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Energy Storage as a Solution for Increasing Feeder Hosting Capacity: Concepts and Analysis Methods

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SUMMARY

There is a growing interest in utilizing Energy Storage Systems (ESS) as ‘non-wires’ alternatives to traditional solutions for managing distribution feeders. As the cost of ESS reduces, several use cases, where these systems can be utilized, are being considered by utilities. One of these use cases is increasing the capacity of traditional distribution feeders to host Distributed Energy Resources (DER), either as generation sources or as load, depending upon the time of day and the mode in which the DER operates. Despite growing interest, there is no concrete roadmap or analysis method which utilities can follow to analyze ESS (in terms of sizing and location) from a hosting capacity perspective. This paper attempts to bridge this gap in knowledge by demonstrating a set of solutions developed by the Electric Power Research Institute (EPRI) in collaboration with Hydro One Limited, which can be used to analyze ESS as a tool to enhance feeder hosting capacity for DER.

KEYWORDS

Distributed generation, Distributed energy resources, Energy Storage Systems, Hosting capacity

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Introduction

Conventional solutions for distribution utilities to address the growth in electric demand and to integrate DER include reconfiguration; reconductoring; and constructing new line sections, feeders, and substations. Distribution planners identify capacity needs based on infrequent worst-case load and DER generation conditions. Energy Storage Systems (ESS) have the potential to be used as non-wires alternative (NWA) to conventional solutions. The potential benefits that ESS could provide have been widely discussed in literature (e.g. references [1-5]) However, these studies do not consider the physical model of the distribution feeders by assuming that any thermal constraints would occur at the feeder head. However, this assumption may not always hold true. In particular, on feeders with high DER penetration the highest loading may not take place at the feeder head and thus, a more detailed approach is required. Despite the potential advantages of ESS, the approaches to consider ESS as an NWA are in their infancy. For example, there are no well-established methods to site and size an ESS as an NWA to increase the feeder hosting capacity. As shown in [6], integrating ESS as an NWA introduces new considerations and analytics in the various stages of the distribution planning process. Considering ESS as an NWA requires more advanced modelling and simulation methods as compared to conventional distribution planning assessments that are based on assessing the system peak/minimum load conditions. Due to the energy-limited nature of ESS, time-series simulations are recommended for addressing ESS particularly. Quasi-static time-series (QSTS) load flow simulations solve static power flows in chronological order over a time-period to model the time-dependent operation of a feeder [7]. While various approaches have been proposed to reduce its computational time [8], QSTS simulation can still be time-consuming and requires data sets that are not always readily integrated into utility planning tools. Studying the implementation of ESS on numerous feeders, each with multiple ESS sites, sizes, etc., becomes quickly impractical for distribution planners. This paper attempts to address these problems by demonstrating a set of solutions developed by Electric Power Research Institute (EPRI) in collaboration with Hydro One Limited, which can be used to analyze ESS as a tool to enhance feeder hosting capacity for DER. These solutions are demonstrated on a North American 27.6-kV distribution feeder, which has a high penetration of DER. The remainder of the paper has the following structure: First, the simplifications to the QSTS are discussed. Second, the high-DER penetration feeder is introduced. Third, the method for feeder hosting capacity analysis is introduced and feeder baseline hosting capacity is analyzed. Next, using energy storage to increase the feeder hosting capacity is analyzed. Finally, the paper closes with a discussion of the lessons learned and key conclusions.

Simplifications to the QSTS

To estimate ESS energy capacity requirements, the ESS dispatch logic must be mimicked using time-series simulations that consider ESS state-of-charge (SOC). Some distribution planning software have the capability of modeling various storage control logics but performing multiple QSTS simulations to consider different ESS sizes quickly becomes cumbersome and time-consuming. The method proposed in this paper leverages a sensitivity-based linearized power flow approximation to allow quick ESS project screening on multiple ESS sites and feeders. The controller logic of the ESS is designed for peak clipping based on the currents of the monitored feeder element(s) and the storage SOC where the ESS operates to maintain the current below a chosen threshold. The element currents required in the controller to perform the ESS dispatch can be obtained by chronologically solving the non-linear power flow equations and determining the operation of the ESS for the next time-step. However, the relationship between specific feeder element currents and the feeder load can be linearly approximated with an acceptable error [9] via a sensitivity analysis [10]. This linear (approximate) relationship between the feeder net load S (i.e. the total connected load on the feeder assuming load models with a constant power factor and no voltage-sensitivity) and the current of a monitored element current I_m (such as lines, breakers, or transformers) can be expressed by:

$$I_{m(t)} = \frac{dI_m}{dS} S_{(t)} + b$$

where dI_m/dS and b are coefficients of the linear approximation and $*_{(t)}$ denotes time-dependent variables. The coefficients dI_m/dS and b can be solved, e.g., using ordinary least squares linear regression. The coefficients are specific to a given feeder element but a few power flow solutions within the expected feeder loading range suffice to solve the coefficients for all the feeder elements of interest. Once the load-current relationship has been determined, it can be leveraged to perform the time-series ESS dispatch simulation without the need to solve power flows at each time-step. By stepping through time, the operation of the ESS with a specific discrete controller logic can be determined while still considering the time-interdependencies of the system (e.g. $SOC_{(t)}$). To re-emphasize, this approach requires solving only a limited number of power flows to estimate the linear relationship after which the time-series simulation can be conducted without the need of a power flow solver.

Case Study Distribution Feeder

The analysis tools developed for evaluating ESS as a hosting capacity tool, were demonstrated on an actual North American 27.6 kV feeder that is supplied by a 115/27.6 kV transmission substation feeding two 27.6/8.32 kV distribution substations and other loads. The feeder peak load is ~11.2 MW and it also has an 18 MW wind plant and ~2 MW of distributed PV. Figure 1 shows an overview of the feeder. Due to the high DER penetration, the feeder experiences frequent and very high reverse power flows and thus, was a perfect case study for assessing energy storage as an NWA to increase hosting capacity / DER integration.

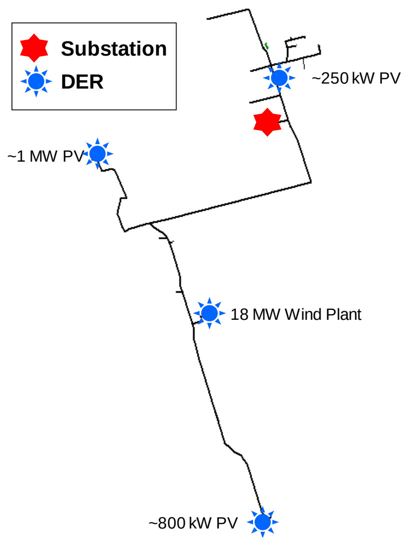

Figure 1 Overview of the case study high-DER penetration distribution feeder

The high reverse power flows were largely caused by the 18 MW wind power plant on the feeder. To perform detailed time-series analysis, it was necessary to construct time-series load profiles for the feeder real and reactive power load (net load without PV and wind), for the wind plant, and for the distributed PV on the feeder. The wind plant power output was modeled using the generation profile provided by the utility and applying a known constant off-nominal power factor of 0.99 (inductive). However, since no PV monitoring data was available, the PV output was modeled using typical meteorological year (TMY) data obtained from the National Renewable Energy Laboratory (NREL) System Advisory Module (SAM). The feederhead native load (without wind and PV) was estimated from the feederhead net load measurements (which include wind and PV), wind plant measurements, and estimated PV measurements. All powerflow analyses were performed in OpenDSS.

Feeder Baseline Hosting Capacity Analysis

This section shows the detailed feeder baseline (no energy storage) hosting capacity analysis. The objectives of this analysis were: 1) Identify the constraints limiting the hosting capacity, 2) Get an indication of what the storage may be required to do to increase the feeder hosting capacity (approximation of the required storage power and energy capacity), and 3) Get an idea of possible/required storage locations.

The hosting capacity was calculated using the EPRI DRIVE© tool [11]. From the many hosting capacity constraint types that can be analyzed by DRIVE, this analysis focused on thermal overloads (due to DER generation and load) and steady-state overvoltages and undervoltages. Typically, hosting capacity is analyzed for the (daytime) feeder peak and minimum load conditions, or other worst-case scenarios that bound the hosting capacity. *Careful selection of the hosting capacity scenarios is very important since hosting capacity is highly dependent on the selected scenarios*. It can be challenging to select the hosting capacity scenarios for feeders with high penetration of DER, such as the feeder analyzed in this paper, due to the large influence that the existing DER has on the feeder. In this study, the feeder hosting capacity was analyzed for three carefully selected hosting capacity scenarios listed in Table 1.

Table 1 Selected hosting capacity scenarios

Scenario Number	Scenario Name	Feeder Net Load [MW]	Feeder Net Load [Mvar]	Total Wind & PV Generation [MW]	Feeder Native Load [MW]	Feeder Native Load [Mvar]	LTC Secondary Current [Amps]
1	Peak load with existing DER generation at max	-8.40	7.22	19.8	10.84	2.00	222.3
2	Peak load with existing DER generation at zero	11.14	2.42	0	10.84	2.00	224.4
3	Min load with existing DER generation at max	-14.92	6.588	19.8	4.28	0.79	328.2

The baseline hosting capacity analysis results are summarized in Table 2. Due to its 27.6-kV voltage class, the analyzed feeder is quite stiff. Hence, the feeder voltage drop was limited in the scenario with peak load and existing DER generation at maximum, and the feeder voltage rise was limited in the scenario with minimum load and existing DER generation at maximum. Nevertheless, under the utility planning criteria, the feeder hosting capacity was mainly limited by overvoltages for DER generation and undervoltages for DER load. A sensitivity hosting capacity analysis was performed with the feeder current ratings reduced from the original 600-A utility limit to 400 A. This resulted in the feeder hosting capacity to be mainly limited by thermal for DER generation and load.

Table 2 Selected hosting capacity scenarios

Scenario Number	Scenario Name	Hosting Capacity Analysis Summary Results
1	Peak load with existing DER generation at max	• Hosting capacity on most feeder locations was limited by primary overvoltages. The hosting capacity was 7 MW at the wind farm and 2.6 MW at the feeder end. • Thermal constraints (600 A limit) and other constraints allowed hosting more DER.
2	Peak load with existing DER generation at zero	• From the substation to the wind farm, the hosting capacity was limited by primary overvoltages. The hosting capacity at the wind farm was 7.4 MW limited by primary overvoltages. • Downstream from the wind farm, the hosting capacity was limited by primary undervoltages for load. The hosting capacity at the feeder end was 4.3 MW. • Thermal constraints (600 A limit) allowed hosting much more DER.
3	Min load with existing DER generation at max	• Hosting capacity was limited by primary overvoltages. The hosting capacity at the wind farm was 5.6 MW. • Thermal constraints (for 600 A limit) allowed hosting much more DER.

Increasing Hosting Capacity with Energy Storage

In this section, the feeder hosting capacity with energy storage is analyzed. As stated previously, with the actual 600 A current limit, the feeder hosting capacity was mainly limited by primary overvoltages for DER generation and primary undervoltages for DER load. However, it is unlikely cost-effective to apply energy storage to increase hosting capacity limited by overvoltages and undervoltages. Instead, it is likely more cost-effective to increase feeder voltage-related hosting capacity by DER off-nominal power factor, DER smart inverter functions, manual changes to the existing voltage regulation equipment (LTCs, voltage regulators, capacitor banks) settings, additional voltage regulation equipment, etc. Compared to increasing voltage-constrained hosting capacity, increasing thermally-constrained hosting capacity is expected to be an economically more attractive energy storage application that may allow avoiding costly conventional distribution upgrade measures such as reconductoring feeder line sections; upgrading transformer(s); constructing a new feeder, new substation, etc. This section analyzes using energy storage to increase the feeder thermal hosting capacity. The purpose of this section is to illustrate concepts and analysis methods assuming a current limit of 400 A (instead of the actual 600 A utility limit). This section also analyzes the storage requirements with respect to different feeder current limits.

Conventionally, it has been sufficient for distribution planners to monitor and plan feeder loading at the feederhead at the substation. However, as observed in this analysis, in scenarios where feeder hosting capacity is thermally-limited by DER generation, the feeder *maximum phase current location may vary depending on the coincidence of load and DER on the feeder and the maximum phase currents may not be experienced at the feederhead*. Also, the feeder maximum phase currents are driven by DER, as opposed to load like conventionally in distribution planning. Similar to the feederhead currents, the maximum phase currents of the feeder elements are also linearly correlated with the feeder DER growth. As a result, it is possible to apply linear approximations to simplify the storage planning process [9], [10]. Figure 2 shows the energy storage power and energy requirements for a range of feederhead current limiting values for a base case without load and DER growth on the feeder. The figure shows that the peak current without energy storage would be 379.4 A and that a 350 A (325 A) current clipping limit would require ~2.0 MW (~3.6 MW) storage power capacity. While the storage power capacity requirement depends linearly on the current limit (until the current limit is sufficiently high not to require any storage), the storage energy capacity requirement increases much faster than linearly with respect to the current limit.

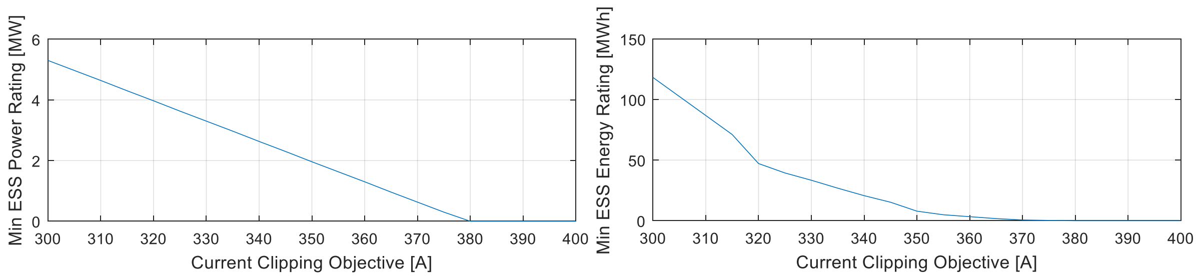

Figure 2 Storage power and energy requirement with respect to the current clipping limit for the base case without load and DER growth on the feeder

In a capacity deferral application, storage is required to discharge at high feeder loading times to limit high feeder forward currents caused by load. In the hosting capacity application analyzed here, storage is required to charge at high feeder DER generation times to limit high feeder reverse currents caused by DER generation. The storage requirements in these two applications are similar just with different current directions. Thus, storage sizing in the reverse current limiting application can be performed leveraging linear approximation. The linear approximation is shown to be very accurate in capacity deferral applications [12], where the feeder currents can be accurately represented with respect to feeder loading level. However, in the reverse current application analyzed here, the feeder currents are significantly influenced not just by the feeder load, but also by the feeder wind and PV generation. Thus, the linear approximation becomes more complicated and its accuracy is unclear. Figure 3 visualizes the linear approximation accuracy with respect to the feeder load, PV generation, and wind generation levels. The linear approximation is very accurate with the maximum approximation error being less than 10 A. The jaggedness seen in the two bottom plots is caused by the LTC tap switching. Note that the accuracy of the linear approximation depends on the number and location of points selected for the linearization.

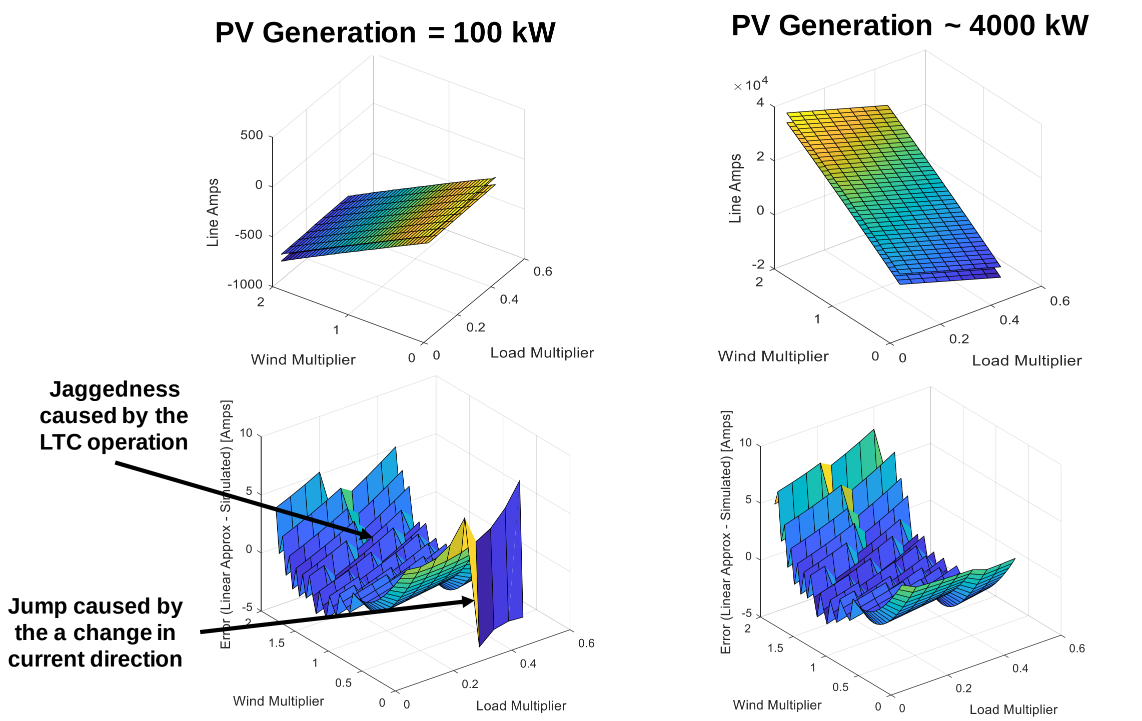

Figure 3 The accuracy of linear approximation in representing the feederhead currents with respect to the feeder loading, PV generation, and wind generation levels. The top left plot shows the simulated and approximated line currents with respect to the feeder load and wind generation for PV generation equal to 100 kW. The top right plot shows the same plot for PV generation equal to ~4000 kW. The two bottom plots show the differences of the two planes (simulated and approximated) in the top plot.

As shown above, the linear approximation becomes more complex on feeders with high DER penetration, particularly on feeders with multiple DER types. Nevertheless, the linear approximation can be a useful screening tool to, e.g., identify the storage sizing requirements across a large number of sensitivities. The advantage of the linear approximation approach is that it allows to very rapidly perform sensitivity analysis on the storage sizing under various operating conditions. For example, Figure 4 illustrates the storage power and energy requirements for different peak clipping limits and DER growth levels. Leveraging the linear approximation, this plot requires running only a handful of powerflows, which takes just seconds to run. Note that each dot corresponds to a time-series simulation. It would take hours to create a plot like this based on QSTS simulations, even with extremely fast QSTS simulations enabled by OpenDSS.

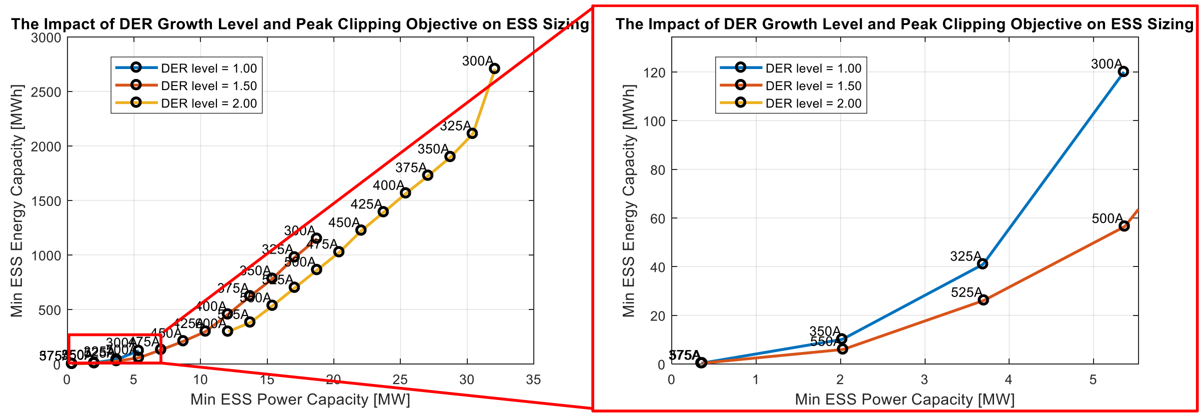

Figure 4 The impact of DER growth on storage power and energy requirements for different ampacities

Key Take-Away and Lessons Learned

The key take-away and lessons learned from this work are as follows:

- It can be challenging to appropriately choose the hosting capacity scenarios with a high penetration of existing DER.
- An approach to leverage the EPRI DRIVE© tool to analyze the feeder hosting capacity, the factors limiting the hosting capacity, and to identify storage operational requirements to increase hosting capacity was shown.
- On the analyzed feeder, the hosting capacity was mainly limited by primary overvoltages for DER generation and undervoltages for DER load. However, it is important to carefully consider the limits applied for the hosting capacity analysis, and how the limits apply to the dynamic operating characteristics of energy storage. For example, using a lower reverse current limit in this study, resulted in completely different hosting capacity results.
- On high-DER penetration feeders, the location of the feeder maximum phase currents may vary depending on the coincidence of load and DER on the feeder. In particular, the maximum phase currents may not be experienced at the feederhead.
- An approach to identify energy storage power and energy capacity requirements leveraging linear approximations was shown. In addition to the feeder load, the linearization must also be performed with respect to the DER on the feeder. The linearization becomes more complex when the feeder has multiple types of DER that are considered separately.
- For the analyzed data set, energy storage power and energy capacity requirements were independent of each other. However, for other feeders with different load and

DER coincidence characteristics, the storage energy requirement may depend on the chosen storage power capacity.

- The accuracy of the linearization depends on the number and location of scenarios (powerflows) used to create the linear approximation. The linearization can be an effective tool to screen storage size for a large number of sensitivities.

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