Advanced Grid Support Energy Storage Resource (AGS-ESR)

Functional Specification and Test Framework for the ERCOT Grid

Version 1.0

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1 Introduction

1.1 Background and Overview

ERCOT has contracted Electranix to help recommend the potential functional specification and test framework for the energy storage resources providing advanced grid support, such as grid forming (GFM)-like capability. The preliminary results[1] were presented to the ERCOT Inverter-Based Resource Working Group (IBRWG) in July 2024 and serve as the technical guidance for ERCOT staff to develop the test framework for qualifying advanced grid support Energy Storage Resources (AGS-ESRs) within the ERCOT system. Notably, this approach is control-agnostic, evaluating system performance without prescribing specific control topologies. This document outlines ERCOT-proposed detailed test protocols and associated criteria to examine and verify resource functionality. The final requirements are subjected to the approved ERCOT Guides and DWG procedure manual.

1.2 Need for Advanced Grid Support

The IEEE 2800-2022 Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) with Associated Transmission Electric Power Systems outlines design and performance requirements essential for the reliable integration of IBRs into the bulk power system. While adopting IEEE 2800-2022, or similar standards, is expected to enhance reliability, a grid experiencing significant IBR growth and penetration will require additional advanced grid support measures to maintain system strength, enhance system resilience, reduce grid impedance, and increase voltage stiffness.

In the ERCOT region, additional concerns are arising along with the growth of IBRs. Existing IBRs rely on sufficient system strength for stable operations and don’t inherently contribute to the system inertia. The continuous growth of IBRs, along with limited online synchronous generators, could lead to weak grid conditions with more volatile voltage and frequency performance in both normal and disturbance conditions. Increasing stability constraints have been created in recent years in real-time operations to maintain stable operation of IBRs. These stability constraints, if binding, would require generation redispatch and curtailment to maintain the stability. Similarly, broader event impact, including voltage and frequency, has been observed in recent years that affects more generators and loads. ERCOT continues to identify ways to improve the grid security and stability, including the adoption of IEEE 2800-2022 and addition of synchronous condensers. Further IBR growth is projected based on the Resource Capacity Trend Charts[2] and could exceed 100 GW IBR installed capacity by 2025. GFM IBRs, especially the application to the energy storage resources, have been widely considered, required, and implemented in several regions[3] also experiencing high penetration of IBRs in their grid. These new technologies, named as advanced grid support ESR (AGS-ESR) in this document, can

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[1] https://www.ercot.com/files/docs/2024/07/10/2024_07_ERCOT_IBRWG_Advanced%20Grid%20Support%20Inverter-Based%20ESR%20Functional%20Specification%20and%20Test%20Framework_v1.pdf

[2] https://www.ercot.com/gridinfo/resource

[3] https://www.esig.energy/working-users-groups/reliability/grid-forming/gfm-landscape/specifications-and-requirements/

offer grid-stabilizing characteristics that support the reliable operation of the bulk power system under growing IBR penetration and can enhance stability margins across the system as these resources are interconnected.

1.3 Advanced Grid Support Provided by ESR

This document focuses on the functional specifications for ESR with respect to the following considerations.

a) The control technology for ESRs can be adapted from grid-following (GFL) to advanced grid support ability (e.g., GFM) via a software control change with no or minimal impact on hardware. For example, there are generally no considerations related to mechanical devices, such as drivetrain impact or pitch/stall characteristics present in wind technology, or maximum power point tracking (MPPT) and energy controllers present in PV technology. While these may be addressed to some extent in PV and wind technologies, there are essentially no such constraints in ESR. The controls can be modified, and if the ESR is not on its AC or DC current limit and has energy available, it can automatically respond up to its limit. Some wind manufacturers are actively researching bringing an “inertia-like” product to market on Type 3 wind generation resources, which have inherent machine response; but they must contend with mechanical design limitations. For example, releasing some control on the current may add stress to the drivetrain, blades, and tower. On the PV side, energy controllers may not be easily adapted to running below Pmax, and there may be other constraints on the DC side of the system. These technical limits should be explored further in collaboration with wind and PV vendors.

b) A notable portion of the time, ESR devices are not expected to operate at their maximum output limit in commercial operation due to the need to maintain sufficient state of charge for real-time dispatch and/or ancillary service support, yielding good overall advanced grid support benefits. Once a Pmax/Pmin limit is encountered, it can only provide limited theoretical benefits that depend on over-current capacity.

c) Advanced grid support ESR is currently commercially available based on the feedback from multiple ESR manufacturers and is not yet available from other forms of IBR, such as wind and PV.

Future work is recommended to investigate the potential advanced grid support provided by non-ESR IBRs. To achieve this, detailed models with advanced grid support abilities and engagement with the industry and OEMs will be needed to develop suitable test protocols.

2 Recommended Test Framework for Advanced Grid Support ESR

To verify the AGS-ESR capabilities through models, two types of model tests are recommended: site-specific model quality tests and technology-specific unit model validation tests. These tests are designed to assess whether the plant meets the expected advanced grid support performance for the ERCOT grid. It is essential to note that this test framework is recommended as a replacement of only IBR model quality test framework for AGS-ESR, and it serves as a supplement to other existing IBR performance requirements, such as those outlined in the ERCOT Nodal Operating Guides. It is not intended to replace or substitute those performance requirements.

2.1 Site-Specific Model Quality Tests (MQT)

Table 1 shows a summary of recommended site-specific model quality tests outlined in this chapter. Each test includes four key components: a) Testbench Setup, b) Test Sequence, c) Required Output/Plot, and d) Performance Criteria. These components guide the user in selecting the appropriate test bench, executing the test, reporting requirements, and the performance criteria. Detailed instructions for each test are provided in the following subsections.

Table 1. The recommended site-specific MQT for AGS-ESR

Test #	Test Name	Testbench System	Applicable Software Platform
1	Flat start	TB1	PSCAD, PSS/E, TSAT
2	Phase angle jump	TB1	PSCAD
3	Small voltage disturbance	TB1	PSCAD, PSS/E, TSAT
4	Frequency change and inertia response	TB1	PSCAD, PSS/E, TSAT
5	System strength	TB1	PSCAD, PSS/E, TSAT
6	Large voltage disturbance	TB1	PSCAD, PSS/E, TSAT
7	Loss of synchronous machine	TB2	PSCAD, PSS/E, TSAT

2.1.1 Testbench Descriptions

Two testbenches are referenced in this framework:

Testbench 1 (TB1): Figure 1 shows TB1, which consists of an ideal voltage source connected to the AGS-ESR being tested through a controllable series impedance, as well as a variable impedance fault component. The source has inputs for voltage (including magnitude, phase, and frequency), and the series impedance (Z_{th}) can be varied such that the short circuit ratio (SCR) of the connection point can be set. The voltage magnitude of the voltage source is also set to 1.0 pu.

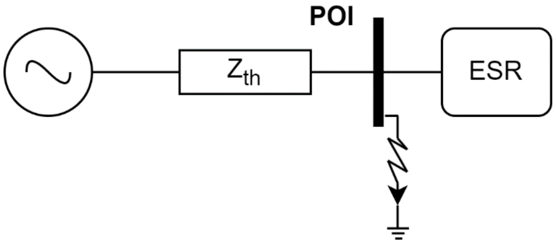

Figure 1. Testbench 1, single-machine variable impedance system

Testbench 2 (TB2): Figure 2 shows TB2, which consists of the following components connected to a single bus without any impedance:

- A voltage source with a circuit breaker to be able to disconnect the source from the system. The voltage magnitude of this source is set to 1.0 pu.
- A constant impedance load with power factor of 0.95
- The ESR model under test (project ESR)
- A duplicate of the ESR model with the same size as the project ESR. The duplicated model is used in these tests to demonstrate effective coordination of multiple ESR devices at different dispatch levels.

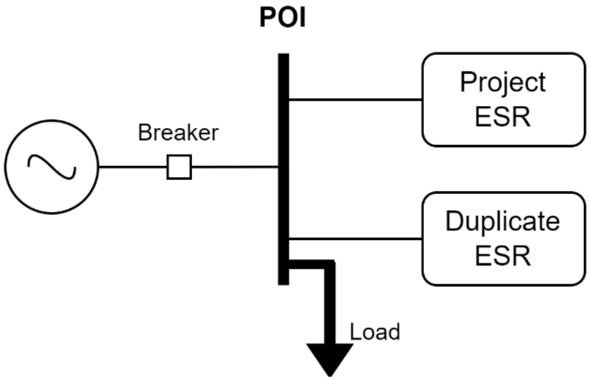

Figure 2. Testbench 2, simplified network with load

2.1.2 Test 1: Flat Start

This test is intended to demonstrate the proper initialization of the model, verify the steady state, and ensure the numerical stability of the simulation. To achieve this, the TB1 is used to run for a minimum of 20 seconds without applying any disturbances. During this period, it is expected that the voltage, active power, reactive power, and frequency shall remain stable and very close to their initial conditions.

2.1.3 Test 2: Phase Angle Jump

This test applies a step change to the phase angle of the 3-phase voltage source connected in TB1 so that the active power response time and magnitude can be measured. This test is set up to examine 1) the capability to maintain the voltage phasor and resistance to angle change, and 2) stable behavior under different angle step changes, when it is working close to the maximum current limit. For large angle changes forcing the controls beyond their maximum current limits, the ESR should be stable and should not degrade the performance of the power grid. Table 2 details the setup and performance criteria for a phase angle jump test.

Table 2. Test setup and performance criteria for Test 2, Phase Angle Jump

Test 2: Phase Angle Jump
Testbench Setup
Using Testbench 1, SCR at connection point is set to 3 with X/R of 6
Initial dispatch of ESR is set to the max discharging for active power with approximately zero reactive power
Test Sequence
1. Angle of the voltage source behind the equivalent grid impedance is decreased instantaneously by 10 degrees
2. A few seconds later, angle of voltage source is increased instantaneously by 10 degrees
3. A few seconds later, repeat steps 1 and 2 with a +/- 25-degree phase angle change
Required Outputs/Plots
1. Phase angle profile applied to the voltage source
2. RMS voltage of POI
3. Active and reactive power of the project plant with appropriate axis resolution to demonstrate all performance criteria
Performance Criteria
A. Instantaneous active power output of the plant should quickly respond to oppose the angle change. The peak active power change should be at least 0.2 pu (based on rated active power) for each 10-degree voltage phase angle change, in opposing direction. (e.g., A 100 MW rated plant should temporarily decrease active power output from 100 MW to 80 MW, or below, when source voltage angle is increasing 10 degrees; and it should temporarily increase active power from 100 to at least 120 MW, if the current limit allows, when voltage source angle is decreased by 10 degrees.) **Note:** If the pre-event dispatch causes the plant to reach the current limit in the inverter when the angle jump is applied, the performance criteria described above (criterion A) may not apply. However, the active power must return to the pre-disturbance level in a stable manner without causing undue degradation of system performance. The active power must be more than or equal to pre disturbance level for at least 3 cycles.
B. For the 10-degree voltage phase angle jumps, response time to 90% of initial change in instantaneous active power should occur within one cycle.
C. Any oscillation shall be damped.

2.1.4 Test 3: Small Voltage Disturbance

In this test, a step change is applied to the voltage magnitude of the voltage source connected in TB1 so that the reactive power response time and magnitude can be measured. The purpose of this test is to demonstrate the capability to resist change in voltage magnitude. Table 3 details the setup and performance criteria for a small voltage disturbance test.

Table 3. Test setup and performance criteria for Test 3, Small Voltage Disturbance

Test 3: Small Voltage Disturbance
Testbench Setup
Using Testbench 1, set the impedance of Zth to zero.
Initial dispatch of ESR is set to the max discharging for active power with approximately zero reactive power
Test Sequence
1. The magnitude of the voltage source behind the equivalent grid impedance is decreased instantaneously by 3% (i.e., from 1.0 pu to 0.97 pu)
2. A few seconds later, the magnitude of voltage source is increased by 3% to return to 1.0 pu
3. A few seconds later, the magnitude of voltage source is increased by 3% to reach to 1.03 pu
4. A few seconds later, the magnitude of voltage source is decreased by 3% to return to 1.0 pu
Required Outputs/Plots
1. Voltage profile applied to the voltage source
2. RMS voltage of POI
3. Active and reactive power of the project plant, with appropriate axis resolution to demonstrate all performance criteria
Performance Criteria
A. Instantaneous reactive power output of the plant should quickly respond to oppose the voltage step change for each of the 3% voltage step changes, with an initial peak reactive power change of at least 0.03 pu on the rated power base (e.g., A 100 MVA rated plant with 0 MVAR initial output should instantaneously increase reactive power output from 0 MVAr to at least 3 MVAr when source voltage magnitude is decreased by 3%.) Note: Reactive power does not return to the pre disturbance level within 6 cycles.
B. Response time to 90% of initial change in instantaneous reactive power should occur within 1 cycle
C. Any oscillation shall be damped.
D. The final reactive power after each 3% step change is expected to reach to the maximum reactive capability of the plant in an attempt to regulate the original voltage set point at 1.0 pu.

2.1.5 Test 4: Frequency Change and Inertia Response

This test is intended to evaluate the active-power frequency response capability of the ESR and estimate its inertia response in opposing frequency change.

Table 4 details the setup and performance criteria for this test.

Table 4. Test setup and performance criteria for Test 4, Frequency Change and Inertia Response

Test 4: Frequency Change and Inertia Response
Testbench Setup
Using Testbench 1, SCR at connection point is set to 3. System Equivalent X/R is set to 6.
Initial dispatch of ESR is set to zero for active power with approximately zero reactive power
Test Sequence
Apply the frequency profile shown in Figure 3 to the controllable voltage source of Testbench 1. The frequency goes down from 60 Hz to 59 Hz by RoCoF of 1 Hz/s to provide the condition, which is used for examining the inertia responses as described in performance criterion C. The frequency stays for 2 seconds at 59 Hz and then returns back to the 60 Hz by the same RoCof and stays at 60 Hz until the output power reaches steady state. The rest of the frequency profile aims to test the active power response of the ESR for the small frequency up and down (+/-0.3 Hz), which is the same frequency change test of the existing IBRs.
Required Outputs/Plots
1. Frequency profile applied to the voltage source
2, Active and reactive power of project plant
3. Inertia calculation using formula in performance criterion C
Performance Criteria
A. Plant real and reactive power output should be well controlled. System frequency and voltage should not oscillate excessively or deviate from steady state levels for any significant amount of time.
B. Voltage settles to a stable operating point when frequency is not ramping
C. The equivalent inertia constant, calculated as below, should be greater than 2.5 s. $H \approx 60 * \Delta E$ [s][4], where: ΔE is the area under the per unit active power production of the ESR from 0 to 0.5 s, when the RoCoF is 1 Hz/s.
D. Active power should settle according to its frequency droop and deadband settings when frequency is not ramping. Note: According to ERCOT Nodal Operating Guide Section 2.2.7 Turbine Speed Governors, the droop setting of ESR shall not exceed 5%.
E. Any oscillation shall be damped.

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[4] More details of this formula can be found in Appendix A.

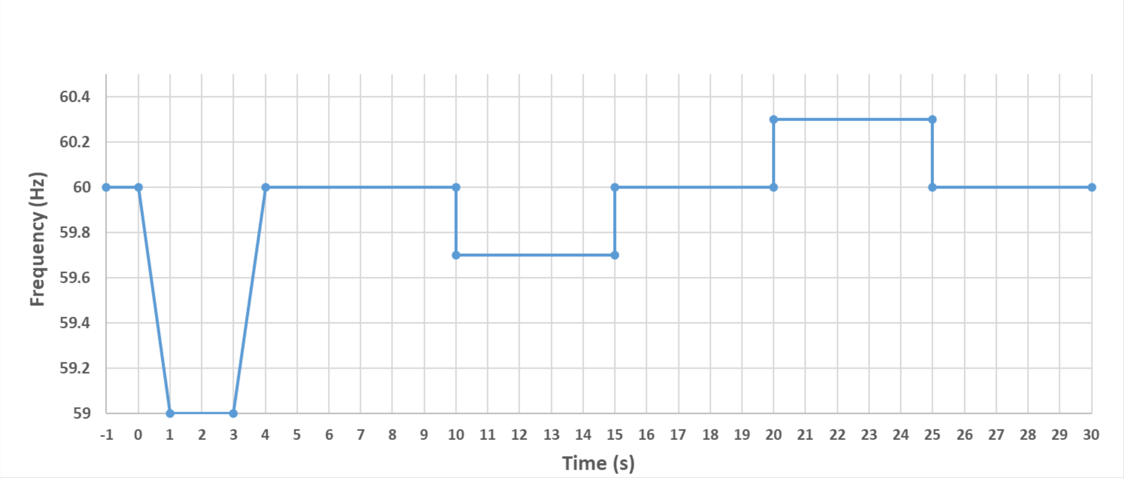

Figure 3. The frequency profile for frequency change and inertia response test

2.1.6 Test 5: System Strength Test

This test is similar to the existing system strength test for all IBRs, except AGS-ESRs shall demonstrate stable response for all tested SCR values from 10 to 1.2. Table 5 details the setup and performance criteria for system strength test.

Table 5. Test setup and performance criteria for Test 5, System Strength

Test 5: SCR Step-Down with Fault
Testbench Setup
Using Testbench 1, initial SCR at connection point is set to 10. System Equivalent X/R is set to 6.
Initial dispatch of ESR is set to the max discharging for active power with approximately zero reactive power
Test Sequence
SCR at connection point stepped down repeatedly in this progression: 10, 5, 3, 1.5, 1.2
A 3-phase, bolted, 4-cycle fault is applied just before each SCR transition. The SCR transition occurs at fault clearing time.
Required Outputs/Plots
1. SCR profile
2. RMS voltage of POI
3. Active and reactive power of project plant
Performance Criteria
Plant real and reactive power output and RMS voltage should be well controlled, and plant shall not trip nor reduce power or voltage (outside of the fault period) for any extended period of time down for all tested SCR range from 10 to 1.2

2.1.7 Test 6: Large Voltage Disturbance

Large voltage disturbance test, which includes low voltage ride-through (LVRT) and high voltage ride-through (HVRT), are the same tests of the existing IBRs. Details are described in sections 3.1.5.4 and 3.1.5.5 of the DWG procedure manual[5].

2.1.8 Test 7: Loss of Synchronous Machine Test

This test is to examine the ability to form voltage and work in parallel with another AGS-ESR. It is not intended to examine the black start capability of AGS-ESR nor to require ESRs operate on a grid without synchronous resources represented as the voltage source in TB2.

Table 6 details the setup and performance criteria for loss of synchronous machine test.

Table 6. Test setup and performance criteria for Test 7, Loss of Synchronous Machine

Test 7: Loss of Synchronous Machine
Testbench Setup
Using Testbench 2, with a constant impedance load (L), with power factor of 0.95, and the project plant initial dispatch (P1), the duplicated plant initial dispatch (p2) and the load value are as follows: Scenario 1: P1 = 0.3 pu discharging, P2 = 0.1 pu discharging, and L = 1.3 pu Scenario 2: P1 = 0.6 pu charging, P2 = 0.4 pu charging, and L = 0.7 pu Scenario 3: P1 = 0, P2 = 1 pu discharging, and L = 1.65 pu Note 1: The dispatch and load values are provided based on the project plant rating.
Test Sequence
1. Simulate the system until a stable response is achieved for the given scenario, ensuring there are no oscillations.
2. Disconnect the voltage source (no fault) and continue simulation for at least 10 seconds.
Required Outputs/Plots
1. RMS voltage of POI
2. Active and reactive power of project plant, duplicated plants, load, and the voltage source
3. Frequency of POI
Performance Criteria
A. Immediately following the disconnection of voltage source, both plants' output should be well controlled. System frequency and voltage should settle to a stable operating point (within 5 seconds) and not oscillate excessively and damped within 10 seconds or deviate from steady state levels.
B. Active and reactive power from each plant should move immediately to meet the load requirement, while response time to 90% of initial change should occur within one cycle.
C. Active and reactive power from each plant should move immediately and settle according to its droop setting.

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[5] Available at the ERCOT Dynamics Working Group webpage: https://www.ercot.com/committees/ros/dwg

2.2 Technology-Specific Unit Model Validation Tests

PSCAD models of AGS-ESR must be accompanied with results from the unit model validation tests performed by the Interconnecting Entity or Resource Entity as required in paragraph (5)(d) of Planning Guide Section 6.2. These validations shall demonstrate the accuracy of the PSCAD models against actual inverter testing and should be performed for all inverter-based device types and employed synchronization/power control strategy within the facility. The testing is inverter- and control-strategy-specific but is not site-specific. The report should include a description of the test set up as well as the simulation plots of relevant quantities for each test. Guidelines on how these tests should be performed and the expected model performance are provided in the DWG procedure manual.

- Voltage Angle Step Test
- Step Change in Voltage
- System Strength Test
- Voltage Ride Through
- Sub-Synchronous Test

3 Tests for Future Considerations

It should be noted that not all of Electranix's recommended tests for AGS-ESRs are included in Section 2 of this report. While the series compensation step test and frequency scan test, as recommended by Electranix[6], offer additional insights into the capabilities of AGS-ESRs, ERCOT does not currently plan to recommend these tests as part of the model quality requirements due to their complexity and the relatively new concepts for examining AGS-ESRs. ERCOT plans to continue evaluate these tests in the future and may consider incorporating them once clear test procedures and criteria are established.

4 Future Work

This report will be used as the technical reference for ERCOT staff to propose the requirements to adopt the AGS-ESRs for the ERCOT grid. As described in this report, the recommended tests are for AGS-ESRs and are not applicable to other non-ESR IBRs. ERCOT plans to continue work with the stakeholders, developers, consultants, and manufacturers to investigate the application of advanced grid support to non-ESR IBRs as well as the potential application of black start support by IBRs.

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[6] Description of this series compensation step test and frequency scan test can be found as Test 8 and Test 11, respectively, in Electranix in their presentation available on: https://www.ercot.com/files/docs/2024/07/10/2024_07_ERCOT_IBRWG_Advanced%20Grid%20Support%20Inverter-Based%20ESR%20Functional%20Specification%20and%20Test%20Framework_v1.pdf

5 Appendixes

A) Quantifying Inertia Response of ESR

To estimate the inertia response of an ESR in opposing frequency change and estimate its equivalent inertia constant, the swing equation can be used.

$$\frac{2H}{f_n} = \frac{\Delta P}{df/dt}\ , \tag{A1}$$

where

H is the equivalent inertia constat of the ESR in s,

f_n is the nominal frequency,

∆*P* is the change of output power in pu based on the ESR rating,

df/dt is the rate of change of frequency (RoCoF) in Hz/s.1

To quantify the inertia response of a resource using the swing equation, a disturbance needs to be applied. For this purpose, the frequency of the controllable voltage source is changed by a fixed rate and the output active power is measured. Since the output power changed during the time, the average ∆*P* (∆P_{av}) during the study time is used for quantifying the inertia constant. Therefore,

$$H = 0.5\,f_n \frac{\Delta P_{av}}{df/dt} = 0.5\,f_n \frac{\frac{1}{T}\overbrace{\int_{t_0}^{t_0+T} \Delta P(t)\,dt}^{\Delta E}}{df/dt} = 0.5\,f_n \frac{\Delta E/T}{df/dt}\ [s], \tag{A2}$$

Considering, f_n =60 Hz, *df/dt* = 1 Hz/s, and *T*= 0.5 s, then:

$$H = 60 * \Delta E\ [s], \tag{A.3}$$

where ∆*E* is the area under the active power production change of the ESR from *0* to *0.5* s in pu. Figure 4 illustrates how to calculate ∆*E from the active power output of the resource.*

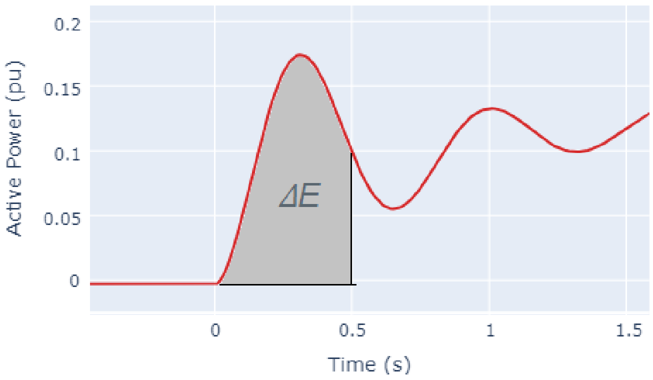

Figure 4. The output active power of the resource and illustration of ∆*E*