RRS-PFR Study: Summary of Recommendations

Study summary prepared for

Electric Reliability Council of Texas (ERCOT)

Submitted by: General Electric International, Inc.

Revision No. 2

December 4, 2023

FOREWORD

This report was prepared by General Electric International, Inc. (GEII), acting through its Energy Consulting group, based in Schenectady, New York. Questions and any correspondence concerning this document should be referred to:

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Document Revisions

REV #	AUTHOR(S)	DATE	DESCRIPTION
0	MacDowell, Rao, Miller, Manz	May 27, 2023	Initial Issue
1	MacDowell, Rao, Miller, Manz	June 9, 2023	Updated based on comments from ERCOT
2	MacDowell, Rao, Miller, Manz	December 4, 2023	Updated based on further comments from ERCOT

Relevant Engineering Terms & Acronyms

BESS	Battery Energy Storage System
ECRS	ERCOT Contingency Reserve Service
ERCOT	Electric Reliability Council of Texas
ERS	Essential Reliability Services (per NERC)
ESR	Energy Storage Resource
ESR-CLR	Energy Storage Resource – acting as a Controllable Load Resource
ESR-GR	Energy Storage Resource – acting as a Generating Resource
FR	Frequency Response. A measure of response.
FRO	Frequency Response Obligation (per NERC BAL-003)
Fsetl	Settling frequency (upon a loss of generation in the network)
IBR	Inverter Based Resource (includes Wind, Solar or Photovoltaic, BESS)
IFRO	Interconnection Frequency Response Obligation (per NERC BAL-003)
LR	Load Response (to a frequency event) (a.k.a UFR) A portion of ERCOT's Responsive Reserve Service (RRS) provided by Load Resources by using under frequency relays.
NP	Network Protocols; ERCOT's set of reliability requirements
PFR	Primary Frequency Response
P_{REF}	Power reference – the amount of active power in MW delivered by a resource to the grid.
RRS	Responsive Reserve Service
SM	Synchronous Machine
SMIB	Single machine infinite bus. A simple modeling setup used for control and model refinement.
SOC	State of Charge
STP	"South Texas Project" – South Texas Nuclear Plant, in context of this project, equivalent 2805MW
UFLS	"Under Frequency Load Shedding" - the point at which energy consumers will trip off due to a grid disturbance
UFR	(a.k.a. LR) A portion of ERCOT's Responsive Reserve Service (RRS) provided by Load Resources by using under frequency relays.
V_{REF}	Voltage Reference – the voltage command set by the grid operator or plant controller to maintain a certain voltage level

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Acknowledgments

The GE project team would like to acknowledge and sincerely thank the leadership and guidance provided by ERCOT's planning and operations teams throughout this study, including **Nitika Mago, Pengwei Du, Weifeng Li, Luis Hinojosa, Shun Hsien (Fred) Huang and Jeff Billo**.

The GE project team would also like to sincerely thank the stakeholders from the ERCOT Performance, Disturbance, Compliance Working Group (PDCWG) and attendees from the study stakeholder workshop for kind questions and input that improves the overall quality and deployment of recommendations in this report.

Sincere thanks also to the GE Energy Consulting team and Hickory Ledge, LLC, particularly Shruti Dwarkanath Rao, Nicholas Miller, Sheila Manz and Sebastian Achilles for their leadership and major contributions to this work.

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1 INTRODUCTION

ERCOT is experiencing a period of great change regarding its resource mix. Over the past decade, ERCOT's energy mix has been shifting from constant-fuel synchronous generators to variable-fuel inverter-based resources (IBRs). ERCOT presently manages approximately 37 GW of wind and 15 GW of solar PV[1] and is rapidly adding battery energy storage systems. As IBR penetration levels continue to increase, ERCOT is also evaluating how to increasingly revise its Ancillary Services to accommodate Inverter-Based Resources (IBRs) while maintaining grid reliability. ***At the time of this report, ERCOT has 33 GW wind, 143 GW PV solar and 125 GW batteries that have applied for interconnection and are in the study queue[2].*** This number continues to grow monthly.

The focus of this study is to evaluate the need for new limits on resources that provide Primary Frequency Response (PFR) given that IBRs (and particularly battery Energy Storage Resources) are increasingly applying to provide these services. IBRs have performance characteristics that can differ from those of synchronous machines. These performance characteristics, such as capability for lower droop settings which provide more rapid response, seem to offer advantages with respect to maintaining stable frequency. However, to fully take advantage of these characteristics, the system impacts must be studied to assess whether there may also be reliability risks, including but not limited to frequency performance risks, associated with these enhanced capabilities. Identified reliability concerns will advise recommendations on future resource qualification, procurement structure, and operational practices. The effort is in-line with recommendation in the newly released NERC document *Impacts of Electrochemical Utility-scale Battery Energy Storages on the Bulk Power System* (February 2021) that "System planners ...must ensure that deployed energy storage provides the necessary ERSs to maintain BPS reliability, security, and resilience."

The question this study is intending to answer is *"What are the risks of allowing BESS (or any IBR) on 1% frequency droop to displace PFR from synchronous machines on 5% frequency droop and what should ERCOT do to mitigate those risks?" While this study was focused on BESS resources, the recommendations and limitations apply to all other resources that have 1% dynamic performance equivalent to what was studied.*

2 SUMMARY OF APPROACH AND ANALYSIS

The focus of this study is to devise an approach and methodology to assess risks and impacts of deploying and procuring PFR from battery energy storage systems (BESS) through ERCOT's Responsive Reserve Service (RRS) market, and consequently deploying limitations and practices to any resource providing this service to ensure compliant, stable and robust response. This is not a planning study, nor can this analysis be used in place of a planning study. Rather, it is an illustrative design-of-experiments to identify areas of risk when considering provision of RRS-PFR from BESS deployed with 1% frequency droop (as opposed to the prevalent fleet of synchronous resources which primarily operate with a 5% droop). Droop is the percent change in nominal frequency that will cause generator output to change from no Load to full

[1] https://www.ercot.com/misdownload/servlets/mirDownload?doclookupId=962307654

[2] https://www.ercot.com/mp/data-products/data-product-details?id=PG7-200-ER

Load. Under ERCOT's current Market Rules, Droop of 1% allows for the Resource Entities to offer up to 100% of its facility full capacity, rather than the 20% limit presently associated with 5% droop. Since the 1% droop represents response that allows 100% of rating to be offered, the accompanying high gain was upper limit of the analysis and represents the upper bound of the findings and recommendations. Device droops between 1% and 5% are allowed and covered by the results.

The focus on BESS reflects the present reality that (essentially) all new and presently proposed (queued) ESR are battery systems. Analysis here is based on realistic dynamic performance that is presently available from commercial BESS systems. In the future, should other IBR based systems including other ESR systems offer functionally equivalent dynamic performance, these results and recommendations should apply.

2.1 Study Methodology

The study methodology was designed to hypothesize and test areas of risk to allow BESS using 1% frequency droop to participate in the RRS-PFR Ancillary Service. The main tasks of the study are listed below.

Task 1: Data collection. GE began by collecting databases and current assumptions as a foundation for this study. ERCOT created a load flow and dynamic stability case in PSS/e for a low inertia (122GW.s) condition, with feedback from GE. This case was converted by ERCOT from TSAT which included representation of wind and solar IBR as negative loads (with no dynamic voltage or frequency support).

Task 2: Benchmarking of current practices. GE demonstrated that we could re-create ERCOT's current PFR requirement calculations and have a working base case model as a reference for the scenarios we later studied.

Task 3: Establish study framework—risk areas, scenarios, assumptions. GE collaborated with ERCOT to develop a matrix of scenarios that cover three potential types of risk: systemic, locational, and other risks.

Task 4: Initial risk assessment—simulation, risk screening, propose mitigations. GE performed both steady state and dynamics simulations for the initial scenarios to test for compliance to frequency performance obligations. A variety of tests were designed and performed on a subset of these scenarios to examine a variety of risks. We assessed the level of risk across the scenarios and proposed preliminary mitigations.

Task 5: Identify preliminary recommendations. Given the simulation results and risk screening, GE proposed recommendations that mitigate the areas of high risk.

Task 6: Refine risk assessment & test recommendations. Given the risks and mitigations highlighted in Task 4 and 5, we refined the initial scenario and performed additional simulations to understand the level of risk and tested the effectiveness of mitigations.

Task 7: Finalize recommendations & reporting. GE and ERCOT worked together to refine our proposed and tested recommendations such that they are practical and implementable for ERCOT.

Task 8: Stakeholder Presentation. GE and ERCOT held a stakeholder workshop, presenting the methodology, risk screening, study results and recommendations to stakeholders and ERCOT staff.

In order to identify limitations on new IBR-based resources providing PFR, the GE team began with a hypothesis regarding the potential risks that we investigated in our simulations. These risks were analyzed in a few different categories, namely, systemic, locational and other risks including Procurement and Operational.

A. **Systemic risks:** Systemic risks apply to the overall performance and compliance of the entire interconnection.
   1) **Meet FRO?** Will ERCOT meet its frequency response obligation (FRO) when the new PFR is procured using the present methods and tools? This focuses on compliance risk.
   2) **Stable?** Are there systemic risks of frequency instability (e.g. common-mode frequency oscillations? Over-shoots? interaction with UFLS? Are there risks of systemic interaction with other functions or controls? This study was able to investigate these risks between BESS facilities as well as BESS and synchronous machines as much as the model allowed. This study did not evaluate the control interaction risk between BESS and other IBR because the wind and solar plant controls were not modeled in the dynamic simulations.
   3) **Resilient?** How robust is the performance? (e.g. how vulnerable to single point of failure, or common-mode failures is it?)

B. **Locational risks:** Locational risks may advise limitations on amount (or other features) of procurement by zone, for example. These types of risk would be in addition to the systemic risks mentioned above. For example, for procurement and deployment that satisfies systemic needs, are there still locational limitations that must be respected? Such issues include:

   1. **Cross-regionally stable?**
      - Are there transient and voltage stability constraints that depend on location within ERCOT? (e.g. would having too much high response PFR in one zone risk causing a system separation for a large event?)
      - Are there regional interaction constraints within ERCOT? (e.g. would having a large amount of fast, high response PFR in one area, adversely interact with predominantly slower, lower response PFR in another area).
      - Will coordination with UFLS protection based on locational attributes be required?
      - Will cross-regional oscillations be stimulated, or transient voltage stability risks be exacerbated?

2. **Inter-equipment stable?**

    - Are there proximity concerns? The study evaluated the risk of BESS controls interacting with each other or with synchronous machines but could not evaluate the control interaction risk between BESS and other IBR because the wind and solar plant controls were not modeled in the dynamic simulations.
    - Are there local density concerns for interaction with other functions (e.g. could too much high response PFR in one place or in tight proximity, adversely interact with UFLS?).
    - Are there local performance issues? (e.g. could excessive high response PFR cause voltage problems locally?)

3. **Locally resilient?** For example, is there a single point of failure resulting in a resource or a number of resources providing PFR in a one location or in close proximity being unavailable when needed?

C. Other risks

1. **Modeling risk:** The study identified limitations with the models we used in PSS/e, particularly regarding the lack of IBR dynamic models in the ERCOT system representations developed for this study.
2. **Procurement risk:** Transmission limitations preventing a resource or a number of resources from full deployment of PFR.
3. **Under-performance risk:** issues from deployment failure or lack of deployment for those resources with low droop settings.
4. **Torsional risk:** High gain, high bandwidth controls of active power may present a risk for interaction with torsional modes of existing synchronous generation, particularly fossil units. Such risks are highly locational, and sensitive to rating and control details. We evaluated the impact of BESS PFR at 1% droop on torsional stress of nearby synchronous machines.
5. **IEEE 2800 Compliant?** Does the performance of BESS resources meet IEEE 2800 capability requirements?

System simulations in this work are intended to illuminate and help quantify risks that must be considered in ERCOT practice. While the results are expected to be qualitatively meaningful, the primary value of the study will be to provide risk management methods for ERCOT to use in their procurement process that will be relevant as the system evolves. They are not intended to be exhaustive or replace planning or interconnection analyses to determine individual or systemic risks relative to any project.

2.2 Scenarios and Evaluation

In the first stages of the study, GE and ERCOT worked closely together to build a model of the ERCOT grid in PSS/e. This model was based on a 2021 real-time snapshot of the ERCOT system in TSAT at 122 GW.s inertia. Later in the study, another base case was configured for 244 GW.s for spot checking some results at a higher inertia level. Generation and loads were configured such that there were no voltage violations and the dynamic simulations initialized with flat lines and no issues. This baseline case contained no battery models and the wind and solar generation was modeled as negative load. Loads were modeled as 50% constant current and 50% constant admittance for real power; 50% constant admittance 50% constant power for reactive power. A set of baseline simulations were performed on this case to confirm the "quality" of the system model and its ability to replicate known attributes of the grid. These baseline simulations were then used for comparison with later scenarios when BESS was added. Figure 1 shows a geographical view of the baseline case with location of resources.

Figure 1: Baseline Scenario

To effectively evaluate the risks, we identified 5 different scenarios of BESS placement with multiple disturbances, equipment configurations and sensitivities to test and illustrate various phenomena listed above. The scenarios were meant to illustrate classes of risk, but not necessarily reflect real system conditions. They are meant to identify "bookends" or indicative situations where the grid would be placed under stress to identify where potential problems may occur. Figure 2 illustrates the 5 scenarios.

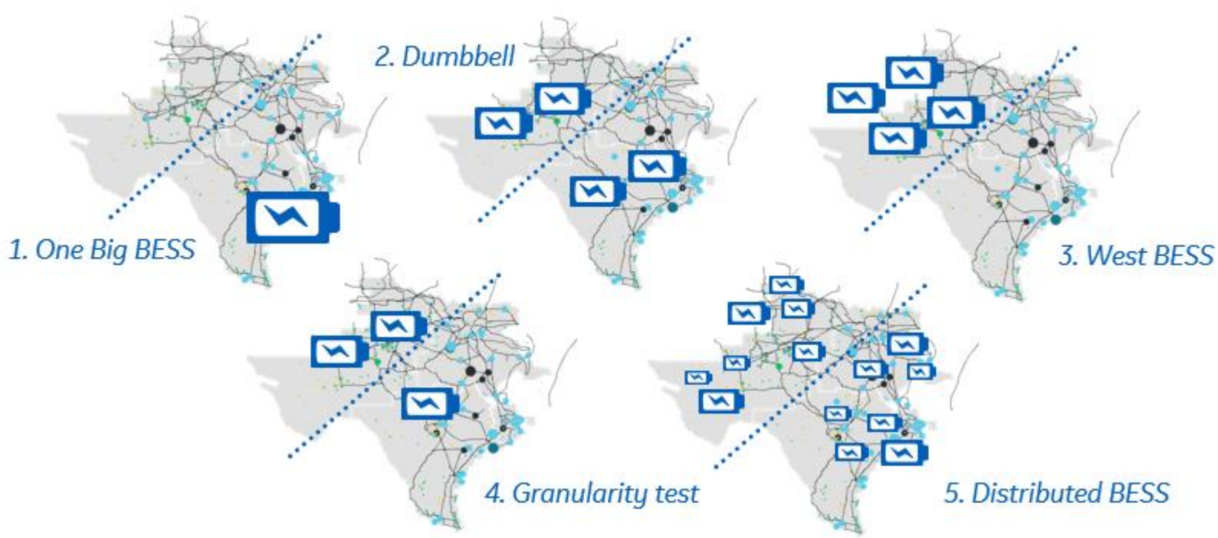


Figure 2: Five Study Scenarios

1. **One big BESS in the east** mainly to evaluate systemic behavior and frequency compliance
2. **Dumbbell (2 BESS around Odessa and 2 in the east coast)** to evaluate locational risk, nodal vs. common-mode frequency issues, transient stability concerns, frequency compliance, inter-area instability and interactions
3. **West BESS.** This was evaluated in two stages:
   a. **One big BESS in the west** to assess voltage collapse, transient stability and provision of PFR from a weak and remote part of the grid
   b. **4 BESS in the west** to assess provision of PFR from multiple BESS in weakest and remote parts of the grid, transient stability, fault and clear transmission to stronger zones and interaction between PFR resources
4. **Granularity tests (2 BESS responding in the west + 1 BESS responding in the east coast)** to assess under-performance (relative to Scenario 2) and risk elements related to the granularity (how much PFR comes from one resource) in the ERCOT system. The specific intent of these tests was to examine the risks associated with individual resources failing to perform with a view towards advising the methodology proposed that sets maximum allowable size of individual resources.
5. **Distributed BESS (based on installed and queue locations)** to assess most realistic scenario of BESS distribution based on projects in the interconnection queue. Performed various simulations and sensitivities based on location, displacement, droop gain, speed of response, and homogeneity. A brief conceptual test was also performed to understand the impact of Fast Frequency Response (FFR) response.

Figure 3 illustrates a summary of the evaluation candidates in the study that reflect the tested locational scenarios, system disturbances, configuration of equipment and sensitivities simulated.

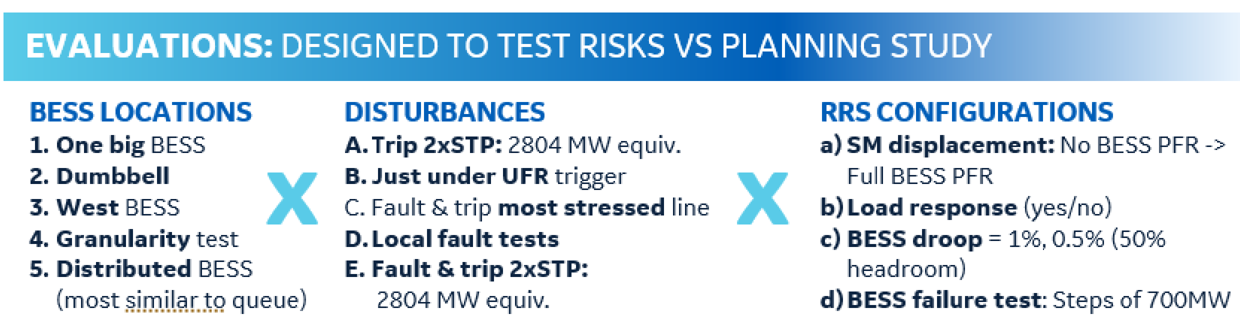


Figure 3: Summary of evaluations

DISTURBANCES

A. **Trip 2 x STP:** simulate the loss equivalent to two STP nuclear plant generators; 2805 MW. This disturbance is the design-basis planning event for ERCOT and forces the nadir frequency below 59.7Hz, triggering under-frequency load response (UFR)
B. **Just under UFR:** simulate the loss of less MW than disturbance (A) (was determined case by case) that caused the frequency to dip but not below 59.7Hz. This disturbance was used to evaluate PFR from generation only without triggering UFR
C. **Fault and trip most stressed transmission line:** simulate fault and clearing of one transmission line for cases where PFR is coming from remote resources in the west. This disturbance was used to investigate interarea transient stability risks with IBR PFR is upstream of stressed bulk transmission interfaces.
D. **Local fault tests:** investigate a fault on a bus near BESS. This is used to test risk of interaction between BESS units and also BESS-SM.
E. **Fault and trip 2xSTP:** a more severe case of (A) where the trip of 2805 MW was initiated by a fault.

RRS CONFIGURATIONS

a) **SM Displacement:** various amounts of BESS were added up to 2800 MW total displacement of synchronous machines [0 MW, 700 MW, 1400 MW, 2800 MW]
b) **Load Response:** this was tested based on the selected disturbance and whether the frequency dropped below 59.7 Hz
c) **BESS Droop:** tested 5%, 1% and 0.5% effective droop by limiting headroom on BESS units
d) **BESS Failure Test:** investigated failure of 700 MW, 1400 MW and 2800 MW BESS during a PFR event

The BESS models were configured to reflect realistic performance as would be expected from a BESS resource (reasonably fast but not unwieldy) and compliant with IEEE 2800 capability requirements.

3 SUMMARY OF RESULTS AND RECOMMENDATIONS

Following the framework of scenarios, disturbances and sensitivities outlined in the previous section, a substantial number of cases were simulated to evaluate anticipated risks. A big portion of the evaluations analyzed frequency vs. time performance at predetermined nodes around ERCOT's system (consistent with nodes that ERCOT typically monitors in planning analysis). An example of results from this analysis may be found in Figure 4. This figure shows the outcome comparing the base case with no BESS (all SM droop as provided, representative of 5% droop) with 2800 MW BESS on 1% droop in one location in the east coast, displacing equivalent SM (this is the "One big BESS" scenario 1). The disturbance stimulus is tripping of 2xSTP (~2805 MW), the design-basis planning event where UFR was triggered. The response, despite the difference in droop, is quite similar where the total PFR in both cases is effectively the same, the settling frequencies are identical, and the nadir frequency is slightly higher by 40 mHz in the all-BESS case. The frequency in all-BESS case recovers faster, within 2-3 sec vs. 15 sec for the SM case. The response is well-mannered. This result was indicative of most cases.

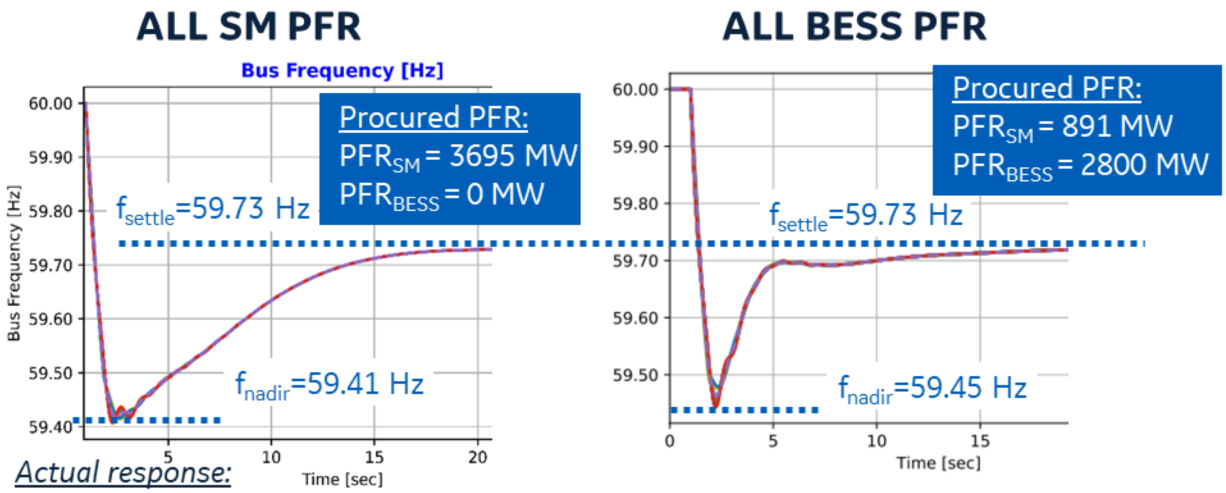
The top conclusions from analyzing study results around compliance are simply summarized as[3]:

1) **Reliance**: ERCOT can fully rely on 1% droop resources for PFR if recommended practices in this report are followed
2) **Equivalency**: 1 MW procured PFR of 1% resources is equivalent to 1 MW procured PFR of 5% resources
3) **Consistency:** Nadir results were **independent** w/BESS displacement. Specifically, the proportion of 1% resources to 5% resources has marginal impact.

Reliability, in terms of managing risks, depends on performance expectations

- ✓ **PFR response:** quick enough to support frequency but not so quick that it's unstable
- ✓ **IEEE 2800** compliance: PFR resources tuned towards fast end of compliance to best support frequency recovery
- ✓ **Qualification:** Individual resources **qualified** based on rating, location, and performance including torsional, protection, voltage, interactions and other systemic concerns
- ✓ **Operational Management:** Assurance that resources can deliver contracted services, including maintaining necessary state-of-charge and headroom

[3] Supporting details of these conclusions are found in Sections 3.1-3.3



Actual response:

	ALL SM PFR	ALL BESS PFR
PFR_{SM}	1519MW	322MW
PFR_{BESS}	0	1181
PFR_{TOTAL}	**1519**	**1503**

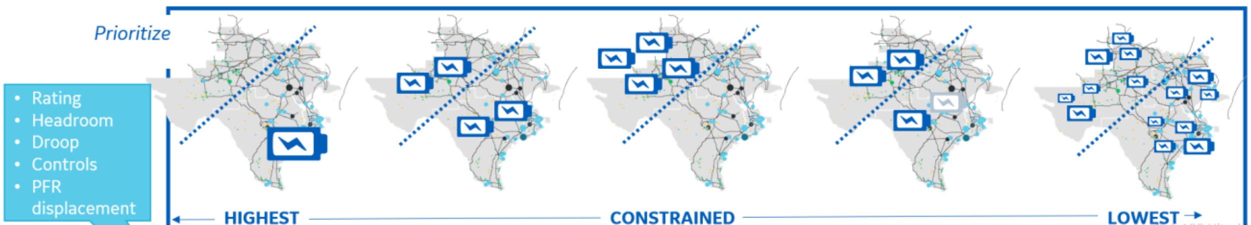
Similar response despite droop difference!

RISK ASSESSMENT

Frequency compliance	✓ **Total FR > FRO** ✓ **f_{nadir} >59.4 Hz**
Voltage stability	✓ Stable voltage
Freq stability	✓ f_{settle} > 59.7 Hz ✓ Stable settling
Small signal stability	✓ Damped oscillations
Control stability	✓ No instabilities
Transient stability	✓ No loss of synchronism
Common mode failure	✓ No issue if 10% limit

Figure 4: Most cases resulted in low risks despite droop difference

The risks evaluated in each scenario are summarized in Figure 5. The “X” in the table indicates the risk was evaluated in the scenario, where the dark blue signifies the primary risks for which that scenario was devised. The first two scenarios (One big BESS and Dumbbell) had no violations and were compliant. Scenario 3 (West BESS) exhibited voltage collapse in the model due to insufficient reactive support during the disturbance caused by modeling with wind and solar IBR as negative load as well as the consequent reduction in the wind and solar output due to the voltage dependency of the “negative load”. In reality, wind and solar has sufficient voltage regulation capability and this collapse will not happen. UFLS was triggered in the model due to stability limitations and inability to deliver PFR long distance, caused by the voltage collapse. This issue was mitigated (as a theoretical test of the hypothesis that the root cause of the failure was the sagging voltage in west) by adding STATCOMs to the model to support voltage. The exercise is an example of the project recommendation to qualify specific ESR resources, to avoid localized problems. Scenario 4 (Granularity Test) had some cases with high displacement of synchronous machine PFR, and insufficient BESS PFR fail (frequency dipped below acceptable 59.4Hz margin or tripped UFLS when BESS under-performed as compared to procured amount). The most cases were tested on Scenario 5 (Distributed BESS), investigating various sensitivities around location, displacement, droop gain, speed of response and homogeneity with a wide variety of acceptable results. These cases indicate that which synchronous machine PFR being displaced by BESS PFR is not very important. GE did not find a need to worry about location ***any more than current practice***.



RISK	5 SCENARIOS (LOAD FLOWS)				
	1: One big BESS	2: Dumbbell *4 BESS: 2 Odessa, 2 coast*	3: West BESS *4 BESS close proximity… weakest zone*	4: Granularity test *2x+1x – 25%FO*	5: Distributed BESS *Used queue distribution*
1. Freq **compliance**	**X**	**X**	**X**	**X**	**X**
2. Voltage collapse	X	X	**X**	X	X
3. Freq instability	X	**X**	**X**	X	X
4. **Interactions**		**X**	**X**		**X**
5. **Dysfunction**		X	X	**X**	X
6. **Transient** stability	X	X	**X**		X
7. **Common mode**	X	X		**X**	**X**
RESULTS	No Violations PFR comparable to no BESS	FR Compliant	Voltage collapse due to IBR models UFLS triggered due to stability limits Model issue resolved via STATCOM	Some cases with high displacement of PFR_{SM} and insufficient PFR_{BESS} failed.	*Which* SM PFR that is displaced by BESS is not very important. No need to worry about location any more than you do now.

Figure 5: Summary of results showing evaluated risks and scenarios

3.1 Individual resource qualification recommendations

The first critical element of assuring safe and reliable frequency performance is to assure that individual resources intending to bid in to the RRS-PFR market are qualified to do so. Figure 6 offers a framework of analyses to simulate individual resource behavior, assess performance risk of that resource across the full array of grid conditions it will be exposed to and determine if the performance of the resource is adequate to bid into the RRS-PFR market. This tollgate process is meant to give more confidence to ERCOT that resources bidding into the market can solidly deliver on their commitment to do so. Resources that fail qualification have an opportunity to mitigate the cause of failure and re-qualify.

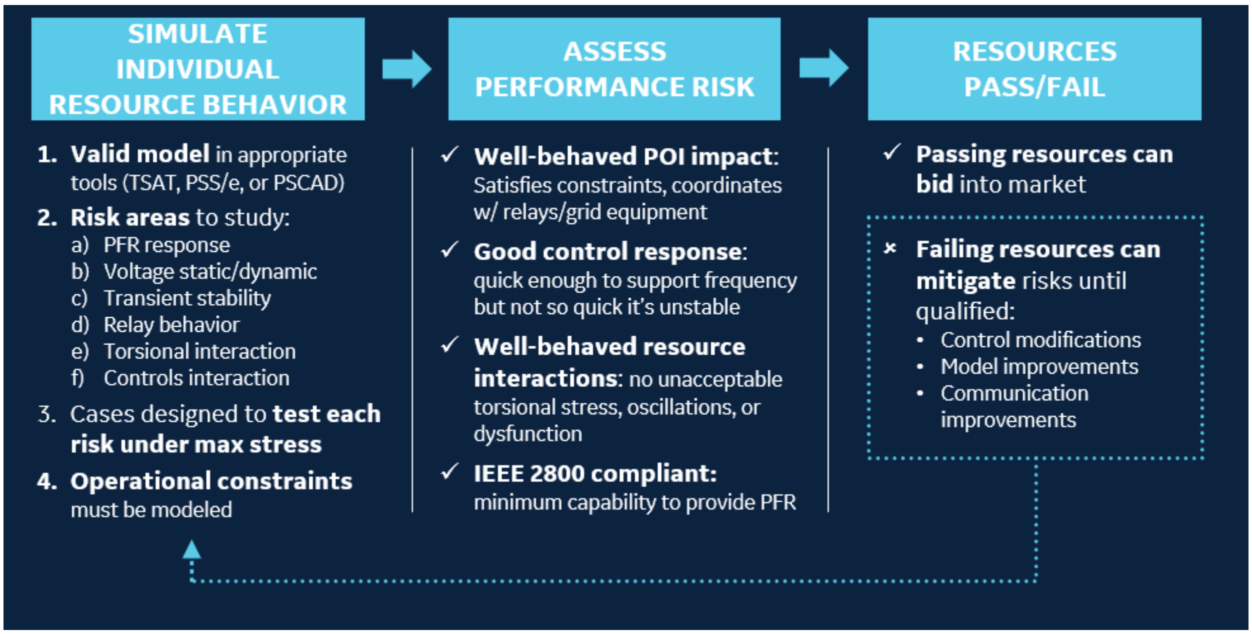


Figure 6: Resource qualification is a crucial part of assuring adequate PFR performance & mitigating system risks

A qualified resource should have the following attributes and address the following risks:

1. **Grid POI is able to accept the PFR power when necessary to do so.**
    a. Thermal and voltage constraints in the vicinity of the resource are satisfied during the provision of PFR
    b. Provision of PFR does not cause sympathetic or unwanted protective relay action or other unwanted responses from or interactions with other grid equipment
2. **RRS-PFR resource has good control response.**
    a. Response to frequency events is well-mannered, sufficiently damped and stable
    b. Response is fast enough with acceptable overshoot and settling time for any expected grid condition
    c. Is IEEE 2800 compliant, where applicable

3. **Does not have adverse impact or interact with other devices or resources.**
    a. Does not cause unacceptable torsional tress on synchronous machines within electrical proximity
    b. Does not create unacceptable oscillations in any system quantity (e.g. voltage, power, etc.)
    c. Does not cause discretely operating devices, resources or actions (e.g. UFR) to act unacceptably
4. **Has a valid model.**
    a. Model accurately demonstrates the dynamic performance of the qualified resource in necessary tools (TSAT, PSS/e or PSCAD). This includes, but is not limited to, the specific requirement that the model reflects the actual delivery of MW for a 1% frequency depression.

To assess the overall system impact of the qualified resource, ***it is strongly recommended that a qualification study be performed*** any time a resource intends to connect to the grid and/or provide RRS-PFR service. ERCOT has existing processes to assess resource performance of each power plant through interconnection studies that assess individual reliability impact relative to performance risks (including model quality tests) as well as a Quarterly Stability Assessment which determines reliability impact of groups of resources relative to performance risks. These existing analytical practices offer a solid framework to build this RRS-PFR qualification study on. The elements of this qualification study should address the various risks that were analyzed as a part of this RRS-PFR study investigation, such as:

- Ampacity for "maximum" PFR response; thermal limits
- Static voltage stability/support for PFR response
- Control performance delivers satisfactory PFR response
- Dynamic voltage stability and reactive requirements for PFR response
- Transient stability, i.e. risk of separation caused by PFR action
- Protective relay behavior, e.g. distance relays, overcurrent, etc. during PFR
- Torsional interaction with nearby synchronous generation
- Control interaction (esp. of PFR functions) with
    - Nearby IBRs
    - Nearby Transmission devices (e.g. Series caps, SVCs)
    - Other (data centers, crypto mines)

The qualification study should also be designed to test risks under maximum credible stress for each risk element. This includes:

- Qualification modeling needs to have all important elements including wind, solar, and load dynamic models, as well as complete BESS dynamic models. The highest risk system conditions (low inertia, low headroom, low SCR… etc.) that may represent limiting system conditions must be tested at qualification
- Identify operational limitations
- Validation of qualified model to assess PFR, including latency, control response and time constants

This qualification process should account for any new resources intending to bid into the RRS-PFR market or any existing RRS-PFR resources that undergo a material change to their performance, such as an equipment hardware upgrade, control modification or any other alteration that would impact the performance or ability of the individual resource to adequately deliver the PFR service.

RECOMMENDATION: Revisit and update existing individual resource interconnection & RRS-PFR qualification processes to address the needs and risks outlined above.

3.2 RRS-PFR procurement recommendations

When processes are in place to suitably qualify RRS-PFR resources, the next critical element is to ensure that the RRS-PFR service may be procured to deliver acceptable frequency response and recovery from grid disturbances. ERCOT now has processes to procure PFR, predominantly today with synchronous generators on 5% frequency droop. These recommendations are intended to provide incremental changes to these existing processes (rather than recommend a completely new process), that will allow successful participation and procurement from all qualified PFR resources.

RECOMMENDED CHANGES FOR INDIVIDUAL PARTICIPATING RESOURCES INCLUDE:

(A) Allowed MW (% of rating) offering is determined by the effective frequency droop

The maximum allowed MW offered for PFR is that which would be delivered for a 1% frequency excursion. Presently, resources by default are usually limited to 20% of MW rating to provide RRS-PFR. This is based on the expectation that these resources will be able to deliver 20% of their MW rating with a 5% frequency droop. Today, resources with lower droops can offer more than 20%, based on their demonstrated/verified droop settings and capability. A demonstrated effective 1% droop allows a resource to offer 100% of its power rating. To a first approximation, the power available for PFR is equal to the MW rating of the resource divided by the % droop.

This creates a uniform basis for the "expected" performance of the PFR: the "algebraic" response to a given frequency excursion is the same fraction of MW offered but allows for accommodation of physical (or control) constraints that are non-linear with frequency, as is the case with fossil units offering PFR services today.

Considerations of frequency droop equivalency:

- Speed of response is not included in this recommendation (as is the case today). Based on the experience of the authors, ignoring a degree of diversity in speed of response has not created significant performance problems or equity constraints. With IBRs, more diversity in response is possible.
- This study tested IBRs with "reasonable" controls and with a variety of control sensitivities. This recommendation is conservative, and the GE project team expects this approach will result in similar or better frequency performance vs. today's all synchronous practice. This approach has the benefit of simplicity and transparency.

PFR/FFR IBRs in weak systems or remote from other resources providing the response may be limited in their ability to provide useful PFR. The primary vehicle for addressing these concerns is the qualification study. However, under systemic conditions that are *substantively different from normal* (or those under which the qualification studies were performed), further tests of dynamic performance, particularly transfer & stability limits and voltage collapse may be warranted. (Such conditions might be identified during the qualification study)

The efficacy of BESS providing PFR with 1% droop is a 1:1 displacement of "typical" (e.g. effective 5%) PFR. That is, each MW of PFR from a BESS with 1% droop is "worth" a MW of PFR from a resource with 5% droop.

- Differences happen when a higher total MW rating of qualified resources are providing PFR. For a simple example, twice as many MW (in terms of nameplate rating) of 5% droop resources could offer 10% of their nameplate each, compared to fewer resources offering 20% of their nameplate, and still meet procurement rules. However, the effective *system-wide* droop in this example is halved (twice the effective gain), resulting in more aggressive response. The study did not identify any performance concerns with such conditions.

- For procured operation in which many resources are providing response substantively less than their maximum qualified PFR power, tests of satisfactory dynamic performance may be warranted. In existing ERCOT processes, PFR performance for every resource is evaluated for every eligible frequency event (FME).

- Monitoring of performance for events should continue.
- As noted for procurement, for a qualified Energy Storage PFR resource, the available power (i.e. MW headroom) *and* energy (e.g. state of charge) must be sufficient to deliver the procured power for promised services for the specified duration.

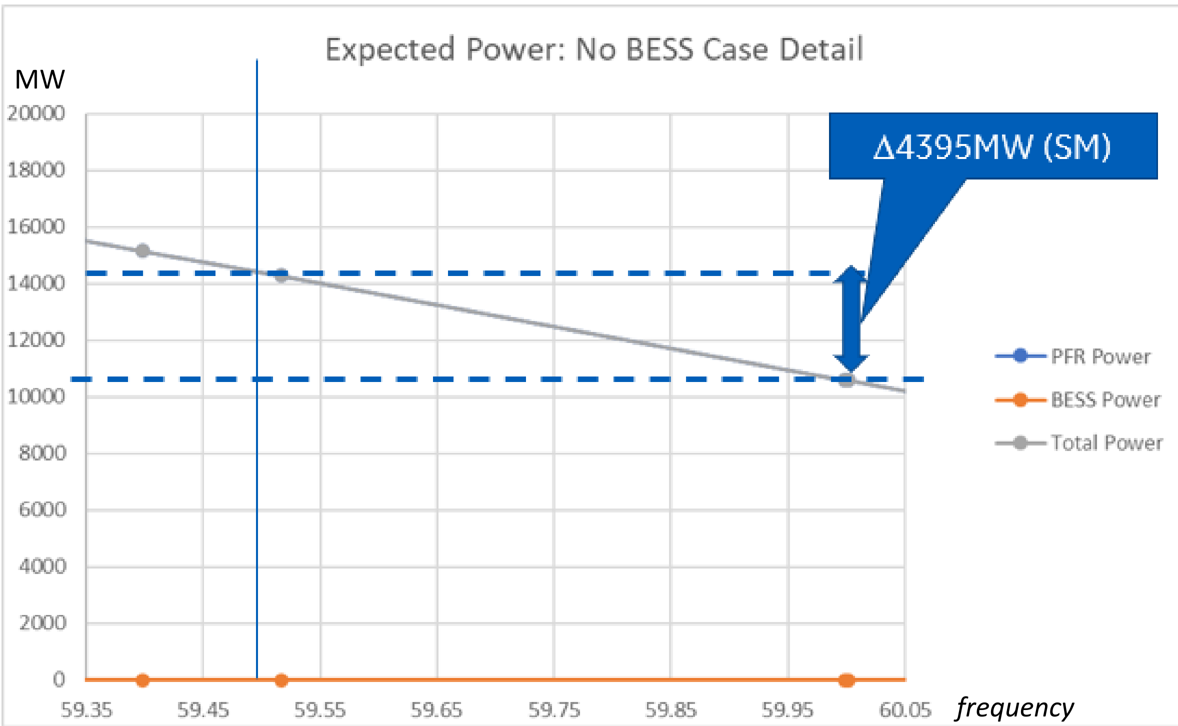


Figure 7: SM PFR for a 1% (600mHz) frequency depression event

To prove this point, the plots in Figure 7 and Figure 8 show that displacement of synchronous resources on 5% droop (yielding 20% of their nameplate response) with BESS on 1% droop (yielding 100% of their nameplate response) is effectively equivalent.

The specific details are that the total PFR power in Figure 7 for all 21,973 MW nameplate of participating synchronous machines is Δ4395 MW for a 1% (600 mHz) frequency depression event. Figure 8 shows that a total of 14,187 MW nameplate of SM + 1,400 MW BESS will yield Δ4237 MW for the same frequency depression. These are effectively the same response. Slight differences are a result from headroom averaging <20% on 5% PFR synchronous resources.

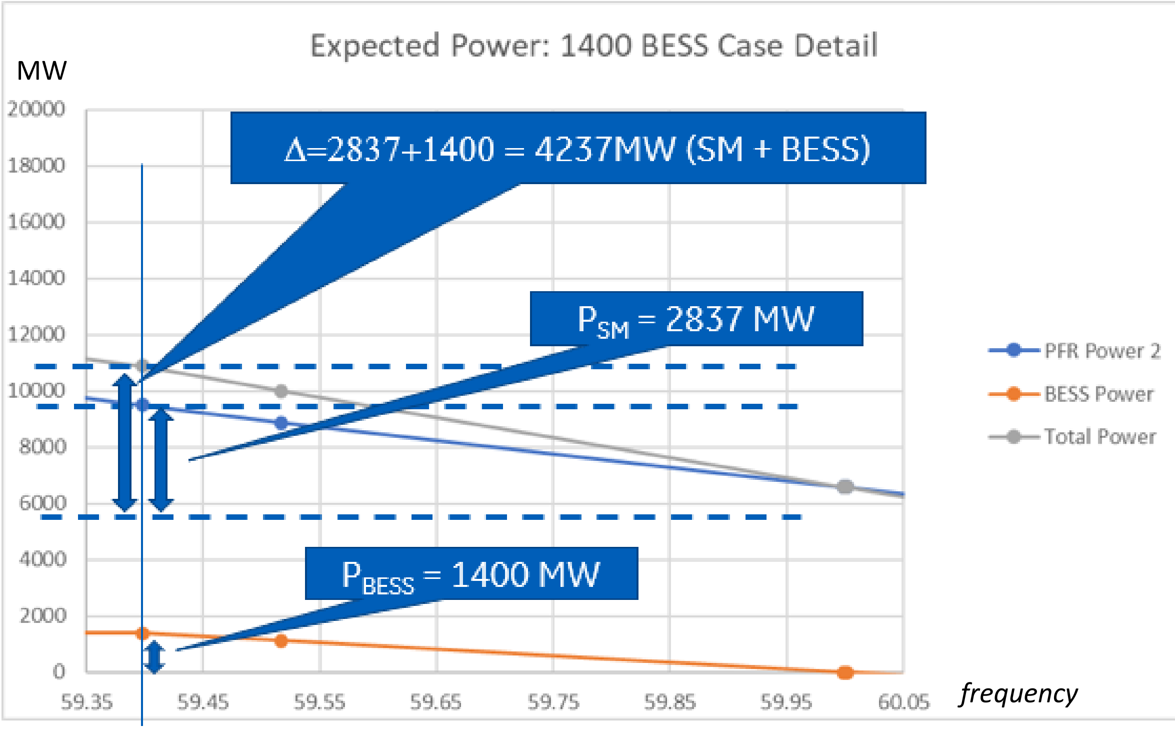


Figure 8: SM plus 1400MW BESS PFR for a 1% (600 mHz) frequency depression event

(B) Max MW offer accepted from a single resource should initially be no more than 10% of the total systemic PFR MW

Failure of a contracted resource to provide PFR during a frequency event will degrade system frequency response and could result in UFLS triggering that might not otherwise occur. Failure to perform is arguably an N-2 event and need not meet the same performance criteria.

The 20% limit for 5% droop resources has naturally enforced a degree of diversity and placed a lower limit on the number of resources needed. ERCOT has not historically needed to worry about too few resources providing PFR. But, with individual IBRs able to offer 100% of rating (with 1% droop), supply of PFR is likely to be in fewer and larger chunks. Industry (NERC) practice dictates that extreme degradation (e.g. cascading failures, etc.) be avoided. This study tested scenarios in which varying amounts of contracted PFR (from IBRs) failed to respond.

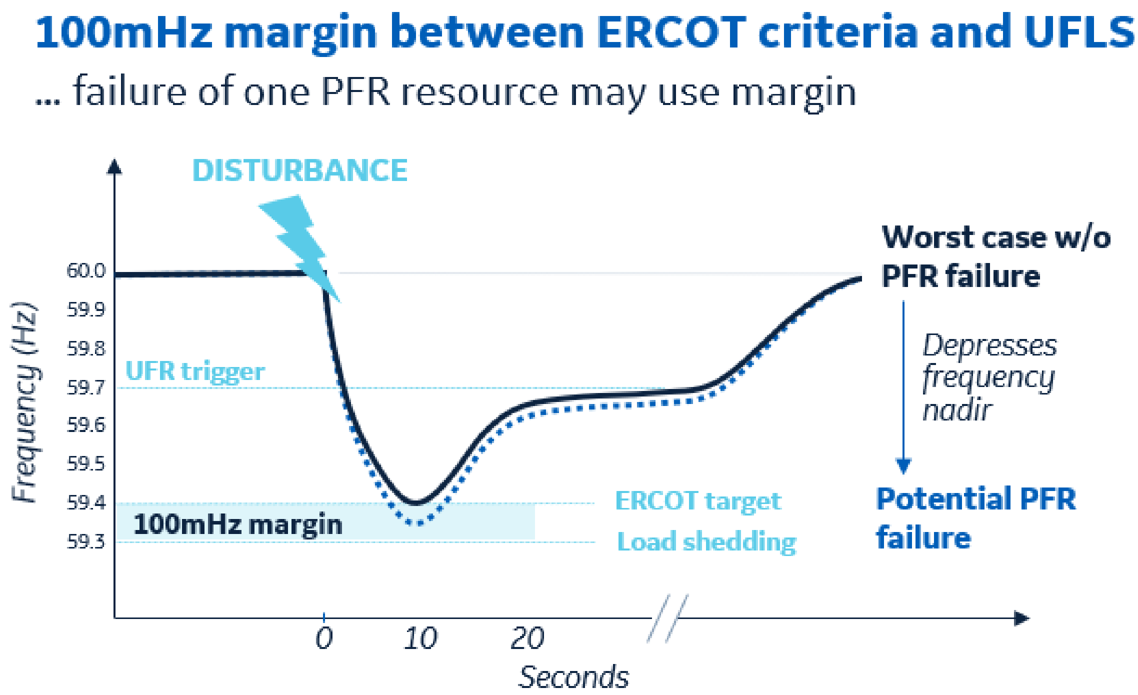


Figure 9: Common mode risk - what amount of PFR is acceptable from an individual resource based on risk of resource failure?

Figure 9 illustrates the concept of conservatism in the practice of planning for “worst case” acceptable frequency events. To date, ERCOT has utilized a 100 mHz margin above the first stage of automatic underfrequency load shedding (UFLS) trigger of 59.3 Hz. During planning analysis, if any event under any feasible operating condition resulted in the frequency nadir dropping below 59.4 Hz, this has been considered a failure of acceptable frequency performance. Going forward, with the consideration of BESS providing frequency response on 1% droop (delivering 100% of its nameplate for PFR), it is plausible that a substantial portion of PFR could be provided by one resource. If that resource fails to provide the expected PFR when needed (due to equipment failure or otherwise), grid frequency performance will be compromised. The initial 10% limit on the size of a PFR resource was evaluated under two system conditions; one at 122 GW.s and another at 244 GW.s synchronous inertia. Figure 10 summarizes the results of that analysis, showing the relationship of maximum allowed PFR failure at the two different system inertias and the impact of that failure on frequency nadir margin degradation.

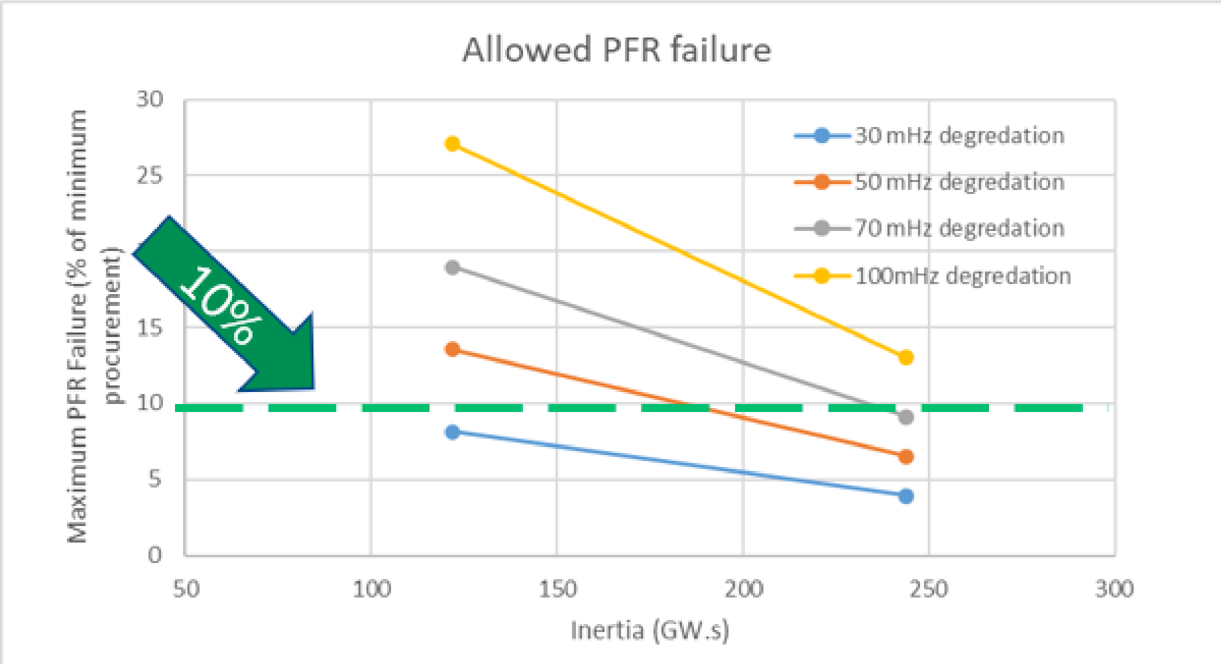


Figure 10: Allowed PFR failure at two system inertia conditions and impact on frequency nadir margin from UFLS

Some key observations about this analysis include:

- GE's study only included 2 inertias (122GW.s & 244GW.s), so curve-fit is necessarily linear but may not be linear in actuality.
- Failure of some PFR to respond will degrade the nadir, eating into the 100 mHz margin (above 59.3Hz).
- It is expected that more data, for a wider range of inertias will produce a curve (rather than a straight line). For consistency, ERCOT may use an exponential curve fit, as done for the RRS curves now.
- The orange curve here would indicate the PFR for tolerance of 50 mHz risk – i.e. ½ of the built-in margin.
- So, at 244 GW.s inertia level, the maximum PFR procured from a single resource would be 200 MW. Similarly at 122 GW.s, the maximum PFR procured from a single resource would be 900 MW.
- Regardless of the curve-fit, it is not expected that the sensitivity, nor the allowable PFR failure to drop to zero.
- The system is less sensitive to PFR failure, per MW, as inertia drops. This may be counter-intuitive at first. But, as the inertia drops, the system needs more PFR to meet target of 59.4 Hz nadir. Therefore, each MW of PFR has less impact.

- At higher inertias, enforcing a maximum MW granularity based on frequency nadir degradation result in much smaller blocks. There are likely to be **economic consequences.**
- Allowing maximum MW granularity that causes deeper frequency nadir degradation at higher inertias makes some holistic sense: there is more time to act and there may be less risk of UFLS.
- ERCOT needs to decide if, and how much, this risk needs to be mitigated.
- Setting an initial granularity limit of (e.g.) 10% of total procured PFR (green line) is simple and may satisfy ERCOT's desire for a more conservative approach.
- With the present outlook (as modeled) this granularity limit is not binding. But, future even larger ESR could hit against this limit.
- The risk of PFR failure is not limited to BESS, and the results can be applied to any type of resource ERCOT is relying on for RRS.
- **Setting any limit is somewhat heuristic because this is beyond standard NERC reliability practice. Should there prove to be significant economic penalty with this initial 10% limit, a higher level or different approach may be adapted.**
- **ERCOT should monitor performance of new IBR resources providing PFR and expect to learn and refine the approach with experience and analysis, with the objective of determining if there is significant reliability risk of non-performance.**

RECOMMENDATIONS FOR THE TOTAL AMOUNT OF PFR PROCURED INCLUDE:

(C) Present rules, that include quantitative guidance based on inertia, FFR, and UFR, should be retained.

It is possible that experience, and adaptation of more aggressive controls than those suggested by this work, will allow for IBRs to be rewarded for "better" contribution to overall frequency performance. Faster controls can be advantageous but also problematic in terms of oscillatory issues or control interactions. Careful studies are warranted to select the appropriate control tuning and coordination for the application.

Successful operating experience may result in more economic rules, such as lower quantities procured, and higher MW rating allowed for individual suppliers. Future gain reductions or other control refinements could also contribute to rule changes.

(D) Present practice that does not limit PFR based on location may continue. ERCOT should watch for necessary changes.

ERCOT presently does not limit procurement of PFR based on location in the grid or on physical distribution (i.e. "spread the PFR around").

A variety of tests regarding physical location of resources providing PFR were performed in this study.

This study found no compelling reason to force specific geographic distribution of PFR during procurement. Adding additional rules to force locational diversity does not appear to be warranted.

Several issues and possible risks related to location and rating of individual resources were identified. Recommendations for examination of these risks, which could result in individual resources being limited (in the amount of PFR they can offer) are included in the qualification study recommendations.

Differences in systemic performance (outside of the risks mentioned) for different physical locations and resource density were minor. ERCOT should establish or continue processes to continuously monitor frequency performance and make adjustments along the way; make sure performance is consistent with the model.

KEY ELEMENTS THAT DO NOT CHANGE INCLUDE:

(E) Resources must be dispatched so that it is possible for the resource to deliver the full PFR MW offered.

Resources offering PFR must have the headroom to do so. This is elementary and consistent with present practice. In the case of batteries and most other IBRs, the maximum output is a relatively hard limit compared to thermal resources. This is a question of managing dispatch and other offered services: active power output serving other functions must not preclude delivery of the maximum procured PFR for that procurement period. This includes other services that might also count on reserved headroom (e.g. ramping or other reserve services).

(F) Resources must have the energy necessary to provide PFR MW offered for the duration specified by the ERCOT Nodal Protocols

The ability of conventional (fossil) resources to respond – from an energy perspective – is not normally an issue; i.e. the expectation is that there will be enough fuel to respond when expected. With energy storage resources, there must be sufficient state-of-charge (or the equivalent) available to meet the duration of delivery defined by the PFR market. This includes other services that might also count on reserved energy (e.g. ECRS).

3.3 Operations planning recommendations

A third critical element to ensuring deployment of RRS-PFR from any resource is to assure operational capability for the PFR MW to be delivered at the time and under the system conditions when it is needed. Once a resource is qualified and means for procurement are in place, the resource must be operated and positioned in a manner to have the capability to deliver the needed PFR MW when needed and not be constrained by other operational constraints (e.g. headroom, energy availability, etc.).

(A) PFR/FFR IBRs in weak systems or remote from other resources providing the response may be limited in their ability to provide useful PFR.

The primary vehicle for addressing these concerns is the qualification study. However, under systemic conditions that are *substantively different from normal* (or those under which the qualification studies were performed), further tests of dynamic performance, particularly transfer & stability limits and voltage collapse may be warranted. (Such conditions might be identified during the qualification study)

The efficacy of BESS providing PFR with 1% droop is a 1:1 displacement of "typical" (e.g. effective 5%) PFR. That is, each MW of PFR from a BESS with 1% droop is "worth" a MW of PFR from a resource with 5% droop.

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- For procured operation in which many resources are providing response substantively less than their maximum qualified PFR power, tests of satisfactory dynamic performance may be warranted.

Monitoring of performance for events should continue. As noted for procurement, for a qualified Energy Storage PFR resource, the available power (i.e. MW headroom) *and* energy (e.g. state of charge) must be sufficient to deliver the procured power for promised services for the specified duration. Energy Storage has the potential to provide a wide range of capabilities and grid services, from time shifting and energy arbitrage, to variability/uncertainty management with wind and solar resources, to frequency and voltage regulation. While BESS has potential to do all of these, the ability to perform any one of these capabilities or grid services is determined by its capacity and energy ratings and how it's operated to manage state of charge and headroom/foot room at any given instant. From the perspective of counting on BESS to provide RRS-PFR, it is essential to ensure via the procurement process and during grid operations that providing other services does not interfere with providing contracted PFR.

RECOMMENDATION: ERCOT should have operational practices, requirements, and mechanisms in place to address the following considerations.

1) **DISPATCH: Resources must be dispatched so that it is possible for the resource to deliver the full PFR MW offered.**
2) **ENERGY STORAGE STATE OF CHARGE NEEDS TO BE MANAGED so that the resource can provide the full procured PFR.**
3) **ENERGY DELIVERY: PFR resources must be operated to provide PFR MW procured for the duration specified by the ERCOT protocols.**

4 CLOSING THOUGHTS AND NEXT STEPS

The focus of this evaluation is to make recommendations on provision of RRS-PFR and outline a methodology to determine any limits for procuring or deploying RRS-PFR from all resources. The state-of-charge necessary to provide the energy for PFR is more than an order of magnitude less than that required for an hourly reserve product. The GE study did not specifically address this issue as this is not an RRS-PFR issue alone. Longer timeframe energy requirements cannot be addressed with this type of simulation. There is an opportunity to further evaluate this in a future study to assess whether it is reasonable to combine PFR and slower reserve services into a single product.

Overall, this study concluded that ***ERCOT can fully rely on 1% droop resources to provide RRS-PFR if the recommended processes in this report are followed.*** That is, all PFR resources must be qualified to participate in the RRS-PFR market and individual resource PFR must not exceed 10% of the total PFR requirement. Operational recommendations to prioritize and ensure the delivery of PFR when called on to do so must also be followed.

There are other aspects identified in this study effort that the GE team did not investigate (due either to the fact that they weren't included in the scope of this study or other modeling constraints did not allow them to be evaluated in the timeframe of this evaluation), but future investigation of these items would be prudent. These aspects deal with additional BESS coordination risks and how well-mannered the BESS would perform with respect to other IBRs (e.g., wind and solar generation) in ERCOT's grid or frequency responsive services in timeframes outside of PFR delivery. Some open questions that would benefit from future analysis include:

1) **Do wind and Solar help or hurt grid stability and frequency performance with BESS?** Does including wind & solar in models help stabilize network disturbances or small signal stability? Are there any negative interactions that would occur between wind, solar, BESS and other SM generation that risks grid reliability? The grid models in this study accounted for wind and solar generation as negative loads and not explicit dynamic representation of the resources. Adding wind and solar dynamic models to low inertia PSS/e cases is a substantial and tricky effort, but this will be necessary to answer open questions about impact, efficacy and potential issues with IBR and BESS coordination.

2) **Do FFR and inertia coordinate well with BESS PFR?** Does provision of FFR by IBR resources provide economically attractive alternative or adjunct to PFR? Does adding grid forming BESS into the grid alter FFR performance? Would there be benefit to altering ERCOT's FFR service definition? Does FFR cause misbehavior or complexities regarding proper tuning of frequency responsive controls, interactions with initial response of IBRs or synchronous machines and is there a proper hand-off with PFR? This study focused on PFR and did not dig deeply into FFR but coordination and impact with FFR will be needed.

3) **Do regulation and redispatch coordinate well with BESS PFR?** This study did not investigate coordination with longer-term frequency responsive services and behavior but coordination of PFR with these longer-term services is both a need and opportunity to assure sufficient frequency control across timescales.