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Accuracy of Translating Generic DER 'Agnostic' Hosting Capacity to Specific DER Types

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SUMMARY

Distributed Energy Resources (DERs) offer new opportunities for both customers and utilities, but they can also introduce safety and power quality issues. The amount of DER that can be installed in a given location without negatively impacting reliability and power quality or requiring circuit changes or upgrades is called hosting capacity [1]. Hosting capacity studies can reduce uncertainty for distribution planners, who can make more informed decisions about infrastructure upgrades based on how much DER they need to host in the future, and for DER developers who can get a better idea of where interconnection requests are likely to be approved.

Many existing hosting capacity methods determine agnostic hosting capacity, which means that the study is run for a generic DER type with certain assumed characteristics [2,3]. These assumed characteristics typically represent inverter-based DER such as solar, storage, and some types of wind generators. However, these DER types can still have very different power and fault current characteristics. The existing agnostic methods assume the agnostic DER hosting capacity can then be translated to specific DER types to account for those differences. Furthermore, there is additional uncertainty in how those translation methods apply for synchronous generators, other non-inverter-based DER types, and aggregate DER composed of a portfolio of DER types.

This paper is the first to challenge the assumption that agnostic hosting capacity can accurately be translated to different DER types. In doing so, a method for translating agnostic hosting capacity for DERs with different fault current and power output variability characteristics is developed. In the method, a detailed hosting capacity study for a single generic or "agnostic" DER type is performed, then the results are translated into hosting capacities for specific DER types through a set of linear multipliers. Results from the agnostic hosting capacity translation method are compared to results from detailed hosting capacity studies for four specific DER types and two portfolios of multiple DER types. The comparison shows that this agnostic hosting capacity technique can approximate voltage-based hosting capacities but needs improvement for protection-based hosting capacity especially for non-inverter-based DERs.

KEYWORDS

Agnostic, Distributed Energy Resources, Distribution Planning, Hosting Capacity, Generation

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Introduction

Hosting capacity depends on many factors including feeder topology, voltage level, load, protection schemes, existing voltage control equipment, and specific DER characteristics [2]. Hosting capacity can be highly sensitive to some of these factors while others have less influence. There are several methods in use and under development for determining hosting capacity, and these methods exist on a spectrum from detailed, resource and time-intensive methods to faster approximations. The most detailed method involves doing a full interconnection study for DER placed at every possible location. This method is incredibly resource- and time-intensive and is not practical for system-wide planning. Other methods include stochastic, iterative, streamlined, and hybrid analyses [2].

Some methods also focus on a specific DER type which is defined by the full characteristics of the resource, however other methods determine agnostic hosting capacity, which means that DER type is not specified (but application is limited to inverter-based DER) [3]. Thus, individual DER characteristics for the full variety of potential DERs are not modelled yet are determined based on translating the characteristics of the generic DER to each specific DER type.

This paper explores the possibility of translating agnostic hosting capacity into specific hosting capacities for DER with different characteristics using a simple set of multipliers. Agnostic hosting capacity is applied to both inverter-based and non-inverter-based DERs with a wide range of power fluctuation and fault current characteristics. Those results are compared to hosting capacity calculated explicitly for each individual DER type to determine the accuracy of the proposed agnostic translation method.

Hosting Capacity Criteria

Five criteria were used to determine hosting capacity: Overvoltage, Voltage Deviation, Regulator Voltage Deviation, Breaker Reduction of Reach, and Fault Flow. These criteria are detailed below and summarized in Table 1. Thermal overloading is excluded from this analysis because in all methods, the current flow impacts from any DER type with the same kVA rating should be identical.

Overvoltage

Voltage is not allowed to rise above 1.06 Vpu anywhere on the feeder. This criterion is used in place of ANSI standards due to existing voltages above 1.05 Vpu on the IEEE 123-bus test feeder.

Voltage Deviation

Voltage is not allowed to change by more than 3% at any node on the feeder when the DER output is changed by the expected power fluctuation value for that DER type. This criterion preserves voltage quality by avoiding large, rapid changes in voltage that could impact customer equipment.

Regulator Voltage Deviation

Voltage at the secondary side of the voltage regulator is not allowed to change by more than half of the regulator's bandwidth when DER output is changed by the expected power fluctuation value for that DER type. For regulators with line drop compensation, the effective voltage change including line drop compensation is considered. This criterion prevents increased regulator operations which can impact maintenance costs and equipment lifetime.

Breaker Reduction of Reach

When a fault occurs near the end of the feeder, the fault current through the main circuit breaker must not be reduced by more than 10% from its initial value before the DER was added. This criterion ensures that the breaker will likely trip for faults anywhere within its protection zone.

Fault Flow

When a fault occurs downstream of the DER location, the fault current through the protection element just upstream of the fault must not be increased by more than 10% from its initial value before the

DER was added. This criterion ensures that fault current through a protection device remains within the interrupting rating of the device so that faults can be isolated safely and reliably.

Table 1. Hosting capacity criteria

Criteria	Value	Threshold
Overvoltage (OV)	Voltage at any primary nodes	1.06 pu
Voltage Deviation (VD)	Voltage change at any primary nodes	0.03 pu
Regulator Voltage Deviation (RVD)	Effective voltage change at any regulator secondary nodes	50% of regulator bandwidth
Fault Flow (FF)	Fault current through the element immediately upstream of the fault location	10% increase
Breaker Reduction of Reach (BRR)	Fault current through the feeder breaker	10% decrease

Methods

A detailed hosting capacity method using power flows and fault studies in OpenDSS [7] is used to find the actual hosting capacity for each specific DER type. Then, the detailed hosting capacity values found for one DER type are translated using agnostic translation factors to approximate hosting capacity for all other DER types. The translation results are compared with the actual values to determine the accuracy of the translation method.

Detailed Hosting Capacity Method

A detailed method is used to determine accurate hosting capacity at each location for each DER type as a benchmark. In this method, each DER type is considered on its own and analyzed at each location independently.

First, a location for DER is chosen. A base-case power flow is run to find the initial voltages $\mathbf{V^0}$ at each bus without any DER. Then, base-case fault currents are found without DER using dynamic fault flows. One three-phase fault is applied near the end of the feeder and the resulting fault current through the feeder breaker I_b^0 is recorded. A second three-phase fault is applied just downstream of the DER location and the fault current through the element between the DER location and the fault I_e^0 is recorded. These base-case fault values are used to set the thresholds for breaker reduction of reach and fault flow.

Next, a single DER is added to the feeder with a starting capacity of 10 kW. The voltage criteria are tested first. With all regulator and capacitor controls locked so that the DER impacts can be assessed without assuming additional control operations, a power flow is run at full output and the voltages at each bus $\mathbf{V}^{100}$ are recorded. Each bus is checked for voltages above the overvoltage threshold. Then, a power flow is run at (100-ΔP)% output to simulate a fluctuation of ΔP%. The resulting voltages $\mathbf{V}^{low}$ are recorded. The difference in voltage at each bus between the 100% case and the low output case is checked against the voltage deviation threshold. The same voltage difference at regulator secondary buses is checked against the regulator voltage deviation threshold. Equations 1 to 3 are used to account for line drop compensation at each regulator secondary bus.

$$\Delta V_{R,LDC} = \frac{\left({I_R}^{hi} - {I_R}^{low}\right)}{I_{prim}} \times \frac{N_{PT}}{V_{LN}} \times R_{LDC} \tag{1}$$

$$\Delta V_{X,LDC} = \frac{\left({I_X}^{hi} - {I_X}^{low}\right)}{I_{prim}} \times \frac{N_{PT}}{V_{LN}} \times X_{LDC} \tag{2}$$

$$\Delta V_{reg} = \Delta V_{terminal} - \Delta V_{R,LDC} - \Delta V_{X,LDC} \tag{3}$$

A second voltage deviation test is then run to account for the differing change in losses when the power fluctuation occurs from a different initial power output. A power flow is run with the DER at ΔP% output and the resulting voltages $\mathbf{V}^{hi}$ are compared to the original node voltages without DER $\mathbf{V}^0$. This simulates a ΔP% to 0% drop in output. In the case of energy storage, $\mathbf{V}^{hi}$ is instead compared to voltage results from a power flow where storage is discharging at 100% output. The voltage deviation and regulator voltage deviation are assessed again for this case.

After the voltage tests are finished, the protection tests are run. A three-phase line-to-ground fault is placed near the end of the feeder and a dynamic fault flow solution is found. The fault current through the breaker I_b is checked against the breaker reduction of reach threshold $90\% \times I_b^0$. Finally, a three-phase line-to-ground fault is placed on the node just downstream of the DER location and the resulting fault current through the element between the DER and fault I_e is checked against the fault flow threshold $110\% \times I_e^0$.

If any of the violation criteria are exceeded, the hosting capacity for that criterion is recorded at the current capacity level minus 10 kW. Hosting capacities are recorded for each individual limiting criterion so that they can later be translated based on the characteristics relevant to each criterion. If all five of the tests have resulted in violations, the algorithm is finished. Otherwise, the DER capacity is increased by 10 kW and the tests are run again until every test shows violations or the capacity reaches 30 MW. The detailed algorithm is shown in Fig. 1.

Detailed Hosting Capacity Algorithm

```
Step 1.   Run base-case power flow and record node voltages $\mathbf{V}^0$
Step 2.   Run fault flow with 3-phase line-to-ground fault at end of feeder and record breaker fault current $I_b^0$
Step 3.   Run fault flow with 3-phase line-to-ground close-in fault and record element fault current $I_e^0$
Step 4.   Add 10 kW DER
          While capacity < 30,000 kW
Step 5.       Run power flow with DER at 100% power output and record node voltages $\mathbf{V}^{100}$
              If $\max(\mathbf{V}^{100}) > 1.06$ pu
                  Overvoltage HC = capacity-10
Step 6.       Run power flow with DER at $(1-\Delta P)\%$ power output and record node voltages $\mathbf{V}^{low}$
              If $\max(\mathbf{V}^{100} - \mathbf{V}^{low}) > .03$ pu
                  Voltage Deviation HC = capacity-10
              If $\Delta V_{reg}$ > regulator bandwidth
                  Regulator Voltage Deviation HC = capacity-10
Step 7.       Run power flow with DER at $\Delta P\%$ power output and record node voltages $\mathbf{V}^{hi}$
              If $\max(\mathbf{V}^{hi} - \mathbf{V}^{0}) > .03$ pu
                  Voltage Deviation HC = capacity-10
              If $\Delta V_{reg}$ > regulator bandwidth
                  Regulator Voltage Deviation HC = capacity-10
Step 8.       Run fault flow with three-phase line-to-ground fault at end of feeder
              If $I_b < I_b^0 \times 0.9$
                  Reduction of reach HC = capacity-10
Step 9.       Run fault flow with three-phase line-to-ground fault at close-in fault bus
              If $I_e > I_e^0 \times 1.1$
                  Fault flow HC = capacity-10
Step 10.      If not all HC have been found
                  Increase DER capacity by 10 kW
              Else
                  END
```

Fig. 1. Detailed Hosting Capacity Algorithm

Agnostic Translation

The detailed method is used to determine hosting capacity for each specific DER type and a generic "agnostic" DER type. Then, the agnostic hosting capacity values are translated to specific hosting capacities for each DER type using a set of multipliers based on the specific DER characteristics. Two multipliers are used: $k_{\Delta P}$ addresses differences in power variability and k_{If} accounts for differences in fault current contributions. $k_{\Delta P}$ is the ratio between the expected power fluctuation assumed for the agnostic DER and the expected power fluctuation for the specific DER type.

$$k_{\Delta P} = \frac{\Delta P_{agnostic}}{\Delta P_{type}} \tag{4}$$

$k_{\Delta P}$ translates the capacity of agnostic DER that it takes to cause the maximum allowed voltage change to the capacity of the specific DER type that would cause the same power output change and thus similar voltage change. This is an approximation that does not account for the differing change in losses when the power fluctuation occurs from a different initial operating point.

k_{If} is the ratio between the maximum per-unit fault current assumed for the agnostic DER and the maximum per-unit fault current for the specific DER type.

$$k_{If} = \frac{I_{f,agnostic}}{I_{f,type}} \tag{5}$$

k_{If} translates the agnostic DER capacity that produces enough fault current to violate protection criteria to the specific DER capacity that it takes to produce the same fault current, assuming fault current is a constant per unit value for each DER type.

Agnostic hosting capacity is translated to specific hosting capacity by multiplying the agnostic hosting capacities based on each criterion by the associated translation factors. For hosting capacity in terms of voltage deviation or regulator voltage deviation, the agnostic value is multiplied by $k_{\Delta P}$ for each DER type. For hosting capacity limited by breaker reduction of reach and fault flow, the agnostic value is multiplied by k_{If} for each DER type. For overvoltage, the agnostic hosting capacity value is used directly because the maximum voltage for a given power output is the same regardless of technology as long as all DERs have the same power factor.

In addition to the individual DER studies, hosting capacity analysis can also be performed for portfolios of DER at a single location, such as a solar farm with battery storage or a microgrid with several different DERs. The hosting capacity values for the portfolios are translated from the detailed agnostic hosting capacity using the combined translation factors shown in equations 6 and7. The denominators represent the average power fluctuation or fault current respectively for all DER types included in the portfolio.

$$k_{\Delta P} = \frac{\Delta P_{agnostic}}{\frac{1}{N}\sum_N \Delta P_i} \tag{6}$$

$$k_{If} = \frac{I_{f,agnostic}}{\frac{1}{N}\sum_N I_{f,i}} \tag{7}$$

Test Cases

Hosting capacity values are found for several locations on each of two IEEE test feeders: IEEE 123-bus and IEEE 34-bus. The IEEE 123-bus feeder is a highly unbalanced 4.16 kV feeder with existing overvoltage issues [4]. The IEEE 34-bus feeder is a long 24.9 kV/4.16 kV feeder with light but slightly unbalanced load and existing under-voltage issues [4]. Both feeders have existing line voltage regulators and capacitor banks.

For each feeder, three DER locations were chosen as shown in Fig. 2 and Fig. 3: one close to the substation, one near the middle of the feeder, and one near the end of the three-phase portion of the feeder. Each location has an associated close-in downstream fault location which is used to test fault flow. Additionally, there is a single fault location near the end of each feeder which is used to test breaker reduction of reach.

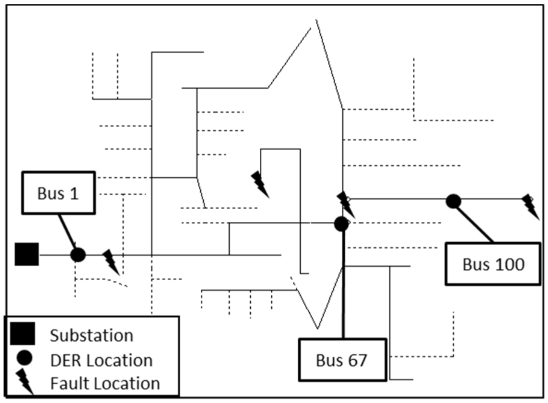


Fig. 2. IEEE 123-bus system with DER and fault locations highlighted.

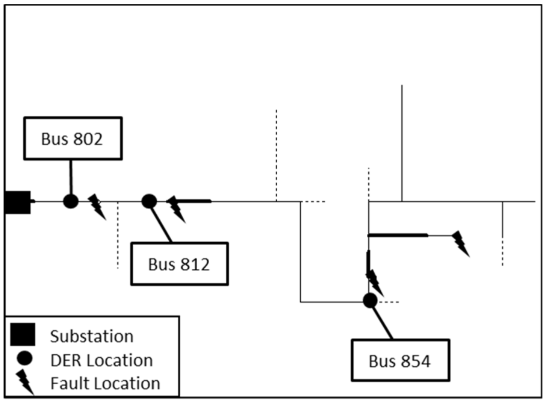


Fig. 3. IEEE 34-bus system with DER and fault locations highlighted.

Five generator types are considered: solar (PV), storage, wind (induction), synchronous, and an "agnostic" inverter-based DER type. Additionally, two portfolios of DER are considered: 50% each of PV and Storage and 33% each of PV, storage and synchronous. Table 2 to Table 4 shows the parameters for each DER type.

A detailed hosting capacity analysis is performed for each of the five DER types at each location on both feeders for a single time period at peak load. Then, the hosting capacity values for the agnostic DER type are translated into specific DER values for the other four DER types. The agnostic translation factors based on each generator's parameters are listed in Table 5. The hosting capacity values from each method are compared to determine the accuracy of the agnostic translation method.

Table 2. Inverter-based generator parameters

Inverter-Based Generators			
	Agnostic	PV	Storage
Power fluctuation	100%	60%	200%*
Fault current limit	2 pu	1.2 pu	2 pu
Power factor	1	1	1
* Storage can fluctuate from 100% charging to 100% discharging for a total change of 200%.			

Table 3. Synchronous generator parameters

Synchronous Generator	
Power Fluctuation	20%
Transient reactance	0.2 pu
Nominal Fault Current	6.13 pu
Power factor	1

Table 4. Wind generator parameters [5]

Wind Generator	
Power fluctuation	40%
Rotor resistance	0.0071 pu
Rotor reactance	0.119 pu
Stator Resistance	0.0057 pu
Stator Reactance	0.113 pu
Magnetizing reactance	5.5 pu
Nominal fault current	4.36 pu
Power factor	0.91 to 0.93

Table 5. Agnostic translation factors for each DER type

Agnostic Translation Factors		
	$k_{\Delta P}$	k_{If}
PV	1.66	1.66
Storage	0.5	1
Synchronous	5	0.33
Wind	2.5	0.46
50% PV + 50% Storage	0.77	1.25
33% PV + 33% Storage + 33% Synchronous	1.07	0.64

Results

Middle and End of Feeder Results

Fig. 4 and Fig. 5 compare the detailed hosting capacity values with the translated agnostic hosting capacity values for the two feeders for locations at the middle and end of the feeders.

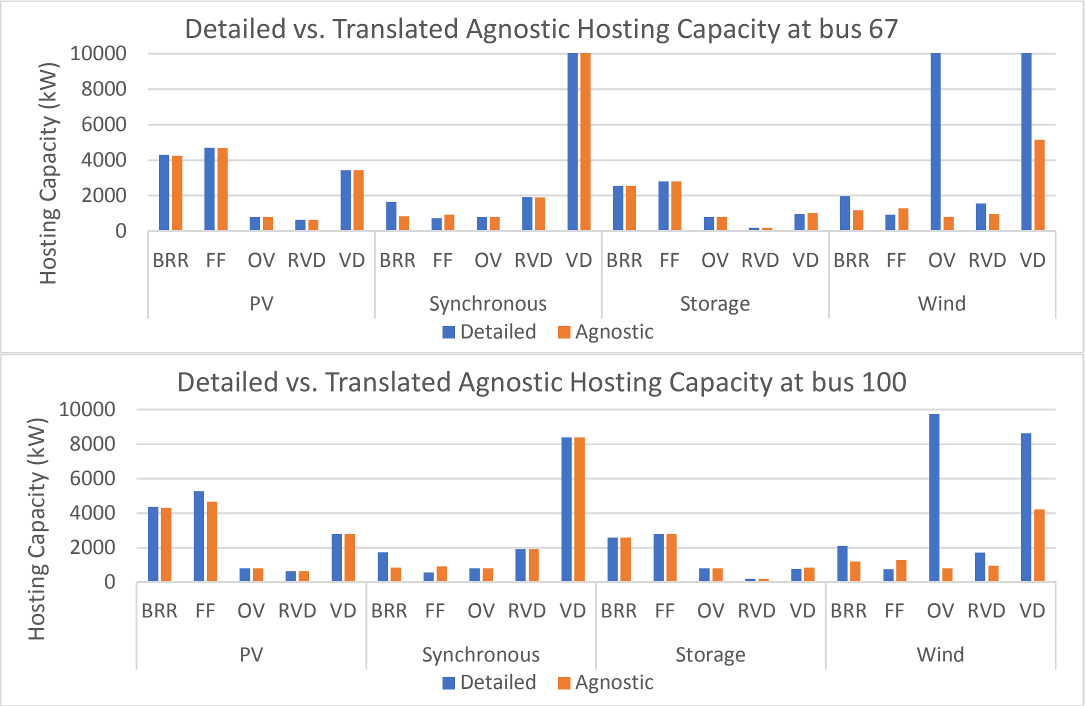


Fig. 4. Comparison of detailed and translated agnostic hosting capacities at the middle (bus 67) and end (bus 100) of the IEEE 123-bus test feeder.

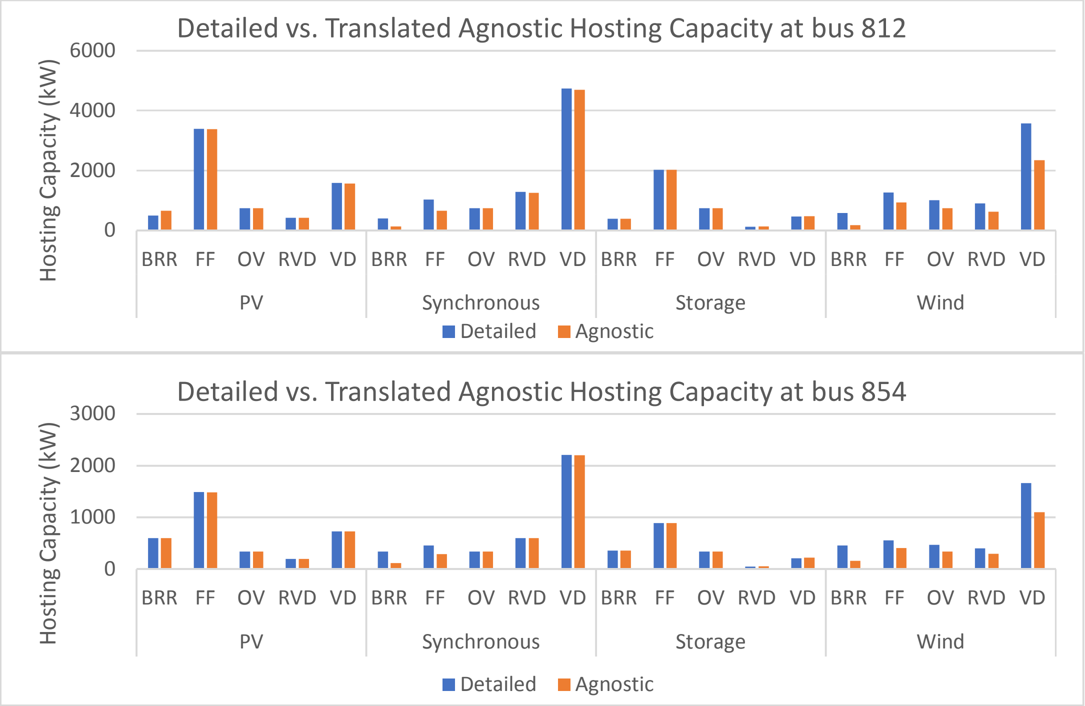


Fig. 5. Comparison of detailed and translated agnostic hosting capacities at the middle (bus 812) and end (bus 854) of the IEEE 34-Bus test feeder.

The translated hosting capacity values match the detailed values closely for overvoltage, voltage deviation and regulator voltage deviation for all DER types except wind. This is because the voltage effects from the induction wind generator's non-unity power factor are not accounted for in the agnostic translation.

Fig. 6 compares the maximum voltages that occur as DER size increases for DER with unity power factor and a wind induction generator with .91 power factor (absorbing reactive power). The non-unity power factor reduces the voltage rise caused by the DER significantly. An additional factor could be designed to translate hosting capacity for DER with different power factors, which would depend on the DER power factor and the feeder's X/R ratio. However, the accuracy would still be affected by the larger change in losses that comes with changing reactive power flow.

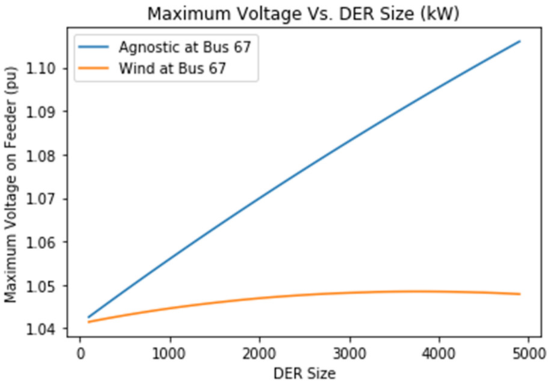


Fig. 6. Maximum voltages that occur for different DER types as size increases.

The accuracy of the voltage deviation hosting capacities is contingent on the use of both voltage fluctuation cases: from 100% to low output and from high output to 0%. Fig. 7 compares the voltage deviation resulting from each case. The difference becomes more significant as DER size increases and as the variability in DER output decreases. Fig. 8 shows the difference in resulting hosting capacities when each case is used on its own. The significant difference in results indicates that the voltage change sensitivity to operating condition is an important consideration for any hosting capacity method.

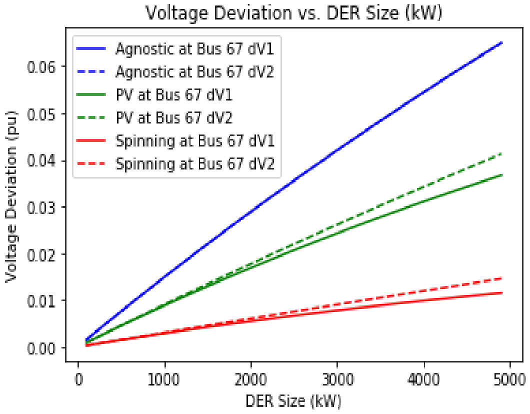


Fig. 7. Voltage deviation resulting from 100% to low output (dV1) and high output to zero output (dV2).

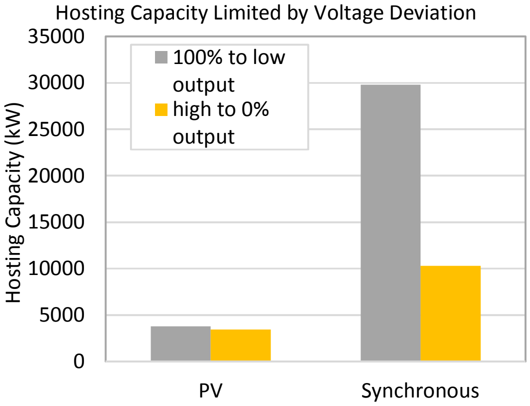


Fig. 8. Comparison of voltage-deviation-based hosting capacities for bus 67 of the 123-bus feeder when simulated at two different initial operating points.

The protection-based hosting capacities for inverter-based DER are very accurate. For wind and synchronous DERs, the translated hosting capacity is slightly lower than the detailed result for breaker reduction of reach. The translated hosting capacity is slightly higher for forward fault flow on the 123-bus feeder and lower on the 34-bus feeder for those same DERs.

Non-inverter-based DERs produce fault current depending on the impedance between the DER and the fault, as opposed to inverter-based DERs which produce a consistent fault current for any fault reasonably close to the DER. For example, the synchronous generator at bus 67 only outputs about 85% of its nominal fault current, while the PV at the same location outputs about 100% of its maximum fault current during the close-in fault. Varying fault current magnitude accounts for some of the error in the synchronous and wind hosting capacity values. Another factor impacting fault currents is phase angle. Inverter-based DER produces fault current that is out of phase with the overall system fault current. This means that the change in total fault current magnitude when inverter-based DER is added is much less than the total DER fault current magnitude. For non-inverter-based DER, the DER fault current is more in phase with the system fault current, so the change in fault current is closer to the total amount of DER fault current. This is illustrated in the two phasor diagrams in Fig. 9. To correct for this effect, an additional factor accounting for the feeder's X/R ratio would be needed to convert protection-based hosting capacity between inverter-based and non-inverter-based DER.

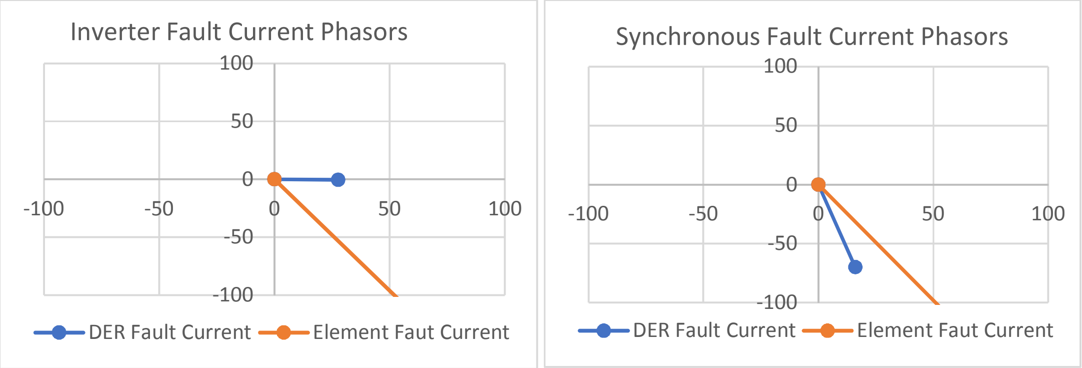


Fig. 9. Fault current phasors for inverter-based and synchronous DER.

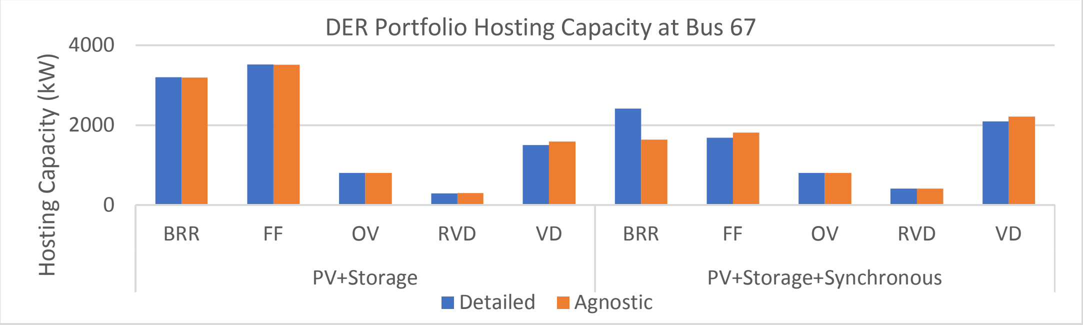
Aside from the forward fault flow hosting capacities for wind and synchronous generation at buses 67 and 100, the agnostic hosting capacity values are all nearly equal to or less than the detailed hosting capacity, which makes the agnostic translation a conservative method for these DER locations.

Top of Feeder Results

The hosting capacity results for DER at other locations on the feeder can be less consistent. Near the top of the feeder, where hosting capacity is typically much higher, convergence issues using detailed DER models as well as the dynamics of the specific models themselves can have a more significant role. High hosting capacities lead to higher error surrounding assumptions on losses in the translation. Similarly, fault current output even from inverter-based DER can become more variable due to terminal voltage during the fault. Thus, the translation becomes less accurate between different DER types.

Portfolio Results

Fig. 10 shows the hosting capacity comparisons for portfolios of DER on the 123-bus feeder. Similar to the individual results, the voltage-based hosting capacities are very accurate for DER at the middle and end of the feeder.



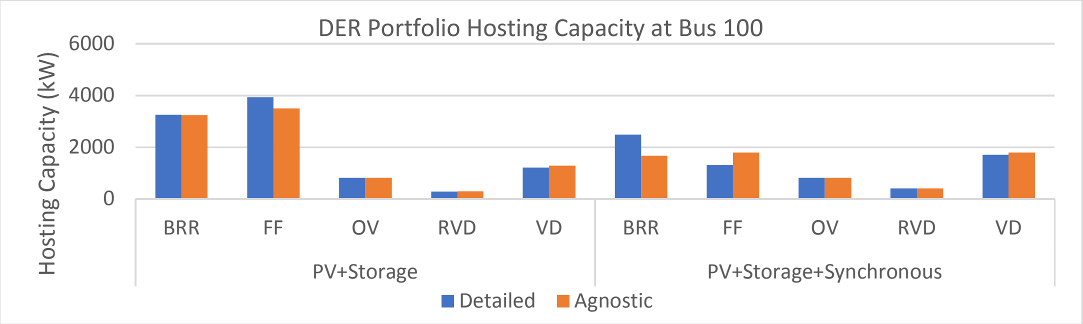


Fig. 10. Comparison of detailed and agnostic hosting capacities for portfolios of DER at each location on the 123-bus feeder.

Conclusions

It is possible to accurately translate hosting capacity values from one DER type to another in some cases. The agnostic method is most accurate for voltage-based hosting capacity for DER locations far from the top of the feeder. It also works well for protection-based hosting capacity of inverter-based DERs whose fault current is less dependent on location. Further research is needed to develop a more accurate translation to non-inverter-based DERs and DERs operating with non-unity power factor. This method provides a fast alternative to accurately account for different DER characteristics without running the detailed hosting capacity analysis multiple times.

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