ELECTRIC POWER RESEARCH INSTITUTE

# UNDERSTANDING FLEXIBLE INTERCONNECTION

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"Flexible Interconnection" is a term that is likely to rapidly become familiar within the distributed energy resource (DER) integration community. As described in this paper, it refers to the number of options that are available for DER interconnection, and in particular to options that involve real-power control. These modes of control are increasingly available in DER but are not typically used.

Flexible Interconnection seeks to increase distribution system utilization allowing more DER while lowering the cost of integration. The possibilities of flexible interconnection are becoming well known to solar and storage developers and these stakeholders are vocal in forums such as IEEE1547 meetings to express interest. The US Department of Energy is accelerating research in the area, making flexible interconnection a central focus of a recent funding opportunity announcement from the Solar Energy Technologies Office.[1]

When flexible interconnection is offered and demonstrated in one region, it is likely that DER developers and other industry stakeholders will expect similar options everywhere. This likelihood underscores the importance of understanding the concept and how it might impact utility processes.

## DER Interconnection

Interconnection rules and processes are applied when utility customers and third parties desire to grid-connect equipment that generates or stores energy. These rules are designed to ensure that distribution system performance and reliability are maintained at acceptable levels following the deployment. The processes ensure that technical screening, studies and inspections are carried out as needed. Interconnection rules have gained attention recently because of the rapid deployment of DER such as photovoltaic (PV) and battery storage systems.

The technical requirements of interconnection, generally referred-to as grid codes, establish performance criteria that DER must meet to be eligible. Grid codes are usually set up on a regional basis (e.g. utility by utility) and are typically based on broader technical standards such as the IEEE 1547. In recent years, the complexity of grid codes has risen sharply, moving from simple "do no harm" rules to "grid-friendly" requirements. Modern inverter-based DERs such as PV and storage can perform a wide range of grid-supportive services, and as they have become more common, it has become necessary that some of these capabilities be made mandatory in order for distribution systems to accommodate the increasing levels of DER.

Options available to utilities and DER developers at the time of interconnection depend on many factors, including technical and policy aspects. They also depend heavily on the availability of the communication and control systems necessary to support particular options. In keeping with societal interest in more distributed resources, utilities are operating more complex systems and managing additional equipment.

## Hosting Capacity

Before delving into flexible interconnection, it is useful to review the concept of hosting capacity, which describes the limits in scale and quantity of DER that can be accommodated on a distribution system. There are technical constraints for voltage regulation, thermal loading, protection, and power quality. These constraints derive from time and location varying load, existing distributed generation, and the electrical characteristics of the power system. "Hosting capacity" is a broad term that encompasses several individual factors that characterize a power system's ability to host DER.[2] While it is outside the scope of this document to provide a complete treatment of hosting capacity, the aspects most germane to flexible interconnection are described in the following sections.

1 https://www.energy.gov/eere/solar/funding-opportunity-announcement-fy-2018-solar-energy-technologies-office

2 Impact Factors, Methods, and Considerations for Calculating and Applying Hosting Capacity. EPRI, Palo Alto, CA: 2018. 3002011009.

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*This white paper was prepared by Brian Seal, Electric Power Research Institute.*



## Single-Site and Multi-Site Hosting Capacity

The term "hosting capacity" may refer to the distributed multi-site hosting capacity of a power system or may refer to the centralized, single-site hosting capacity at one point where DER can be connected to the grid. Multi-site hosting capacity is reflective of the aggregate hosting capability of a circuit (total MW) and depends on the locational distribution of the DERs. Single-site, on the other hand, relates to a given *point of DER connection*.[3] For either, it is possible to identify:

- The total hosting capacity – what would be possible if no DER were yet deployed
- The remaining hosting capacity – what DER can be deployed in addition to existing plants

Each time a DER is deployed at any location on the grid, the remaining hosting capacities change throughout the system.

## Hosting Capacity is Time Varying

Hosting capacity is inherently time-varying because the underlying load, generation, temperature, control settings, circuit configuration and other system parameters vary with time. In Figure 1, the single-site hosting capacity (black-dashed curve) is determined by the lesser of the time-varying thermal and voltage limits. The capacity changes over time, including daily, weekly, and seasonal variations. To be permitted at this site, a DER's output cannot exceed the single-site hosting capacity at any time.

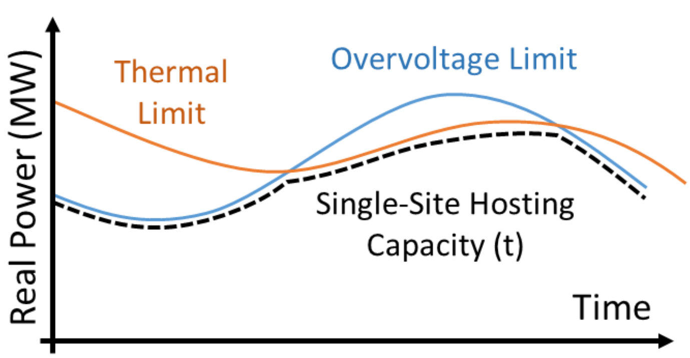



*Figure 1. Time Dependence of Hosting Capacity*

When an analysis is conducted for a single DER interconnection, it is common practice to focus on the time-period(s) at which the DER can be at maximum output. As illustrated in the solar photovoltaic (PV) example of Figure 2, this allows a single value to be used, rather than a curve, to describe the DER nameplate capacity that can be deployed at that site. The DER output waveform (blue curve) is an example of what actual PV production could look like in a given day, varying within the *DER Capacity(t)* envelope. This example is referenced later.

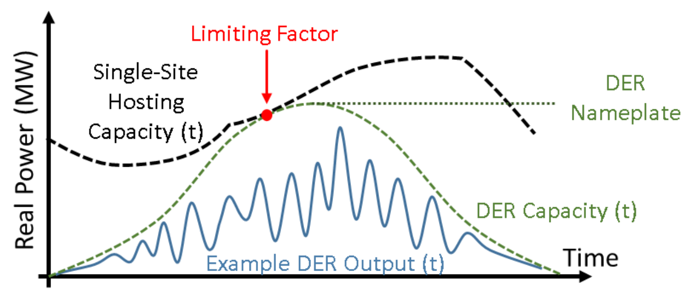



*Figure 2. PV Hosting Capacity Example*

## Hosting Capacity is Location-Dependent

Both single-site and multi-site hosting capacities are location dependent due to the nature of circuit characteristics, control elements, load concentrations and other DER. This means that the single-site hosting capacity can vary from location to location as illustrated in Figure 3.


*Figure 3. Location Dependence of Single-Site Hosting Capacity*

The multi-site hosting capacity of a power system is similarly dependent on locations (distribution of deployment) of DERs on the system. This is illustrated in Figure 4 with additional details provided in several prior EPRI reports.[4] For example, if DER's are

3 Reference IEEE 1547-2018 definitions.

4 *Distributed Photovoltaic Feeder Analysis: Preliminary Findings from Hosting Capacity Analysis of 18 Distribution Feeders*. EPRI, Palo Alto, CA: 2013. 3002001245



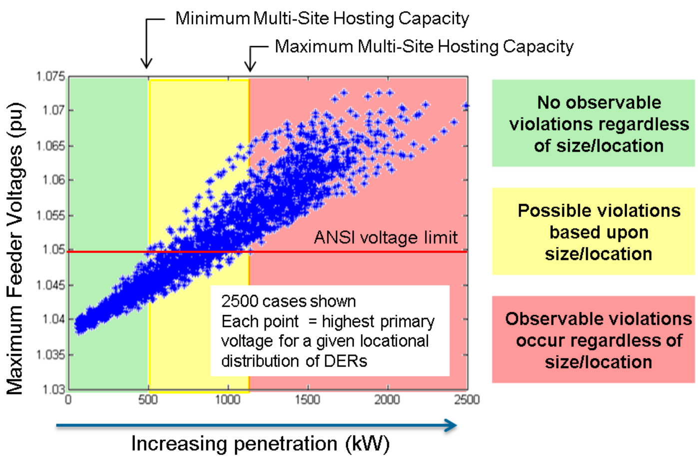



*Figure 4. Locational Dependence of Multi-Site Hosting Capacity*

concentrated toward the ends of a feeder, the hosting capacity may be less than if they are concentrated near the substation.

## Conventional Interconnection Options

Because solar PV systems have traditionally functioned in peak-power-tracking, unmanaged modes of operation, it is common for just a few interconnection options to exist, such as:

1. Limit the scale of the PV system so that its output will remain below the single-site hosting capacity (may or may not involve Var support)
2. Make infrastructure improvements that increase the single-site hosting capacity

Limiting plant scale is straightforward, but in some cases may result in a system size that is less than the plant developer would like to deploy. Infrastructure improvements are more involved and may include any number of asset, grid-configuration or control changes that have the effect of increasing the hosting capacity at the location of interest. These changes can have varying degrees of impact on distribution system performance and result in both firm and non-firm grid capacity improvements, as explained below. Determining the cost of infrastructure improvements and who pays is complex and is beyond the scope of this paper.

What these options have in common is that they limit the extent to which the distribution system asset is utilized. This observation has raised the question of what other options might be available to utilities and those seeking to interconnect—how DER operation, and interconnection, might become more flexible.

## Flexible DER Operation & Real-Power Management

The foundations of conventional interconnection are built on the assumption that DERs operate in a free-running unconstrained way—potentially producing at their full power capability at any time, according to their design and owner's interests. As a result, distribution systems are expected to absorb this full power whenever it appears. Alternatively, if DER operation could be managed, and reliably so, then in theory grid utilization might be increased, supporting more average energy transfer and larger DER sizes in more locations. For example, the illustration in Figure 5 shows a single-

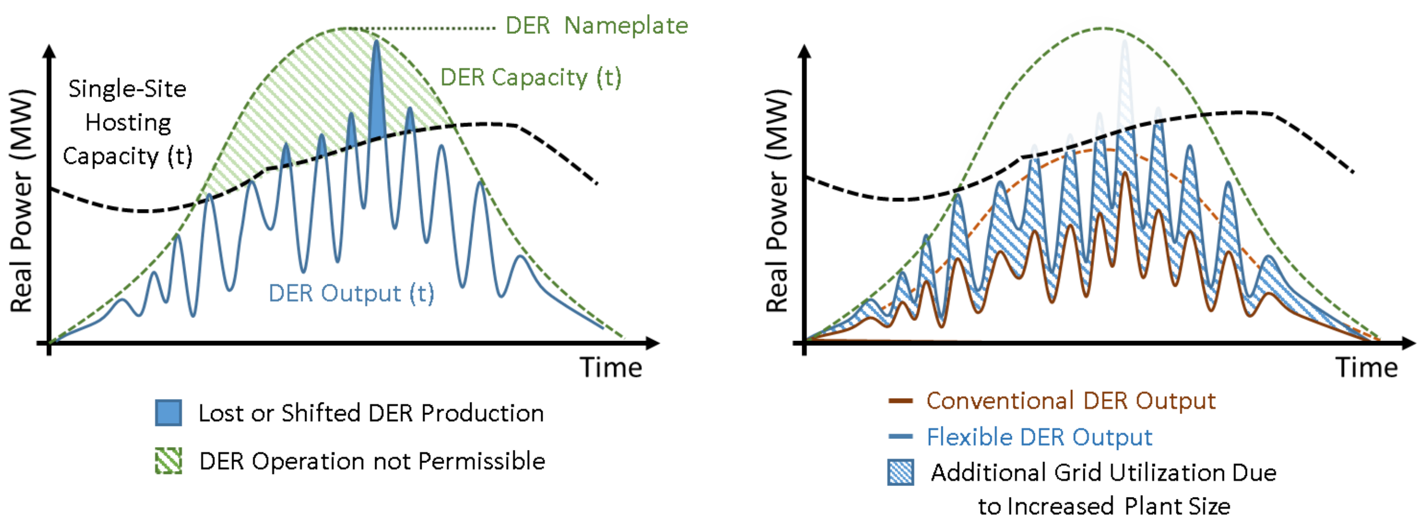



*Figure 5. Example Real-Power Management Scenario*

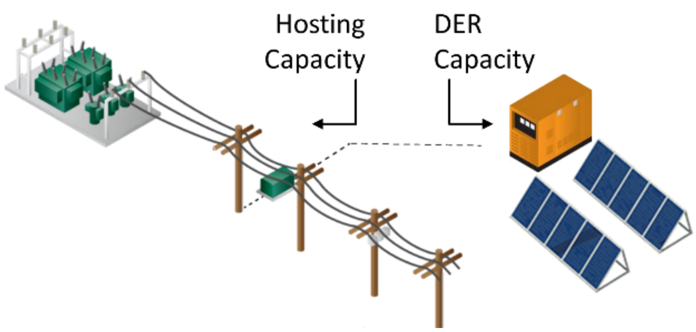


site hosting capacity with DER sized well above the unconstrained limit. Plant operation in the green hatched area is not permissible, so the DER output is curtailed as needed. This is an example of flexible operation of DER, and the availability of such options constitutes "flexible interconnection". The solid blue shaded area represents watt production that was possible from the plant, but shifted or curtailed due to power system constraints. The blue hatched area in the right pane emphasizes the additional grid utilization that results from the increased plant size.

When management of real-power (Watts) comes into play, it is necessary to think separately about the hosting capacity parameters that describe what the grid can accommodate and those that describe the scale of the DER that can be connected. For example, when operating under a given real-power management scheme, a DER with a 1.2MW nameplate rating might be connected at a location with a remaining hosting capacity of only 1MW. Similarly, multiple DERs totaling 7MW capacity might be connected to a feeder with a maximum capacity of 5MW if real-power is managed. Making this distinction can help provide clarity in hosting capacity considerations that involve flexible interconnection.

*Table 1. Types and Attributes of Grid Hosting and DER Capacity*

| Grid Hosting Capacity[1] | DER Capacity[2] |
|---|---|
| Single-Site Hosting Capacity | Single-Site DER Capacity |
| Multi-Site Hosting Capacity | Multi-Site DER Capacity |




[1] Attributes of the grid, influenced by grid configuration, control, load, existing DER, etc.

[2] Attributes of the connected DER, nameplate ratings made permissible through management of DER real-power.

## Flexible Interconnection Perspectives

"Flexible Interconnection" adds to available options for connecting DER to the grid. Realization of these options involves challenges in that it requires coordinated control of the DER output. The result, however, has potential appeal to both utilities and DER developers.

### *DER Developer Perspective*

For an entity proposing to construct a new DER, flexible interconnection has the potential to improve overall economics. It provides alternatives to the conventional options of limiting DER size or making grid infrastructure upgrades. Larger plants, with greater output and better economies of scale may be permitted at more locations through managed operation of the DER's real-power. The expected losses in production, together with the control costs, may (or may not) be more appealing than other options. Figure 6 illustrates this idea.

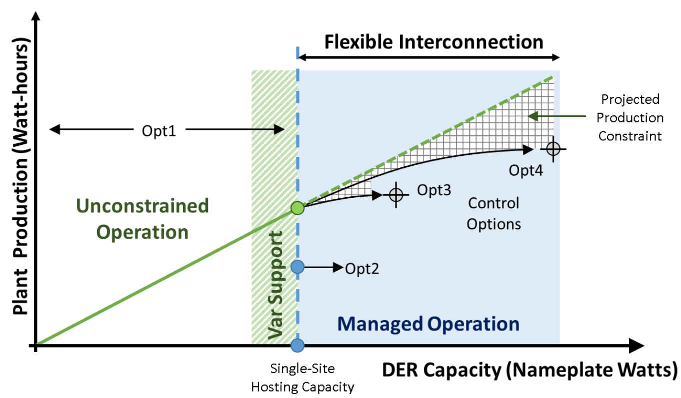



*Figure 6. Developer View of Flexible Interconnection*

The horizontal axis represents the scale (Watts) of a proposed plant, at a given location of interest. The vertical axis represents the productivity that might be expected from the plant, such as annual PV energy output. In the "Unconstrained Operation" area, the plant can run at its full capability and grid availability is firm. This might be thought of as "Option 1", and is the most commonly used limit for hosting today. Unconstrained operation is only possible up to the Single-Site Hosting Capacity at which point some firm hosting limit would be exceeded in the planning horizon. As illustrated by the hatched "Var Support" area, it may be possible to increase the unconstrained operation range by using reactive power functions, but this too has its limitations. Option 2 is also common and represents upgrades to the power system that mitigate some limitation and increase hosting capacity at the site.

Flexible interconnection options may enable larger plants to interconnect without the need for immediate infrastructure upgrades, albeit with reductions in annualized plant productivity. Although energy reductions are not ideal, the opportunity to deploy a larger plant may be attractive to the entity considering the deployment. In Figure 6, the dashed green line represents the ideal plant production that would result if there were no hosting capacity limitations. As illustrated by the example control options 3 and 4, each control strategy results in a different estimated "plant productivity curve" that drops below the ideal line as the plant size is increased above the single-site hosting capacity limit.

The difference between the ideal line and the plant productivity curve is of critical business importance to a plant developer who may have multiple locations and multiple control options to choose from. To estimate these differences involves forward-looking estimations of weather (e.g., solar irradiance), the circuit model, load distribution and shape, existing or new DER, and distribution system control specifics. EPRI research is developing reference calculation methods to provide insight into these curves.

## *Utility Perspective*

For the entity that operates the distribution system, flexible interconnection can be viewed from the perspective of infrastructure utilization. Just as product manufacturers seek to reduce per-unit costs by maximizing production from a given plant, utilities aim to reduce power delivery costs by maximizing the quantities of energy that can be handled by a given circuit infrastructure. In some circumstances, flexible interconnection could work together with infrastructure investments to optimize costs for customers.

Figure 7 illustrates this view. In this case, the horizontal axis is the aggregate, multi-site capacity of DER connected to the circuit of interest. The vertical axis represents the resulting transported energy

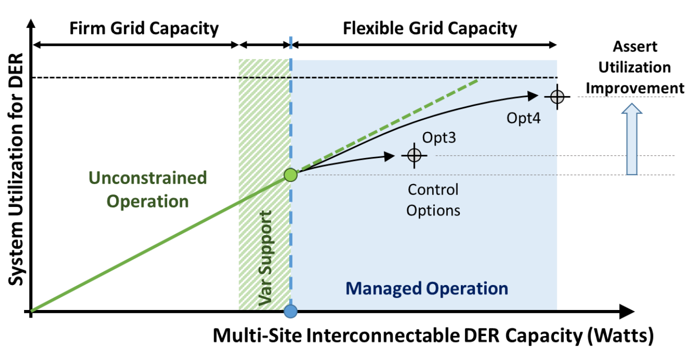



*Figure 7. Utility View of Flexible Interconnection*

(Watt-hours) from these DER – one factor in system utilization. As in the prior section, this is best viewed as a long-term figure, such as annual PV production.

Across the horizontal range, the grid provides firm capacity and additional flexible capacity. *Firm capacity* is the range of multi-site DER production that can be accommodated with no constraints-— DER can generate as their capabilities allow, and the power system always has the capacity to transport the energy. *Flexible capacity* indicates additional capacity that can be supported by the grid under various managed modes of DER control. The increases in hosting capacity achieved through Var support may or may not be viewed as "firm", depending on the level of confidence in the present and future availability of these services.

The green line depicts a 100% capacity factor, meaning full energy production relative to plant rating. For PV systems, for example, the slope of this line would be the annual kWh production per kW of plant (dependent on geographical location, PV technology, DC:AC ratios, etc.). A typical PV plant maximum capacity factor is ~20%. In the *firm* capacity region, this line is straight—i.e., increasing the deployed capacity increases the energy production proportionally. When the total connected DER reaches the limit for unconstrained operation, no more can be connected without some form of DER management.

Flexible capacity is realized through the utility DER control option(s) that are made available. Each control option allows some increase in supportable DER, and results in some corresponding increase in energy production and grid utilization. For example:

- The option of activating the DER's autonomous Volt-Watt function to mitigate a local overvoltage constraint
- The option of connecting the DER to a management system (DERMS) that variably limits its power output when needed to mitigate a thermal or other constraint

Each control option may achieve a certain increase in aggregate interconnectable DER Capacity, but next-level limits always exist. Options that lead further up and to the right on the chart are the highest performing, but each has costs in terms of losses, controllers, networks, and operation so comparing one option to another requires analysis.



## Challenges of Flexible Interconnection

While Flexible Interconnection has potential benefits, it also creates technical challenges and concerns. Foremost is the requirement for reliable output control. One concern is that a DER management system (whether local or remote) will fail to function and the DER will produce power levels that the grid cannot accommodate at that time and location. Failsafe mechanisms would have to be developed that ensure that this could not happen. For example, plant design could be such that permission to operate in the non-firm capacity region is granted by continuous connectivity to a utility control system, the loss of which would result in immediate fallback to firm levels. In addition, secondary protection equipment could be installed at the point of connection that trip under certain grid conditions or if loss of control is detected. More research is needed to develop these mechanisms and to make them readily commercially available.

Utility systems, both the communication networks and control applications, suitable to perform flexible interconnection are emerging technologies and are not deployed at scale at most utilities. This is a substantial component of overall distribution modernization and requires new skill sets and investments.

Other concerns involve the permanence, or lack thereof, of grid support coming from non-utility assets and the question of how planning and operations could take into account the possibilities of DER plants that are unexpectedly taken offline for maintenance or closed/shutdown permanently.

In addition to the technical challenges, contractual arrangements and tariff structures that support flexible interconnection have yet to be decided at the distribution level. There are many parallels to firm and non-firm transmission service which has been well defined through years of regulatory activity through FERC. How contractual ownership of the physical or firm distribution capacity is managed and the rules associated with flexible operation of DER in a non-discriminatory basis may yet be determined in many jurisdictions. Further, each state may decide their own rules at the distribution level. Deciding how these flexible arrangements are coordinated with the bulk power system is also an area that needs more attention.

## Looking Ahead

As DER levels rise, the methods by which they are managed will likely progress to include real-power management. Grid codes like IEEE 1547, CA Rule 21, and others in Germany, Japan, and worldwide are laying the foundation for this progression by requiring that DER have the core capability and communication interfaces that will be needed. As this capability becomes common in products, DER developers and policy makers may become interested in taking advantage of these features to enable more or larger scale DER to be deployed.

This future scenario is technically and economically complex. Preparing for it will require research and experimentation as well as a range of key utility capabilities:

- Advanced two-way communication systems: Real power management of DER is typically more frequent and interactive than Var support schemes, many of which can be autonomous. The latency requirements may drive the need for higher speed networks and, if used for residential DER, the total throughput may be higher than present SCADA or AMI systems can support, driving the need for advanced Field Area Networks. Reliability and availability must be high, including redundancy and carry-over to minimize communication system outages.
- Distributed Energy Resource Management Systems (DERMS): Most of the conceptual methods for flexible interconnection and real-power management cannot be achieved autonomously and depend on DERMS that compute and transmit time-varying requests to devices. As described in EPRI's recent whitepaper[5] DERMS may be centralized software or distributed control systems such as facility, community, or microgrid controllers.
- Cyber security: The communication systems and applications needed to manage high levels of DER become critical to system operations and accordingly demand advanced cyber and physical security end-to-end.
- Updated planning and interconnection processes. As discussed herein, flexible interconnection tends to decouple the grid's hosting capacity from the quantity/scale of DER that are deployed on it. Real-power management changes the profile and characteristics of the DER which in turn impacts planning analysis.

EPRI is conducting research and working with member utilities in laboratory and field projects aimed at securing these capabilities. These projects are evaluating control systems (DERMS), assessing the impacts of various control algorithms, developing new tools for hosting capacity calculation (DRIVE), and advancing the state of interconnection processes and screening.

5 *Understanding DERMS*. EPRI, Palo Alto, CA: 2018. 3002013049

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***Distributed Energy Resource Integration***

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