3, Bus 4, and Bus 18 after Re-parameterization of Positive Sequence

Case 9: Lowering the threshold for *Vstall* in the positive sequence performance based model achieves the desired response as compared to the detailed EMT model. However, validation of this performance is yet to be carried out in detail. A similar acceptable comparison with the presence of DERs along with dynamic voltage support is shown in **Figure 2.7**. Although a reasonable level of accuracy can be achieved by lowering the threshold value of *Vstall* in the positive sequence simulation, a commentary is necessary regarding the applicability of the composite load model for unbalanced faults. The single-phase induction motor representation in the model is a performance based model whose region of applicability lies primarily for three-phase balanced faults. The EMT studies discussed in Case 0, 3, and 9 have shown that the impact of a single-phase fault on the stalling of induction motors is lower when compared to a three-phase fault. Thus, unless care is not taken to appropriately parameterize the composite load model for unbalanced events, a conservative representation of the behavior of the motors will be observed in a positive sequence simulation study.

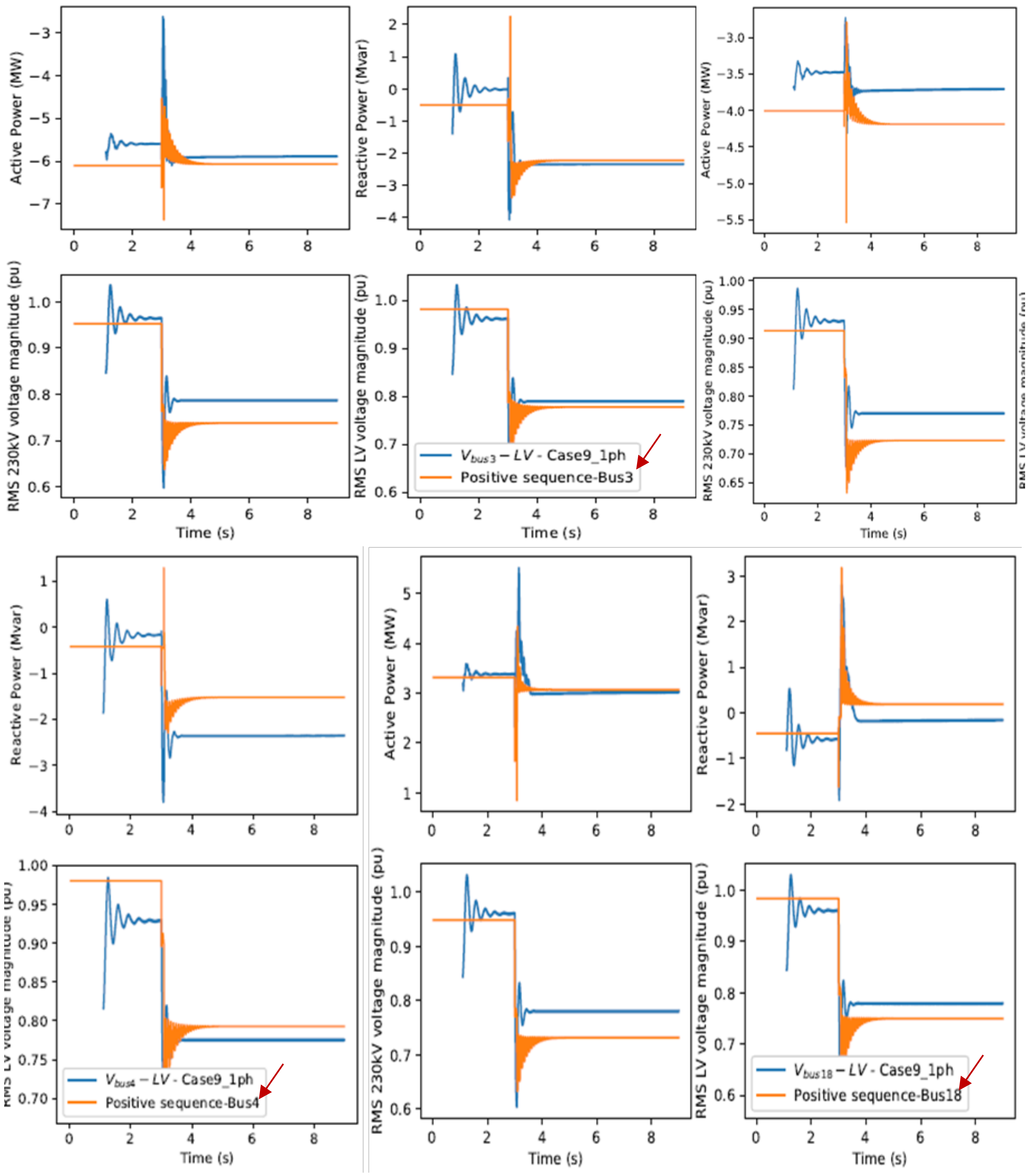

Figure 2.5: Case 9—Bus 3, Bus 4, and Bus 18 after Re-parameterization of Positive Sequence Model

Use Case 2: Modeling in Aggregate over Full Distribution System

If aggregated models are to be used for assessing the impact of DERs, then there is a need to identify under what conditions deficiencies arises. Are these deficiencies edge cases or categorized under larger classes[19] of cases? T&D co-simulation is a tool that can be used for this baseline comparison against state-of-the-art transmission only simulation. This use case is designed to provide insights to questions, such as the following:

- Is there a need for a T & D co-simulation tool?
- Are aggregated models adequate under the scenarios of interest?
- Is hybrid simulation, where only a portion of the system is represented in detail, a viable trade-off between full model co-simulation and aggregated models?

Response of a model largely depends on its parameters. This is true for both aggregated models as well as for detailed model representation. However, for aggregated models, this becomes even more important considering different operational characteristics[20] combined into a single/few aggregated models. This case uses suggested DER_A model parameterization while accounting for a range of permissible values as defined in different interconnection standards for different scenarios and compares the result against T&D co-simulation to quantify the differences. The goal is to understand when the differences are large enough to warrant a re-parameterization of DER_A model and establish under what conditions, if any, T&D co-simulation might be needed. The use case also evaluates if there are alternate ways of representing the existing models to enable state-of-the-art aggregate models to effectively capture the characteristics of the detailed model to the best extent possible. While the suggestions are not universal, the hope is that the use case will provide better insights and a solid methodology to follow for future analysis.

The studies presented below were conducted on a modified version of a 68-bus, 5-area test system as described in Reference 7 in **Appendix B**. Different scenarios are created by modifying the default base case with different levels of solar penetration. All the loads are modeled as composite load model with model parameters obtained from a load model data tool developed in Reference 8 in **Appendix B**. It should be noted that the model parameters do not represent a particular area/scenario; they are randomly picked manually from the tool. The selected parameters remain consistent across all loads and across all scenarios. Renewable generation is modeled using standalone DER_A model on a non-load serving feeder, whose parameters are obtained from previous SPIDERWG reliability guideline on the DER_A model.[21] Rationale along with the modified parameter and its value is provided whenever parameter(s) are modified from the values given in the guideline document for a particular study.

The study has three phases. In Phase 1, a subset of load buses (i.e., Buses 39, 44, and 49) in the New York power system were replaced with an equivalent distribution system representation with the IEEE 123-node test system. While in Phases 2 and 3, all load buses are replaced with the same distribution system equivalent as in Phase 1. This setup allows the evaluation of a hybrid approach where a portion of the system is replaced with a detailed model to help identify edge cases. At a high level, Phase 1 establishes confidence in the comparisons: for instance, do the initial conditions match? This is a necessary condition before any meaningful comparison can be made. In addition, it also provides an opportunity to look at limited area of interest and understand the differences between T-only and T&D co-simulation. In Phase 2, DER modeling is studied in detail, particularly that of mixed vintage cases. In Phase 3, the study is setup in a manner that is complementary to Phase 2.

[19] e.g., greater than 30% DER penetration relative to feeder peak load
[20] e.g., different interconnection standard for DERs
[21] https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_DER_A_Parameterization.pdf

In addition to the conventional comparison, this study also views the comparison results from a control theory perspective. The premise of the study is that if the different setups[22] start from the same operating point, transition through a disturbance,[23] and settle at a post disturbance equilibrium point adequately close to each other, then the aggregated model was determined to behave in a similar manner to the co-simulation model. Hence, the SPIDERWG made comparisons not only in the transient period of interest but also the pre- and post-disturbance equilibrium points as well.

For the co-simulation case, each transmission-distribution interface (T&D Interface) has two loads as seen from the transmission system perspective: one represented with a composite load model and the other represented with a distribution system. The transmission only model, in comparison, uses a single composite load model. While this might seem counter intuitive, the distribution feeder is used in this case to represent the static load portion of the composite load model with appropriate parameters for the conventional constant impedance, current, and power loads. The static load portion is assumed to vary between 60% of the total load. A detailed model of DERs is placed randomly across the length of the feeder. Note that the DER placement is not uniformly random. That is, the DERs are not placed equally spaced across the length of the feeder. While the detailed DER model that is connected to the distribution system is fundamentally different from DER_A model, it still has exact same ride through logic and the ride through parameters used are the same for a given standard. Since the primary purpose of this study is to compare the post-disturbance equilibrium point, what matters for DERs is whether they remain online or trip following a disturbance.

Phase 1

In Phase 1, the NERC SPIDERWG took three different scenarios and varied the solar photovoltaic penetration up to 18% at particular buses in the system. Furthermore, the NERC SPIDERWG provided some high level observations for this particular phase for TPs and PCs to use when determining their own efforts and initiatives. The major question to be answered is if a hybrid setup is sufficient to catch edge cases for a full system co-simulation model opposed to a typical, positive sequence approach.

Phase 1, Scenario 1: No Solar Penetration

To establish comparable setups, the phase starts with a no solar penetration case. A six-cycle three-phase fault at Bus 49 is applied at t=0.2 seconds and cleared at t=0.3 seconds with net power recorded. As shown in **Figure 2.8**, **Figure 2.9**, **Figure 2.10**, and **Figure 2.11**, trajectories look similar across the cases at Buses 39 and 44. Notice the pre-fault condition comparison that establishes confidence that the initial conditions are very similar across the setup and the post disturbance steady state solution being relatively close. Buses 39 and 44 are electrically distant from fault location at Bus 49, also indicated by the relatively smaller drop in voltage magnitude as shown in **Figure 2.11**. The trajectory at the fault Bus 49 shows difference between the two setups after the fault is cleared as shown in **Figure 2.10**. Unlike at Bus 39 and 44, the trajectories begin to diverge once the fault is cleared and the post-disturbance steady-state value is considerably different.

[22] i.e., aggregated transmission only simulation and co-simulation
[23] Such a disturbance may or may not result in outages.

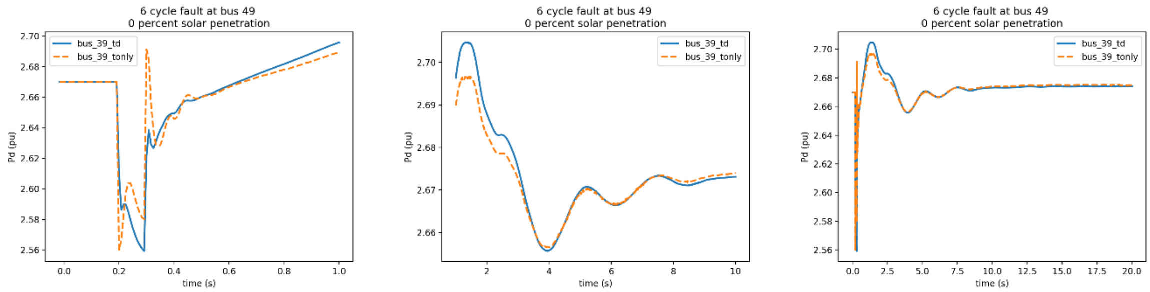

Figure 2.6: Net Real Power Demand Comparison for Bus 39

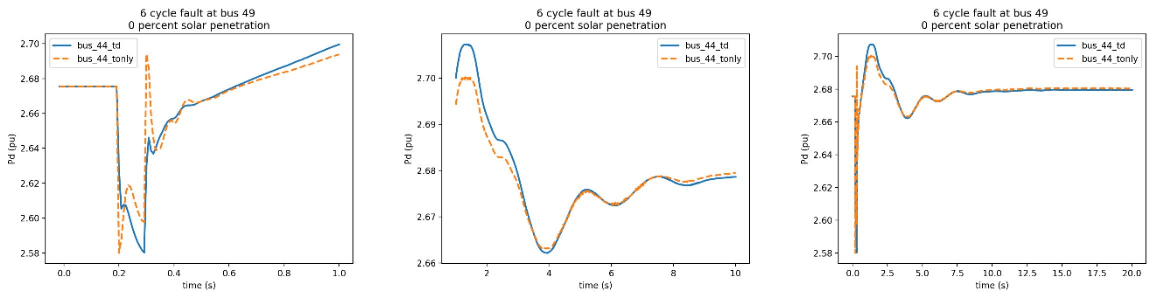

Figure 2.7: Bus 44 for the Same Scenario and Setup Described in Figure 2.8

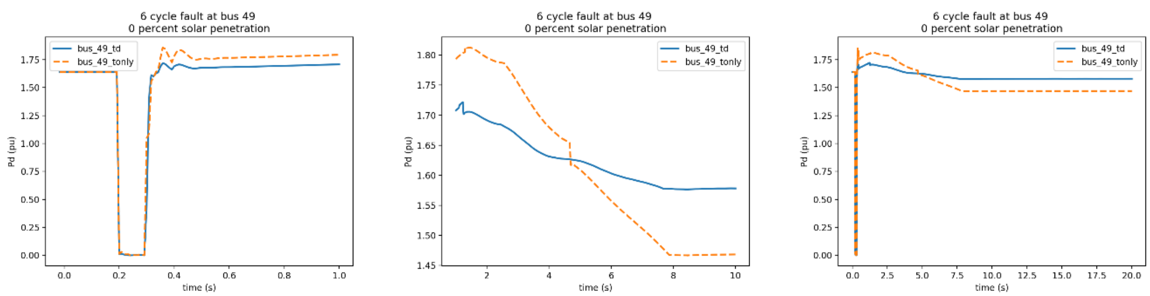

Figure 2.8: Bus 49 for the Same Scenario and Setup Described in Figure 2.8

A comparison of the voltage trajectories show similar behavior; Buses 39 and 44 have pre- and post-disturbance steady-state solutions that are near identical while Bus 49 shows a comparatively higher deviation as shown in **Figure 2.11**.

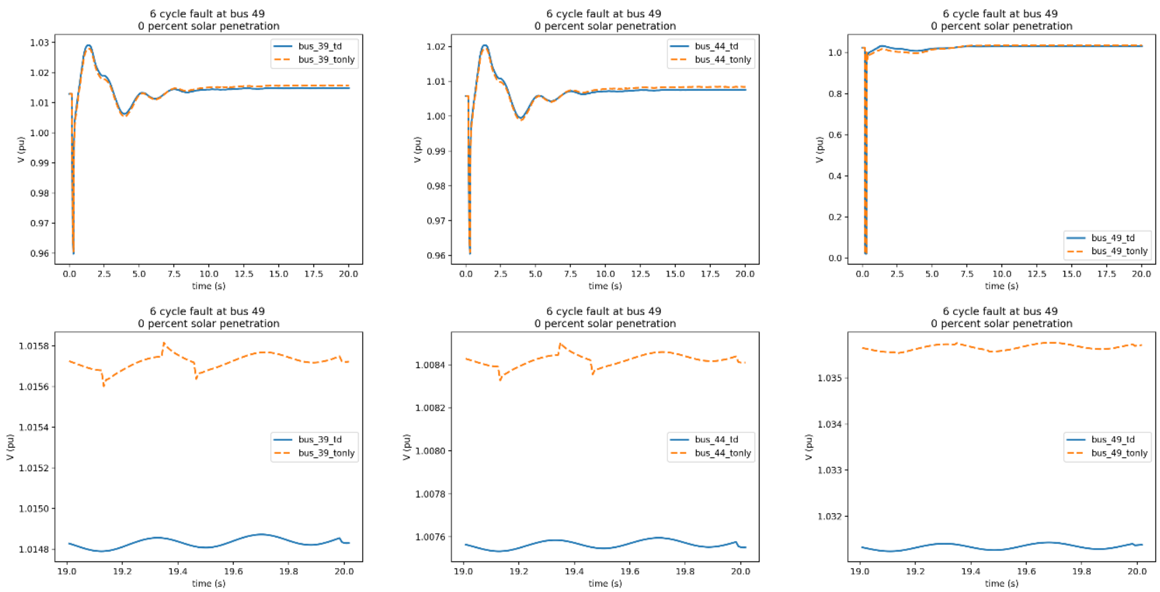

Figure 2.9: Voltage Magnitude Trajectory across Buses 39, 44, and 49 (top) and at the End of Simulation (bottom) for Scenario One

Phase 1, Scenario 2: 6% Solar Penetration at Buses 39, 44, and 49

The setup for this case is the same as Phase 1, Scenario 1 with 6% of load at Buses 39, 44, and 49 being replaced with DERs. The conventional generators, all 16 of them, had their inertia constants reduced equally based on the percentage of load that was replaced. Since it is unknown which conventional generators will be committed, it is reasonable to assume that the system-wide inertial reduction will be approximately equal. As before, there are two load identifiers at the said buses, one for composite load model that has 40% of the load and one for 60% of the load represented through distribution feeders. A total of 10% of the feeder load is supplied by solar generation, translating to 6% reduction in net load as seen from the transmission side. **Figure 2.12**, **Figure 2.13**, and **Figure 2.14** describe the trajectory of Buses 39, 33, and 49, respectively, in the simulation for the same six-cycle fault at Bus 49. The trajectories of all buses follow similar patterns to the no solar case, Scenario 1. **Figure 2.15** shows the comparison of all buses monitored with similar trajectories as Scenario 1.

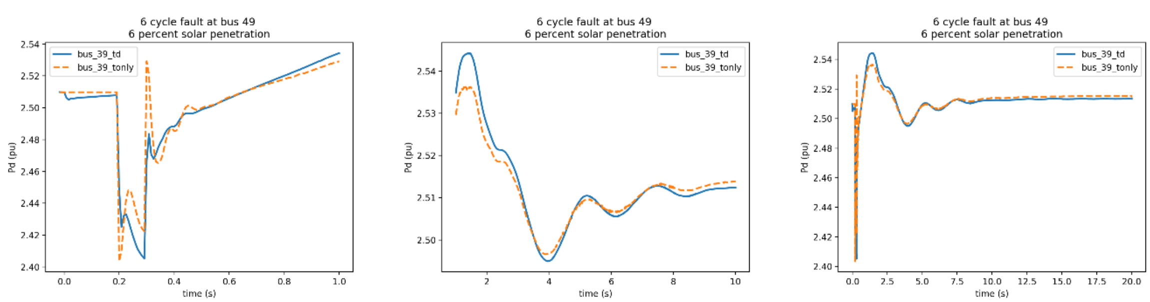

Figure 2.10: Net Real Power Demand Comparison for Bus 39

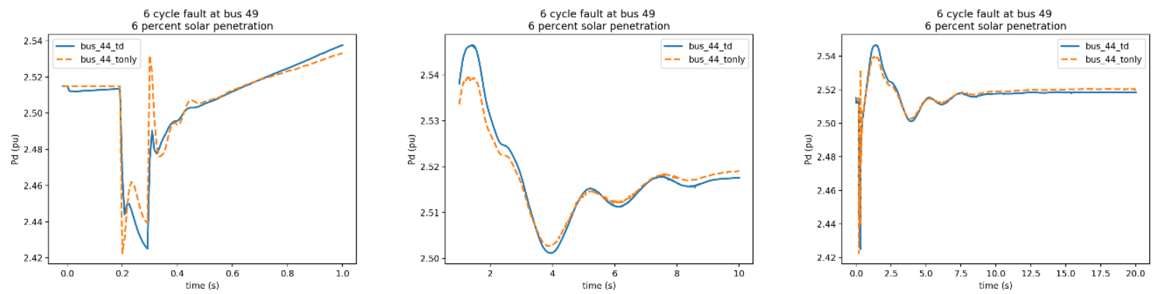

Figure 2.11: Bus 44 for the Figure 2.12 Scenario and Setup

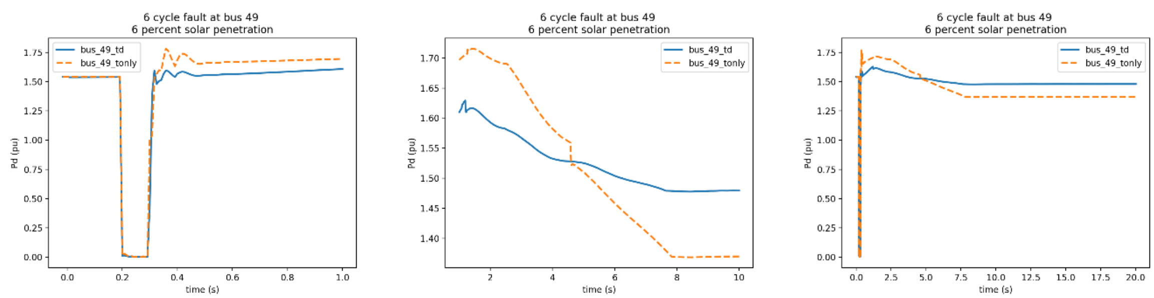

Figure 2.12: Bus 49 for the Figure 2.12 Scenario and Setup

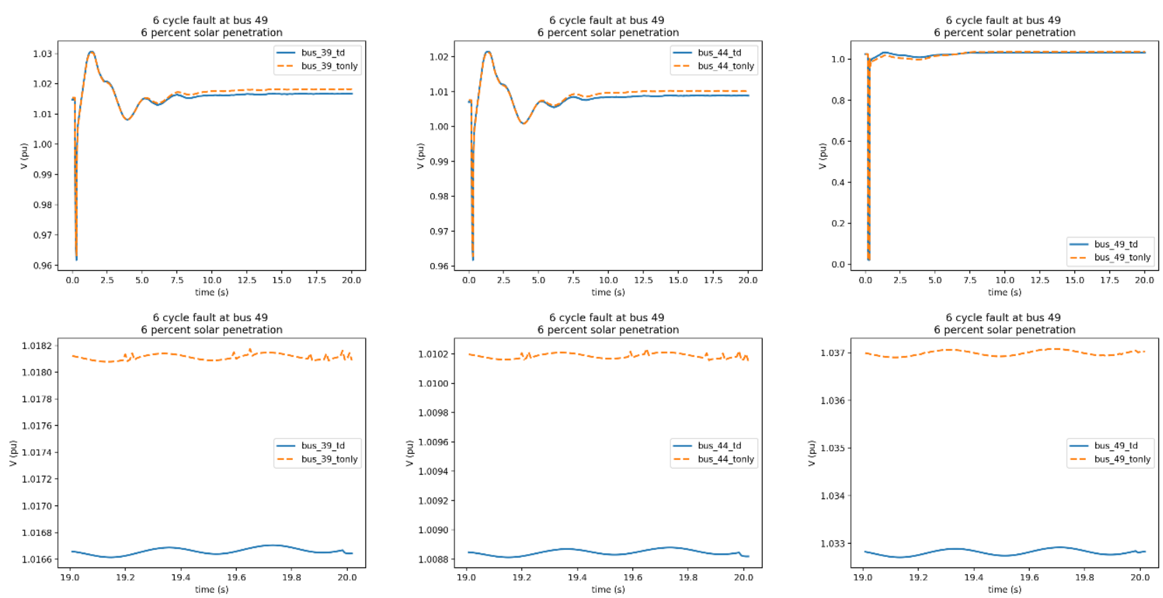

Figure 2.13: Buses 39, 44, and 49 (top) and at the end of Simulation (bottom)

Phase 1, Scenario 3: 18% Solar Penetration at Buses 39, 44, and 49

This setup follows the same pattern as Phase 1, Scenario 2. In this case, the solar penetration at Buses 39, 44 and 49 is raised to 18%. As seen in **Figure 2.16**, the increased solar penetration results in a slightly larger difference in pre-disturbance conditions. The trajectories, however, follow similar pattern to the no solar and 6% solar penetration case. This is true also for Buses 44 (**Figure 2.17**) and 49 (**Figure 2.18**). As with the other scenarios, **Figure 2.19** supplies the comparison between Buses 39, 44, and 49 for the entire simulation. Co-simulation studies with higher penetration of renewables, which implies larger changes to base case, have shown that there is a correlation between this difference and level of renewable penetration. There are a number of numerical challenges that result in this difference. The primary of which is non-zero derivative values for state variables at t=0. Nonetheless, given adequate time in the order of few seconds, the co-simulation setup reaches a steady state point that is comparable with aggregated transmission only results.

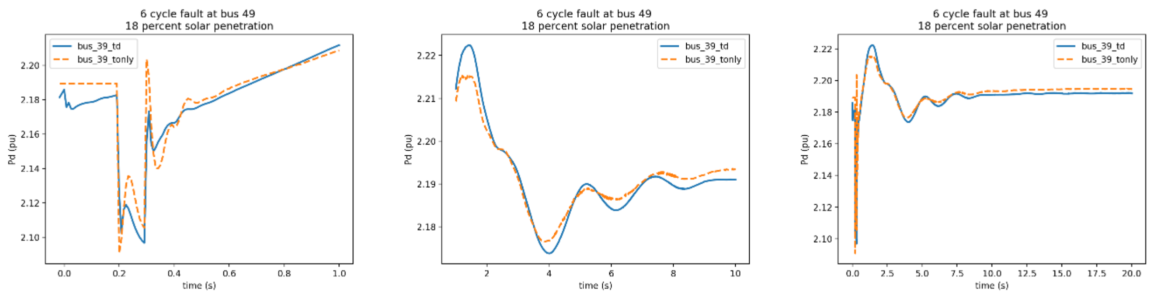

Figure 2.14: Net Real Power Demand Comparison for Bus 39

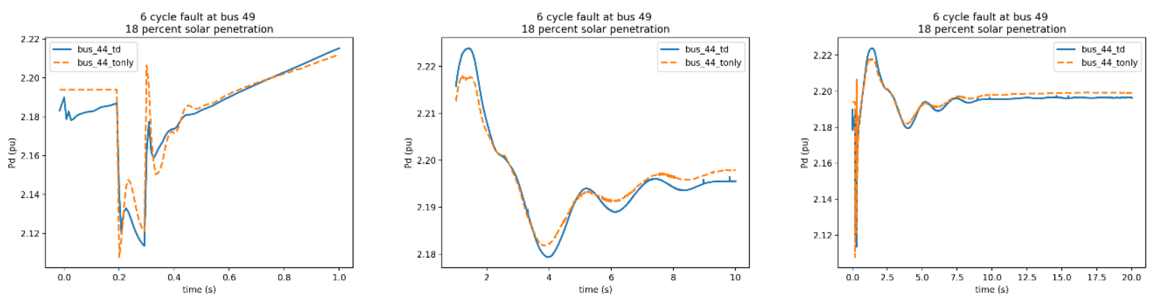

Figure 2.15: Results for Bus 44 for the Same Scenario and Setup Described in Figure 2.16

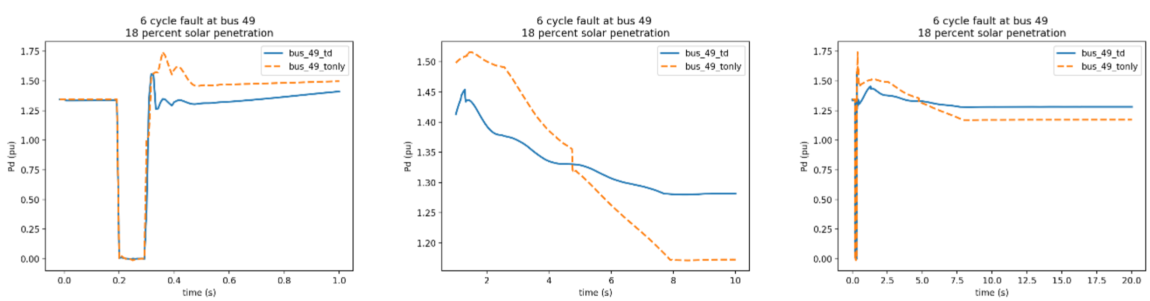

Figure 2.16: Results for Bus 49 for the Same Scenario and Setup Described in Figure 2.16

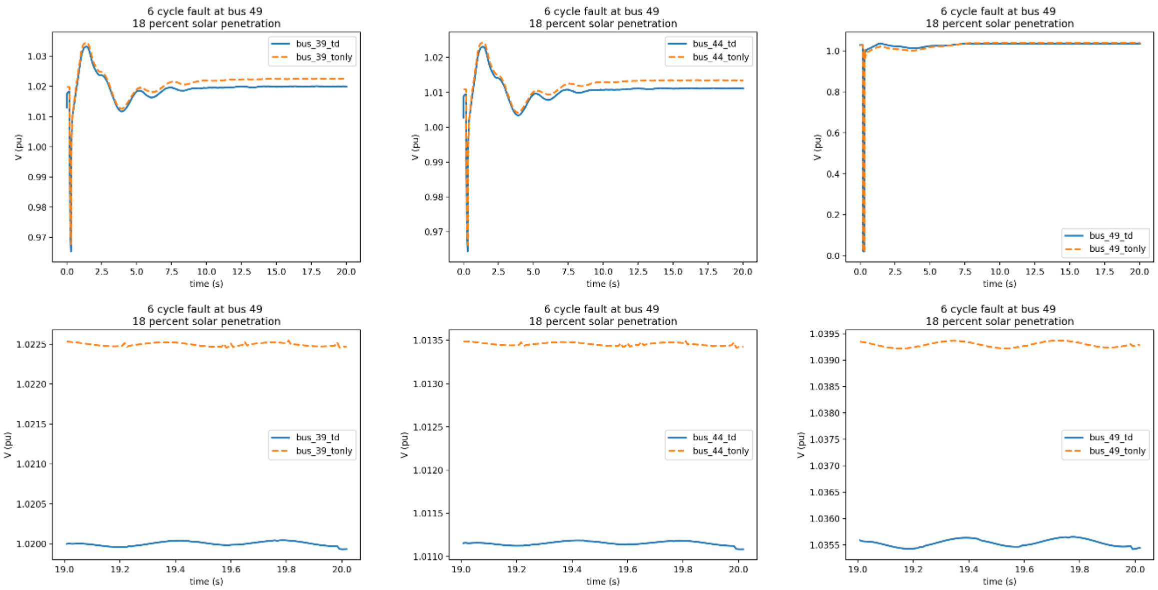

Figure 2.17: Comparison of Voltage Magnitude at Buses 39, 44, and 49

Observations from Phase 1 Studies

While the number of scenarios are not statistically significant to make concrete observations, the fact that the results across different solar penetration scenarios follow a similar pattern allows SPIDERWG to make the following observations when comparing aggregated transmission only simulation with co-simulation:

- Buses that are electrically distant from disturbance location tend to show a behavior that is very similar during the disturbance and their post-disturbance steady state values are also similar.
- Buses that are close to the disturbance location show a behavior that is different to warrant further examination through co-simulation.

Phase 2

SPIDERWG explored a different objective with the simulations performed in Phase 2 of their investigation. Some of the high level objectives to be answered in Phase 2 are as follows:

- Phase 2 will allow to further examine whether a hybrid approach as described in Phase 1 is a reasonable setup with regards to determining the edge cases.
- Help validate if the patterns observed in Phase 1 hold true in Phase 2.
- Explore different ways in which DERs can be represented such that the aggregated approach (i.e., using DER_A) produces results that are comparatively closely aligned with the detailed model.

Table 2.2 shows the low-voltage ride through parameters used in Phase 2 for DER_A model. DERs used in T&D co-simulation used the same parameters as that of 1547-2003 and 1547-2018. DERs used in T&D co-simulation are modeled individually using IEEE 1547-2003 and 1547-2018 interconnection standards using the same parameters for the appropriate zones as shown in **Table 2.2**. Similar to Phase 1, the emphasis is on pre- and post-disturbance equilibrium condition to compare positive sequence tools versus "beyond positive sequence" methods.

Table 2.2: Low voltage ride through parameters used in phase 2					
Scenario	**Standard**	**vl0**	**vl1**	**tvl0**	**tvl1**
1	30% 2003–70% 2018	0.44	0.49	0.16	0.16
2	1547-2003	0.5	0.55	0.16	0.16
	1547-2018	0.3	0.35	0.16	0.16

Phase 2, Scenario 1: 10 percent system wide solar penetration with mixed vintage of DERs Represented with single DER_A

Phase 2 comparison revolves around DER representation in transient stability studies. For the transmission only simulation, the modeled DERs are represented with a single DER_A model with parameters from a previous SPIDERWG reliability guideline on DER_A parameterization.[24] For co-simulation case, each transmission-distribution interface, as seen from the transmission systems perspective, has two loads: one represented with a composite load model and the other represented with a distribution system. In comparison, for the transmission-only model, a single composite load model is used. While this might seem counter intuitive, the distribution feeder in this case is used to represent the static load portion of the composite load model with appropriate parameters for the conventional constant impedance, current, and power loads. The static load portion is assumed to be 50% of the total load.[25] A detailed DER model is placed randomly across the length of the feeder. Unlike Phase 1, where a small subset of buses were modeled with distribution feeder, Phase 2 models every T–D interface except for Buses 3, 17, 18, and 64 due to the inability to match generic feeders to match T–D interface conditions.[26]

In this scenario, a fault is placed at Bus 41 for 250 ms. This long fault is representative of a large disturbance as Bus 41 has 1,000 MW and 250 MVAR of load. The fault impedance is adjusted to ensure that the voltage magnitude is right at the boundary between the lower most voltage zones defined for IEEE 1547-2003 (V<0.5) and IEEE 1547-2018 Category 2 (V<0.3). This setup allows evaluation of DER_A representation when vl0 parameter between the standards represented in the mixed vintage case are different. Note that the tvl0 (160 ms) parameter is the same for both the standards. **Figure 2.20** demonstrates the differences in net power and voltage mangitude between the positive sequence results in comparison to the results for a co-simulation model at Bus 41. The dashed line represents the filtered voltage seen by DER_A model. As Bus 41 has 100 MW of DER generation (10% of Bus 41's load), the total DER generation was plotted in **Figure 2.21** to investigate and compare results from a beyond positive sequence tool. The total DER response (top), individual DER response (middle), and id and iq plots of the DER_A model (bottom) were recorded and compared. Further notice in the figures that the initial condition between the two cases are approximately the same. The post disturbance condition for net load is different for buses that are close to the disturbance—an observation that is consistent with Phase 1 results.

[24] Available here: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_DER_A_Parameterization.pdf

[25] The choice of composite load model parameters does not impact the findings of this section due to the fundamental nature of the timer logic modeled. The number chosen here was based on analysis of generated data sets.

[26] This is a limitation due to high quality data being available on the distribution side to match the response of the modeled feeders to measured data.

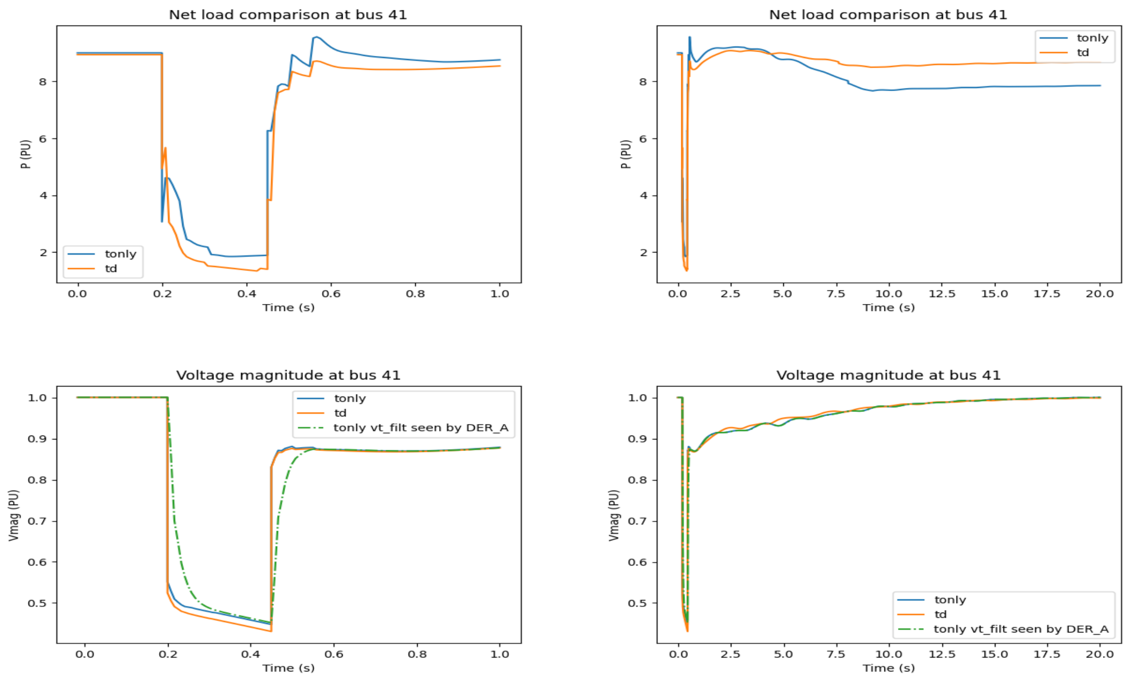

Figure 2.18: Comparison for Bus 41 under Mixed Vintage of DERs.

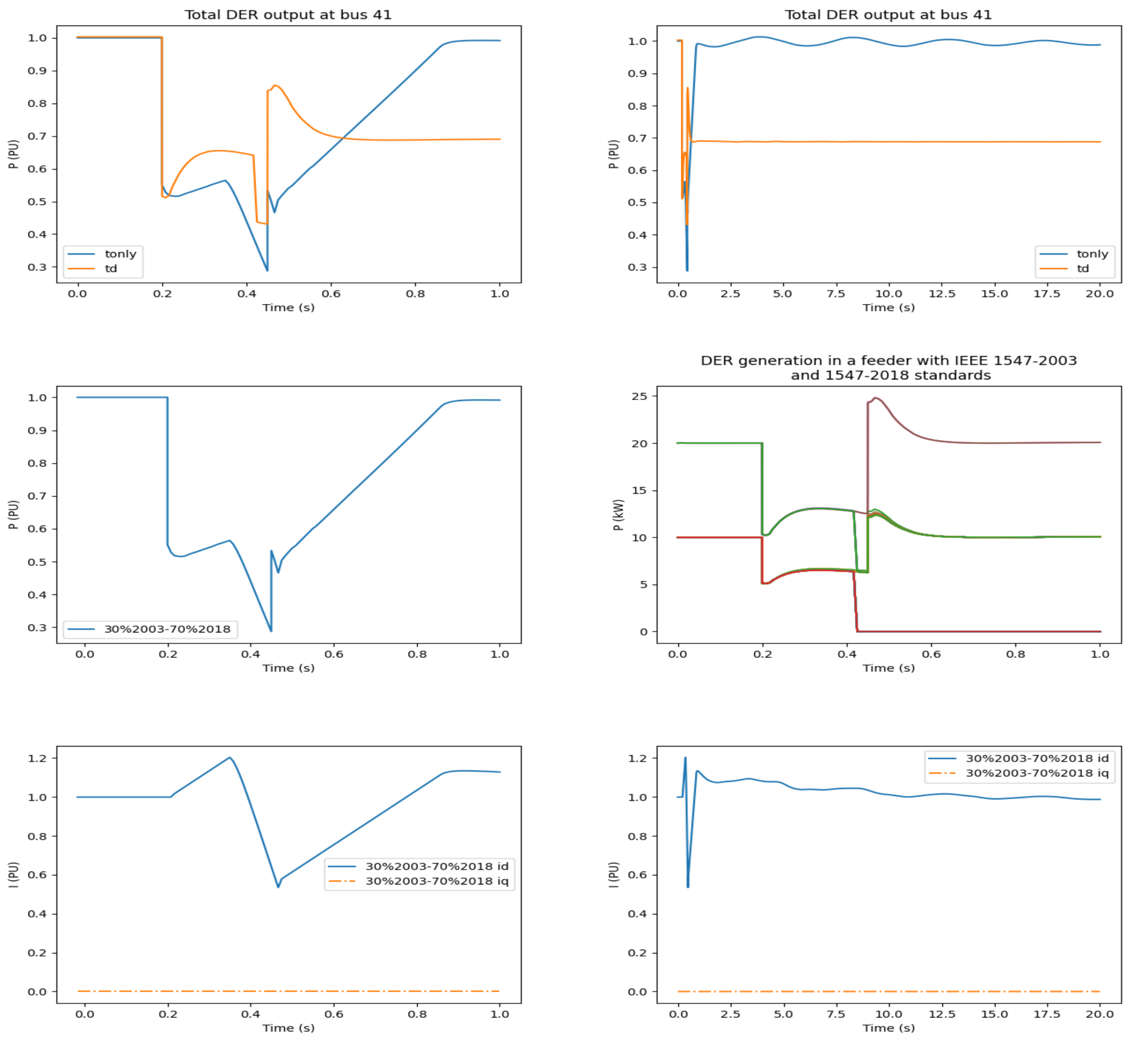

Figure 2.19: Comparison of at Bus 41 for mixed vintage of DERs.

Phase 2, Scenario 2: 10 percent system wide solar penetration with mixed vintage of DERs Represented with two DER_A models

In Scenario 2, the setup is the same except for the fact that in transmission only simulation, two DER_A models were used at each node instead of one DER_A model as in Scenario 1. Specifically, 30% of the DER generation is modeled with the DER_A model parameterized to IEEE 1547-2003 standard and the remaining 70% parameterized to IEEE 1547-2018 Category 2 at each bus with a unique identifier for each. This representation allows to model DER_A with the right set of parameters without the need to find suitable parameters for mixed vintage case. The increase in computation complexity is incremental, and since the studies are done offline, greater accuracy over speed can be chosen.[27] It is worth mentioning that the total DER capacity in Scenarios 1 and 2 are the same. The comparison of net load and voltage magnitude is shown in **Figure 2.22**. Notice that the post-disturbance steady-state point operating is closer to the T&D co-simulation plot than as seen in Phase 1 (**Figure 2.20**) that can be attributed to a greater matching of DER output between T-only and T&D simulations. As in Scenario 1 of this phase, **Figure 2.23** plots the relevant generation quantities of both aggregate DER models versus a T&D co-simulation. Notice that the aggregated response matches with individual representation in T&D co-simulation. The total DER output (top), individual DER model

[27] Studies for decisions in the operational online time frame may not be able to perform such separation of one larger aggregation into a number of smaller aggregations.

behavior (middle) and filtered voltages (bottom) are shown in **Figure 2.23.** The filtered voltage seen by the DER model (solid line) and the simulated substation voltage (dashed line) is shown for comparison.

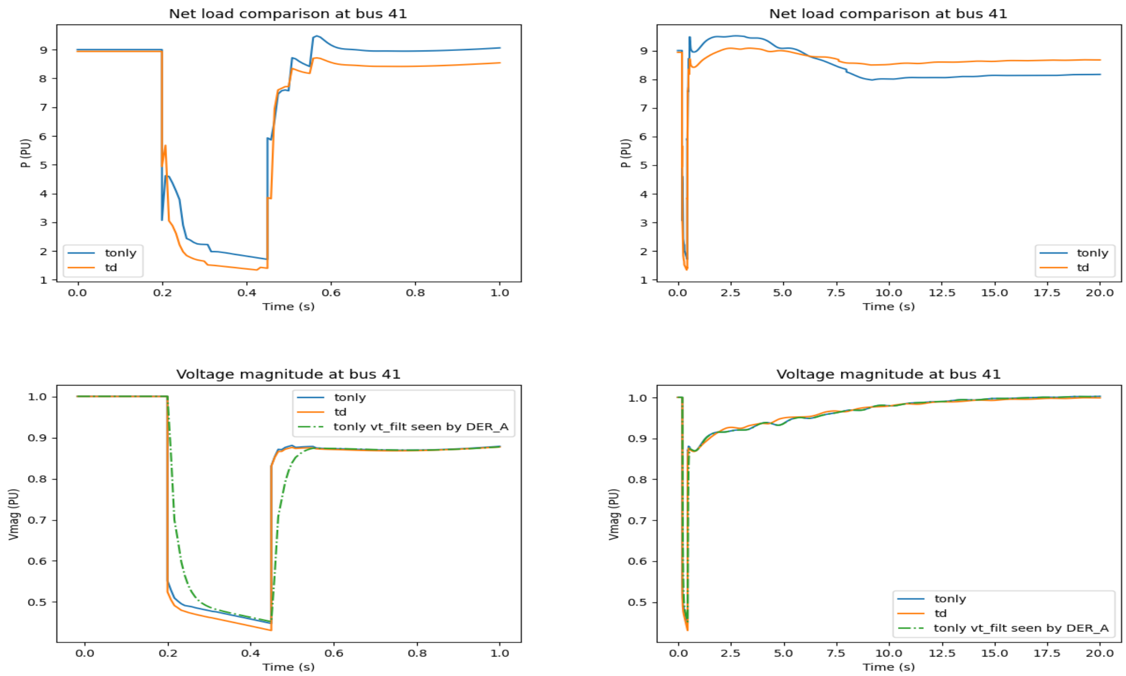

Figure 2.20: Comparison for Bus 41 under Mixed Vintage of DERs.

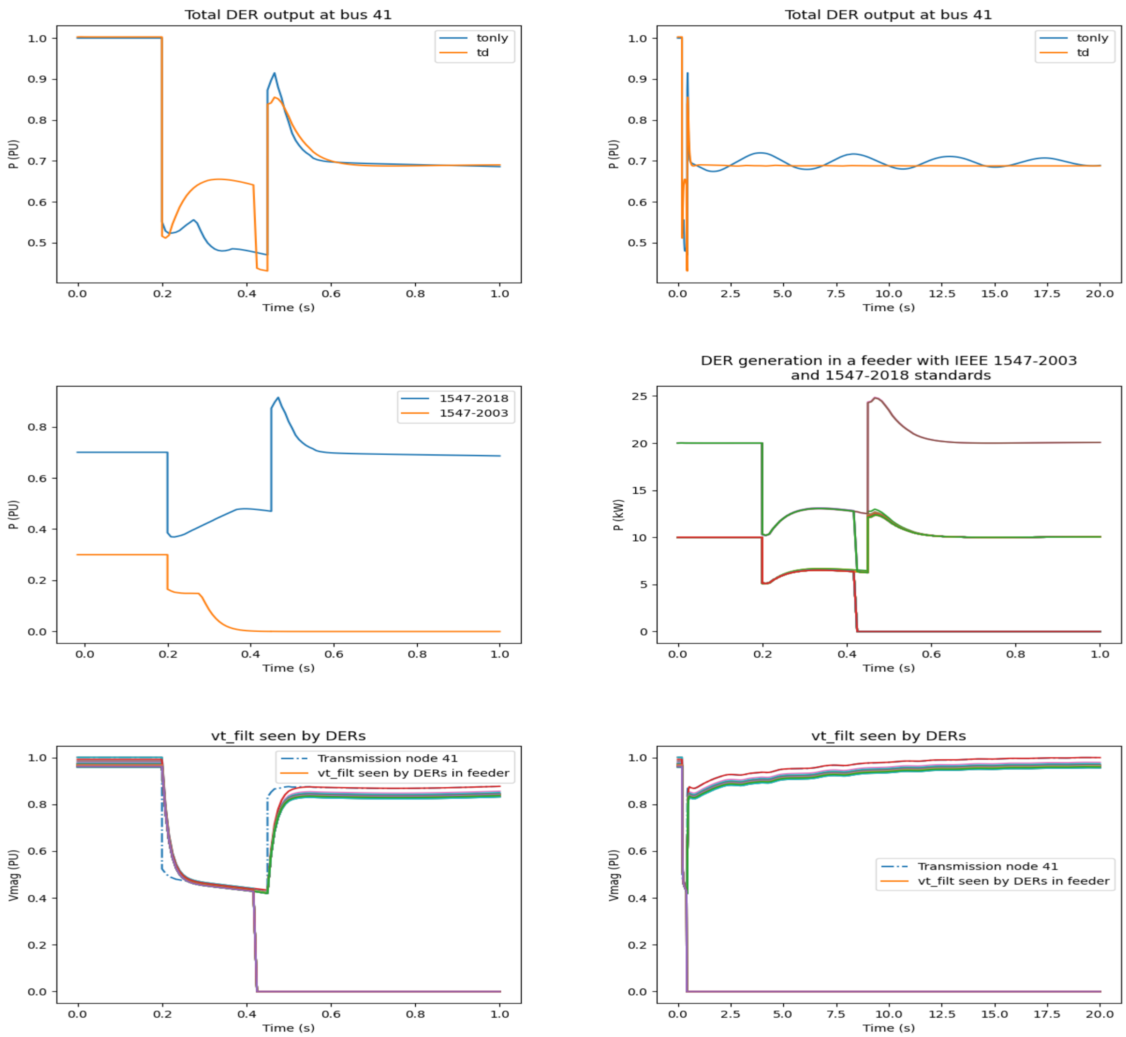

Figure 2.21: Comparison of aggregated DER output at Bus 41 for mixed vintage of DERs.

Figure 2.24 shows the id and iq commands sent to the DER_A model for this scenario for both aggregations (that is, both the aggregation parameterized for IEEE 1547-2003 and IEEE 1547-2018). Figure 2.25 plots the net load and voltage magnitude at Bus 42 in the simulation. Bus 42 is electrically distant from disturbance location (Bus 41). Similar to Phase 1 results, the difference in post disturbance equilibrium points are closer when the bus is electrically distant from fault location. However, notice that the oscillation in Figure 2.26, which is a plot showing the aggregated output of DERs at Bus 42, is only seen in the positive sequence representation. The oscillation was not seen with the co-simulation model for the same disturbance. This is a good scenario in which a beyond positive sequence tool was appropriate for use in studying a transmission system with respect to the impact of aggregate DERs.

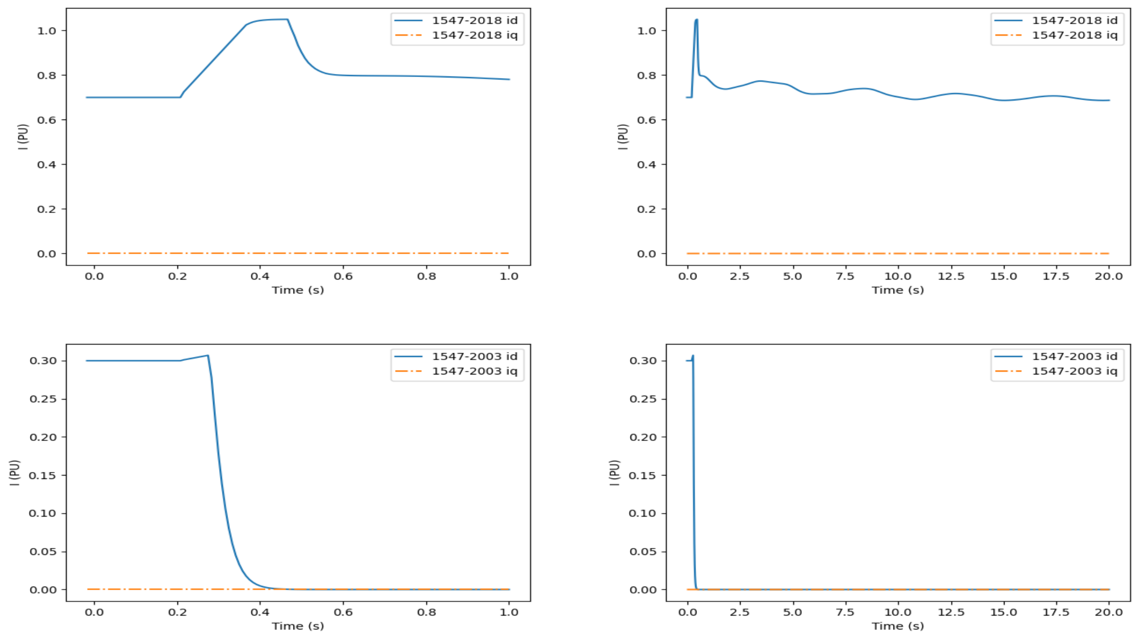

Figure 2.22: Comparison of DER_A id and iq modeled using 1547-2003 and 1547-2018 standards at Bus 41.

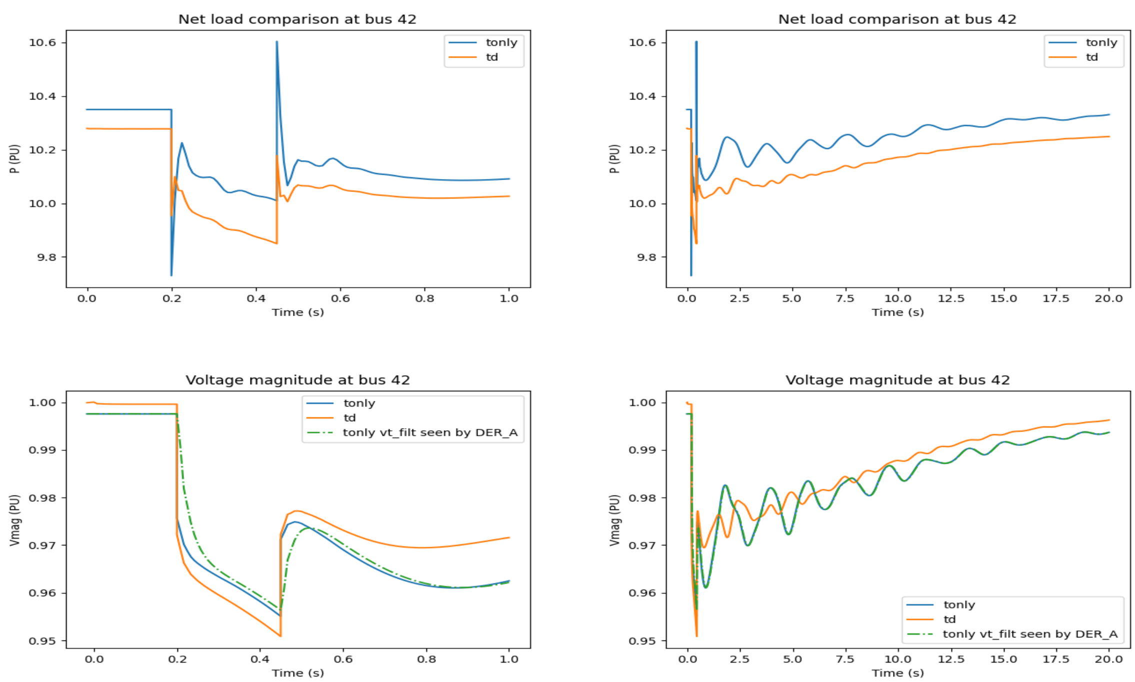

Figure 2.23: Comparison of aggregated DER output at Bus 42 for mixed vintage of DERs.

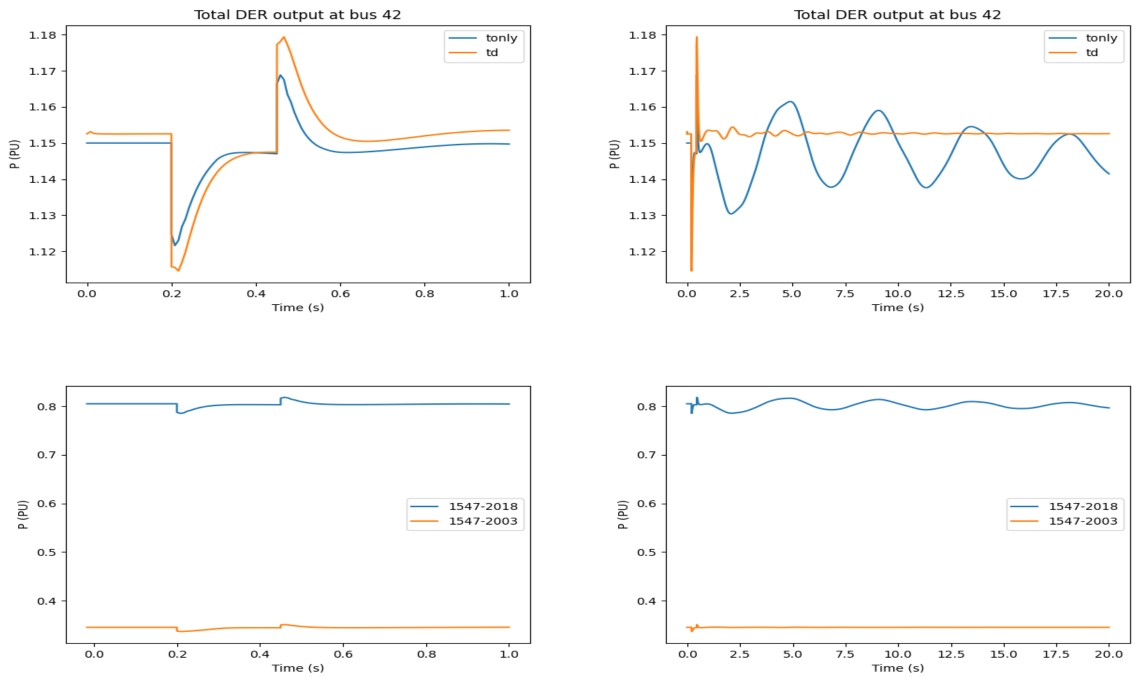

Figure 2.24: Comparison of aggregated DER output at Bus 42 for mixed vintage of DERs

Phase 3

After the conclusion of Phase 2 of SPIDERWG's study, there was a question raised to the validity of the observations in Phase 2 holding for differences in the time to trip over the change in voltage trip threshold. That is, does the observation seen in Phase 2 hold when vl0 and vl1 are reset[28] back to guideline values?

In Phase 2, SPIDERWG examined the impact of having different voltage settings (i.e., vl0 and vl1) but used the same timer settings for mixed DER vintages where DERs are modeled using DER_A model. In Phase 3, SPIDERWG investigated the same setup while resetting the voltages back to guideline parameters.[29] Specifically, tvl0 was set at 80 and 160 ms for 1547-2003 and 1547-2018 standards respectively. In this scenario, a fault is placed at Bus 41 for 150 ms. **Table 2.3** shows low voltage ride through parameters used in Phase 3 for DER_A model. DERs used in T&D co-simulation are modeled individually with IEEE 1547-2003 and 1547-2018 interconnection standards with the same parameters for the appropriate zones as shown in **Table 2.3**.

Table 2.3: Low voltage ride through parameters used in Phase 3

Scenario	Standard	vl0	vl1	tvl0	tvl1
1	30% 2003–70% 2018	0.44	0.49	0.16	0.16
2	1547-2003	0.44	0.49	0.08	0.16
2	1547-2018	0.44	0.49	0.16	0.16

[28] i.e. same vl0 and vl1 for 1547-2003 and 1547-2018 standards while tvl0 parameter is different.
[29] i.e. same vl0 and vl1 between 1547-2003 and 1547-2018 standards but allowing different timer settings

Phase 3, Scenario 1: 10 Percent System wide Solar Penetration with Mixed Vintage of DERs Represented with Single DER_A

As with the other phases, the net load and voltage magnitude are compared at Bus 41 in **Figure 2.27**. The dashed line in the figure represents the filtered voltage seen by DER_A model. As in the other phases, Bus 41 has 100 MW of DER generation, which is 10% of load at Bus 41. As such, the total DER output and relevant generation comparisons were graphed in **Figure 2.27**.

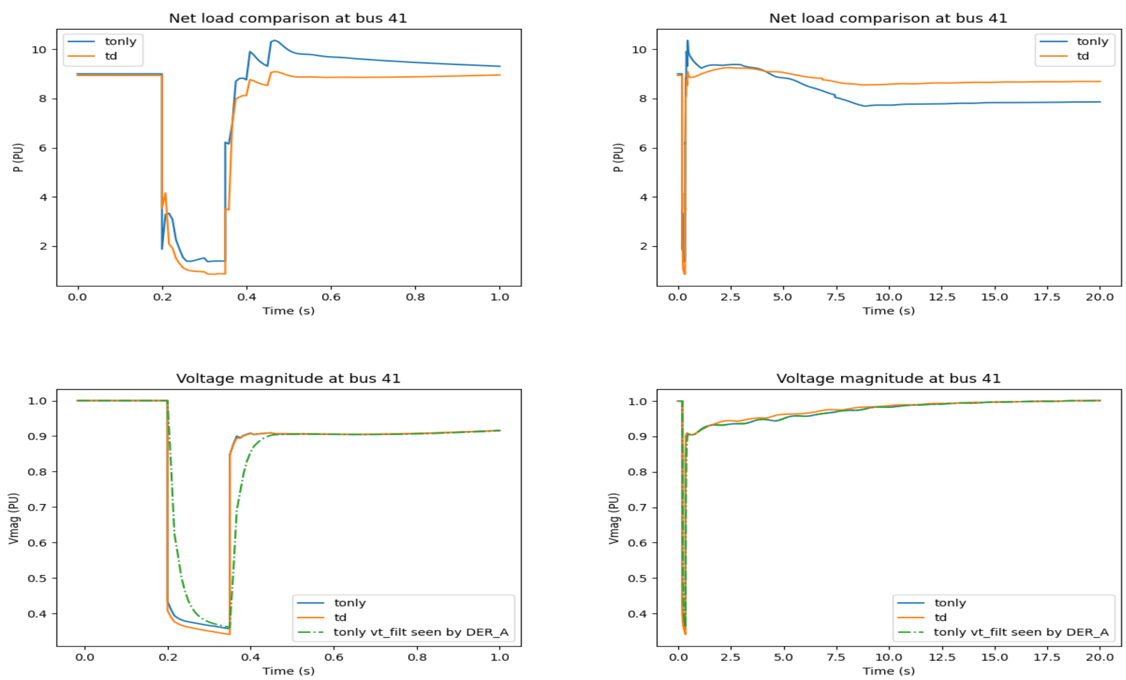

Figure 2.25: Comparison of net load and voltage magnitude trajectory for Bus 41 with mixed vintage of DERs

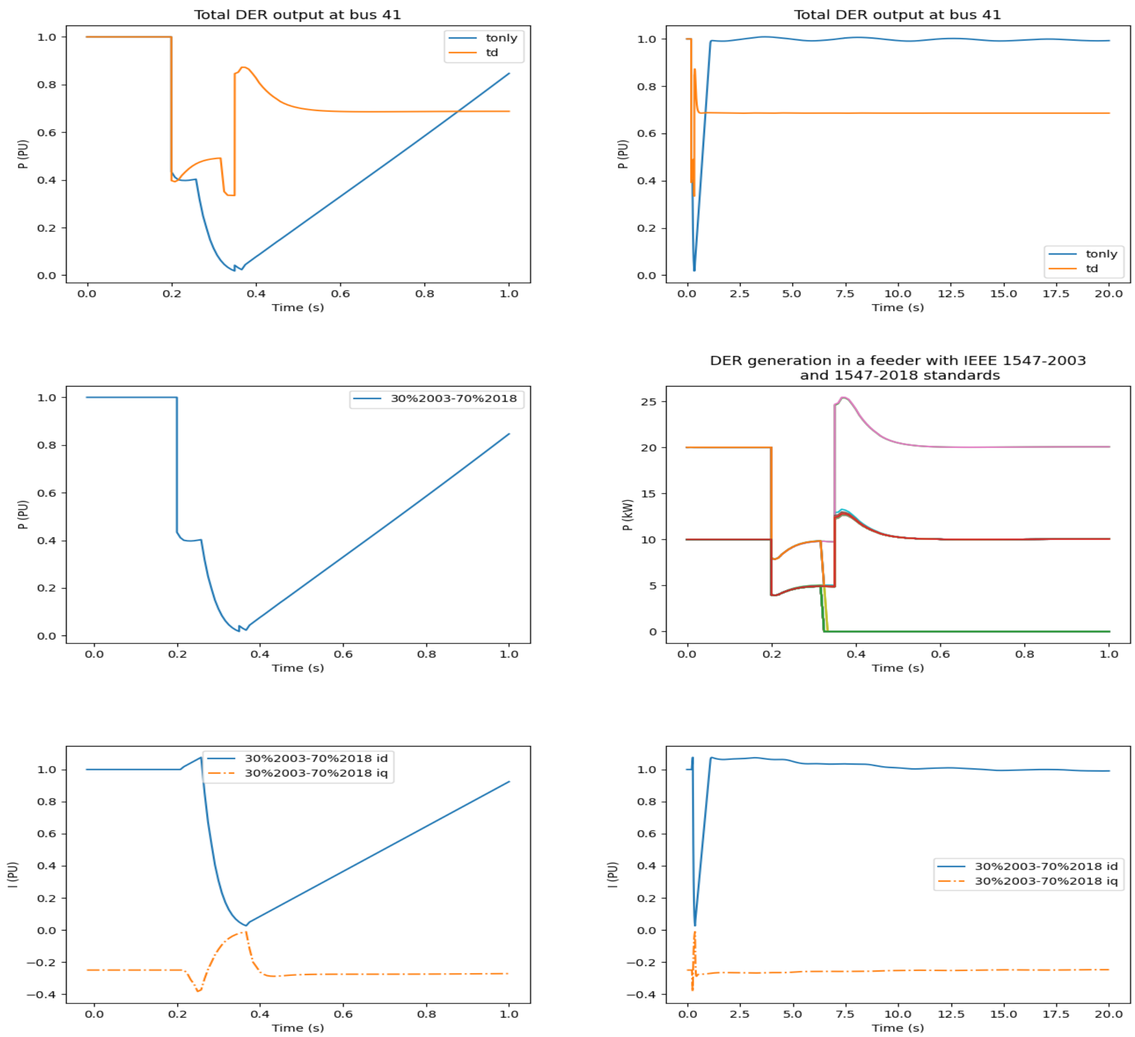

Figure 2.26: Comparison of aggregated DER output[30] at Bus 41 for mixed vintage of DERs.

Phase 3, Scenario 2: 10 Percent System wide Solar Penetration with Mixed Vintage of DERs Represented with Two DER_A Models

In the second scenario studied in Phase 3, SPIDERWG took the single DER model in Scenario 1 of this phase and performed the same split into two DER_A models in the transmission only model. The results of the net load (top) and voltage magnitude (bottom) at Bus 41 is shown in **Figure 2.29**. In the top right of the figure (comparing the net load), notice the post-disturbance steady-state point being closer to T&D when compared to Phase 2, Scenario 1 (**Figure 2.20**). Part of this reason can be attributed to the DER output matching between T-only and T+D. As with the other phases, Bus 41 has 100 MW of DER generation, which is 10% of load at Bus 41. **Figure 2.30** plots the total DER generation and relevant parameters for comparison at Bus 41. The total DER response (top), individual DER response (middle), and filtered voltages (bottom) are plotted for comparison. Notice that the aggregated response matches with individual representation in T&D co-simulation. The bottom plot in **Figure 2.30** shows the filtered voltage seen by DERs in distribution system (solid line) and the substation voltage (dashed line) is shown for comparison. **Figure 2.31** shows the id and iq commands for the DER model[31] at Bus 41. **Figure 2.32** compares the net load and voltage magnitude at Bus 42. Bus 42 is electrically distant from disturbance location when compared to Bus 41. Similar to

[30] The total DER response (top), individual DER response (middle) and the iq and id commands (bottom) are plotted.

[31] Plot lines show id and iq current for the DER models using 1547-2003 and 1547-2018 standard parameterization.

Phase 1 results, the difference in post disturbance equilibrium points are closer when the bus is electrically distant from fault location, as seen in **Figure 2.32**. This is confirmed by the plot of total DER generation at Bus 42 in **Figure 2.33**.

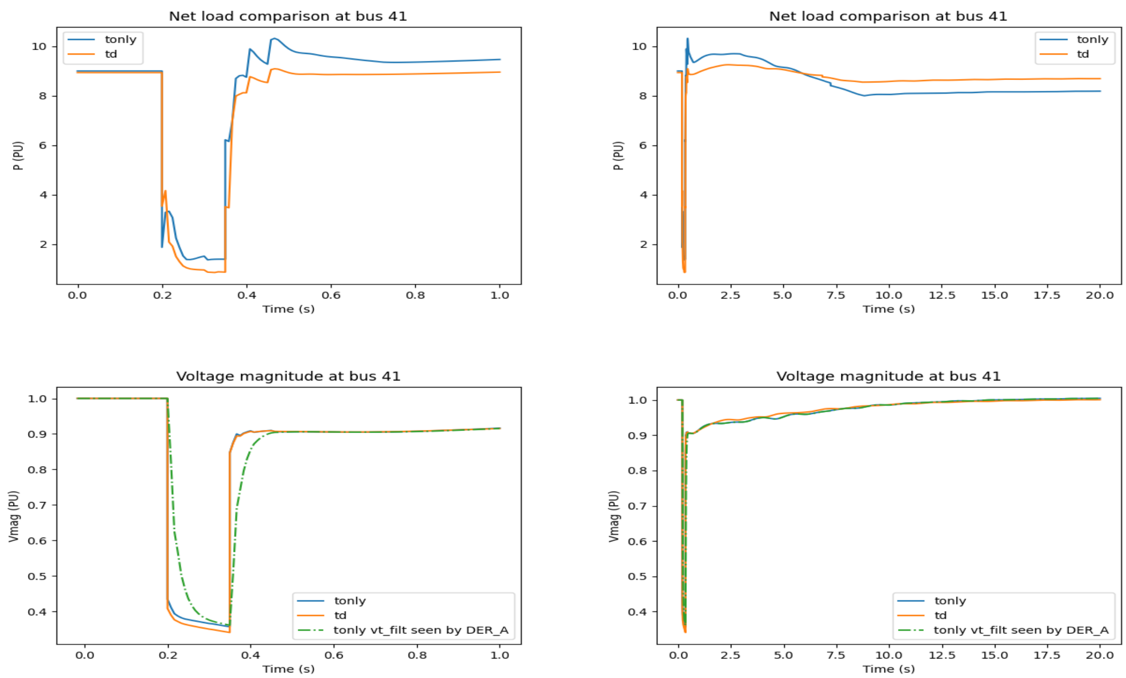

Figure 2.27: Comparison for Bus 41 when mixed vintage of DERs.

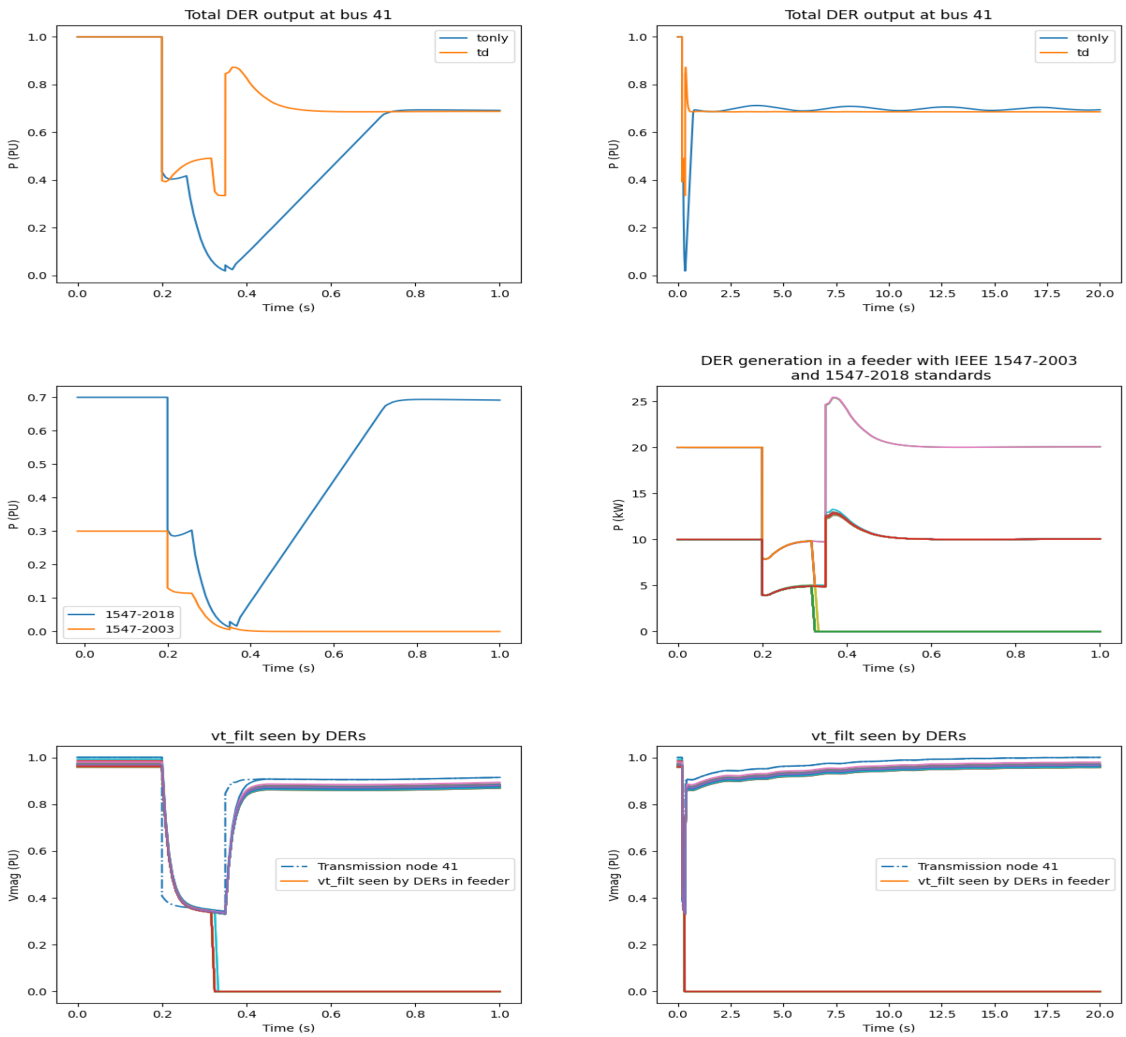

Figure 2.28: Comparison of aggregated DER output at Bus 41 for mixed vintage of DERs.

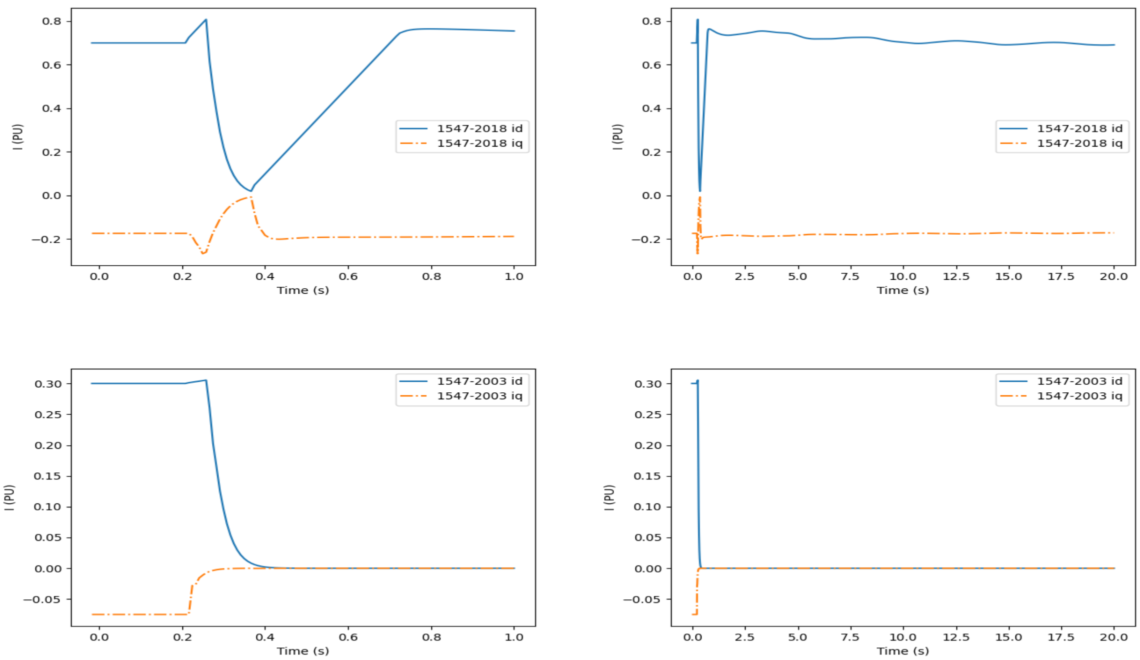

Figure 2.29: Comparison of DER_A id and iq at Bus 41.

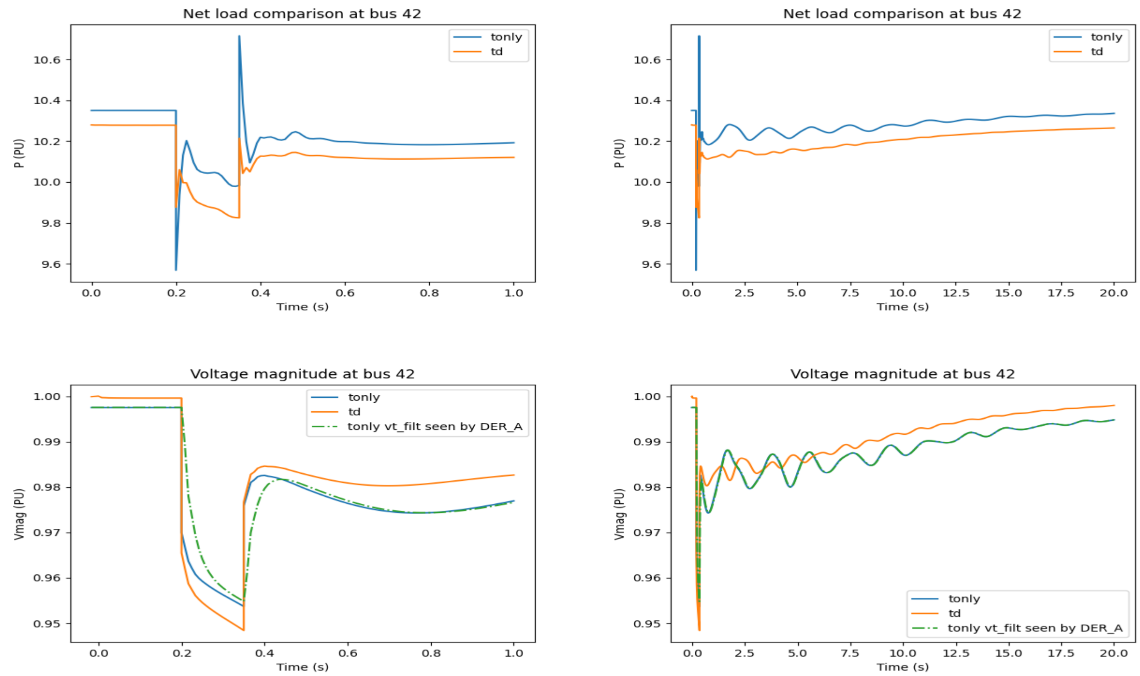

Figure 2.30: Comparison of Aggregated DER Output at Bus 42 for Mixed Vintage of DERs

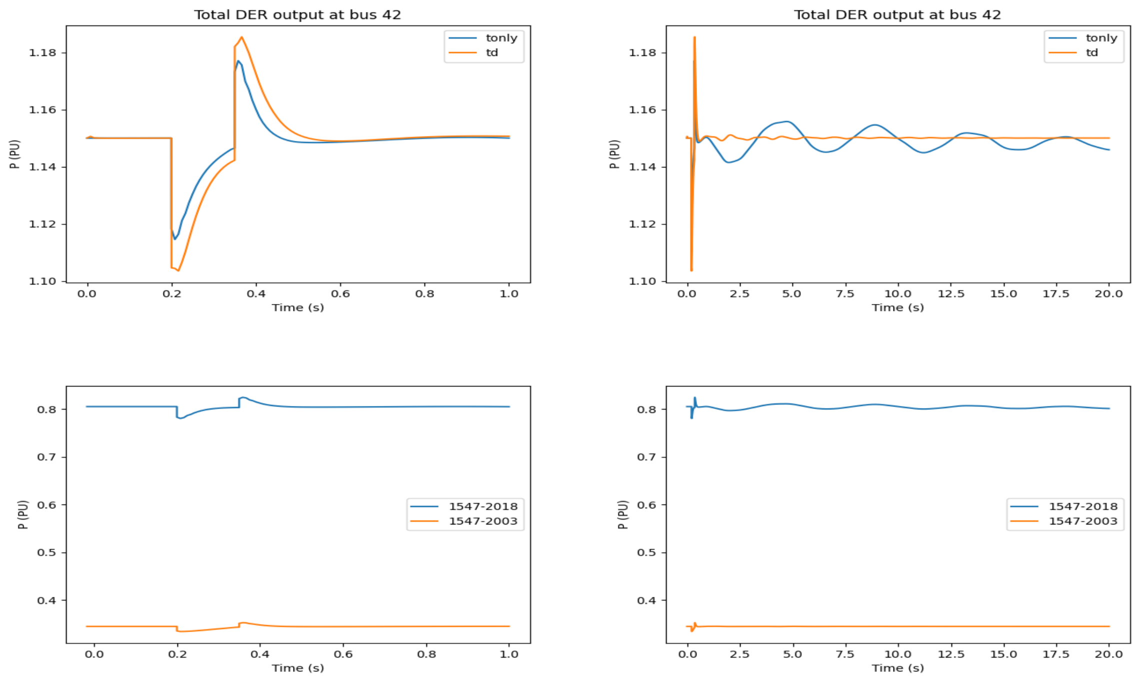

Figure 2.31: Comparison of Aggregated DER Output at Bus 42 for Mixed Vintage of DERs.

Potential for EMT Simulations

The above sections discussed use cases are informative to describe when to move into a "beyond positive sequence" tool; however, there is cause to determine if a TP can perform an EMT study with information at hand. The following points and checklist are provided to assist in determining the pursuit of an EMT study:

- **Data Increase:** Am I prepared to handle anywhere from two times to ten times (if not more) of extra data to model the local area?
- **Time to Study:** Am I prepared to handle any snags that could delay[32] the study?
- **Hardware Support:** Am I able to support multithreading and parallelization without external scripts? Is my hardware capable of simulating many individual models in parallel?
- **Personnel Support:** Do I have enough engineers with technical expertise to run this study? Do I have a consultant and what cost does that impose?
- **Coding and Scripting:**
  - Am I able to support easy, passive model building?
  - Can I acquire robust scripting APIs?
  - Am I able to use fast and accurate solution methods such that no numerical instabilities occur?
- **Modeling Support:** Do I have a robust model vetting and acceptance requirement so that model problems do not propagate into the study?

[32] SPIDERWG members have seen a delay for large cluster EMT studies take 4–6 months.

To help identify cases where high DER penetrations might warrant an EMT study, the following two major scenarios below are provided as indicators:

- The local area load is coincident with high DER penetration and does not rely on transmission to deliver the generation to load.
- The local area DER is near a BPS-connected IBR facility. Here, it is important to understand local interactions and impact that may occur between the DER and the IBR facility.

Key Observations

The NERC SPIDERWG had the following key observations when investigating the use cases for going "beyond positive sequence" by using a T&D co-simulation tool:

- Buses that are electrically distant from disturbance location tend to show a behavior that is very similar during the disturbance and their post-disturbance steady state values are also similar.
- Buses that are close to the disturbance location show a behavior that is adequately different to warrant further examination in "beyond positive sequence tools", elaborated further as follows:
  - This observation is consistent across both Phase 1 and 2 results.
  - This difference can be attributed to a modeling difference between one of:
    - T-only and T&D co-simulation, but further work in this area is needed for this to be conclusive.
    - The implementation, class, and type of numerical method used, requiring support of software vendors for the used beyond positive sequence tool.
    - Other implementation details, such as load model changes at low voltage that aid in numerical convergence, also requiring software vendor support.
- Aggregated DER representation with DER_A model was adequate under the tested conditions, elaborated further as follows:
  - Partial trip characteristics of DER_A works adequately well under tested conditions. The voltage zone between vl0 and vl1 (i.e., vdrop) ranges from 2–8% with a reasonable value of 5%. Differences because of partial trip characteristics can arise at a given DER_A model if voltage is within this zone and if the DERs are not linearly distributed along the length of the feeder. Even under such conditions, the difference will be marginal and is dependent on how the DERs are distributed in the feeder.
- In instances where the DER model represents 1547-2018 and other vintages, the following were observed:
  - Mixed vintages of DERs can be represented with a single DER_A model with appropriate parameters when voltage and frequency zones and associated timers involved are the same between the different standards that are being represented.
  - If voltage and frequency zones are different, such as the one presented in Phase 2 results, there can be difference in the observed DER behavior[33].
  - If the timers associated with voltage and/or frequency zones are different, such as the one presented in Phase 3 results, there can be difference in the observed DER behavior[34].

[33] Within SPIDREWG's identified use cases, this observed behavior was reflected the amount of active power produced by the DERs in simulation.

[34] Within SPIDREWG's identified use cases, this observed behavior altered the amount of active power produced by the DERs in post disturbance steady state condition

  - For completeness, the scenario where both voltage zones and timers associated with it are different was also studied (i.e., a combination of Phases 2 and 3). The observation made in Phases 2 and 3 holds.
    - The above issue is not a limitation of DER_A model but rather a limitation of how DER_A is represented under mixed vintage scenario. This issue can be mitigated by modeling DER_A individually as shown in **Phase 2** and **Phase 3**.
    - In general, it is difficult to model different voltage and/or frequency zones with different timers between the standards that make up mixed vintage scenario (e.g., 30% 1547-2003, 70% 1547-2018 standards) with a single mixed-vintage model.
- Based on a fundamental understanding of the models and their representations and backed by limited but significant results, it is reasonable to explore alternative ways to represent existing models within the existing positive sequence simulation tools. For this analysis, it is important to have a detailed model to compare against; T&D co-simulation tools satisfy this requirement.
- While engineering judgement is a viable tool, leveraging approaches like T&D co-simulation to understand aggregate model usage, representation, and parameterization will improve understanding of the system behavior and augment engineering judgement.
- It is worth pointing out that the results provided here for the mixed vintages of DERs scenarios do not rule out the possibility of a set of parameters that will result in appropriate response of single DER_A model used to represent mixed vintages. The rationale to explore alternative means of modeling stems from the following:
  - Potential challenge in deriving generic and universal parameter values, especially the parameters associated with voltage and/or frequency zones and associated timers
  - Simulation of scenarios where there could be more than two interconnection standards in mixed vintages of DERs (While engineering judgement could be used for a single DER_A model to provide a TP with the trend of the response, the need for increased accuracy in simulation results can warrant the use of multiple DER_A models.)

Appendix A: Survey of Existing and Ongoing Tools and Their Capabilities & Limitations

If the comparison and the subsequent observations made in the previous sections are of interest, then this appendix serves as a summary of an industry survey of beyond positive sequence tools. This survey gives an overview of available open source and commercial software and their current development status. The listed software falls under both current state-of-the-art and beyond positive sequence categories at time of publishing. Further efforts in the industry may yield tools that expand, improve, or alter **Table A.1** in the future. **Tables A.2 – A.10** contain some comparison of high level responses from representatives of the software tools SPIDERWG polled in **Table A.1**.

Table A.1: Beyond Positive Sequence Tools and Capabilities

Name	Developer	Main Components	Status	Capabilities
GridSpice[35]	Stanford University	**MATPOWER**: bulk power system simulation and analysis **GridLAB-D**: distribution system simulation	No active development or update in last five years.	Open source. Steady-state simulation only; no dynamic simulation capabilities, capable to be used with distributed computing, allows Python based scripting.
Framework for Network Co-Simulation (FNCS)[36]	PNNL	**PowerFlow**: PNNL's inhouse transmission grid simulator **GridLab-D**: distribution system simulation **ns-3:** communication network simulator	Available to download as use from Github. No recent update in last two years	Open source. Steady-state simulation only; no dynamic simulation capabilities.
Integrated Grid Modeling System (IGMS)[37]	NREL	**FESTIVE**: wholesale markets, UC and AGC **MATPOWER**: bulk AC power flow **GridLAB-D**: distribution system simulation	On-going development	Open source. Steady-state simulation only; no dynamic simulation capabilities.
T&D dynamics analysis tool[38]	IIT	**TS3ph:** A new solution technique that solves the transmission-distribution system equations simultaneously	On-going development for three years	Proprietary. Dynamic simulation only.
TDcoSim[39]	ANL	**Transmission simulator:** PSSE **Distribution simulator:** OpenDSS	On-going development	Open source. Steady-state and dynamic simulation capable;

[35] https://tomkat.stanford.edu/fellowships/seed-grants/gridspice-virtual-platform-modeling-analysis-and-optimization-smart-grid
[36] https://controls.pnnl.gov/research/project_2_5.stm#:~:text=FNCS%2C%20pronounced%20%22phoenix%2C%22,and%20inter%2Dsimulator%20message%20delivery.
[37] https://www.nrel.gov/docs/fy16osti/65552.pdf
[38] https://www.mcs.anl.gov/~abhyshr/downloads/papers/HiPCNA2011-2.pdf?origin=publication_detail
[39] https://github.com/tdcosim/TDcoSim

Table A.1: Beyond Positive Sequence Tools and Capabilities				
Name	**Developer**	**Main Components**	**Status**	**Capabilities**
		T&D interface written in Python.		
Three-phase Dynamic Analyzer (TPDA)[40]	Virginia Tech	TPDA uses a sequential or partitioned method for solving the digital and algebraic equations; the differential equations are solved using the trapezoidal method as implemented in the ode23t function of MATLAB while the Distributed Engineering Workstation software is used to solve the algebraic equations.	Existing	Proprietary. Capable of simulating combined T&D networks due to its ability to model three-phase unbalanced networks. Capable of performing dynamic simulations.
PSS®SINCAL[41]	SIEMENS	T&D combined tool capable of imbalance fault calculations	Existing	It can model and simulate multi-phase radial as well as meshed networks, which are applicable to both T&D networks. Capable of steady-state, dynamic, and EMT simulations. It comes with a comprehensive library of T&D components and controls. Not sure about the scalability of the tool.
DigSILENT PowerFactory[42]	DigSILENT	T&D combined modeling and simulation tool capable of balanced and unbalanced RMS and EMT simulation	Existing	Capable of multi-core simulation in a T&D co-simulation framework. Natively models T and D side and scalable to ~100s of 1000s of buses.
OpenDSS[43]	EPRI	T&D combined tool (although primarily used for unbalanced distribution simulations now)	Existing	Typically used for unbalanced distribution system, this tool does allow for similar above T&D co-simulation capabilities.
EMTP_RV[44]	EMTP Alliance	EMT tool capable of T&D system modeling. Not recommended by software	Existing	Production grade EMT tool. Can simulate both T&D systems with proper

40 https://vtechworks.lib.vt.edu/bitstream/handle/10919/74234/Jain_H_D_2017.pdf
41 https://new.siemens.com/global/en/products/energy/energy-automation-and-smart-grid/pss-software/pss-sincal.html
42 https://www.digsilent.de/en/powerfactory.html
43 https://www.epri.com/pages/sa/opendss#:~:text=OpenDSS%20is%20an%20electric%20power,grid%20integration%20and%20grid%20modernization.
44 https://www.emtp.com/

Table A.1: Beyond Positive Sequence Tools and Capabilities				
Name	**Developer**	**Main Components**	**Status**	**Capabilities**
		vendor for co-simulation due to cycle delay between RMS and EMT		modeling. Can scale based on CPU availability, so more CPUs available decreases computation time to a certain extent.
PSCAD[45]	Manitoba Hydro	EMT tool capable of T&D system modeling. Co-simulation capable if modeled natively and dependent on T system if not native.	Existing	Production grade EMT tool. Can simulate both T&D systems with proper modeling. Has scalability depending on expertise of software.

Table A.2: Grid Spice[26]	
Aspect of Tool	**Notes**
Developer	Stanford University
Usage Grade	Research and Educational
License Type	Open Source
T-system Simulator	MAT Power
D-system Simulator	GridLAB-D
Communication Simulator	Not available
Market Simulator	Mentioned as ongoing work as of 2014
Distribution Management System Simulator	Not available but allows integration with DMS software
Simulator Capabilities	
Unbalanced T System Simulation	Not available
Steady State Simulation	Capable
Dynamic Simulation	Not available
Protection Simulation	Not available
Distributed Computing	Available
EMTP Simulation	Not available
Standalone software	No; cosimulator that requires Gridlab-D and MATPower
Scalability	Reported as highly scalable due to "loose coupling" between simulators and as simulators are CPU bound

[45] https://www.pscad.com/software/pscad/version-comparison

Table A.3: Framework for Network Co-Simulation (FNCS) [27]	
Aspect of Tool	**Notes**
Developer	Pacific Northwest National Laboratory
Usage Grade	Research
License Type	Open Source
T-system Simulator	PowerFlow/MATPOWER
D-system Simulator	GridLAB-D
Communication Simulator	ns-3
Market Simulator	Transactive Energy System Platform (TESP)
Distribution System Management Simulator	GridAPPS-D
Simulator Capabilities	
Unbalanced T System Simulation	Not available
Steady State Simulation	Capable
Dynamic Simulation	Not available
Protection Simulation	Not available
Distributed Computing	Available
EMTP Simulation	Not available
Standalone software	No; cosimulator and supports integration with multiple softwares
Scalability	Scales well for few thousand federates, but not to tens of thousands

Table A.4: Integrated Grid Modeling System (IGMS) 28	
Aspect of Tool	**Notes**
Developer	National Renewable Energy Laboratory
Usage Grade	Research
License Type	Open Source
T-system Simulator	MAT Power
D-system Simulator	GridLAB-D
Communication Simulator	Not available
Market Simulator	FESTIV
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Not available
Steady State Simulation	Capable
Dynamic Simulation	Not available
Protection Simulation	Not available
Distributed Computing	Available
EMTP Simulation	Not available
Standalone software	No; cosimulator with T+D+Market
Scalability	1M+ buses and distributed energy resources

Table A.5: TS3PH29	
Aspect of Tool	**Notes**
Developer	Illinois Institute of Technology
Usage Grade	Research and Education
License Type	Proprietary
T-system Simulator	TS3PH
D-system Simulator	Integration with CYME
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Capable, integration with CAPE
Distributed Computing	Available
EMTP Simulation	Not available
Standalone software	Yes; can be used in cosimulator
Scalability	Scalable up to 10s of 1000s of buses for faster than real-time-simulation

Table A.6: TDcoSim[30]	
Aspect of Tool	**Notes**
Developer	Argonne National Laboratory
Usage Grade	Research and Education
License Type	Open Source
T-system Simulator	PSSE
D-system Simulator	OpenDSS
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Not available
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Not available
Distributed Computing	Available
EMTP Simulation	Not available
Standalone software	No; cosimulator
Scalability	1M+ buses and 10s of 1000s of DERs

Table A.7: Three Phase Dynamic Analyzer (TPDA) 31	
Aspect of Tool	**Notes**
Developer	Virginia Tech
Usage Grade	Research and Education
License Type	Proprietary
T-system Simulator	TPDA
D-system Simulator	OpenDSS
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Not available
Distributed Computing	Not Available
EMTP Simulation	Not available
Standalone software	Yes
Scalability	Yes, due to parallel computing capabilities

Table A.8: PSSE Sincal32	
Aspect of Tool	**Notes**
Developer	Siemens
Usage Grade	Industry
License Type	Commercial
T-system Simulator	Sincal
D-system Simulator	Sincal
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Capable
Distributed Computing	Not sure
EMTP Simulation	Capable
Standalone software	Yes
Scalability	Not available

Table A.8: Digsilent Powerfactory[33]	
Aspect of Tool	**Notes**
Developer	Digsilent
Usage Grade	Industry
License Type	Commercial
T-system Simulator	Digsilent
D-system Simulator	Digsilent
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Capable
Distributed Computing	Capable of multicore simulation
EMT Simulation	Capable
Standalone software	Yes
Scalability	~ 100 k buses

Table A.9: OpenDSS[34]	
Aspect of Tool	**Notes**
Developer	EPRI
Usage Grade	Industry
License Type	Opensource
T-system Simulator	OpenDSS
D-system Simulator	OpenDSS
Communication Simulator	Not available
Market Simulator	Not Available
Distribution System Management Simulator	Not available
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable (electromechanical)
Protection Simulation	Capable
Distributed Computing	Capable of multicore simulation
EMT Simulation	No
Standalone software	Yes
Scalability	~ 100k buses

Table A.9: PSCAD[35]	
Aspect of Tool	**Notes**
Developer	Manitoba Hydro International
Usage Grade	Industry
License Type	Commercial
T-system Simulator	PSCAD/EMTDC natively or using E-Tran, or PSS/E or PSLF using E-Tran Plus co-simulation
D-system Simulator	PSCAD/EMTDC natively or using E-Tran, or PSS/E or PSLF using E-Tran Plus co-simulation
Communication Simulator	N/A
Market Simulator	no
Distribution Management System Simulator	Can support custom models, or allows integration with DMS software using interfacing
Simulator Capabilities	
Unbalanced T System Simulation	Capable if used natively, no if T system is done using co-simulation with rms tools that don't support it.
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Capable
Distributed Computing	Capable
EMT Simulation	Capable
Standalone software	Yes, and can also interface with external rms tools
Scalability	100s of nodes. 1000s of nodes reachable for specialists in the software.

Table A.10: EMTP®[36]	
Aspect of Tool	**Notes**
Developer	PGSTech
Usage Grade	Industry
License Type	Commercial
T-system Simulator	EMTP® (co-simulation is an option but we do not recommend it to our users. We prefer recommending the multi time-step approach which does not introduce a cycle delay between RMS and EMT)
D-system Simulator	EMTP® (same answer as above)
Communication Simulator	Not available
Market Simulator	Not available
Distribution Management System Simulator	Allows integration with DMS software
Simulator Capabilities	
Unbalanced T System Simulation	Capable
Steady State Simulation	Capable
Dynamic Simulation	Capable
Protection Simulation	Capable
Distributed Computing	Capable
EMTP Simulation	Capable

Table A.10: EMTP®[36]	
Aspect of Tool	**Notes**
Standalone software	Yes
Scalability	On a given number of CPUs, simulation time is ~ proportional to number of buses. In the best scenario, the simulation time may be divided by the number of CPU used. I practice, it is not the case because of communication delays and the difficulty to evenly load each CPU

Appendix B: For Further Reading

The NERC SPIDERWG would like to provide the following resources as further reading for knowledge around co-simulation and other capabilities of positive sequence software versus beyond positive sequence.

1. D. Ramasubramanian, I. Alvarez-Fernandez, P. Mitra, A. Gaikwad and J. C. Boemer, "Ability of Positive Sequence Aggregated Distributed Energy Resource Model to Represent Unbalanced Tripping of Distribution Inverters," *2019 IEEE Power & Energy Society General Meeting (PESGM)*, Atlanta, GA, USA, 2019, pp. 1–5
2. K. Anderson, J. Du, A. Narayan and A. E. Gamal, "GridSpice: A Distributed Simulation Platform for the Smart Grid," in *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2354–2363, Nov. 2014, doi: 10.1109/TII.2014.2332115.
3. Selim Ciraci, Jeff Daily, Jason Fuller, Andrew Fisher, Laurentiu Marinovici, and Khushbu Agarwal. 2014. "FNCS: a framework for power system and communication networks co-simulation. In Proceedings of the Symposium on Theory of Modeling & Simulation - DEVS Integrative (DEVS '14)." Society for Computer Simulation International, San Diego, CA, USA, Article 36, 1–8.
4. D. Ramasubramanian, I. Alvarez-Fernandez, P. Mitra, A. Gaikwad and J. C. Boemer, "Ability of Positive Sequence Aggregated Distributed Energy Resource Model to Represent Unbalanced Tripping of Distribution Inverters," *2019 IEEE Power & Energy Society General Meeting (PESGM)*, Atlanta, GA, USA, 2019, pp. 1–5
5. Y. Liu, V. Vittal, J. Undrill, and J. H. Eto, "Transient model of air conditioner compressor single phase induction motor," IEEE Transactions on Power Systems, vol. 28, no. 4, pp. 4528–4536, 2013
6. Applicability of T&D CoSimulation for Accurate Capture of Load and DER Dynamic Behavior, EPRI, Palo Alto, CA: 2020. 3002019452
7. H. Bevrani, M. Watanabe, and Y. Mitani, "Power System Monitoring and Control." Appendix A: New York/New England 16-Machine 68-Bus System Case Study. John Wiley & Sons, 2014, pp. 249–253.
8. P. Etingov and Y. Liu, "Load model data tool." [Online] Available: https://www.pnnl.gov/projects/open-source-high-fidelity-aggregate-composite-load-models-emerging-load-behaviors-large

The NERC SPIDERWG would also like to point out that the following NERC reliability guidelines[46] are applicable to the development of this technical reference document and can be reviewed by any interested party:

- *NERC Reliability Guideline: Developing Load Model Composition Data*, March 2019
- *NERC Reliability Guideline: Parameterization of the DER_A Model*, Sept. 2019
- *NERC Reliability Guideline: Modeling Distributed Energy Resources in Dynamic Load Models*, Dec. 2016

[46] These can be accessed on the RSTC webpage available here: https://www.nerc.com/comm/Pages/Reliability-and-Security-Guidelines.aspx

Contributors

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