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Analysis and Impact of Autonomous Fast Frequency Response Relative to Synchronous Machine Sources on Oahu

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SUMMARY

The increasing penetration of power-electronic-based generation sources like wind and solar photovoltaics are displacing conventional, synchronous machine-based technologies. This is fundamentally changing the way power system stability is analyzed and managed and alternatives must be procured to continue to maintain frequency stability and reliability. This paper uses Oahu as a case study to examine the impact of shifting away from conventional plants and utilizing fast frequency response (FFR), potentially from a variety of technologies on the generation and load side to maintain system stability.

This analysis implements a novel approach to dynamic stability modelling. In particular, it coordinates the fast frequency response from non-synchronous generation with conventional synchronous machines. The analysis also compares FFR with the response from a synchronous machine to establish an "equivalency ratio," that relates the number of MW of a typical synchronous machine (contributing inertial response and governor response) that must be online in order to achieve the same frequency nadir as a single MW of FFR in response to the same loss of generation and serving the same initial load.

The analysis identifies four important conclusions related to integrating FFR for frequency stability; 1) it is important that FFR is coordinated with other contributors to frequency response, including synchronous inertia, governor response, and under frequency load shedding, 2) FFR has significant benefits to the system's frequency stability, but its efficacy diminishes at high penetrations, 3) FFR has a minimal impact on initial RoCoF because it requires time to detect and respond to changes in system frequency, 4) the equivalency of FFR to conventional synchronous generation (from a frequency stability perspective) is always greater than one (FFR is more beneficial to system frequency), but this relationship is non-linear.

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KEYWORDS
Hawaii – Oahu – South Australia – Grid Stability – Fast Frequency Response – Inertia – Dynamic Stability – Power Electronic – Wind and Solar – Renewable Integration – Distributed Energy Resources – Equivalency Ratios – Island Power System

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INTRODUCTION

The increasing penetration of power-electronic-based generation sources like wind and solar photovoltaics are displacing conventional, synchronous machine-based technologies. This is fundamentally changing the way power system stability is analyzed and managed. Frequency stability is just one of several aspects of power system stability that is changing significantly as power systems shift away from synchronous machine technology. Historically, frequency stability has been maintained through conventional sources of generation like coal, gas, nuclear, and hydro plants and in extreme scenarios, by loads through under-frequency load-shedding (UFLS) relays. As conventional generation plants are retired or dispatched less frequently, alternatives must be procured to continue to maintain frequency stability and an acceptable level of system reliability.

The island of Oahu in Hawaii has already undergone a significant shift away from conventional sources and towards renewables and understanding the impact on system performance and reliability is critical to continuing the shift. This paper uses Oahu as a case study to examine the impact of shifting away from conventional plants and utilizing fast frequency response (FFR), potentially from a variety of technologies on the generation and load side to maintain system stability. As an island and low inertia power system, maintaining frequency stability is more challenging and thus provides a valuable lens to future mainland grid operations

There are potentially many sources of FFR available – any resource that is capable of exchanging active power with the system can play a role in the frequency stability of the system if the active power exchange can be controlled in some fashion as responding to system frequency. This includes not only conventional power plants but also new generation assets like wind and solar PV, emerging technologies like battery energy storage systems (BESS), as well as existing loads on the system. While all of these technologies can play a role, they can vary considerably in the speed in which they can respond. If the system frequency moves so quickly that a resource cannot even begin to respond, then its contribution to frequency stability is negligible. Synchronous machines inherently respond to deviation in system frequency, so their inertial response tends to be the fastest. However, their sustained response, via governor action, is relatively slow and thus may not be a significant contributor to frequency response in low inertia conditions.

The examination of FFR considers that the assets are frequency-responsive, and therefore respond to a local measurement of system frequency. In this way they are also autonomous in that they do not need external communication or instruction to perform their primary duty. This property is prevalent in the existing power system today, and part of what makes it reliable in that the critical stabilizing functions are contained locally and that the failure of a communications system does not necessitate a failure of the power system. Assets that respond as a result from external direction that are not autonomous can still provide value to a power system but are not considered in this analysis.

The timing and magnitude of active power response to a system event like a sudden loss of generation are the critical factors in determining the frequency stability of a power system. Each responding asset affects system frequency, which in turn affects the response of each other asset. In Oahu, the network is electrically concentrated around its 138kV network such that system frequency is essentially common to all parts of the Oahu network. This property does not necessary hold for large networks with long lines where the dynamics of system frequency may look different depending on the location of the observed frequency.

ANALYSIS METHOD

This analysis implements a novel approach to dynamic stability modelling. In particular, it coordinates the fast frequency response from non-synchronous generation with conventional synchronous machines. It does so by decoupling the grid's frequency response contribution from inertia, governor response, FFR, and UFLS by quantifying the power and energy injected into the system before the frequency nadir.

The analysis approach is to first examine the impact of FFR on the Oahu system in response to a representative loss of generation, in this case being the trip of AES at full output, the single largest generating unit on the system. This event causes a net change of 200MW to the system. The impact to the Oahu system is characterized by three metrics: the frequency nadir, the rate-of-change-of-frequency (RoCoF), and the amount of under-frequency load shedding (UFLS). Then a sensitivity analysis on the speed of response of FFR is evaluated through these metrics.

The Oahu system is modeled and simulated using GE's Positive Sequence Load Flow (PSLF) program on a transmission planning model of the Oahu system that captures utility-scale generation and distributed generation as aggregated with the same attributes described in prior study work [5].

The FFR is modeled as an inverter-based generation very similar to the models of solar PV, but with special-purpose user-written controls determining the active power output in response to system frequency. A total of six scenarios are evaluated, as shown in Table 1, spanning a range of system inertias that correspond to levels of instantaneous penetration of wind and solar generation assuming an economic dispatch determined by production cost simulation that captures the characteristics of the system and known operating rules, as was developed in prior study work [2].

Table 1 - Scenarios Analyzed

Scenarios	1	2	3	4	5	6
% Inst. Penetration	17%	20%	30%	39%	50%	53%
System Inertia (MW-s)	5306	4791	4075	3223	2531	2243

The second part of this analysis compares FFR with the response from a synchronous machine to establish an "equivalency ratio," that relates the number of MW of a typical synchronous machine (contributing inertial response and governor response) that must be online in order to achieve the same frequency nadir as a single MW of FFR in response to the same loss of generation and serving the same initial load.

This equivalency ratio is determined from the results of simulations based on the same six scenarios from Table 1, in which a pair of scenarios are used together to determine the contribution to frequency stability due to a synchronous machine [3]. For instance, consider the pair of scenario 2 and scenario 3. Scenario 2 is run with a generation trip event and the resulting frequency nadir is observed. Then scenario 3 is generated from scenario 2, in which one or more synchronous machines are decommitted from the system (reducing the total system inertia, which is calculated as the sum of ineritia contributions from all committed synchronous machines in MW-seconds). The power generated by the decommitted synchronous machine(s) is redispatched to utility-scale and distributed generation sources, which do not have any under-frequency response enabled. Finally, the MW rating of the FFR is increased until the frequency nadir of scenario 3 matches that of scenario 2, as shown in Figure 1. The change in system inertia is divided by the average inertia constant of a synchronous unit on Oahu to arrive at an MVA value of synchronous machines that would need to be committed to the system to achieve the same change in total system inertia. Finally, the equivalency ratio is calculated as the ratio of the FFR MW rating divided by the MVA calculated from the change in total system inertia.

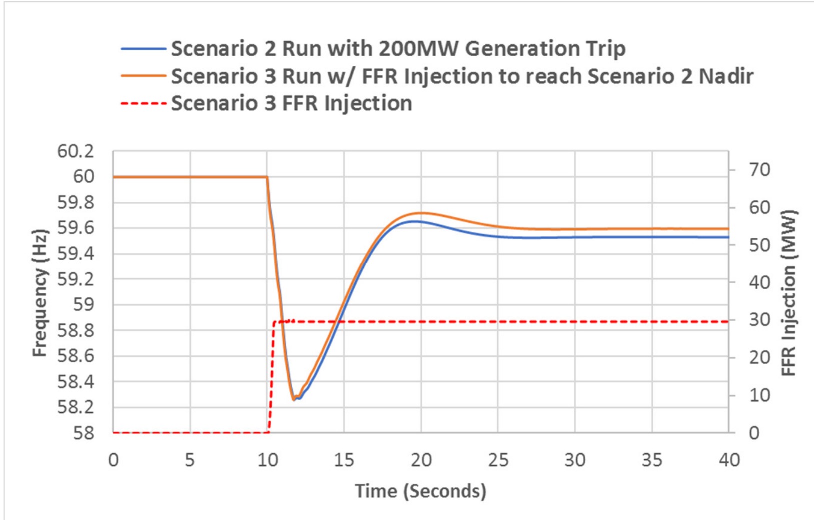


Figure 1 - System Frequency Response to a Generation Trip for a Pair of Scenarios

FFR IMPACT ON THE SYSTEM

The impact of FFR on the frequency stability of the system is evaluated through a series of dynamic simulations for each of the six scenarios and for varying levels of FFR. From each of the simulations, the frequency nadir, RoCoF, and UFLS is recorded and plotted to show trends. A total of thirty-six dynamic simulations were used to show the impact of FFR on frequency nadir shown in Figure 2. In each scenario, the FFR is represented with the "baseline" speed of response. The overall trend is clear in that increasing the capacity of FFR improves the frequency nadir for all scenarios evaluated.

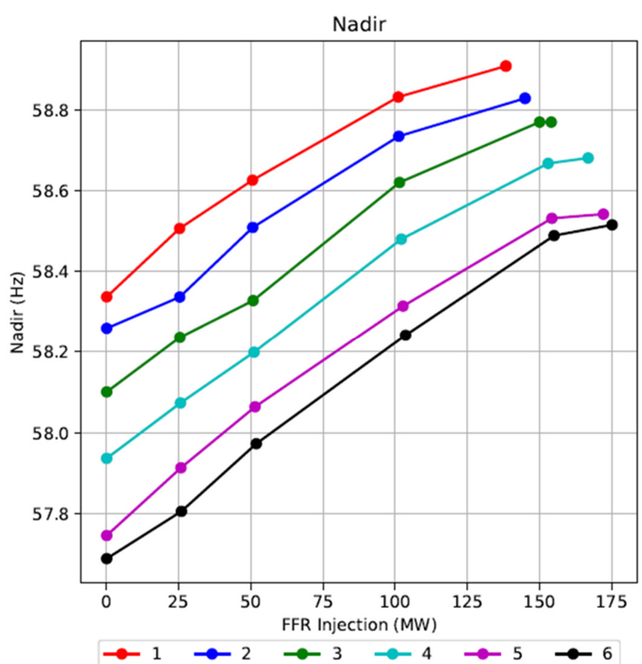
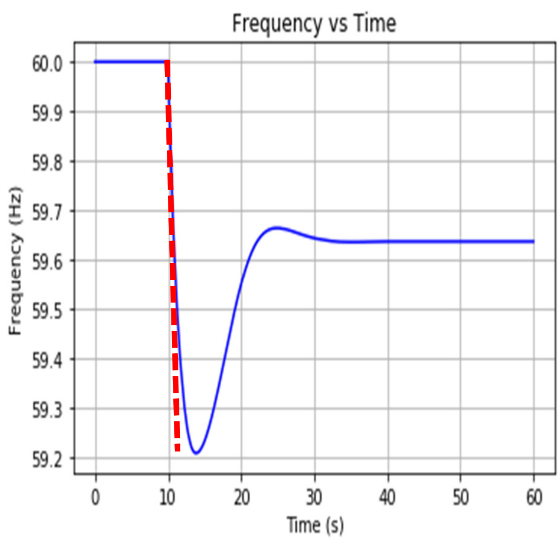


Figure 2 - Frequency Nadir Resulting from a Generation Trip as a Function of FFR Capacity

If it is considered that the FFR capacity on the x-axis of Figure 2 is a cost to the system in terms of the FFR equipment cost and that the y-axis is a benefit in terms of frequency stability and system reliability, then the slope of the curves are qualitatively indicative of a benefit-to-cost relationship.

Note that there are some points that do not fall exactly on the expected curves (i.e. 25 MW FFR injection 2). This "noise" in the plots resulting from the UFLS scheme which occurs in five relatively large blocks. This indicates that the benefit-to-cost relationship of FFR is similar across the scenarios evaluated, as shown by the similar slopes of the curves. For very high levels of FFR, the curves begin to flatten. This is due to the controls response beginning to saturate where the change in active power injection where a shallower frequency excursion results in reduced active power injection from the FFR model. This diminishing return is expected as very high levels of FFR capacity would have less and less effect on nadir for autonomous, frequency-responsive controls it gets progressively more difficult to limit the nadir due to the fast speed of response required to limit the frequency deviation to small values while at the same time having a small deviation with which to trigger a response of active power injection.

Another important metric used to characterize the performance of a power system is the maximum RoCoF. As RoCoF is a function of the size of the contingency event, the maximum RoCoF is found when evaluating the largest generation trip event. In this analysis, RoCoF is calculated as the average of the derivative of the frequency with respect to time for the first 200 mHz of the frequency excursion, as shown in Figure 3a. The 200 mHz time frame was selected because it measures the RoCoF immediately following a contingency event that must be detected by frequency responsive technologies.



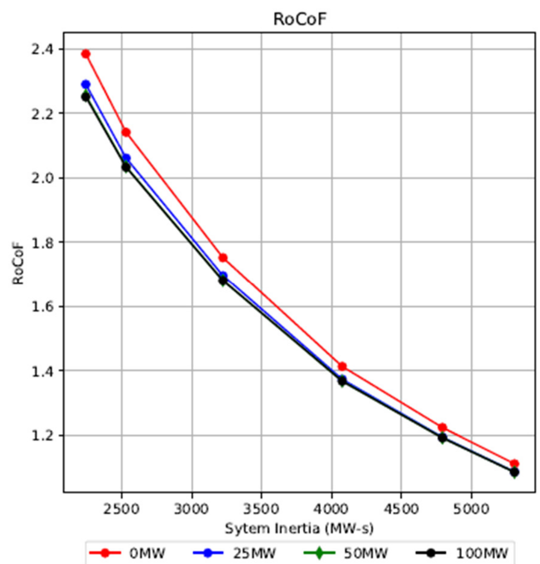


Figure 3a, 3b - RoCoF Determination from Dynamic Simulations

The resulting trends in RoCoF as a function of system inertia and as a function of FFR capacity are plotted in Figure 3b. As expected, RoCoF increases exponentially as system inertia decreases, where a theoretical infinite RoCoF would occur at zero system inertia. The impact of FFR on RoCoF is shown to be minimal by the tight grouping of all of the curves for the varying levels of FFR capacity. This indicates that the FFR is not able to response substantially within the first 200 milliseconds of the event.

The active power shed by the UFLS system for all six scenarios with varying levels of FFR capacity are scatter-plotted in Figure 4. The scatter plot shows a spread of points due to the relatively large size of the five discrete UFLS blocks. Despite the spread, a decreasing trend in UFLS power with FFR is clear. This result is consistent with the improving frequency nadir, as the UFLS scheme is a static scheme that triggers on preset frequency thresholds. The line drawn on the plot shows the one-to-one correspondence of FFR capacity with UFLS, coarsely indicating that one MW of UFLS may be reduced for one MW of FFR added, provided the FFR has the controls response modeled. As distributed energy resources (DERs) continue to proliferate on the grid, the efficacy of the UFLS will deteriorate during certain time periods. Based on this analysis, FFR provides an in-kind replacement to the existing UFLS.

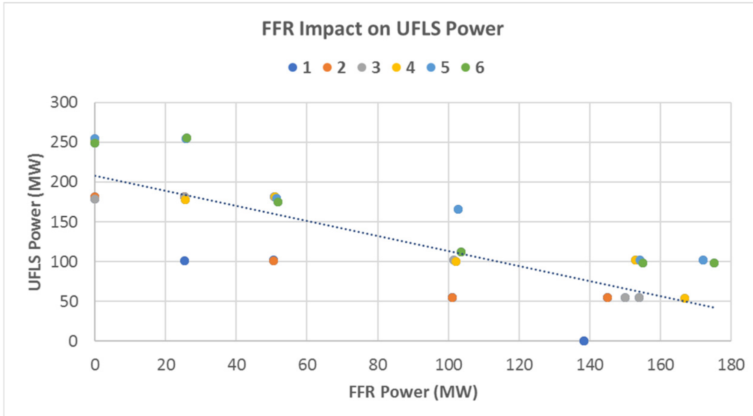


Figure 4 - UFLS Power as Function of FFR Capacity

In order for the FFR to be effective in improving the frequency nadir of the Oahu system, it must provide a significant response relative to the size of the contingency prior to the time of the nadir after the event. The time to reach the nadir on Oahu for the scenarios evaluated is in the range of 1.5 to 3 seconds. This period of time is sufficient to accurately determine the frequency of the system and for FFR assets like switches, circuit breakers, or power electronics to respond with significant levels of active power. However, these simulations show that FFR is not very effective is changing the initial RoCoF due to an event.

IMPACT ON THE THERMAL FLEET

The interdepencies of frequency responsive assets is important to understand as each contributor to frequency-response is affected by every other contributor. The results have clearly shown the interplay between frequency-responsive assets like FFR and UFLS. To assess the interplay between FFR and synchronous machines, the inertial energy and inertial power from synchronous machines have been pulled out from the dynamic simulations with methods described in prior study work [1]. It is assumed that for these scenarios, the governor response from synchronous machines is insignificant in the period of time prior to the nadir, as shown in Figure 8.

As FFR capacity increases, the energy injected into the system prior to the nadir by a synchronous machine due to its inertia decreases for all scenarios, as shown in Figure 5. This indicates that the FFR is relieving some of the burden from the synchronous machine fleet in arresting system frequency. This is a result of the FFR helping to turn system frequency around from declining to increasing sooner, thereby reducing the time to nadir. By reducing the time to nadir, less energy is contributed to the system prior to the nadir for a similar power injection prior to the nadir.

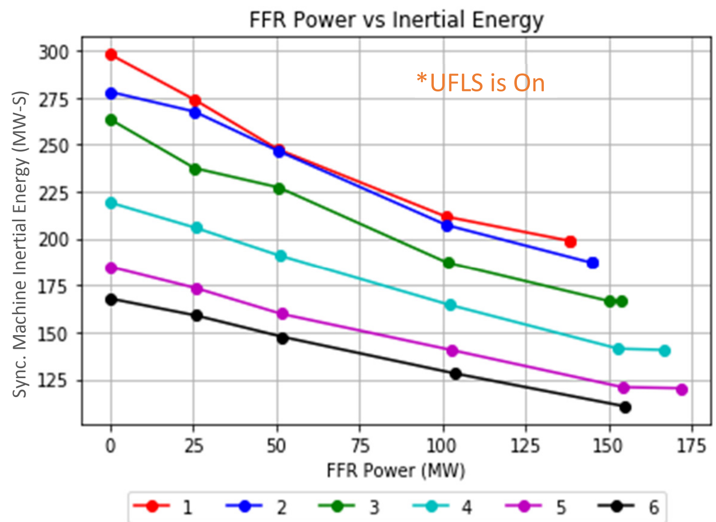


Figure 5 - Synchronous Inertia Energy as a Function of FFR Capacity

The power injected to the system by the synchronous fleet as a function of FFR capacity or total system inertia is essentially constant over the scenarios studied. This result is somewhat unexpected in the sense that FFR is not relieving the burden of synchronous machines injection of arresting power. It is also surprising to see that the peak power injected by the synchronous fleet remains unchanged even at the number of synchronous machines online decreases. The reason is that the power injected by synchronous machines is proportional to the derivative of machine speed, or RoCoF. As total system inertia decreases due to fewer synchronous machines online, the RoCoF increases, as shown in Figure 3. Therefore, the synchronous machines that remain online are each contributing more power during the period of falling frequency such that the net power from the fleet remains relatively unchanged. And from the finding that FFR does not respond quickly enough to impact RoCoF as shown in Figure 3, then the power injected from synchronous machines due to the their inertia is also unaffected by the level of FFR capacity on the system. The effect on synchronous inertia energy and power for two contrasting scenarios is shown in Figure 7 and Figure 8.

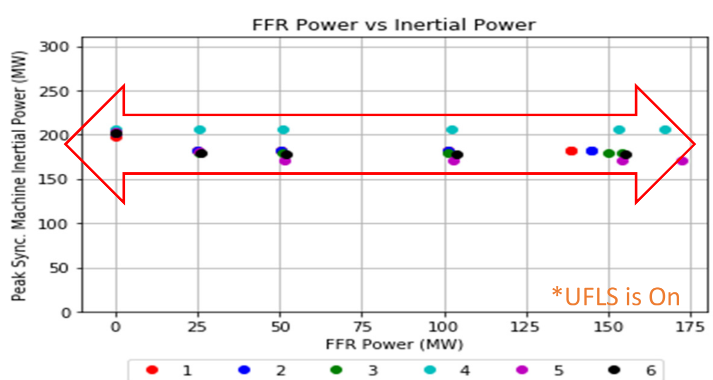


Figure 6 - Synchronous Inertia Power as a Function of FFR Capacity

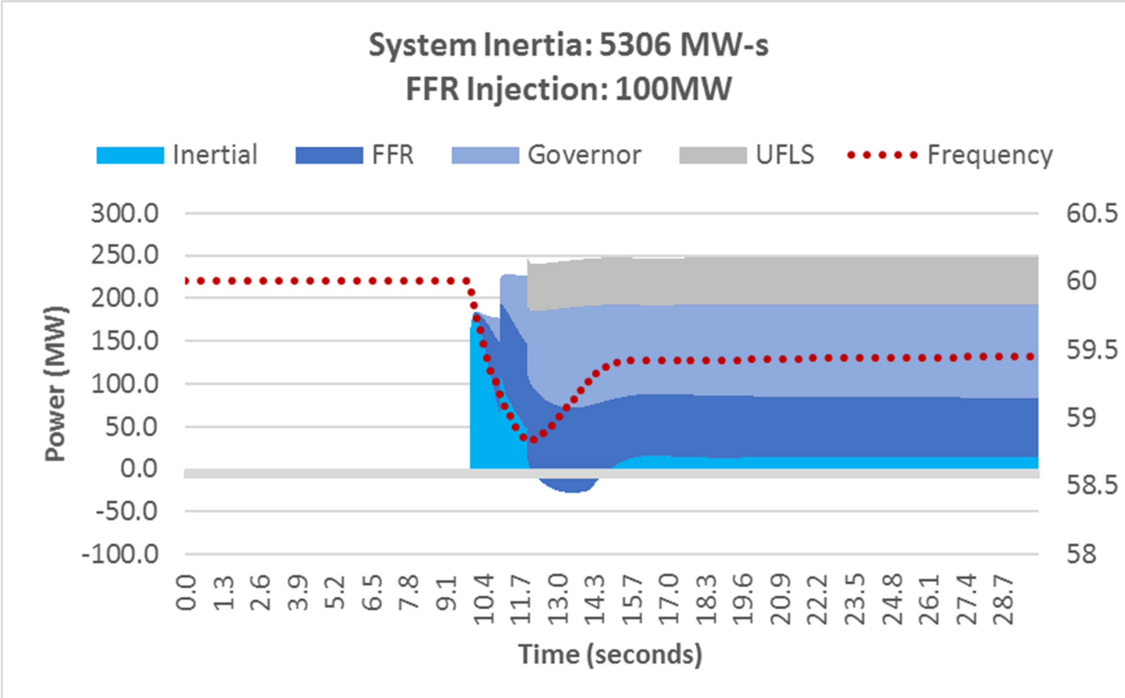


Figure 7 - Contributors to Frequency Stability by Resource for a High Inertia Scenario

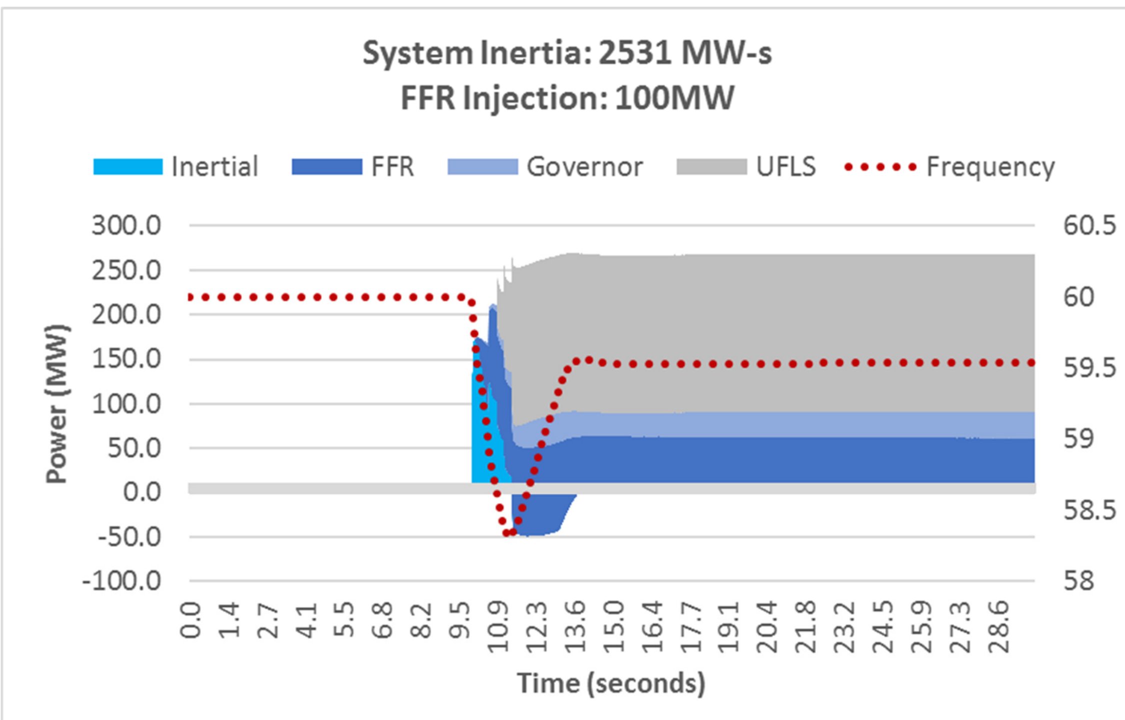


Figure 8 - Contributors to Frequency Stability by Resource for a Low Inertia Scenario

EQUIVALENCY

The introduction of an equivalency ratio is an attempt to quantify the value of FFR in terms of more traditional assets on the power system like synchronous machines. The methodology of developing the equivalency ratio described an equivalency between a synchronous inertia quantity of MW-seconds with an FFR capacity quantity of MW. As these values are difficult to compare in a meaningful way, one additional translation is made from MW-seconds of inertia to MVA of synchronous machines. This is done by calculating the average inertia constant for units on Oahu, which is the ratio of the rotational energy of a synchronous machine drivetrain to the machines' MVA rating. This value is calculated to be 4.2. Therefore, 42 MW-s of system inertia is roughly estimated to be provided by a representative 10MVA synchronous machine. This is acknowledged to be a rough calculation that is intended to provide a "ballpark" relationship between the value of a representative FFR asset to a synchronous machine asset from the perspective of frequency stability. It is important to note that this analysis takes a relatively narrow view comparing synchronous machines with FFR devices. It only compares the frequency stability attributes of the technologies and does not consider other aspects of the technologies like short-circuit strength or voltage support that are important to power system stability.

Using this methodology, the resulting equivalency ratios are plotted in Figure 9 as a function of total system inertia for the five pairs of scenarios, that being scenarios (1,2), (2,3), (3,4), (4,5), and (5,6).

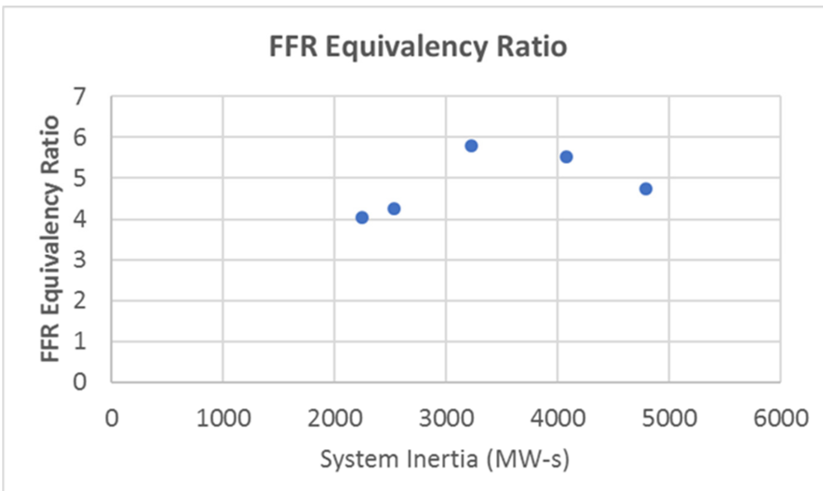


Figure 9 - FFR Equivalency Ratio as a Function of Total System Inertia

The plot in Figure 9 has two noteworthy characteristics. The first is that the equivalency ratio is greater than unity for all the scenarios evaluated. This shows that the value of one MW of FFR capacity is several times that of one MVA of synchronous machine from the perspective of frequency stability.

The second notable characteristic is that the trend shows competing factors that result in an optimum equivalency value. As system inertia increases, the FFR equivalency decreases. This is because for higher level of system inertia, the time to nadir increases, allowing more time for the governors on the synchronous machines to respond, as shown in Figure 10. In these timeframes, the response of synchronous machines to the event is greater, making the relative value of FFR lower.

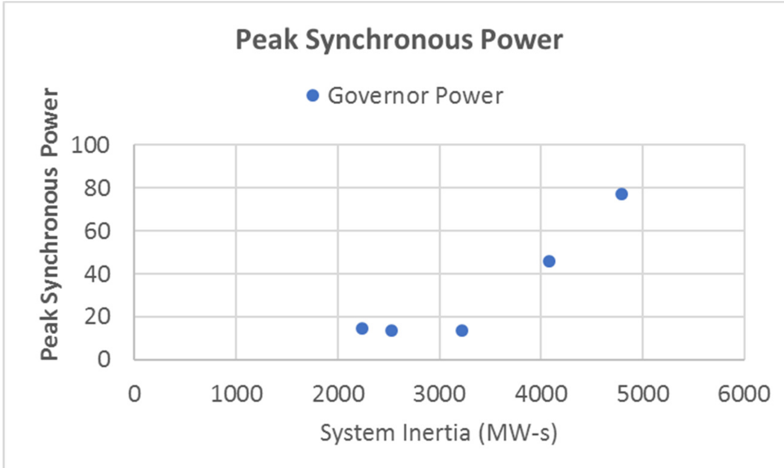


Figure 10 - Peak Power from Synchronous Machine Governors as a Function of System Inertia

As the total system inertia decreases, the system RoCoF increases and the time to respond to system frequency prior to reaching a collapse point of 57Hz (where many protective functions are triggered) on the Oahu system decreases. This is plotted in Figure 11 where the time to system collapse is calculated as the maximum survivable frequency deviation of 3Hz for Oahu divided by the RoCoF for a given scenario. As the total system inertia decreases, there is less time for FFR to respond and therefore the impact of FFR becomes limited for very high RoCoFs. Therefore, the value of FFR from a frequency stability standpoint diminishes with respect to the value of synchronous machines, which have an inherent, and therefore, instantaneous response.

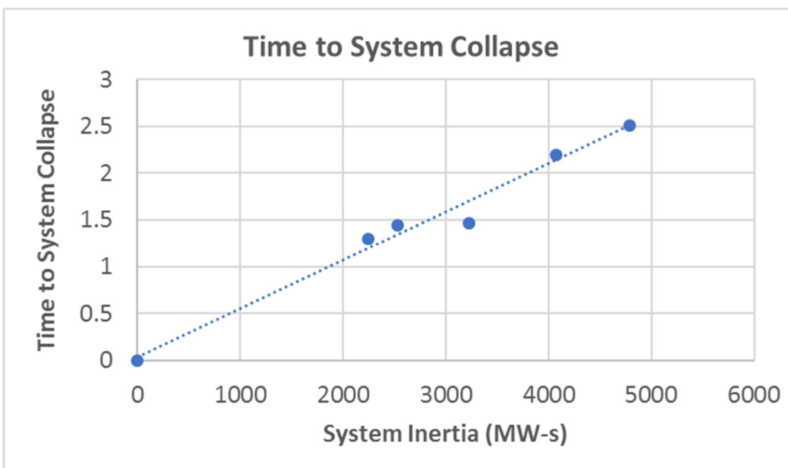
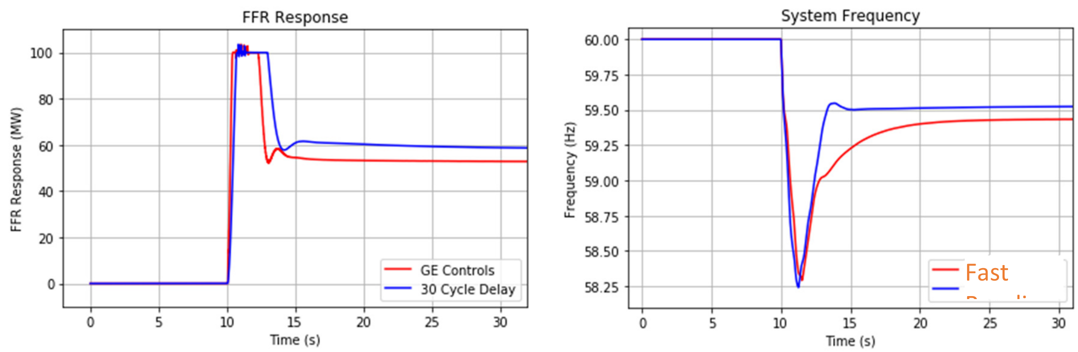


Figure 11 – Time to Oahu System Collapse as a Function of System Inertia

SUMMARY

A natural conclusion is that if FFR can respond more quickly, it could also improve RoCoF as well as stay in front of the frequency nadir, which will continue to move closer in time to the originating event (assuming the system recovers) as system inertia continues to decrease. The practical challenge is that detecting system frequency involves a trade-off between speed and accuracy. Determination of frequency more quickly means that there are fewer cycles over which to determine frequency. Couple that with the distortion of the voltage waveform that results from large switching events like the opening of a generator circuit breaker, and there are practical limits to how quickly frequency can be determined with sufficient confidence to change the active power injected or absorbed in a system by large amounts. Errors in frequency detection could result in overshoots where an under-frequency event suddenly becomes an over-frequency event, which can also trigger protective functions that can result in the collapse of the system.



The analysis identifies four important conclusions related to integrating FFR for frequency stability; 1) it is important that FFR is coordinated with other contributors to frequency response, including synchronous inertia, governor response, and under frequency load shedding, 2) FFR has significant benefits to the system's frequency stability, but its efficacy diminishes at high penetrations, 3) FFR has a minimal impact on initial RoCoF because it requires time to detect and respond to changes in system frequency, 4) the equivalency of FFR to conventional synchronous generation (from a frequency stability perspective) is always greater than one (FFR is more beneficial to system frequency), but this relationship is non-linear. These conclusions identify the role of FFR in low inertia power systems as the integration of power electronic equipment continues to displace conventional generation.

BIBLIOGRAPHY

[1] Hawaii Natural Energy Institute, "Oahu Distributed PV Grid Stability Study," https://www.hnei.hawaii.edu/projects#GI, 2015-2017.

[2] S. Newell, et al. "Cost-Benefit Analysis of ERCOT's Future Ancillary Services (FAS) Proposal." Prepared for Electric Reliability Council of Texas, December 21, 2015.

[3] D. Stenclik, M. Richwine, N. Miller, L. Hong, "The Role of Fast Frequency Response in Low Inertia Power Systems." CIGRE Session, Paris, August 2018.

[4] Hawaiian Electric Company. "Power Supply Improvement Plans (PSIP): Book 4." Appendix J. December 23, 2016.

[5] Ackerman, et al. "Paving the Way: A Future without Inertia is Closer than you Think." IEEE Power and Energy Magazine. Volume 15, Issue 6, Nov-Dec 2017.

[6] Miller, N.; Clark, K.; Walling, R., "WindINERTIA: Controlled Inertial Response from GE Wind Turbine Generators." Presented at the 45th Annual Minnesota Power Systems Conference, Minneapolis, Minnesota, November, 2009.

[7] M. Richwine, D. Stenclik, "An Integrated Approach to Analyzing the Impact of Increasing Distributed PV Generation on Dynamic Stability in Oahu." CIGRE US National Committee. Next Generation Network Paper Competition, 2016.