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Impact of Distributed Energy Resources (DER) Voltage Regulation and Ride-Through Settings on Distribution Feeder Voltage Recovery

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SUMMARY

EPRI has done significant research in the modeling of load and renewable generation for past several years. One of the research topics that EPRI has been working on, is understanding the impact of both retail scale (R-DERs) and utility scale (U-DERs) distributed energy resources on the transmission and sub-transmission system. This is particularly significant in part due to the increasing penetration of residential level PV systems, and due to the advanced control capabilities available in the new "smart" inverters. To this end, the paper investigates the impact of smart control functions of residential level PV inverters on the fault induced delayed recovery phenomenon observed in feeders with large penetration of residential HVACs. The report summarizes the findings of the study and indicates the future research in this area.

KEYWORDS

Dynamic voltage support (DVS), Load Model, FIDVR, Low voltage ride through (LVRT), Single phase air-conditioners, Residential PV systems.

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1. INTRODUCTION

Advancements in the photovoltaic (PV) technology and a strong focus on sustainable clean energy, has spurred a significant growth in PV based generation. There has been a substantial increase in both utility scale as well as residential scale PV generators in the past few decades [1], [2]. Due to the large-scale deployment of these resources, many grid codes now require PV systems to ride through abnormal voltage and frequency conditions [3], [4], [5]. Some of these PV systems are required to participate in steady-state voltage regulation as well. Simulation studies have shown that large scale PV deployment without ride-through capability can cause serious voltage issues in the system [6], [7]. Till recently, most of the studies surrounding PV based generation was focused on analyzing the larger utility scale PV units [8], [9], and the residential PVs were modeled merely as static negative loads [10]. However, the proliferation of residential scale PVs and the advancements in their control techniques warrant analyzing their effects on the residential distribution circuits and in turn, on the larger transmission system in more details. To this end, the WECC composite load model is evolving to include some level of detailed representation of residential PV models with certain advanced control options [11].

The fault induced delayed voltage recovery or FIDVR is a phenomenon which is of significant interest in the assessment of transmission and distribution systems [12]. FIDVR is caused by stalling of single phase residential air conditioners (HVAC) due to a fault. FIDVR severely impairs the operation of distribution and transmission systems, and has been investigated at length. With large penetration of residential PV with smart functionalities, it is important to understand whether such smart functions can help with voltage recovery during a FIDVR event.

The study presented in this paper focuses on assessing the impact of single-phase residential scale PV units on the voltage recovery of a strong feeder with a substantial number of residential HVACs. To perform this study, a realistic feeder model was built in PSCAD/EMTDC software with detailed models of residential PV systems, and residential and commercial HVACs. The broad research questions investigated through this study are as follows:

1. Can PV inverters aid the voltage recovery of the feeder, when they are set to provide no active voltage support? In other words, can PV inverters aid voltage recovery by momentarily ceasing operation during the low voltage period
2. Can PV inverters aid the voltage recovery of the feeder, when they are set to provide some form of active voltage support during the low voltage period?
3. Can the PV systems under all or certain operating modes prevent stalling of residential HVACs, which are responsible for a fault induced delayed voltage recovery or FIDVR?
4. Can the PV systems under all or certain operating modes result in transient or sustained over voltages in the distribution feeder?

2. TEST FEEDER AND EQUIPMENT DESCRIPTION

Figure 1 shows the test feeder model in PSCAD/EMTDC. The high side of the distribution substation is a voltage source, which represents the transmission and the sub transmission system. The test feeder model shown in Figure 1, is a reduced model of an actual distribution feeder, within the service area of one of the leading utilities in the United States. As such, the feeder/transformer impedances, and the feeder X/R ratios are representative of a realistic distribution feeder. The total load, and PV generation on the feeder is distributed at 5 load buses (Bus n1-Bus n5). Figure 2 shows the topology of the load, and the PV generation at each load bus. For this study, the single-phase PV inverters shown in Figure 2 were represented with an average model that was developed NREL [13]. Details of the model can be found in [13]. The residential HVACs shown in Figure 2 are represented using an EMTP model of a single-phase induction motor driving a reciprocating compressor [14]. The three-phase induction motor in Figure 2 is the standard EMTDC/PSCAD library model, which is used to represent the large commercial HVAC systems. Table 1 lists the break-down of the load at each bus. Approximately 70% of the load (in kW) at each bus consists of single phase residential HVACs. Table 2 lists the single phase residential PV per phase at each bus. The total PV on each bus comprises approximately 50% of the total load (in kW) on that bus. The ratio between the short-circuit MVA at the feeder head and the aggregate PV systems MVA rating (composite SCR) was around 50. This indicates that the feeder is strong with respect to the total PV connected on it. Table 3 lists the composite SCR at the feeder head and the 5 load buses in the system.

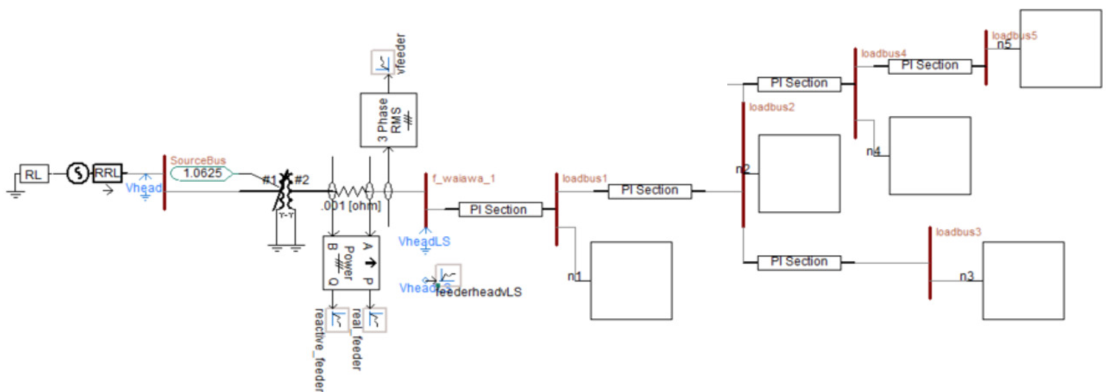

Figure 1: PSCAD Model of the Test Feeder

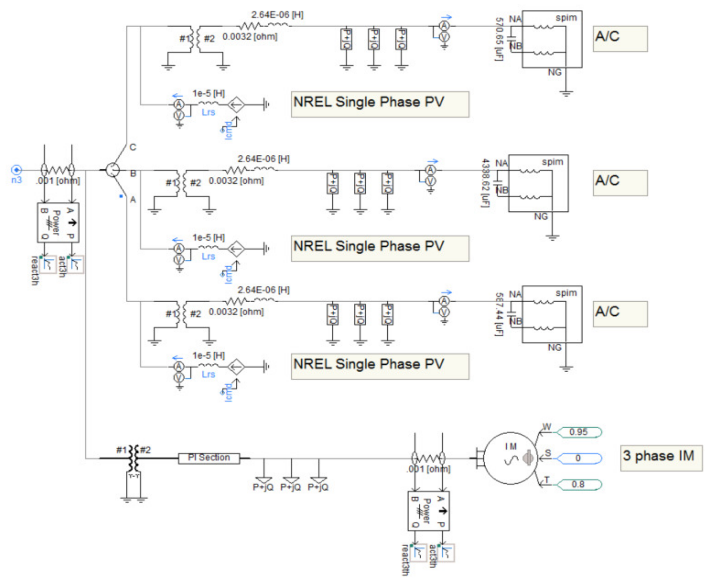

Figure 2: Detailed Load and Distributed PV at Each Load Bus

Table 1 Total Single Phase and Three Phase Load in kW Connected at Each Bus

Load, kW	Bus n1	Bus n2	Bus n3	Bus n4	Bus n5
3-phase	-	26	45	5	159
a-phase	933	26	105	-	159
b-phase	196	253	546	130	185
c-phase	50	317	107	26	310
Total	1179	622	803	161	813

Table 2 Single phase PV generation in kW per phase at each bus

PV, kW	Bus n1	Bus n2	Bus n3	Bus n4	Bus n5
Phase A	468	17	59	-	106
Phase B	100	130	280	66	119
Phase C	26	162	60	14	180

Table 3 Single phase PV generation in kW per phase at each bus

	Feeder head	Bus N1	Bus N2	Bus N3	Bus N4	Bus N5
Fault MVA	70.26	41.48	36.75	36.5	35.38	33.5
PV at each bus (MW)	1.426	0.594	0.274	0.315	0.072	0.171
SCR (on PV base)	49.2706872	69.83165	134.1241	115.87302	491.38889	195.9064
Note	PV at feeder head is the sum of all the PVs at each bus					

3. DESCRIPTION OF THE PV CONTROL MODES

The functional descriptions of common functions for smart inverters have been described in EPRI's *Common Functions for Smart Inverters* reports [15]. Many of these requirements and functions are now being included in the ongoing revision of the IEEE Draft Standard 1547, in the United States [16]. Till recently, the IEEE1547 standard required DERs to trip for any abnormal voltage conditions and did not allow for low/high voltage ride-through. The standard required the DERs to operate solely at unity power factor, and not regulate the voltage at their terminals. These requirements have caused bulk system reliability concerns at high DER penetrations. To address these concerns, the IEEE 1547 standard was amended in 2014. The amendments not only allow for voltage ride-through of DERs, but also allows for advanced DER grid support such as steady-state voltage control and reactive power exchange with the grid. However, the amended IEEE 1547 neither mandates these requirements nor specifies their implementation. The full revision of the IEEE 1547 that started in 2014, aims at filling this gap.

To capture the impact of PV ride through and voltage regulation capabilities, the following different control options and their combinations were studied.

1. *Inverter trip*: In this mode, the PV units trip when the voltage goes below a set threshold. Most legacy inverters on the system are on this mode of operation.
2. *Momentary cessation*: In this mode, the PV units remain connected to the grid but ceases its output when the voltage at its terminal goes below a certain set level. When the voltage recovers above a set threshold the PV units resume their normal operation.
3. *Constant power factor*: In this mode, the PV units remain connected to the grid and operate at a constant operator set power factor. As a practice, for distributed PV, the power factor is typically set at unity or 0.9 leading (absorbing reactive power).
4. *Dynamic voltage support (DVS)*: In this mode, the PV units remain connected to the grid and inject a capacitive reactive current in proportion to the deviation of instantaneously measured fault or post-fault voltage from a moving pre-fault voltage average (calculated over a certain time-period using a wash-out filter) in addition to the pre-fault current into the grid. The DVS is active only if the measured deviation is outside a set dead-band.
5. *P/Q priority*: In P priority mode, the PV units remain connected to the grid and maintain its active power output at the expense of its reactive power output (within its current limits)

during abnormal voltages. In Q priority mode, the PV maintains its reactive power output at the expense of its active power output (within its current limits) during abnormal voltages. These two control options are used in conjunction to the control modes given by 1 through 4.

Further details about these control modes and their implementation in the PSCAD/EMTDC model can be found in [17].

4. SUMMARY OF CASES

To study the impact of the distributed PV on the voltage recovery of the feeder, a set of simulations with different control modes of the PV inverters were performed. The original study has 13 separate cases covering the entire gamut of PV operating modes [17]. However, for the sake of brevity 4 representative cases and the base case are discussed in this paper. The detailed report can be found in [17]. Table 4 provides a summary of the cases studied in this work. The cases will be referred to by their case numbers listed in column 1 of Table 4, in the remainder of the report. Case 0 is the base case without any PV in the system. Case 1 investigates the scenario when the PV units do not ride-through and simply trip at the onset of the fault. Cases 2a and 2b investigates the impact of momentary cessation at unity pf. Case 3 investigate the impact of constant power factor operation of PVs at unity pf. Finally, Case 4 investigate the impact of the DVS mode of operation of the PVs at unity. The investigation of the same cases with the PV operating at 0.9 lead pf can be found in [17]. Table 5 lists some of the important thresholds in relation to the PV control modes. The thresholds listed in Table 5 are commonly used in practice.

Table 4 Description of Cases

Case	Description	Steady state pf	P/Q-Priority
0	No PV in the system (base case)	N/A	N/A
1	Inverter trip	1.0	P-priority
2	Momentary cessation	1.0	Q-Priority
3	Voltage ride through with constant pf	1.0	P-priority
4	Voltage ride-through with DVS	1.0	Q-Priority

Table 5 Settings for Key Control Functionalities

Description	Threshold	Response Time
Inverter trip limit	0.88 pu	90 ms
Momentary cessation limits	0.88 pu	33 ms
DVS dead-band	±0.12 pu around nominal	33 ms

4. SIMULATION RESULTS FOR THE TEST FEEDER

Figure 3, shows the RMS voltages on the three-phase feeder at the 5 buses, and the shaft speed of the HVAC motors in the base case when a 3-phase fault is applied at the substation bus labeled ‘Source bus’ in Figure 1. Figure 4, shows the shaft speeds of all the HVACs in this system. From Figure 3 and Figure 4, the following important observations can be made:

1. Bus n1 is closer to the substation than the remaining 4 buses in the system and hence the voltage is slightly higher that the remaining buses
2. All single phase residential HVACs in the distribution feeder stalled due to the fault. The speeds of all the units overlap and hence only 3 distinct curves are visible in Figure 2. The stalling of HVACs is expected since the fault is at the distribution substation, close to the loads along the feeder. The stalled residential HVACs cause the voltage to remain depressed till around the 3.5 s mark and then the voltage recovers as these HVACs trip due to thermal

overload. It is important to mention that in a real-life scenario the thermal overload trip takes around anywhere from 5 to 20 seconds to operate. However, for the sake of EMTP simulation. the trip time was reduced such that study of the post recovery period is possible

3. As the fault is cleared, the voltage along the feeder recovers close to 0.8 pu for the 3- phase fault. This happens because the distribution feeder is connected to a strong transmission network (represented by a voltage source), which can supply adequate reactive power during the FIDVR period. Distribution systems with relatively strong connection (high short circuit ratio or SCR) to the transmission systems is typical of developed power systems.

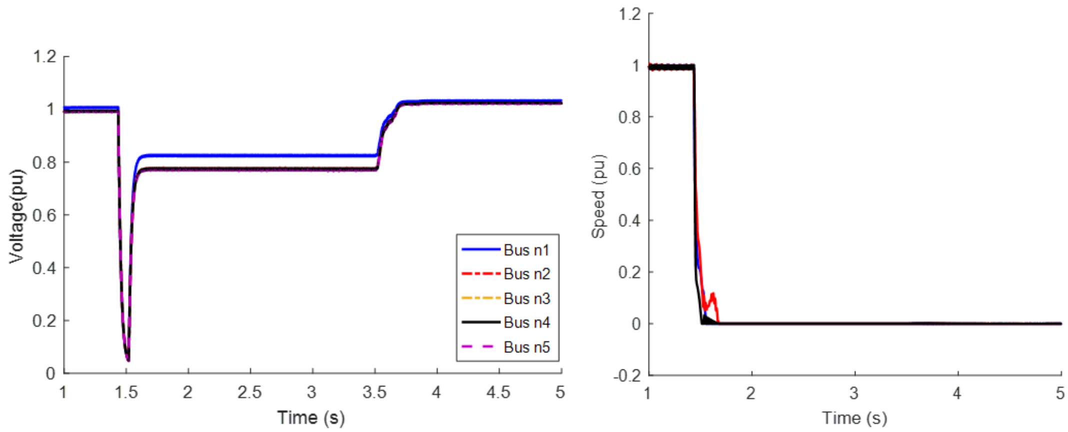

Figure 3 RMS voltages on the three-phase feeder, and the shaft speed of the HVAC units at the 5 buses

Figure 4 shows the voltages at Bus n1 (closest to the substation) and Bus n5 (farthest from the substation) for the cases listed in Table 4. From Figure 4, it can be seen that the bus voltages both at the feeder head (Bus n1) and end (Bus n5) are observably improved from the base case (black curve) when the PV operates in the DRC injection mode (red curve). This is because the PV units inject reactive power proportional to the deviation in voltage from the pre-fault voltage outside the set dead-band of 0.88 pu. Figure 5, shows the total active and reactive power output from the PV at Bus n1 and Bus n5. In Figure 5, the PV output from the three single phase inverters on the three separate phases have been summed up to show the total 3 phase MVA outputs at the two buses. As listed in Table 4, the PV units are operating in Q priority, with DRC in case 9. Due to the Q priority settings, the reactive power increases right after the fault at the expense of the active power, but reduces as the voltage at the bus recovers close to the lower deadband of DRC control. The additional injected reactive power results in the voltage improvement observed in Figure 4. For case 1 the PV trips and for case 2 the PV momentarily ceases its output. Due to the absence of any additional reactive power support, the improvement in the voltages for cases 1 and 2 (blue and magenta) are not significant. Some voltage improvement can be seen for case 3 (green). The voltage improvement in case 3 is due to the PV units remaining connected, and supplying active power at unity pf during the recovery period. Additionally, no overvoltages were observed in any of the 5 buses in the system due the PV operation.

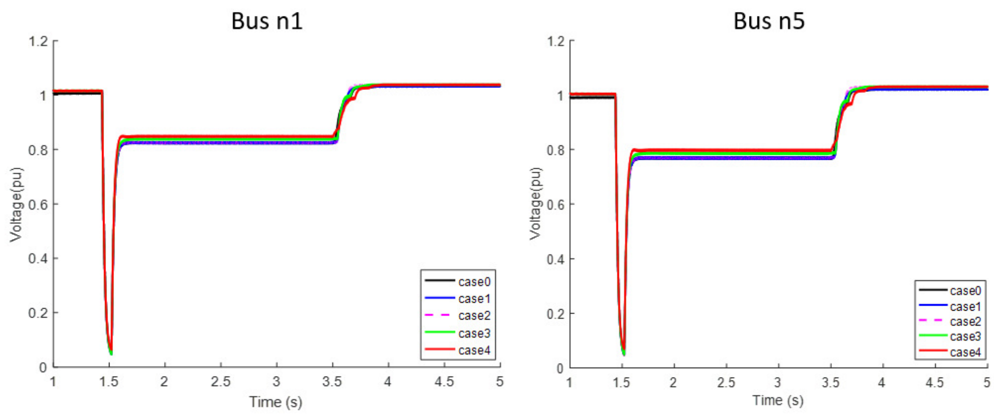

Figure 4 Three phase RMS voltages at Bus n1 and Bus n5

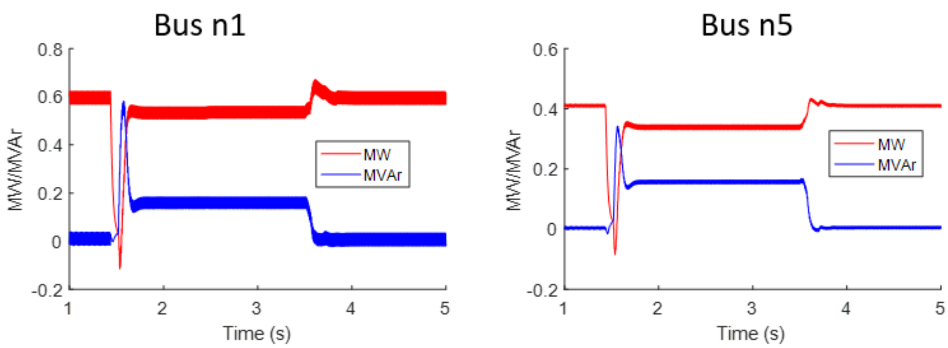

Figure 5 Total active and reactive power injected at Bus n1 and Bus n5

In this study the residential HVACs were found to stall at all buses for all the different cases studied. Figure 6 shows the shaft speed of the HVACs connected at Bus n1 and Bus n5 for case 0 and case 9. The dotted lines indicate the shaft speeds of the HVAC in case 0, whereas the bold lines are the speeds for case 9. From Figure 6, it can be seen that in this case the DRC injection from the PV did not have any significant effect on the stalling of the residential HVACs. The residential HVAC motors have a very small inertia, and decelerate rapidly and stall when the voltage disturbance is close to their location, as in this test system.

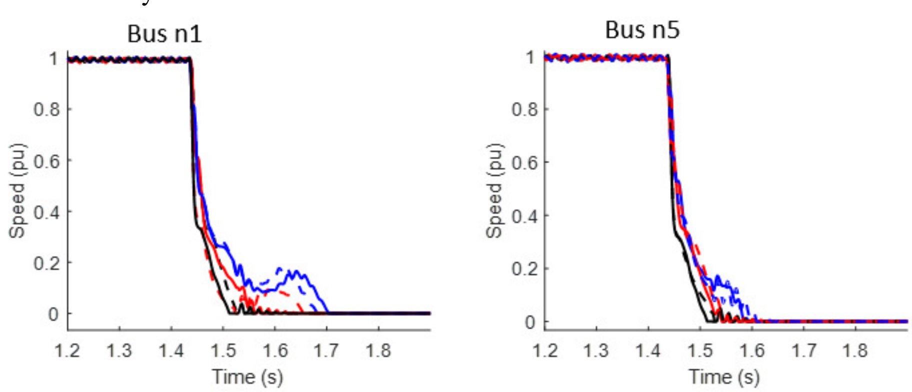

Figure 6 Total active and reactive power injected at Bus n1 and Bus n5

5. MODIFIED TEST CASE AND DEADBAND SENSITIVITY

From section 4, it can be seen that the PV with DRC injection capability can provide observable voltage support during the voltage recovery period. However, due to the nature of the of the test feeder, the voltage recovers to a relatively higher value (0.8 pu) in the post fault condition and the

DRC injection from the PV inverters is limited due to the deadband. It is of interest to study the impact of the DRC injection on feeders where the voltage recovers to a lower value in the post-fault condition. This scenario can be encountered in systems where the distribution network may be at the end of a long radial transmission feeder. To achieve this, a new modified feeder was created by adding external impedance to the existing feeder, effectively reducing the SCR at the substation bus. The analysis with DRC injection was repeated for this modified feeder. Figure 7 shows the voltages at Bus n1 and n5 for case 0 and case 9. In this case, it can be seen that having DRC injection from the residential PVs result in significant improvement in voltage during the recovery period. However, it should be noted that the DRC control in the PV units have a deadband of ±0.12 pu, as such when and if the voltage reaches close to 0.88 pu the reactive current injection backs off.

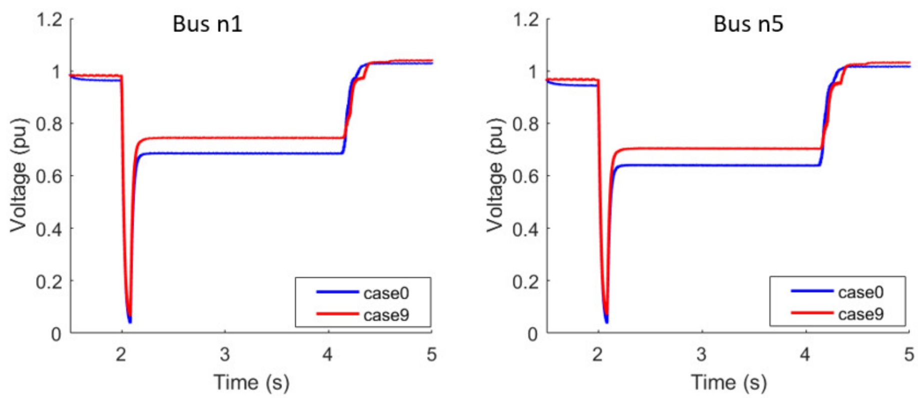

Figure 7 Three phase RMS voltages at Bus n1 and Bus n5

In addition to studying the modified feeder, the sensitivity of the voltage support to the deadband was also investigated in this work. To understand the impact of reducing the deadband, the deadband on the DRC control was reduced from ±0.12 pu to ±0.03 pu and the case 9 simulations were re-run for the modified feeder. The modified feeder was chosen since the impact of DRC injection is more pronounced in this feeder. Figure 8 shows the voltages at Bus n1 and Bus n5 for the full and reduced deadband for the modified feeder. From Figure 8, it can be seen that reducing the deadband in this case did not lead to significant change in the voltage. It should however be noted that the impact of reduction in deadband is strongly dependent on both the system, and size of the PV unit under study. Furthermore, adjusting the deadband would require analyzing the SCR at the point of interconnection, and hence no recommendations for altering the deadband has been made in this study.

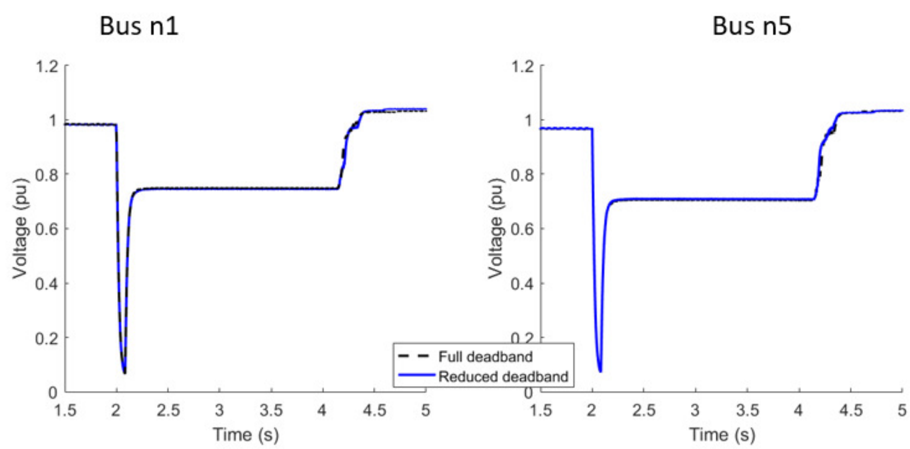

Figure 8 Three phase RMS voltages voltage at Bus n1 and Bus n5 for full and reduced deadband

6. CONCLUSIONS AND FUTURE WORK

The work done in this paper documents the initial findings of the impact of some of the important control modes of smart PV inverters on the voltage recovery of feeder during FIDVR with medium to high PV penetration. Based on the research questions posed in the Section 1, the following key conclusions can be drawn:

1. The results indicate that for the type of feeder studied here (composite short-circuit ratio of 50), the PV inverters did not have any significant impact on the voltage recovery of the feeder, when they tripped (case 1) or went into a momentary cessation mode (case 2).
2. Improvement in the voltage recovery of the feeder was observed when the PV units remained connected and supplied power at unity pf (case 3) or provided DRC injection (case 4). The improvement in voltage was more pronounced and observable when the PV provided additional reactive power support in the form of DRC injection. It should be noted that this observation has some important ramifications. In future, most distribution systems will have a mix of smart inverters and legacy IEEE 1547 inverters that do not have voltage support capabilities. In those scenarios, improvement of voltage due to smart inverters could prevent the tripping of legacy inverters thereby preventing loss of local generation during crucial abnormal voltage periods in the system. This topic is important and needs further investigation.
3. The presence of PV generation did not prevent the stalling of residential HVACs on this feeder. This is expected, since the low inertia HVAC motors decelerate rapidly when close to the voltage disturbance. However, since the PV inverters can potentially improve the voltage when providing active support (DRC), they may be able to prevent stalling of HVACs that are electrically farther from the disturbance. Investigation of such phenomenon will require a system wide study rather than analyzing a single feeder.
4. For the feeders studied in this work, no overvoltages were observed with the different PV controls. However, it should be noted that feeder overvoltages associated with loss of load due to FIDVR [12], and PV back-feed into the system has been reported in literature [10]. This is strongly dependent on the penetration of PVs, the type of PV controls and the characteristics of the feeder under study.

The findings of the study strongly indicate that future work is warranted along these lines:

1. There is a need to analyze the research questions posed here through system-wide studies that include feeders with different characteristics. Co-simulation with hybrid RMS/EMT methods may be an avenue of choice, which allows a user to include detailed models of distribution feeders and loads along with positive sequence equivalents of the transmission system [18]. Such a simulation environment would be apt to study the impact of PVs on feeders located close to and farther away from fault locations with varying SCRs.
2. Another important aspect is to capture the re-dispatch of conventional units due to PV and other DERs. This may reduce the composite SCR at the feeder head and make the voltage recovery more sensitive to the PV units' power output. As this is also difficult to address using only PSCAD/EMTDC type simulations, a co-simulation environment is required.
3. In addition to the system-wide studies, different scenarios with varying fractions of smart and legacy inverters, should be developed and investigated, to identify their interactions, as pointed out in the conclusions.

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