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Modeling Approaches and Studies of the Impact of Distributed Energy Resources on the Reliability of Bulk Electric System

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SUMMARY

New modelling approaches and studies are needed to address the challenges from the deepening penetration of distributed energy resources (DER) on distribution networks insofar as they impact the reliability of the bulk electric system (BES) [1]. Operational challenges on the distribution system can manifest in forms of overvoltage, reverse power flows, difficulties in protection co-ordination etc. Adverse impacts on the BES can be as severe as cascading outages resulting from the simultaneous tripping of large amounts of DER and delayed system recovery due to a lack of voltage and frequency support from DER.

To meet these challenges two distribution system modelling approaches to study the impact of DER on the BES reliability are presented in this paper – an aggregated modelling approach [2] and a full modelling approach. The aggregated distribution system model comprises an equivalent/aggregate distribution system model (including an aggregate load model and an equivalent feeder segment) and an aggregate dynamic DER model. The aggregated distribution system model is connected to a transmission system model to enable studying the impact of DER on the BES. In the full distribution system modelling approach, on the other hand, the non-aggregated distribution system and individual DER are modelled. Connecting the full distribution system model to a transmission system model on the same simulation platform offers another approach to study the impact of DER on the BES. The transmission and the full distribution system modelling as a whole is referred to as the T&D combined model. The performance of both distribution system modelling approaches is compared and contrasted in BES stability studies. While the aggregated modelling approach provides a simplistic and quick way to investigate the impact of DER on the BES, the full modelling approach is more appropriate to account for the full-spectrum of DER dynamics, including phase lock loop (PLL) dynamics, DC link dynamics and time dependency of protection elements as well as various legacy components of distribution systems such as line regulators, switched capacitors [3].

Using the T&D combined model, the paper presents case studies which demonstrate various advanced control and ride-through capabilities of DER that can be used to maintain BES reliability. The case studies demonstrate that (a) lack of DER ride-through can potentially have a detrimental impact on the BES and (b) appropriate DER ride-through settings can help maintain BES stability during severe contingencies. The case studies also show that the use of DER dynamic reactive power can not only support local voltages but can also help maintain BES voltages and frequencies upon contingencies. Insights and observations made in these studies will provide mitigation solutions for secure and reliable BES operations.

KEYWORDS

Bulk Electric System, distributed energy resources, dynamic stability, frequency regulation, voltage stability, T&D combined model, reliability impact.

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I. INTRODUCTION

The growth of distributed energy resources (DER), mostly generation using intermittent renewable energy sources, along with the retirement of central generation (mostly conventional power plants using fossil-fuel-based resources) has implications for the steady-state and dynamic performance of the BES. Among the DER connected to the distribution system, photovoltaic (PV) systems are the most prevalent and have been installed at an increasing rate. Until recently, the penetration level of DER had not been not high enough to create a significant impact on the reliability and security of the power system operation. However, in recent years, the penetration level of DER has risen up to a level that their impact on the bulk electric system (BES) should be considered in a detailed fashion in planning and operations.

The PV and wind systems connected to the transmission network have been well studied and represented in bulk electric system stability studies. However, due to the distributed nature of DER, especially PV systems, and the variability of their support capabilities depending on vendors, manufactured years and costs, modelling of distributed PV systems to accurately capture their impact on the BES is still a challenge.

Dynamic simulations have been an important tool that system operators utilize to assess the stability margin of power systems for various disturbances and contingencies without the need for field testing. Models of synchronous machines have been tried and tested for decades in dynamic studies, but not many models are available for DER especially power-electronic-converter-based DER. Currently, many studies that analyze the impact of DER on the BES, model DER either as a negative load or an aggregate dynamic model that doesn't sufficiently incorporate many features and components of DER [3]. In particular, model aggregation [4] and the use of reduced-order-equivalent models [5] are two common techniques in arriving at an aggregate dynamic DER model.

The negative load representation for DER may be sufficient to study the impact of DER when their penetration level is low [2]. However, for larger penetration of DER, or when DER's effects on the BES is more pronounced, this DER modeling approach falls short. The aggregate dynamic DER model in conjunction with an aggregate load model and an equivalent feeder segment, collectively referred to as the aggregated distribution system model, are connected to the transmission system model to enable the studies of the impact of DER on the BES. The aggregated modeling approach for the distribution system has the advantage of computational efficiency. However, there are various issues associated with the aggregated modeling approach, which if not appropriately addressed can yield misleading results for the planning of the BES. Specific shortcomings of the aggregated modeling approach include:

- Inadequate representation of distribution networks and single-phase DER present in the network.
- Lack of time dependency of the protection elements of DER.
- Insufficient representation of the variations in the response of DER due to the differences in their local voltage. The differences in DER local voltages are related to their various localities in the distribution system caused by the operation of line regulators, switched capacitors, and loading of the distribution system.
- Crude assumptions on the DC circuit and Phase Locked Loop (PLL) that might be crucial for maintaining overall stability of DER themselves.

Moreover, the aggregate DER models have various parameters that need to be tuned accurately to estimate the mix of 'legacy' and 'modern' DER in a distribution system [6], which comply with different DER interconnection standards. Tuning the aggregate DER parameters to represent the overall response of all the DER with mixed vintage can be challenging as DER may disconnect in different amount depending on the severity of voltage sags and individual tripping/ride-through threshold.

Given the abovementioned shortcomings of the aggregated modeling approach, the full modeling approach for a distribution system that includes a non-aggregated distribution system model and individual DER models is needed to evaluate the dynamic stability of the BES. In this paper, a full distribution system model is developed and is connected to a transmission system model. The whole transmission system model and the full distribution system model, referred to as the T&D combined model, is used to investigate the impact of DER on the BES. Recent studies [7] suggest that the functions of DER smart inverters could impact power system steady-state and dynamic responses, thus proper modeling of DER smart inverters is crucial. The DER modeled in the full modeling approach is an average dynamic model of DER with consideration of DC link dynamics but excluding the switching dynamics of DER. The description of the test system (both transmission and distribution systems) and the developed full and aggregated models for the test distribution system are detailed in Section II.

When investigating DER's impact on the BES, one should consider that modern-day DER are capable of providing both active and reactive power to the system, through the use of advanced inverter controls [3]. As a matter of fact, recent DER interconnection standards such as IEEE Std 1547-2018 now require DER be able to provide frequency and voltage support to the power system. These ancillary services can now be utilized to support the overall system reliability subject to the approval of the area electric power system (EPS) operator. The advanced DER control capabilities and ride-through requirements are detailed in Section III.

In Section IV, the key differences between the full modeling approach and the aggregated modeling approach for distribution systems are demonstrated and analyzed. The objective of the comparison between these two distribution system modeling approaches is to observe how the aggregated modeling approach differs from the full modeling approach and provide guidance on developing more accurate aggregated models for BES planning and operational studies. In Section V, the paper presents case studies for various DER penetration levels using the T&D combined model. These case studies demonstrate various advanced control and ride-through capabilities of DER that can be used to maintain BES reliability. And finally Section VI offers concluding remarks.

II. DESCRIPTION OF TEST SYSTEM AND MODELLING APPROACHES

The BES featured in this work is the IEEE 118-bus system [8] and the distribution feeder used is a modified version of the IEEE 123-node test feeder [9]. Different penetration levels of DER on the distribution feeder are created to properly identify the impact of DER on the BES. As DER replace synchronous machines, the reactive power reserve in a BES decreases, which might lead to a lower reactive power margin and a lower system voltage. There are two approaches currently used to consider the loss of the system inertia due to DER displacing synchronous machines. One approach simply reduces the inertia of all the machines proportionally and the other approach disconnects certain generators from the system as the DER penetration reaches a certain threshold. Both approaches are able to emulate the decommissioning of conventional synchronous generators. The first approach is adopted in this work.

Both the full model and the aggregated model for the test distribution system are developed in this work. The full modeling and aggregated modeling approaches are explained in detail herein.

A. The full modeling approach

In the full modeling approach, the non-aggregated distribution system and individual DER are modeled to reflect their dynamic and steady-state behaviors for BES planning and operational studies. The full distribution system model is then connected to a transmission system model. The transmission system model and the full distribution system model as a whole, or the T&D combined model, is shown in Figure 1. The T&D systems are modeled and simulated in DIgSILENT PowerFactory [10] software. In the T&D combined model, select load buses in the BES are replaced with distribution feeders. In this work, it is assumed that all the distribution feeders connected to the same transmission load bus are identical. For a transmission load bus replaced with multiple identical distribution feeders, only one distribution feeder is simulated in reality. This simulated feeder is scaled up n times during the simulation to match the original transmission load bus total load. Here n is the number of identical feeders connected to the same transmission load bus. The active and reactive power mismatches at the transmission load bus between the scaled-up feeders and the original balanced load are compensated by the addition of shunt loads. These shunt loads ensure that the transmission system sees a balanced load at its load buses. This is a practical treatment to alleviate the computational burden and reduce the run time of the simulation studies. The average dynamic model is implemented for the DER in the distribution feeder.

B. The aggregated modeling approach

The aggregated distribution system model for the IEEE 123-node test feeder shown in Figure 1 is developed in this work. The schematic diagram of both steady-state and dynamic aggregated distribution system models are shown in Figure 2. These models consist of an equivalent feeder segment, an aggregate load model, and an aggregate DER model. Both steady-state and dynamic aggregate DER models are illustrated in Figure 2. In this paper, following WECC's recommendation for the aggregated representation of a distribution system, a static load equal to the power drawn by the representative distribution system is used. The dynamic motor loads are not considered in the aggregate load model. The losses in the system are modeled using an equivalent feeder impedance. The aggregate load model and the equivalent feeder segment are the same for both steady-state and dynamic aggregated distribution models. A static aggregate DER model is used in the steady-state aggregated distribution system model. And, the DER_A model developed by WECC's renewable energy modelling task force (REMTF) [11] is utilized for the dynamic aggregate DER model in the dynamic aggregated distribution system model.

III. ADVANCED DER CONTROL CAPABILITIES AND RIDE-THROUGH REQUIREMENTS

With the increasing DER penetration on the distribution system, it is now advisable to study the impact of advanced DER control capabilities on the overall system reliability. DER now have the ability to support both system voltage and frequency during normal as well as abnormal conditions. The latest IEEE 1547 standard (IEEE Std 1547-2018) [12] leaves the use of dynamic voltage support capability from DER to a mutual agreement between the system operator and DER owners. With that if the benefits of dynamic voltage support from DER to the overall system reliability can be demonstrated through studies, the adoption of dynamic voltage support from DER by system operators can materialize and even increase [12]. Regarding the frequency support, depending on the abnormal conditions, DER are now expected to have the capability of mandatory operation with a frequency-power droop control. With regard to the system inertial response, the latest IEEE standard permits an inertial response from DER but doesn't specifically require it. If a DER were to provide inertial support based on the rate of change of frequency, the DER operator must do so with a mutual agreement with the system operator and should coordinate with the regional reliability coordinator. Regarding the ride-through requirements, IEEE Std 1547-2018 categorizes DER into different categories for abnormal system conditions depending on the BES reliability needs and to avoid any adverse impact on the system reliability [12]. The standard also provides leeway on these ride-through settings in that the range of voltage and time settings is intentionally wide and a particular setting for a system is subjected to the EPS operator's judgement. In such a scenario, studies should be performed to identify the impact of different ride-through settings on the area EPS and identify the most suitable set of interconnection rules that enhances the overall system reliability. In lieu of the different categories specified for DER ride-through settings, two sets of interconnection rules are tested in this work to understand the impact of DER ride-through settings on the BES reliability. The trip setting studied in this work closely resembles the category I settings and the ride-through setting studied in this work resembles the category III settings (with the exclusion of momentary cessation) specified in IEEE Std 1547-2018. Please note that the trip setting here allows DER to trip from the distribution system they are connected to even on relatively small voltage deviations e.g. 0.30 p.u. below the nominal value, which is more beneficial for distribution system protection co-ordination and the safety of utility maintenance personnel. And the ride-through setting studied in this work is set up considering the BES reliability which requires DER to remain connected even for large voltage sags up to 0.50 p.u. below the nominal value.

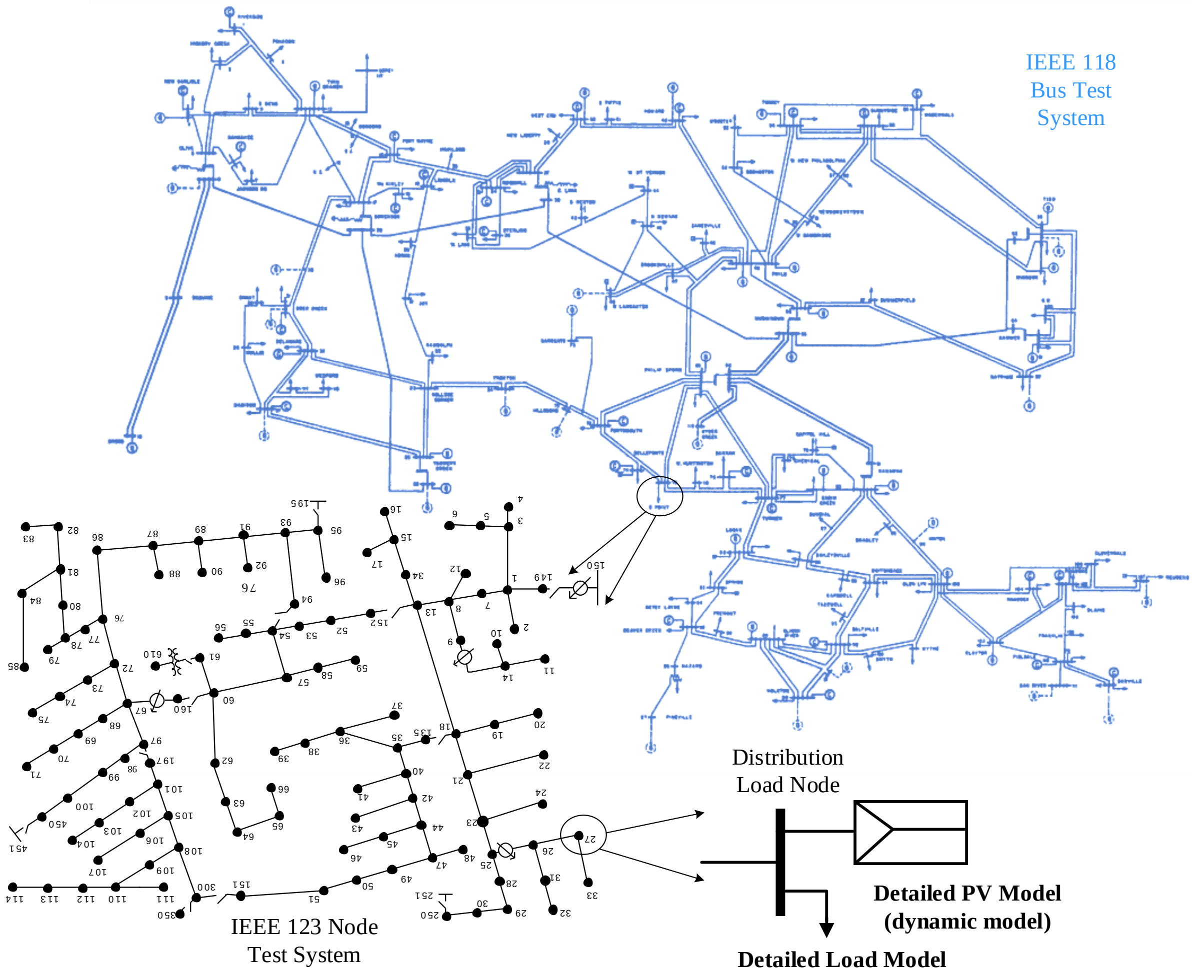

Figure 1: Schematic diagram of a transmission system (IEEE 118-bus system) with partial load replaced by distribution feeders (IEEE 123-node test feeder) integrated with DER.

IV. Validation of Aggregated Modeling Approach and Performance Comparison of Two Modeling Approaches in BES Impact Studies

In this section, the aggregated modeling approach is validated first and then the performance comparison of the two distribution system modeling approaches are compared through two case studies. Transmission system loads connected to transmission buses 80, 78, 77, 82 and 95 are replaced with distribution system models. For the full modelling approach, the transmission system load connected to these buses are replaced with IEEE 123-node distribution feeders per the method described in Section II-A. The number of feeders placed at bus 80, 78, 77, 82 and 95 is 32, 15, 13, 10 and 8, respectively. Within the IEEE 123-node feeder, DER are placed at six different locations based on the voltage diversity within the distribution system impacted by the combination of loads and the use of voltage regulators and load tap changers (LTCs). Among the six DER, three 3-phase DER each rated 120 kW are modelled at nodes 13, 35 and 67 of the IEEE 123-node feeder and three single-phase DER are placed at phase A of node 114, phase B of node 107 and phase C of node 74 each with a rated power output of 90 kW, 60 kW and 66 Kw, respectively. It should be noted that only PV systems are implemented for the DER model and therefore they are referenced interchangeably throughout the paper. The penetration level of DER within each of the distribution system is close to 15% of the distribution system load in the cases studied and close to 1% when compared to the overall IEEE 118-bus system load.

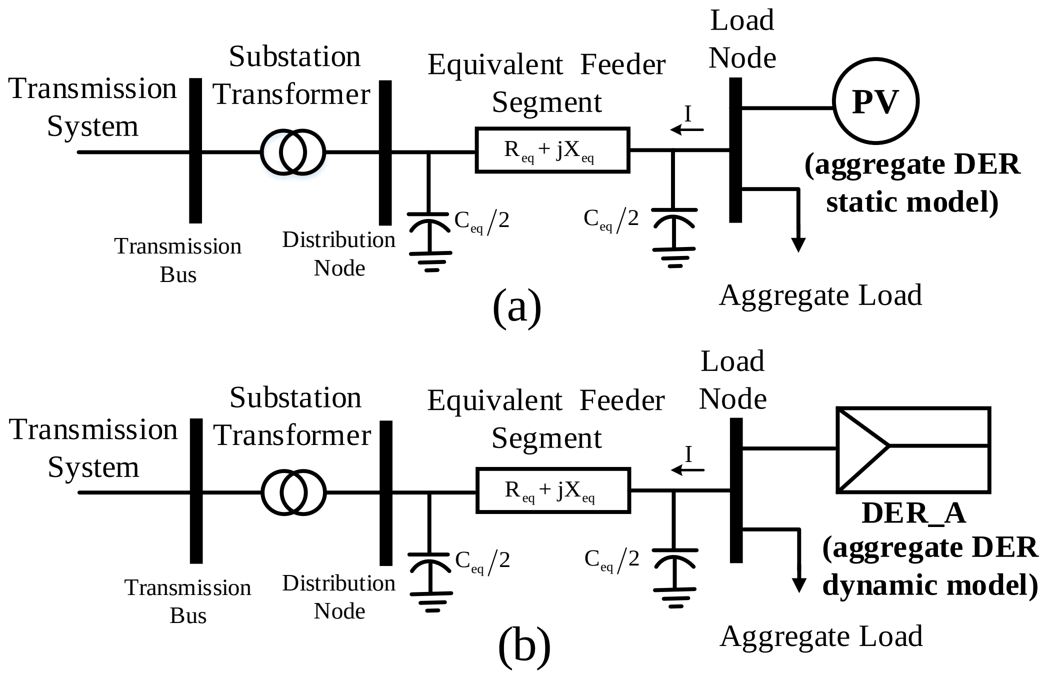

Figure 2: Aggregated steady-state (a) and dynamic (b) model of the distribution system integrated with distributed PV systems.

A. Validation of aggregated modeling approach through a loss of generation case study

A loss of generation case is created to validate the aggregated modeling approach adopted in this work. Figure 3 compares the frequency response of a close by generator (connected at bus 104) for the loss of the generator at bus 100 at time t = 2 secs. The total simulation time is 100 secs. It can be observed that both modelling approaches exhibit comparable frequency responses both prior to and after the disturbance. Only minor differences are observed after the transients die out as can be observed in the zoomed-in portion of the frequency plot in Figure 3. Figure 4 compares the voltage response at bus 102 for the two modelling approaches prior to and after the disturbance. It can be observed that the two modeling approaches show the exactly same bus voltage magnitudes before the disturbance and only minor differences after the disturbance. The mismatch observed can be attributed to the changes in the system operating conditions (like variation in distribution node voltages, power flow within the transmission as well as distribution system) once the generator is tripped offline. Once that happens, the aggregated model differs slightly from the full model as the power flow within the distribution system changes as well. Note that the frequency and voltage deviations in the system caused by the disturbance are not sufficient to trip any DER offline. The results in this study validate the aggregation approach utilized to arrive at the parameters of the aggregated models.

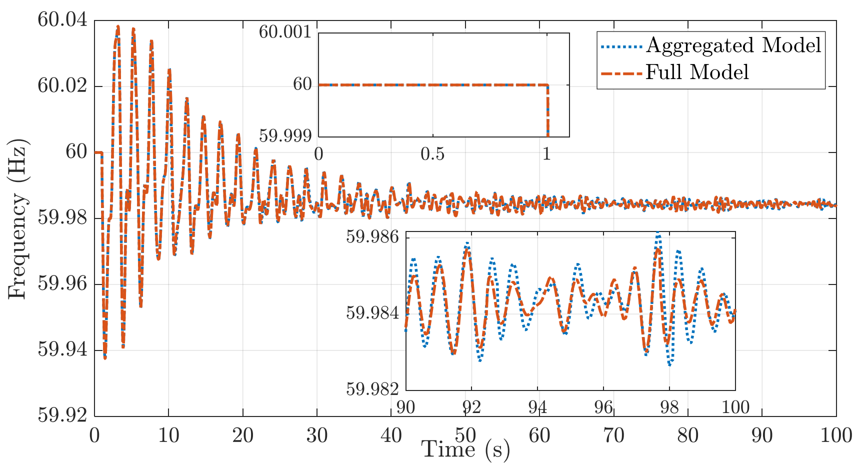

Figure 3: Frequency comparison of generator at bus 104 prior to and after loss of generator at bus 100.

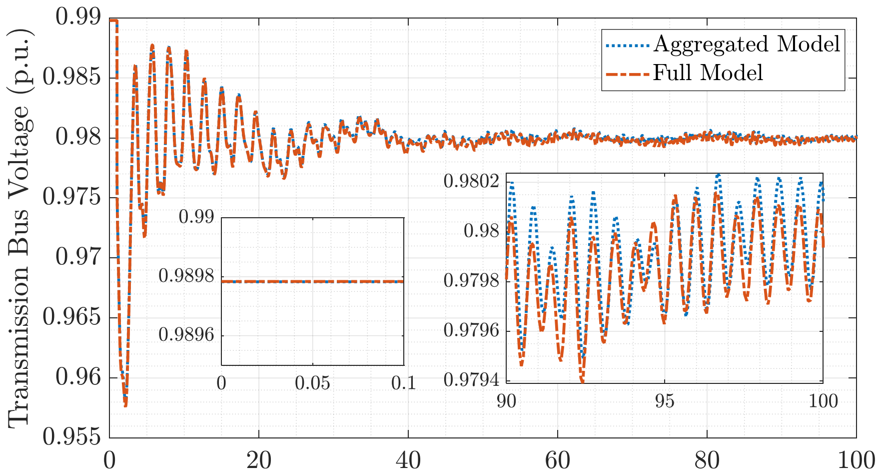

Figure 4: Voltage magnitude comparison at bus 102 prior to and after loss of generator at bus 100.

B. Performance comparison of two modeling approaches through a less-severe three-phase fault case study

In this subsection, a comparison of the two modelling approaches following a system fault is performed. The total simulation duration is 50 secs and a temporary three phase bolted fault for six cycles (100 ms) is applied at transmission system bus 5. Figure 5 compares the voltage response of the two modeling approaches at the faulted bus. It can be observed that the voltage response obtained at the faulted bus shows comparable responses for the two modeling approaches. In this case, the fault is not severe enough to cause DER to trip as the faulted bus is electrically distant from the DER connected buses. This result further validates the aggregation approach utilized for the aggregated models.

On the other hand, some differences are observed between the two modelling approaches for the system frequency response. Specifically, Figure 6 compares the frequency response of the generator which coincide with the faulted bus for the two distribution system modeling approaches. It can be observed that during the transient period, the frequency response generated from the full model is more severe as compared to the aggregated model, which can be attributed to that the responses of individual DER can be different from the aggregated response represented by a single instance of DER_A.

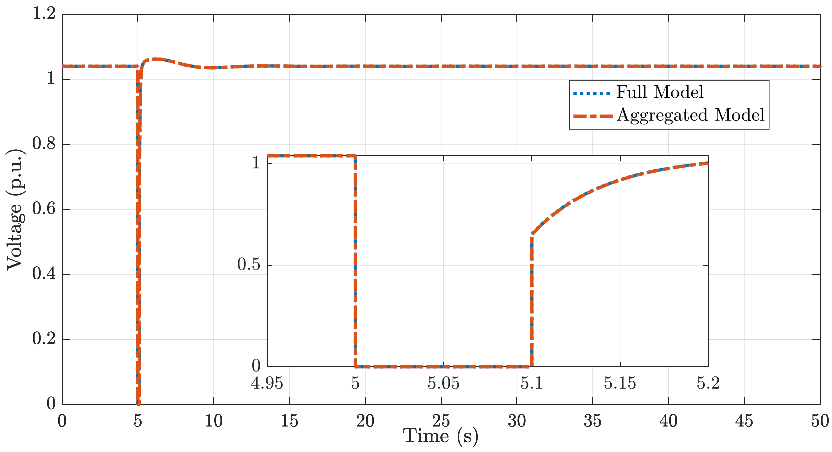

Figure 5: Comparison of the faulted bus voltage for the two modelling approaches considered.

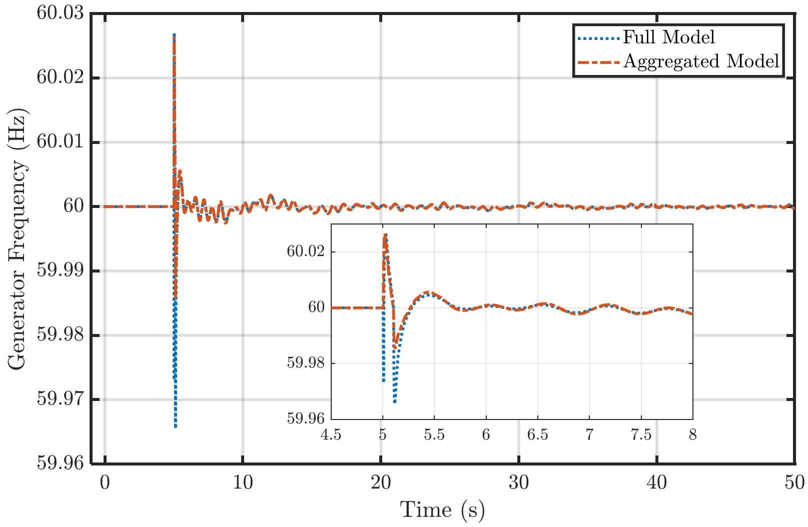

Figure 6: Comparison of generator frequency (coincident with the faulted bus) for the two modeling approaches.

C. Performance comparison of two modeling approaches through a severe three-phase fault case study

In this subsection, a 3-phase self-clearing fault is applied to transmission bus 80, which is close to the DER connected buses. The total simulation duration is 25 sec. The fault is applied at 2 secs and the fault duration is 6 cycles. Figure 7 shows the active power output of the aggregated DER models connected to the transmission buses 80, 78, 77, 82 and 95, respectively. The aggregated DER models are programmed to trip for a voltage below 0.70 p.u. lasting more than 3 cycles. This trip setting resembles the requirement specified for category I DER in IEEE Std 1547-2018 where mandatory operation is specified up to a low voltage threshold of 0.70 p.u. It can be observed from Figure 7 that following the fault at bus 80, all the aggregate DER at these five buses reduce their power output to zero signaling that all the DER trip for this scenario.

Figure 8 depicts the active power output of all six individual DER in the distribution system connected to transmission bus 77 using the full modeling approach. The individual DER active power output shown in Figure 8 does not completely agree with the aggregated DER active power output at transmission bus 77 shown in Figure 7. It is observed that the fault in this case trip five of the individual DER in the distribution feeder. One of the DER is able to ride through the fault as the voltage at its terminals is not low enough to trigger the trip response. The individual DER in the full distribution system model use similar trip settings as the aggregated DER model. In this particular test study, it is observed that the individual DER responses agree with the aggregate DER responses connected at transmission buses 80 and 78 - all of the DER are tripped offline due to the fault. However, only two individual DER are tripped offline in the full distribution system connected at transmission bus 82 and 95 showing quite different results when compared to the aggregated approach.

The consequence of the DER active power output discrepancy between the two modelling approaches is reflected in the nearby generator frequency response plot in Figure 9. Figure 9 shows that the frequency deviation with the aggregated modelling approach is higher comparing to the full modelling approach.

Given the differences observed in the results observed in Figure 6, Figure 7, Figure 8 and Figure 9, it is recommended to use the full modeling approach for impact studies to reach more accurate results. In the next section, the T&D combined model which models the full distribution system is utilized to study the impact of DER on the BES.

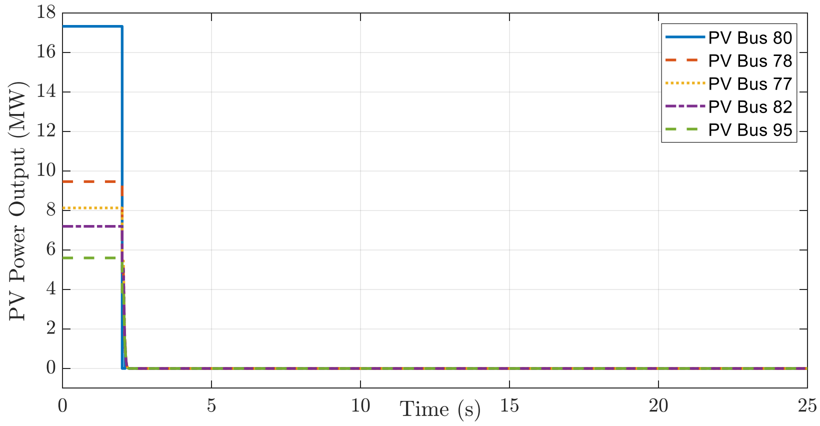

Figure 7: Active power output from aggregate PV models at various transmission buses.

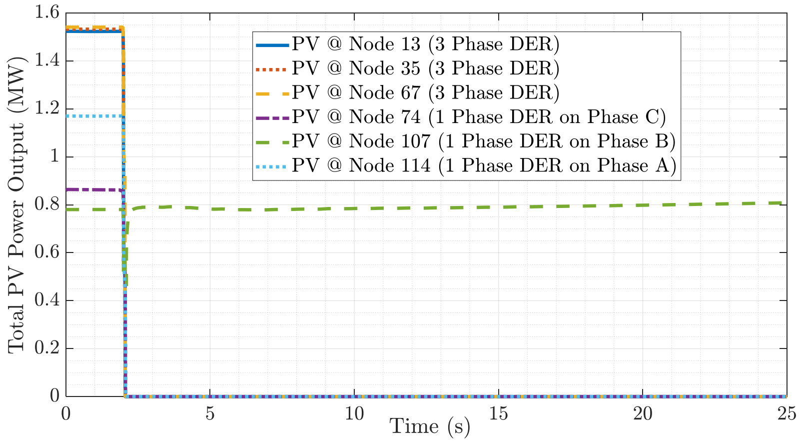

Figure 8: Active power output from all six individual PVs in the distribution system connected at transmission bus 77.

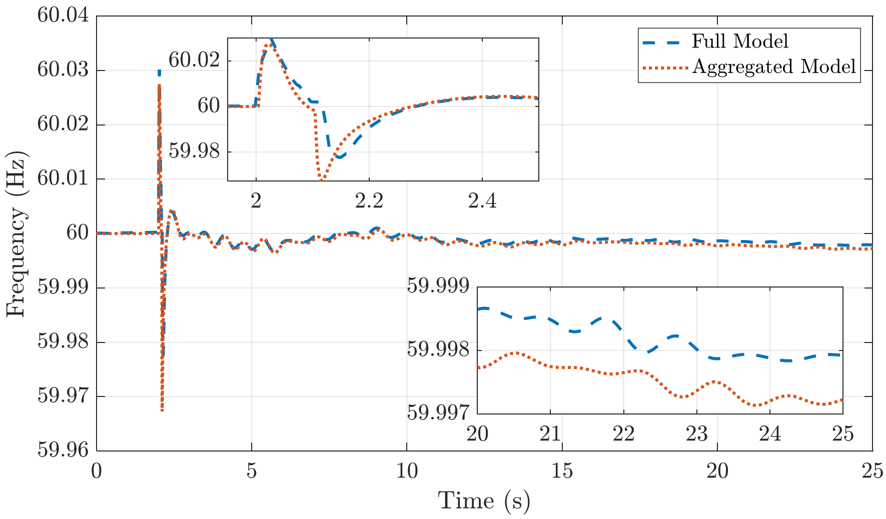

Figure 9: Frequency plot for synchronous generator at transmission bus 80 for the full and aggregated modeling approaches.

V. Impact of DER Trip/Ride-through Settings and Dynamic Voltage Support on BES Reliabilities Using T&D Combined Model

In this section, using the T&D combined model, two levels of DER penetration (2% and 11%) with regard to the BES total load are created to facilitate studies. Specifically, the impact of DER trip and ride-through settings as well as DER dynamic local voltage support on the system frequency and voltages is investigated. The impact studies for the 2% DER penetration level are detailed in subsection A and B. And the impact studies for the 11% DER penetration level are detailed in subsection C.

A. *Impact of DER Trip and Ride-through Settings on BES Reliability*

In this subsection, the impact of DER trip and ride-through settings on BES reliability is studied. Similar to section IV, transmission system loads connected to transmission buses 80, 78, 77, 82 and 95 are replaced with distribution system models. The difference is that a 15% DER penetration scenario is created on the distribution feeder level which amounts to around 2% DER penetration for the BES level. For the trip case, the DER is programmed to trip for a voltage below 0.7 p.u. lasting more than 3 cycles and for the ride-through case the DER trip setting is lowered to 0.45 p.u. lasting more than 3 cycles. The disturbance applied in the BES in this case is a zero impedance three-phase short circuit at bus 80 at 2 secs lasting for 100 ms. The fault normally clears at the end of the 100 ms duration.

Figure 10 captures the frequency comparison of the system generators with DER trip and ride-through settings. Figure 11 shows the frequency comparison of the generator at transmission bus 80 with DER trip and ride-through settings. As can be observed in Figure 10 and Figure 11, the DER trip setting has an adverse impact on the system frequency. When the DER ride-through setting is applied, the system frequency can be restored sooner following the system disturbance and the frequency nadir as well frequency deviation are reduced.

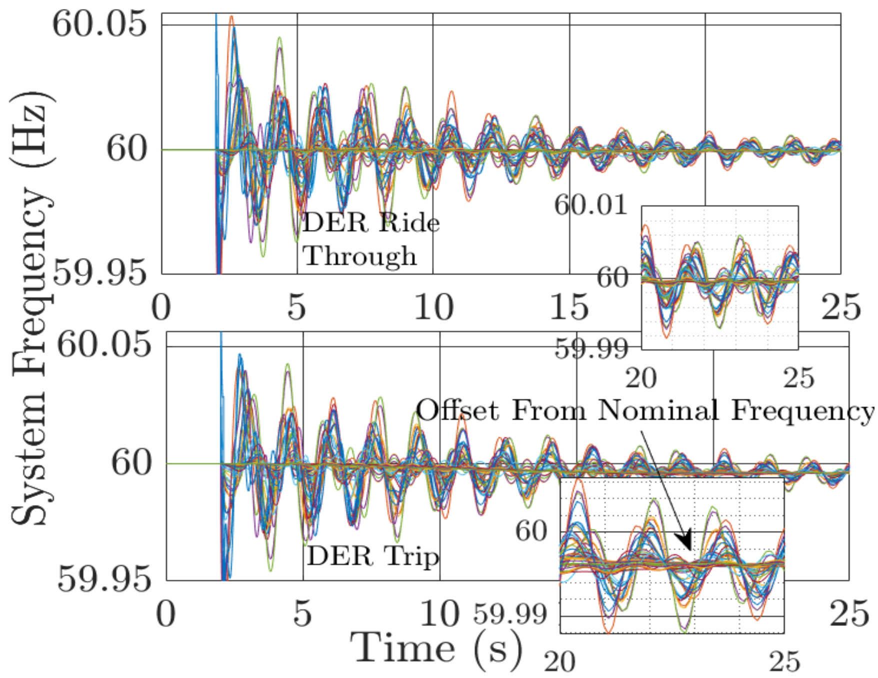

Figure 10: Frequency comparison of the system generators with DER trip setting and ride-through setting. (Note the higher frequency deviation for the trip case)

The impact of DER trip and ride-through settings on the system voltage is observed in Figure 12. Figure 12 shows that when the DER trip setting is implemented, the system voltage following a disturbance is farther away from the nominal value than the case when DER ride through the fault. The results show DER trip and ride-through settings can have different impact on the system reliability.

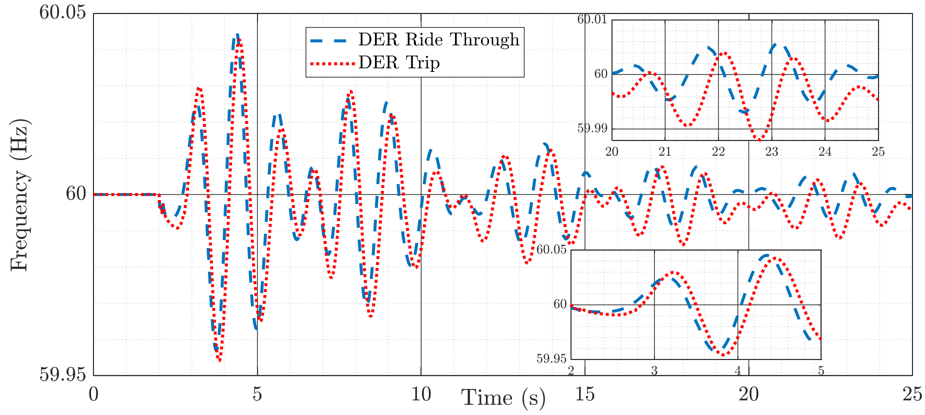

Figure 11: Frequency comparison of the generator at transmission bus 80 with DER trip and ride-through settings. (Note the higher frequency deviation for the trip case)

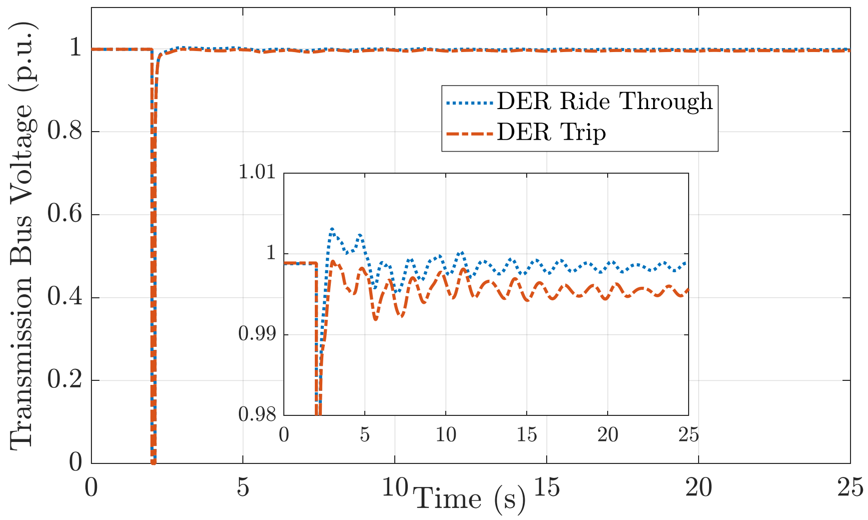

Figure 12: Voltage comparison for faulted transmission bus 80 with DER trip and ride-through settings.

B. Impact of DER Dynamic Local Voltage Support on BES Reliability

In this subsection, the impact of DER dynamic local voltage support on the BES voltages and frequencies is investigated. Similar to the prior subsection transmission system loads connected to transmission buses 80, 78, 77, 82 and 95 are replaced with distribution system models. A 15% DER penetration scenario is created on the distribution feeder level which amounts to around 2% DER penetration for the BES level. Also, the same fault applied in the case study in Section V.A is applied here and the same category I DER trip setting is applied here as well. The difference in the DER setting in this case study is that the DER now have the dynamic local voltage support enabled.

Figure 13 shows the impact of local voltage support from DER on the overall system voltage recovery. It is observed that when DER provide dynamic local voltage support lesser amount of DER is tripped , which is eventually reflected in better system voltage recovery shown in Figure 13. Figure 14 shows the active power output from all six individual PVs in the distribution system connected at transmission bus 77. It can be observed that with the local voltage support from PV inverters by injecting reactive power less number of PV systems trip as compared to case without local voltage support as shown in Figure 8. Note that exactly same trip setting are used for DER in Figure 8 and in Figure 14, the only difference is in Figure 14 DER local voltage support is enabled and in Figure 8 DER local voltage support is disabled. Figure 15 shows the reactive power injected from PV inverters for local voltage support. It can be observed that as soon as the voltages sag due to the system fault, PV inverters start injecting the reactive power output to support their respective local voltage. This in turn contribute to a better recovery of system voltage as evinced in Figure 13.

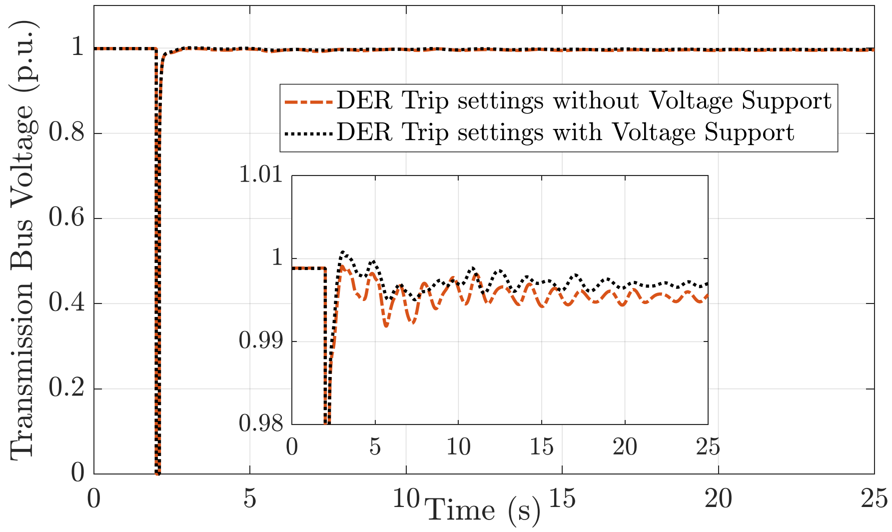

Figure 13: Transmission bus voltage comparison for faulted bus with and without local voltage support from DER.

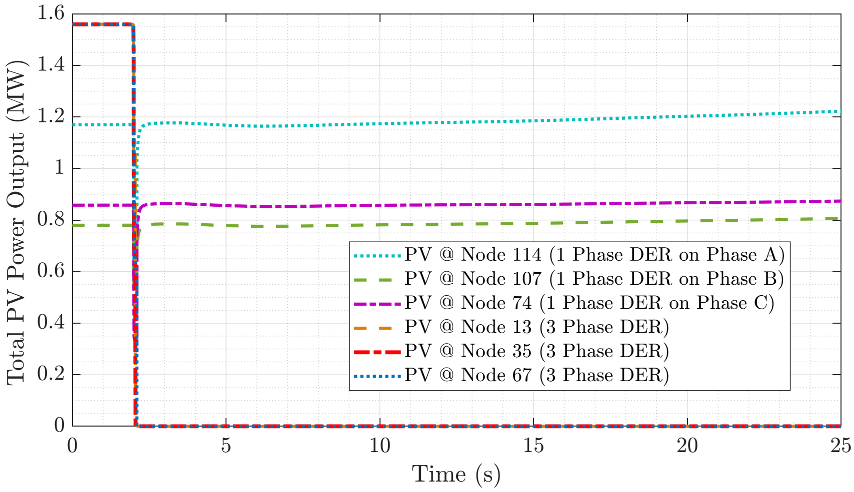

Figure 14: Active power output from all six individual PVs in distribution system at transmission bus 77 with local voltage support from DER. (Note: less number of DER trip in this case compared to Figure 8).

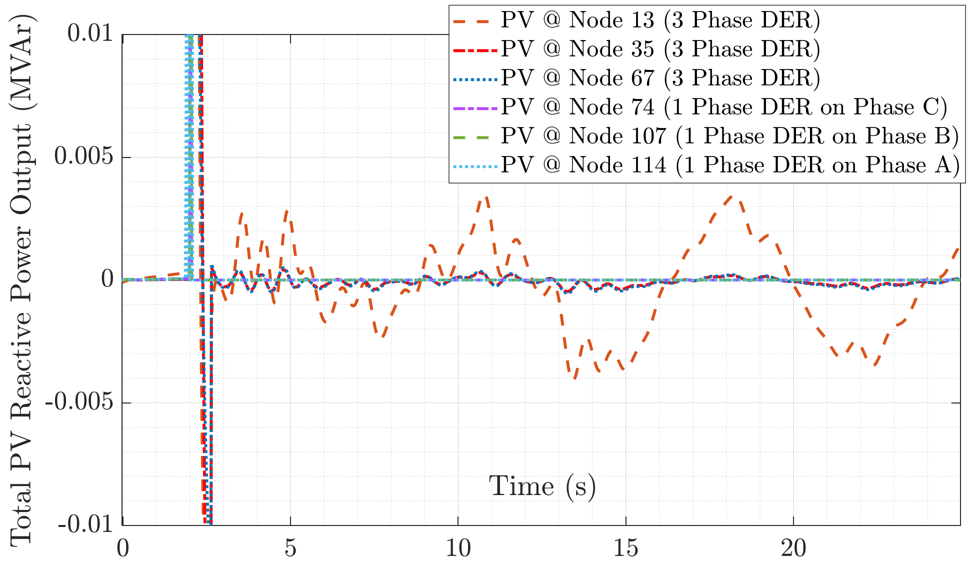

Figure 15: Reactive power output from all six individual PVs in distribution system at transmission bus 77.

C. *Impact Studies at Higher DER Penetration Levels*

In this subsection, the impact of DER trip and ride-through settings as well as the impact of local voltage support from DER at a higher DER penetration level is studied. To facilitate higher DER penetration, a total of 25 transmission system buses are replaced with full distribution system models. The DER penetration level within each feeder is 30%. In total the DER penetration level for the BES is around 11%. The total simulation time is 25 sec in the two case studies conducted in this subsection. A 3-phase bolted fault is applied at transmission bus 80 at 2 seconds for this case study. The fault duration is 6 cycles.

i. Impact of DER trip and ride-through settings on BES reliability

In this case study, for the trip case, the DER is programmed to trip for a voltage below 0.7 p.u. lasting more than 3 cycles and for the ride-through case the DER trip setting is lowered to 0.45 p.u. lasting more than 3 cycles. Figure 16 shows the frequency comparison of the generator at transmission bus 80 with DER trip and ride-through settings. It can be observed from Figure 16 that when the DER ride-through setting is applied, the system frequency can be restored sooner following the system disturbance and the frequency nadir as well frequency deviation are reduced. The impact of DER trip and ride-through settings on the system voltage is observed in Figure 17. When the DER ride through setting is implemented fewer number of DER trip which means the local demand on the distribution system can be met locally and BES generators do not need to meet the distribution system demand, thus leading to better system voltage recovery. Also to be noted here is the lower voltage sag for the DER trip setting case. The initial sag for both cases are the same until 3 cycles after the fault inception. Once the DER trip at that time for the DER trip setting case, the voltage sag deepens.

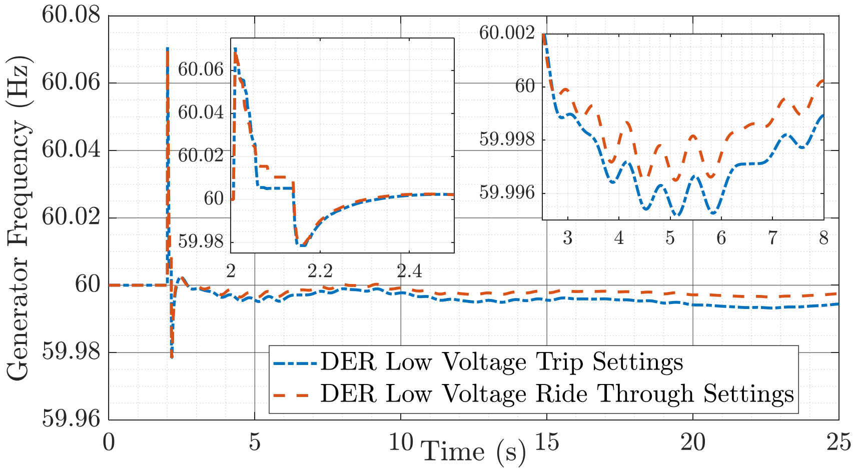

Figure 16: Frequency comparison of the generator at transmission bus 80 with DER trip and ride-through settings. (Note the higher frequency deviation for the trip case)

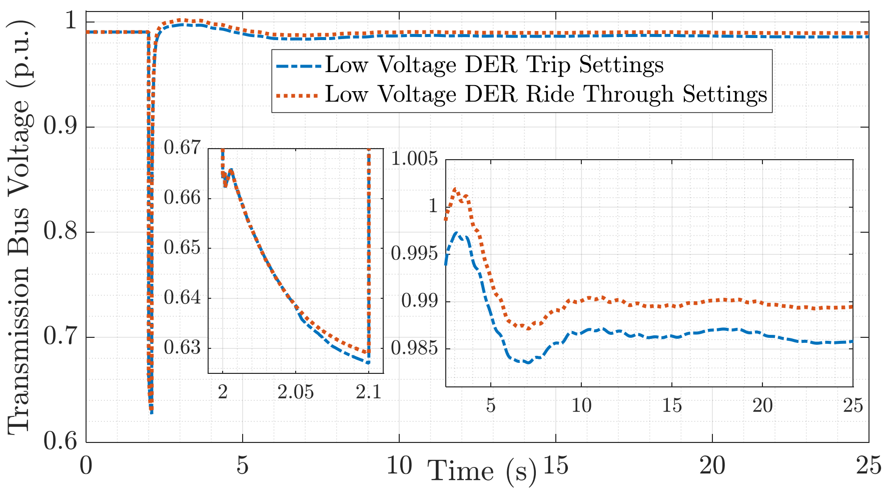

Figure 17: Voltage comparison for transmission bus 82 with DER ride-through and trip settings.

ii. Impact of DER dynamic local voltage support on BES reliability

In this case study, the DER are programmed to trip for a voltage below 0.70 p.u., if the voltage lasted for more than 3 cycles. Two scenarios - with and without local voltage support from DER - are compared to each other. Figure 18 shows the voltage magnitude profile for a bus close to the fault location. It can be observed that with the local voltage support from DER, the voltage sag at this bus during the fault is less severe than the scenario without DER dynamic voltage support. Figure 19 illustrates the frequency response at the generator at transmission bus 80 throughout the event with and without DER dynamic local voltage support. The DER generation loss with and without local voltage support from DER is reported in Table 1. The result demonstrates the impact of local voltage support from DER on BES frequency. When the DER dynamic voltage support is enabled, lesser amount of DER trips which results in smaller frequency oscillations upon the fault occurrence and faster system frequency recovery.

Table 1: Comparison of Amount of Tripped DER with and without Local Voltage Support from DER

Amount of Tripped DER without Voltage Support	Amount of Tripped DER with Voltage Support
180.19 MW	61.85 MW

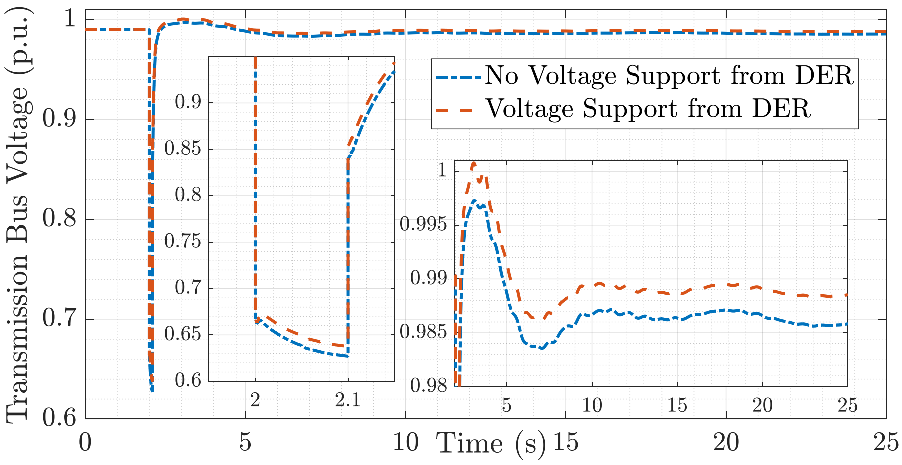

Figure 18: Voltage comparison for a transmission bus near fault location with and without DER dynamic local voltage support.

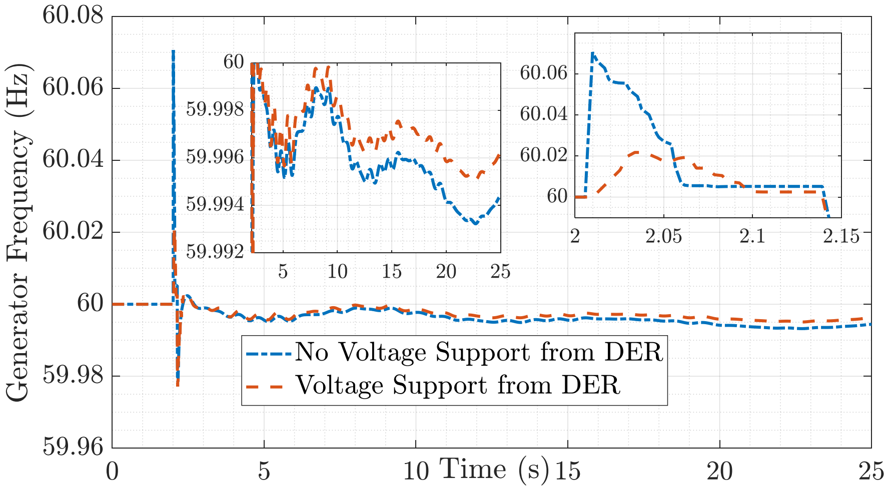

Figure 19: Frequency comparison of the generator at transmission bus 80 with and without DER dynamic local voltage support.

VI. CONCLUSIONS

This paper discusses the various approaches that have been utilized to study the reliability impact of DER on the BES. With the penetration of DER on the rise, it is critical to have a high-fidelity model that can be used by power system operators to understand the possible impact of DER on the BES with a high degree of confidence. Both the aggregated and full distribution system modeling approaches are implemented in this paper. The aggregation approach adopted for the aggregated models is validated through a case study. The performance of both modeling approaches are compared through two case studies. Even though the aggregated modeling approach provides benefits in terms of faster simulation run time and reduced complexity of the system, the results obtained from these models can be considerably different depending on the parameters used for these models and the nature of disturbances in the system. It should be noted that the aggregated model presented in this work is developed for one particular operating point of the system. Both load and feeder parameters of the aggregated model should be adjusted when the circuit topology and loading of the distribution system change.

Given the shortcomings of the aggregated modeling approach, the full distribution system model that includes the non-aggregated distribution system model and individual DER models is more appropriate for studying the impact of DER on the BES stability and reliability. In this work, a T&D combined model is developed in DIgSILENT PowerFactory software. The T&D combined model features the full distribution system models of the IEEE 123-node feeder and the transmission system model of the IEEE 118-bus system.

Various levels of DER penetration (2% and 11%) with regard to the BES total load are created to facilitate studies. Specifically, the impact of DER trip and ride-through settings as well as DER dynamic local voltage support on the system frequency and voltages is investigated. It is observed that DER ride through settings play a critical role in overall system stability and reliability following system disturbances. With the ride-through setting both the system voltage and frequency recover within the allowed system bounds thus maintaining system reliability. For the trip setting, however, even though the BES is able to maintain stability and continue reliable operation for the studied cases, it should be noted that the system deviates from its pre-fault operating point and encounters more difficulties in frequency and voltage recovery. More control actions and effort should be applied along with the use of system reserves to restore the system to pre-fault operating condition when the DER trip during system conditions. The impact of DER dynamic voltage support on the overall system voltage and frequency recovery is also demonstrated in this work. It is observed that with the local voltage support, DER can ride through the fault which eventually results in better system voltage and frequency recovery as opposed to when DER do not support local voltages.

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