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Analysis of Grid Strength for Inverter-Based Generation Resources on Oahu

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SUMMARY

As power electronic sources of generation such as wind, solar, and battery energy storage increase on a grid, the amount of generation from conventional synchronous generators (gas turbines, steam turbines, etc.) is reduced. While the real power produced by the power electronic sources may be the same as that produced by conventional synchronous generators, there are inherent characteristics of synchronous generators that contribute to the stability of the power system that are not inherently shared by power electronic sources. Specifically, the conventional synchronous machines provide a voltage source to the grid that does not change in short timeframes. Colloquially, grid strength is a description of how much (or little) bus voltages on a system are altered due to a perturbation in current in the system. Grids in which bus voltages move relatively little for a current perturbation are considered "strong" and are often associated with many synchronous machines that "anchor" the voltage. Because the performance of power electronic-based generation is dependent on the grid strength at their interconnection, a significant reduction in grid strength (often associated with power electronic sources displacing synchronous machine sources) has implications for grid stability and reliability.

While keeping extra synchronous generators online will benefit grid strength, there is an economic cost of this approach. With additional thermal generators online, units are backed down to lower power output relative to the unit's maximum operating level. In addition, if units are unable to reduce power output further due to minimum stable operating constraints, additional wind and solar may not be able to be accepted by the grid due to over-supply. This wind and solar energy is thus curtailed in lieu of expensive, oil-fired generation. While some degree of synchronous machine support is likely in even a 100% renewable future, the solution to weak grid operations is ultimately through inverter technology development.

The objective of this study is to analyze the trends in grid strength across the Oahu power system as additional distributed photo-voltaic generation (DPV) is added and synchronous generation is decommitted. Quantifying the grid strength across an entire power system is a relatively new endeavor and more information on the performance of DPV inverters is required before full conclusions can be made, minimum thresholds can be drawn, and requirements can be codified. Given this limitation, this study is intended to increase awareness around weak grid issues on Oahu (and other high renewable grids in general), illustrate the trends with increased DPV additions, and to outline a series of next steps to investigate further. While similar analysis has been conducted for remote regions of large mainland power systems, and there are examples of 100% power electronic microgrids, we believe

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Oahu and other island power systems could be the first places where the entire power system is characterized as a "weak grid."

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KEYWORDS

Hawaii, grid stability, grid strength, renewable integration, distributed generation, distributed energy resources, distributed photovoltaics, solar, wind, island power system

INTRODUCTION

As power electronic sources of generation such as wind, solar, and battery energy storage increase on a grid, the amount of generation from conventional synchronous generators (gas turbines, steam turbines, etc.) is reduced. While the real power produced by the power electronic sources may be the same as that produced by conventional synchronous generators, there are inherent characteristics of synchronous generators that contribute to the stability of the power system that are not inherently shared by power electronic sources. Specifically, the conventional synchronous machines provide a voltage source to the grid that does not change in short timeframes. Colloquially, grid strength is a description of how much (or little) bus voltages on a system are altered due to a perturbation in current in the system. Grids in which bus voltages move relatively little for a current perturbation are considered "strong" and are often associated with many synchronous machines that "anchor" the voltage. Because the performance of power electronic-based generation is dependent on the grid strength at their interconnection, a significant reduction in grid strength (often associated with power electronic sources displacing synchronous machine sources) has implications for grid stability and reliability.

To use an analogy, grid strength can be thought of as a measure of the "electrical stiffness" of the voltage at a particular bus in an electrical grid. An infinitely strong bus would have an ideal voltage source connected to it with zero impedance, such that any attempt to change the voltage at that bus would be met with an infinite supply of current that would keep the voltage the same. Conversely, a weak bus would be one where it is relatively easy to change the voltage at the bus by drawing or sourcing current, whether the source or sink of current is an air-conditioning motor or a distributed photovoltaic (DPV) solar inverter. A weak bus could be considered a bus connected to an ideal voltage source by a relatively large impedance such that devices that sink or source current would result in a significant voltage drop across the impedance between the weak bus and the ideal voltage source, thus making for an "electrically flimsy" bus voltage, to return to the mechanical analogy.

The primary advantage of a strong grid, where the buses in the grid are considered "stiff," is that the bus voltages respond less to changing currents in the network, which reduces the potential for unintended interaction among connected equipment, thus making the entire grid more stable. With the loss of the synchronous generation, grid strength erodes. The reduction of grid strength impacts:

1. The severity of voltage excursions and distortion,
2. Protective relaying accuracy, and
3. System stability.

With respect to voltage excursions and distortion, routine grid events like switching shunt capacitors and energizing transformers will produce greater voltage excursions and distortion on weaker grids. Protective relaying refers to the devices that continuously monitor transmission and distribution lines for faults and to disconnect lines quickly when a fault is detected. These relays are designed to operate correctly over a range of grid strength. If the grid strength falls outside of the range, then the protection scheme and relay settings may need to be re-evaluated. Regarding system stability, if a grid becomes too weak, then a disturbance like a fault may cause the grid to collapse, resulting in a blackout for part or potentially all of the system.

With little or no power electronic equipment connected on a network, the control stability concerns described are minimal because the network is dominated by synchronous machines. But even in large interconnected systems where grid strength is typically high, there may be pockets of the grid where a lot of power electronic devices are clustered together and connected to the grid by long transmission lines that separate the power electronics from most of the large synchronous machines on the network. For example, this is the case in the Texas Panhandle, and with the increasing number of power electronic sources of generation from both distributed and utility-scale solar and utility-scale wind projects, there is a risk that weak grid pockets will arise on Oahu that could become unstable [1].

QUANTIFYING GRID STRENGTH

There are a variety of measures for quantifying grid strength, most of which are variations of the short-circuit ratio (SCR) [2]. The nomenclature "short-circuit" may be misleading because this analysis does not pertain to the response of equipment to a fault, but rather it is a historical term used in the industry to determine the grid strength, in which the "short-circuit" function of power flow program is used. SCR in its most basic form is quantified at a particular bus in the network and is calculated as the ratio of short-circuit current (measured in MVA) from only the synchronous machines in the network to the MW rating of the power electronic equipment connected locally at the bus. The short-circuit current contribution of a synchronous machine is not a function of the operating output (MW) of the machine – it is present as long as the machine is magnetized and connected to the network. Generally, larger machines (higher MVA rating) provide more short-circuit strength than smaller machines. The majority of today's power-electronic devices do not contribute to system strength. This includes distributed and utility-scale PV, type 3 (doubly-fed) and type 4 (full conversion) wind turbines, HVDC links, and energy storage devices with a power-electronic interface (commonly used in battery energy storage systems and flywheels), electric vehicles, etc. Instead, most power electronic devices depend on the AC power grid to maintain voltages and waveshapes and a certain level of "grid strength" that assures stability of their internal control functions.

Often, a bus will have many power electronic devices connected to it, or in the local vicinity. If the different power electronic equipment is operating with the same control algorithm (identical inverter model and identical inverter settings), then it tends to act together as one large device and must be evaluated in aggregate. The form of SCR in which two or more local, identical devices are aggregated is called the composite short-circuit ratio (CSCR) [2], which is computed as the ratio of the short-circuit current from only the synchronous machines in the network at a common bus to the aggregate rating of the power electronic devices. The advantage of these measures is that they are a simple, single measure that is generally indicative of risk. However, the trade-off for the simplicity is accuracy, especially as grids become very weak. CSCR values do not convey the complex realities of power systems in deciding how "electrically close" two or more devices must be and "how similar" must their controls be in order to aggregate them.

Another similar measure of grid strength developed and applied by the Electric Reliability Council of Texas (ERCOT) in the Texas Panhandle is the weighted short-circuit ratio (WSCR) [3]. This approach was adapted in this study and applied to Oahu where a single WSCR is calculated for the entire island for a given dispatch condition. The WSCR method assumes that there is complete interaction among power-electronic sources such that many power-electronic sources connected at different point on the network behave as a single, large power electronic source with a rating equal to the sum of the individual ratings. In reality, complete interaction does not happen because there is always some impedance between different sources. Also, different makes, models, and controls on different power electronic equipment will behave differently, so it is unlikely that they will all behave as one device. This is especially true of DPV equipment because for a given MW of power electronic equipment, there is more variety of equipment and more dispersion across the network, including across individual phases. The assumption that power electronic equipment interacts completely and behaves as one large device with the sum of all the individual ratings is conservative. Any incomplete (non-additive) interaction reduces the "effective" MW rating of the equipment.

METHODOLOGY

To analyze the impact of increasing DPV penetration on grid strength, a series of models and statistical techniques were employed in this analysis to simulate both system operations and short circuit strength of the grid. A similar method has been used for frequency stability analysis of the Oahu system [4].

Step 1 - Production Cost Simulations:
The first step in the analysis was to conduct detailed hourly production cost simulations. The model simulates the system operator's unit commitment (on or offline) and dispatch (MW output) decisions

necessary to supply the electricity load in a least cost manner, while appropriately reflecting transmission flows across the grid and ensuring the system is prepared for unexpected contingency events and variability. The chronological modelling is crucial to understanding renewable integration because it simulates temporal changes to electrical load and the underlying variability and forecast uncertainty associated with wind and solar resources. This modelling was performed for two scenarios, Scenario 1 have 400 MW of DPV installed (as well as some centralized PV and wind) and Scenario 2, which is identical to Scenario 1 but with 700 MW of DPV installed, which consequently changes the commitment dispatch of generation.

Step 2 – Selecting System Dispatch Conditions for Grid Strength Simulations:
The production cost analysis (Step 1) generated 8,760 hourly dispatch conditions over the course a year of simulation, of which 21 were selected for further, more detailed, evaluation in the Grid Strength Simulations evaluated in Step 3. A broad range of system dispatches were evaluated to ensure that conclusions could be drawn holistically across a full spectrum operating conditions.

Step 3 – Grid Strength Calculations:
The grid strength of the system due to the connected synchronous machines was calculated at every 138kV bus on Oahu for each of the dispatch conditions. This was done by first disconnecting all of the power-electronic-based generation and then by applying a three-phase short-circuit at each HV bus using PSLF. The resulting short-circuit MVA from a load flow program at each bus is fed into the WSCR calculations.

Step 4 – Weighted Short Circuit Ratio Calculation:
With the short-circuit MVA from synchronous machines calculated and the MW rating of power-electronic-based generation connected to each HV bus known, the WSCR value is calculated according to a recent paper produced by ERCOT [3].

$$WSCR = \frac{Weighted\ \ S_{SCMVA}}{\sum_i^N P_{RMWi}} = \frac{\sum_i^N S_{SCMVAi} * P_{RMWi}}{\left(\sum_i^N P_{RMWi}\right)^2}$$

Where:

S_SCMVA is the short circuit MVA at bus i before the connection of power electronic plant i,
P_RMWi is MW rating of power electronic plant i to be connected,
N is the number of power electronic plants fulling interacting with each other, and
i is the power electronic plant index.

The result is a single WSCR value for the entire Oahu system for the given dispatch condition. The WSCR is therefore a weighted measure of the overall grid strength and can be used to quantify the risk to the power system from a power electronic controls stability perspective during a disturbance or contingency event (generator trip, transmission line fault, etc). Higher WSCR values are indicative of a stronger grid and lower WSCR values are indicative of a weaker grid, which is at a higher risk of controls instability.

Each 138kV bus on Oahu is evaluated in the WSCR calculation where the power electronic equipment associated with each HV bus is assumed to be the equipment most closely connected to that high voltage bus. In reality, the system is not completely radial, but has many loops where the power-electronic equipment may be considered "shared" among two or more high-voltage buses. Attributing all of a utility-scale plant to a single bus is one simplification of the WSCR method. The same approach is applied for DPV, but since the DPV is represented as 31 aggregate generators, it may be considered that the proportionate contribution to each high-voltage bus is factored in to the aggregation of the DPV.

Step 5 – Analyze Relative Grid Strength Within the Network:
The WSCR method for Oahu is augmented by another approach in order to provide insight within the Oahu network to understand the variation of grid strength across the different buses of the network. This method is called the impedance-weighted SCR or "ZSCR" and is calculated as the ratio of the short-

circuit current at a bus from contributions of synchronous machines only (as previously done for SCR, CSCR, WSCR) and dividing by the impedance-weighted rating of the power electronic equipment. The impedance-weighted rating of the power electronic equipment is determined using the short-circuit function in a load-flow program to apply a 3-phase fault at a given bus after disconnecting all synchronous machines and leaving connected all power electronic equipment. The power-electronic devices are represented by Thevenin-equivalent sources where the generator rating is the rating of the power electronic equipment and the subtransient reactance is set to 1.0 to reflect the full rating of the power electronics when the electrical distance from the terminals is zero. This method results in values with only relative meaning and little absolute meaning. In this way, they are used to compare buses to each other.

Step 6 – Estimating Weighted Short Circuit Ratio for all Dispatch Conditions:
As the amount of power electronic equipment online increases, the synchronous thermal commitment will generally decrease as fewer thermal units are required to serve load. For this analysis, these two drivers of grid strength were combined into a single metric, the Power Electronic Ratio (PER), which quantifies the relative amounts of synchronous thermal commitment and power electronic equipment online at any given time. Using the results of the production cost analysis, the PER can be calculated for each dispatch condition across an entire year of operation.

$$Power\ Electronic\ Ratio = \frac{Online\ Power\ Electronic\ MVA\ Capacity}{Total\ Online\ MVA\ Capacity}$$

where the numerator is the sum of the online (generating) MVA rating of the power electronic capacity, and the denominator is the sum of the online MVA rating of synchronous generators and the online MVA rating of power electronic equipment. The Power Electronic Ratio is thus independent of the actual power output (MW) of either the power electronic equipment or the synchronous generators. If the unit is online and generating, the entire MVA rating of the equipment is used for this calculation. As a result, the PER experiences large step changes from nighttime hours to daytime hours as the PV changes from offline to online.

After the short circuit strength and WSCR was quantified for each of the 21 selected dispatch conditions the results were used to estimate the WSCR across an entire year of operation. This was completed by evaluating a curve fit relationship between the PER and the resulting WSCR. The resulting trend line was then applied to each of the 8,760 hourly production cost results to develop an estimated WSCR across each dispatch condition.

RESULTS

Figure 1 provides a geographic map of the relative ZSCRs evaluated with the location of each high-voltage bus represented. Cooler colors (blues) represent areas with higher grid strength whereas brighter colors (reds) represent areas with lower grid strength. From this analysis, the highest grid strength is seen in the West where there is a concentration of synchronous machines, while the lowest grid strength occurs in the North and East, which are electrically distant from the West and have the highest concentration of centralized and distributed power electronic generation, respectively. These results raise important considerations for the decision on where to site new distributed or utility-scale renewable generators, the scheduling of synchronous generator retirements, and the location of potential new synchronous condensers.

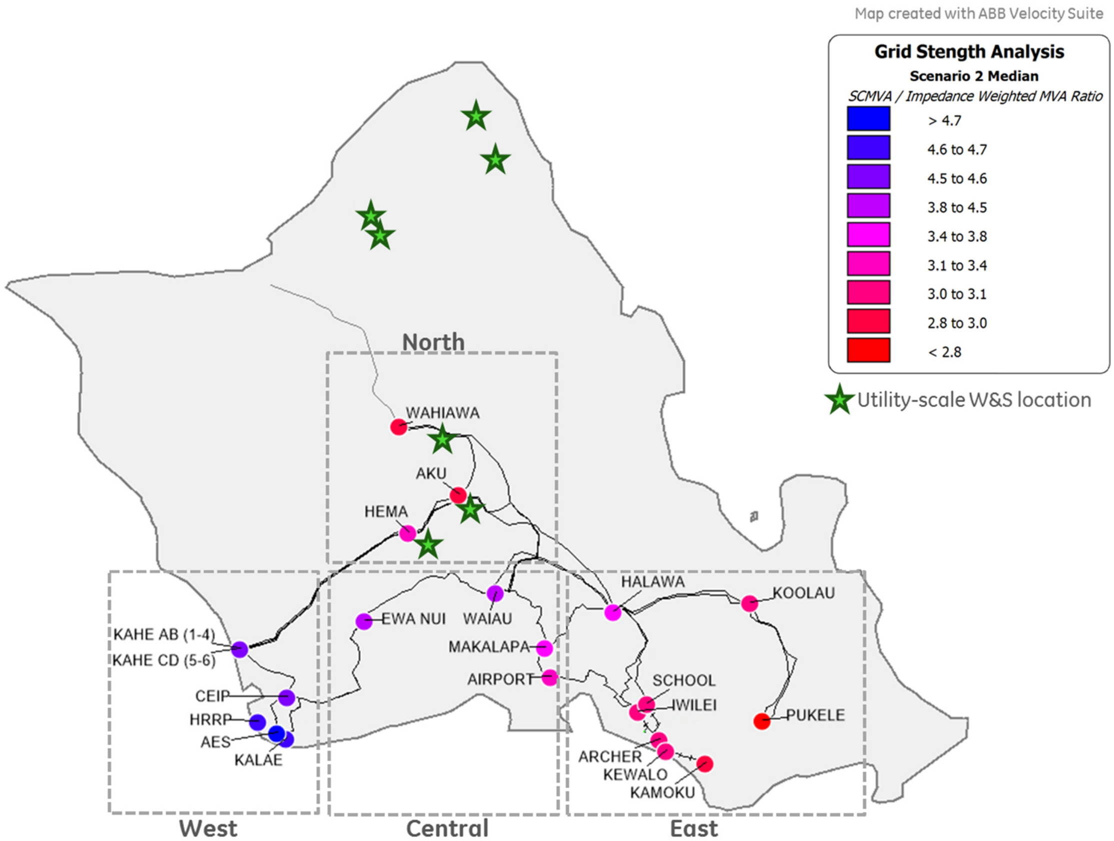

Figure 1 - Grid Strength Analysis of High-Voltage buses in Oahu

It is also important to consider all hours across the year because grid stability must be maintained at all times. In this case, a power regression was estimated between the WSCR from the 21 dispatch conditions analyzed, and the Power Electronic Ratio (PER) (discussed earlier in Section 3.1) for each hour. A regression assumed a power function because of the underlying calculation of WSCR. If there is no power electronic equipment on the system, the WSCR would approach infinity whereas if there was only power electronic equipment on the system, the WSCR would approach zero, thus following a power trend, as shown in Figure 2.

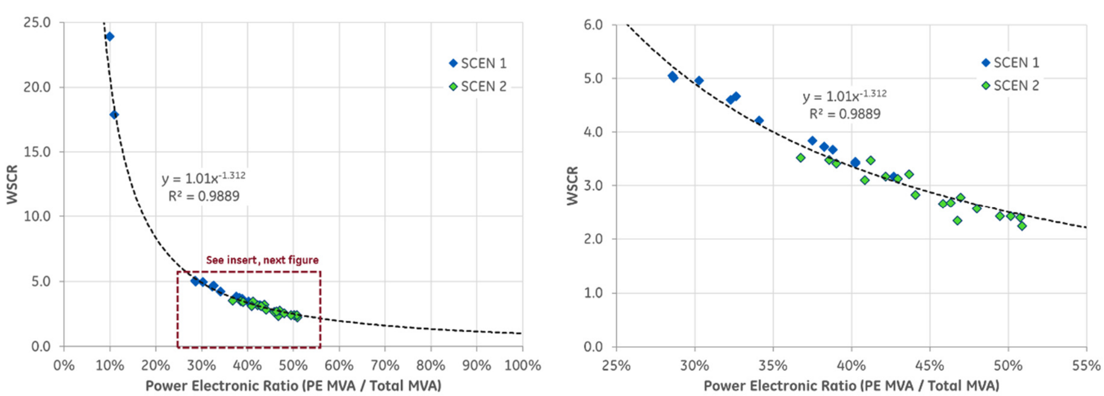

Figure 2 - Regression of WSCR as a Function of Power Electronic Ratio (day-time only)

The resulting trend between the WSCR and the PER, presented in Figure 2, can be used to estimate the WSCR for all 8,760 hourly dispatch conditions analyzed in the production cost analysis, without completing a rigorous power flow analysis each time. In the future, this trend could also be used to create operating rules regarding the amount of synchronous commitment required for a given amount of power electronic equipment online across the system. While Figure 2 provides a representation of the WSCR and PER across a wide range of operations, it is only the lower WSCR that are of concern for system stability. Therefore, the same chart is provided with a zoomed-in view of the lower WSCR region of the trend line in Figure 2.

CONCLUSIONS

The overall grid strength of the Oahu system is trending down as increasing power-electronic-based generation displaces synchronous-based generation during many hours of the year, particularly during daytime hours when all wind and solar resources are online. The increase of power-electronic sources is primarily driven by the growth of distributed PV and, to a lesser extent, by utility-scale wind and PV. As renewable penetration increases further, and technologies like demand response and battery energy storage replace the spinning reserve provision, additional decommitment will take place and the WSCR will erode further. Figure 3 shows the histogram of WSCR reduction over the course of an entire year of operations, where little change at night is observed, but a significant reduction occurs in the daytime.

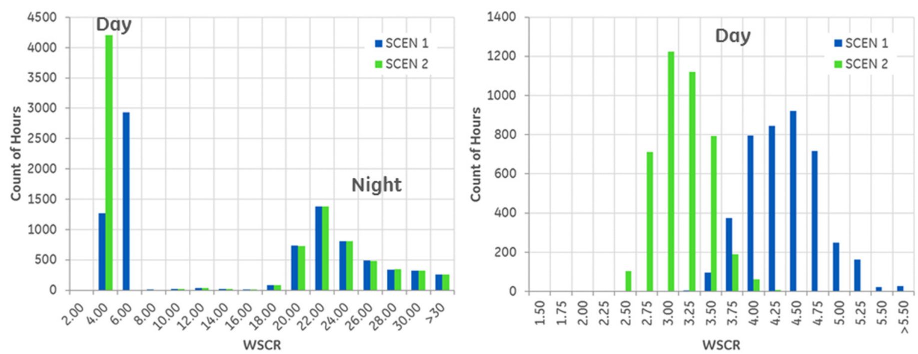

Figure 3 - Histograms of Weighted Short-Circuit Ratio Over a Year of Operation on Oahu

While the analysis conducted in this study provides valuable information on the expected trends in grid strength and an indication to the specific areas of concern, it did not attempt to establish a minimum threshold to system WSCR similar to what was recently done in the Panhandle region of ERCOT. There are two primary reasons for this. The first is that the Oahu system is significantly more complex. Where the Texas panhandle has fewer than one hundred transmission-connected wind plants from only a few different vendors, the Oahu grid has thousands (or tens of thousands) of individual inverters spread over both the high-voltage transmission system and the low-voltage distribution feeders. The second is that weak grid performance of distributed PV inverters is not well understood the way it is for utility-scale wind turbines. Control instabilities emerged years ago and the manufacturers have responded by improving control designs to achieve stable performance under weaker and weaker grid conditions.

Regardless of the minimum threshold of grid stability, the issue of grid strength will have to be addressed eventually. While keeping extra synchronous generators online will benefit grid strength, there is an economic cost of this approach. Over-commitment, resulting in more synchronous generators online than necessary, creates two potential inefficiencies. With additional thermal generators online, units are backed down to lower power output relative to the unit's maximum operating level, and generally operating at a lower efficiency point. In addition, if units are unable to reduce power output further due to minimum stable operating constraints, additional wind and solar may not be able to be accepted by the grid due to over-supply. This wind and solar energy is thus curtailed in lieu of expensive, oil-fired generation. While some degree of synchronous machine support is likely in even a 100% renewable future, the solution to weak grid operations is ultimately through inverter technology development [5].

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