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Revision 0

Idaho Falls Power Black Start Field Demonstration

April 2021

Preliminary Outcomes Paper

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ACRONYMS

AC	Alternating Current
AVR	Automatic Voltage Regulator
DOE	Department of Energy
EPC	Excellence in Power Conversion
HESS	Hybrid Energy Storage System
HPP	Hydropower Plant
HVAC	Heating, Ventilation, and Air Conditioning
HydroWIRES	Water Innovation for a Resilient Electricity System
IFP	Idaho Falls Power
INL	Idaho National Laboratory
MVAR	Mega Volt-Ampere of Reactive Power
PHIL	Power hardware-in-the-loop
PID	Proportional-Integral-Differential
PMU	Phasor measurement units
PT	Potential Transformer
ROCOF	Rate-of-change-frequency
ROR	Run-of-river
SOC	State of Charge

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1. INTRODUCTION

In the week of April 19, 2021, Idaho Falls Power (IFP), Idaho National Laboratory (INL), and American Governor Group of Emerson completed a field demonstration to test the ability of using IFP units for black starting and supporting critical loads on the distribution system in islanded mode of operation. During normal grid operations, IFP balances the city's electrical load using contracts procured from other energy generators within the region. The city's five hydropower plants (HPPs) in this case are operated to maximize efficiency and reduce the amount of procured electricity. Islanded mode of operation would enable IFP to serve city residents in the event the transmission system was not available.

This April 2021 field demonstration builds upon a 2017 field demonstration in which it was determined IFP's HPPs, on their own, can support islanded black start and operation up to 2.5 MW loading. Modeling and hardware-in-the-loop testing was used in the intervening period to design an energy storage solution, specifically using ultracapacitors, to reduce likelihood of generators tripping during the field demonstration. Overall, the 2021 field demonstration tested three different options for meeting IFP's requirements: innovating the hydropower controls, synchronizing multiple HPPs on the system, and integrating an ultracapacitor energy storage system.

National laboratory contributions were funded by the U.S. Department of Energy's Water Power Technologies Office as part of the HydroWIRES Initiative under the Hydro + Storage project. IFP additionally provided significant monetary, staff, and other in-kind support to enable the field demonstration. The HydroWIRES Initiative is a multi-year program to "understand, enable, and improve hydropower's contributions to reliability, resilience, and integration in the rapidly evolving U.S. electricity system" [1]. This activity within the Hydro + Storage project is advancing the ability of small hydropower projects integrated with energy storage to contribute to community electricity resilience via enabling them to support grid islanding.

This report documents the testing performed. Follow-on analysis will provide additional insights, for example, including a complete table of comparative results between the tests and scenarios. The analysis will also propose a refined design for an energy storage system to meet IFP's grid islanded needs.

The plan and procedure carried out during the field demonstration were revised based on the reviews by the team members of the IFP personnel. Lessons from lab-based power hardware-in-the-loop (PHIL) testing were used for finalizing the field test plan. After approval from IFP, the test equipment for ultracapacitor energy storage was transferred to Rack Substation for connections. INL team set up measurement and controls for the ultracapacitor system operation in consultation with IFP. Power connections to electrical systems were performed by IFP.

In preparation of the field demonstration, the substation and sub-transmission bus work were isolated from the city distribution network. Two 4 MW hardware load banks were rented and connected at the Rack Substation bus at distribution voltage of 12.47 kV. Figure 1 shows the expanded schematic for the interconnection of UCAP energy storage system, its auxiliary power supply, and load bank. Three locations are shown to connect phasor measurement units (PMUs). PMU 1 connects to the 4B1-1 relay inside the Rack Substation, PMU 3 connects to the 3B1-10 Lower Bulb generator relay, and PMU 2 connects to the 480 V junction near the UCAP energy storage system.

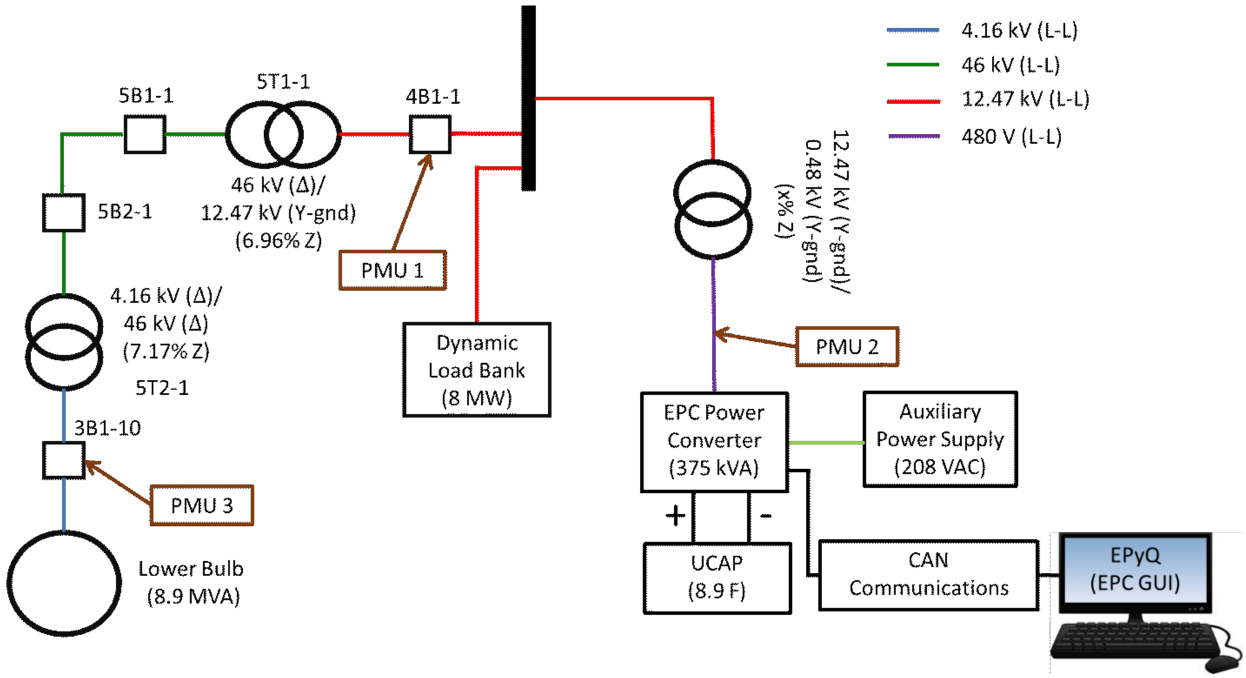

Figure 1. Field testing hardware connection for load bank and UCAP energy storage testing.

IFP, in consultation with American Governor Group of Emerson and Basler, made modifications to the governor systems and automatic voltage regulator (AVR) to optimize island mode performance, and adjusted during the field testing. PHIL results were used to guide these, as needed. All times mentioned in this report are in MDT.

1.1 Nomenclature

The following nomenclature will be used throughout the report:

- CP = 8.9 MVA City Bulb Plant (one horizontal Kaplan "bulb" unit).
- LP = 8.9 MVA Lower Bulb Plant (one horizontal Kaplan "bulb" unit).
- OLP = 1.8 MVA Old Lower Plant (Consists of two 1.8 MVA Francis units. Only one was operated during the demonstration).
- PLC = programmable logic controller.
- UCAP ESS = 375 kVA ultracapacitor energy storage system.
- Hydro-governor "manual" mode = The governor will not respond to frequency deviations. The rotating mass of turbine-rotor will only provide inertial response to frequency deviations.
- Hydro-governor "droop" mode = The governor will respond to frequency deviations through adjusting wicket gates. Thus, the hydropower unit will provide primary frequency response (in addition to inertial response).
- Scenario = Set of intervention implemented for test execution. (e.g., baseline/new hydro-governor control settings, with/without UCAP ESS, single/multiple plants).
- Loading Test = Given a scenario, response of the islanded system to a step load change. The response is recorded in terms of (1) islanded system frequency, (2) voltage and current phasor at LP unit, load bank and UCAP ESS point of interconnection, and (3) wicket gate, and turbine blade position. These

recordings are currently being investigated to assess the stable and uninterrupted load carrying capability at different scenario.

1.2 UCAP ESS Frequency-Watt Curves

Based on the PHIL test, five frequency-watt (f-watt) curves have been prepared for UCAP ESS's fast frequency response in grid-following mode:

F-watt Curve #1 Frequency Range	% of P_{UCAP}
$f \geq 58.1\ Hz$	0
$57.1\ Hz \leq f \leq 58\ Hz$	40
$56.1\ Hz \leq f \leq 57\ Hz$	45
$55.1\ Hz \leq f \leq 56\ Hz$	50
$f \leq 55.1\ Hz$	50

F-watt Curve #2 Frequency Range	% of P_{UCAP}
$f \geq 62\ Hz$	-10
$61.1\ Hz \leq f \leq 62\ Hz$	-10
$59.1\ Hz \leq f \leq 61\ Hz$	0
$58.1\ Hz \leq f \leq 59\ Hz$	40
$57.1\ Hz \leq f \leq 58\ Hz$	45
$56.1\ Hz \leq f \leq 57\ Hz$	50
$f \leq 56.1\ Hz$	50

F-watt Curve #3 Frequency Range	% of P_{UCAP}
$f \geq 62\ Hz$	-10
$60.5\ Hz \leq f \leq 62\ Hz$	-10
$59.1\ Hz \leq f \leq 60.4\ Hz$	0
$58.1\ Hz \leq f \leq 59\ Hz$	40
$57.1\ Hz \leq f \leq 58\ Hz$	45
$56.1\ Hz \leq f \leq 57\ Hz$	50
$f \leq 56.1\ Hz$	50

F-watt Curve #4 Frequency Range	% of P_{UCAP}
$f \geq 62\ Hz$	-10
$60.5\ Hz \leq f \leq 62\ Hz$	-10
$58.5\ Hz \leq f \leq 60.4\ Hz$	0
$58.1\ Hz \leq f \leq 58.4\ Hz$	40
$57.1\ Hz \leq f \leq 58\ Hz$	45
$56.1\ Hz \leq f \leq 57\ Hz$	50
$f \leq 56.1\ Hz$	50

F-watt Curve #5 Frequency Range	% of P_{UCAP}
$f \geq 62\ Hz$	-10
$60.5\ Hz \leq f \leq 62\ Hz$	-10
$59.6\ Hz \leq f \leq 60.4\ Hz$	0
$58.1\ Hz \leq f \leq 59.5Hz$	40
$57.1\ Hz \leq f \leq 58\ Hz$	45
$56.1\ Hz \leq f \leq 57\ Hz$	50
$f \leq 56.1\ Hz$	50

All these curves are shown in Figure 2.

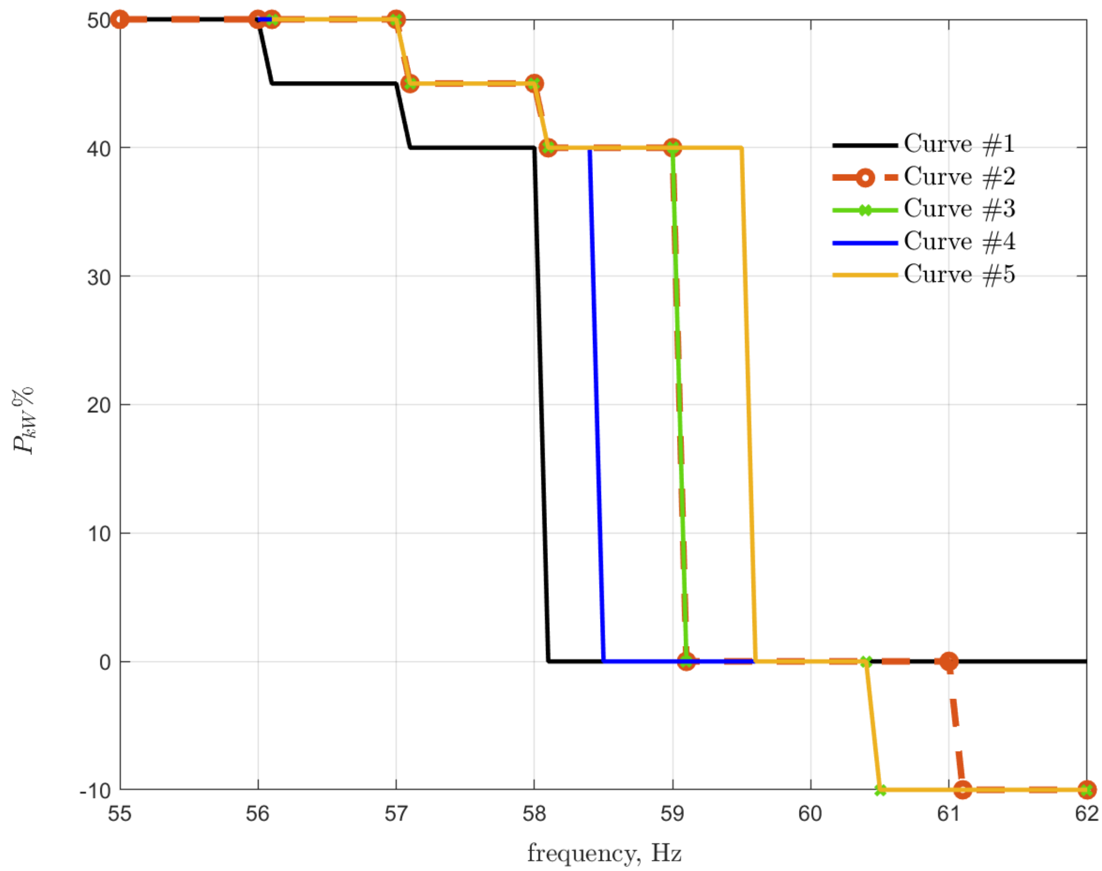

Figure 2. Five f-watt curves designed based on the PHIL test for the field demonstration.

2. ISLANDED MODE PROTECTION SETTINGS

The following are the over and under frequency trip settings for the three units used in the islanded black start field demonstration:

Unit	**Under Frequency**	**Over Frequency**
CP	55 Hz for 5 s	63 Hz for 5 s
LP	55 Hz for 5 s	63 Hz for 5 s
OLP	57.6 Hz for 15 s	62.4 Hz for 10 s

3. PRE-FIELD DEMONSTRATION SETUP

Day	**Activity**
Thursday, April 15th, 2021	Installation and communication setup for three PMUs and data-aggregation laptop were completed.
Friday, April 16th, 2021	IFP connected power to the inverter output and container power panel. All connections inside the container were completed by INL

	personnel and inspected by IFP prior to connection inside the substation.
Saturday, April 17th, 2021	The UCAP ESS were pre-charged to 950 VDC and set standby April 19, 2021 onward field demonstration.
Monday, April 19th 2021	7 a.m.–12 p.m.: The 8 MW ComRent load bank arrived on site and were installed by ComRent and IFP personnel.

4. FIELD DEMONSTRATION SCENARIOS

The four-day field demonstration was based on executing the loading test at four scenarios:

Scenario	**Description**	**Execution Date**
1A (LP Baseline)	Lower Bulb unit is operated islanded mode. Hydro-governor settings from 2017 field test are used.	Monday, April 19, 2021
1B (LP + UCAP)	UCAP ESS is integrated with Lower Bulb unit for fast frequency response in grid-following mode.	
2A (OLP + LP)	Lower Bulb and Old Lower unit are synchronized. OLP was operated in the manual mode (to provide inertia only) till noon, and then, it was operated with 2% droop frequency support in the afternoon. OLP won't carry much electrical load.	Tuesday, April 20, 2021
2B (LP + OLP + UCAP)	UCAP ESS is integrated with Old Lower and Lower Bulb unit for fast frequency response in grid-following mode. During this test OLP provided frequency support with 2% droop.	
3A (OLP + LP + CP)	Old Lower, Lower Bulb, and City Bulb units are synchronized. OLP was operated with 2% droop frequency support and won't carry much electrical load. LP and CP will share load.	Wednesday, April 21, 2021
3B (OLP + LP + CP + UCAP)	UCAP ESS is integrated with Old Lower, Lower Bulb, and City Bulb unit for fast frequency response in grid-following mode.	
4 (LP New + UCAP)	Hydro-governor settings including PID control and blade biasing are tuned with and without the UCAP ESS integration.	Thursday, April 22, 2021

In the following sections, tasks executed in each scenario are described; based on the level of uniqueness of these tasks, some are summarized in tabular form while the rest are put in bullet points.

4.1 Scenario 1 Loading Test

We performed initial comparisons of the Lower Bulb Plant (our main plant for the demonstration), both on its own (with existing controls) and with the ultracapacitors. We found a notable reduction in frequency excursions with the ultracapacitors. Another finding was the physical characteristics of the turbine/generator and waterway (i.e., machine inertia and water inertia) was limiting operational stability for the higher capacity range of the islanded operation. Even with the ultracapacitors, the plant just didn't damp fast enough, and so, it tripped offline in multiple test runs at about 3.5 MW (the nameplate capacity is 8.9 MW). Figure 3 and Figure 4 show the islanded system frequency during the loading test in Scenario 1A and 1B.

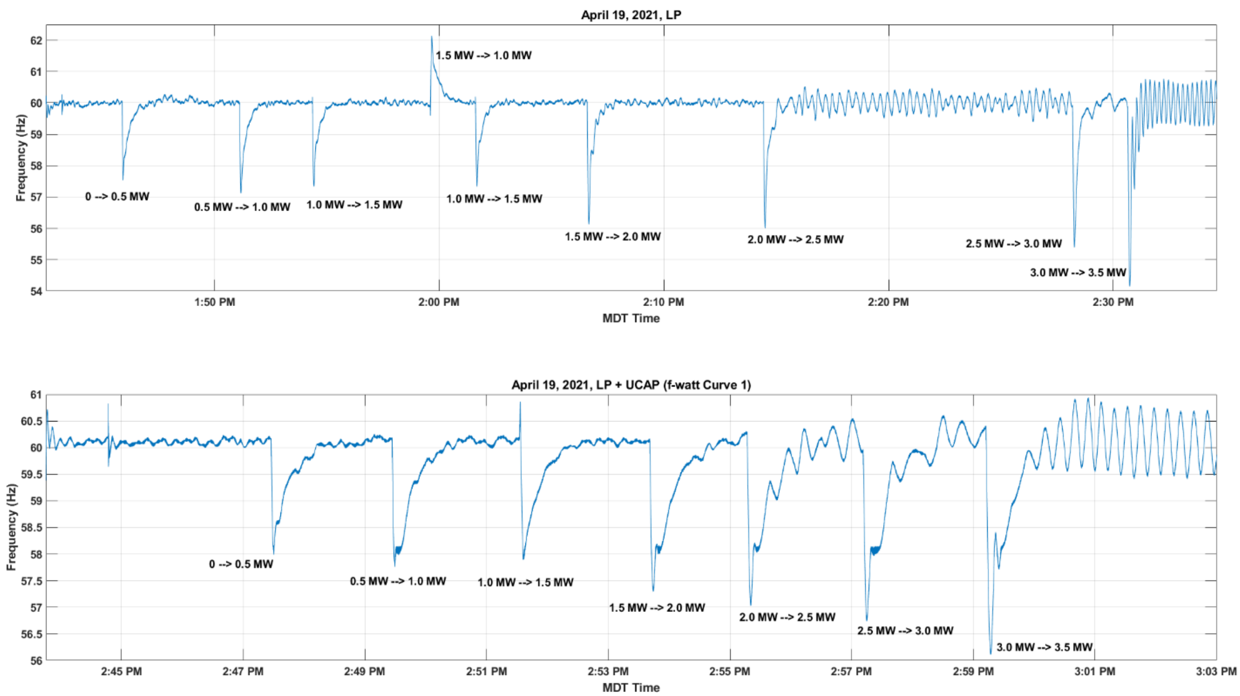

Figure 3. Islanded system frequency during the loading test. Scenario 1A is depicted on the top plot, and Scenario 1B is depicted on the bottom plot.

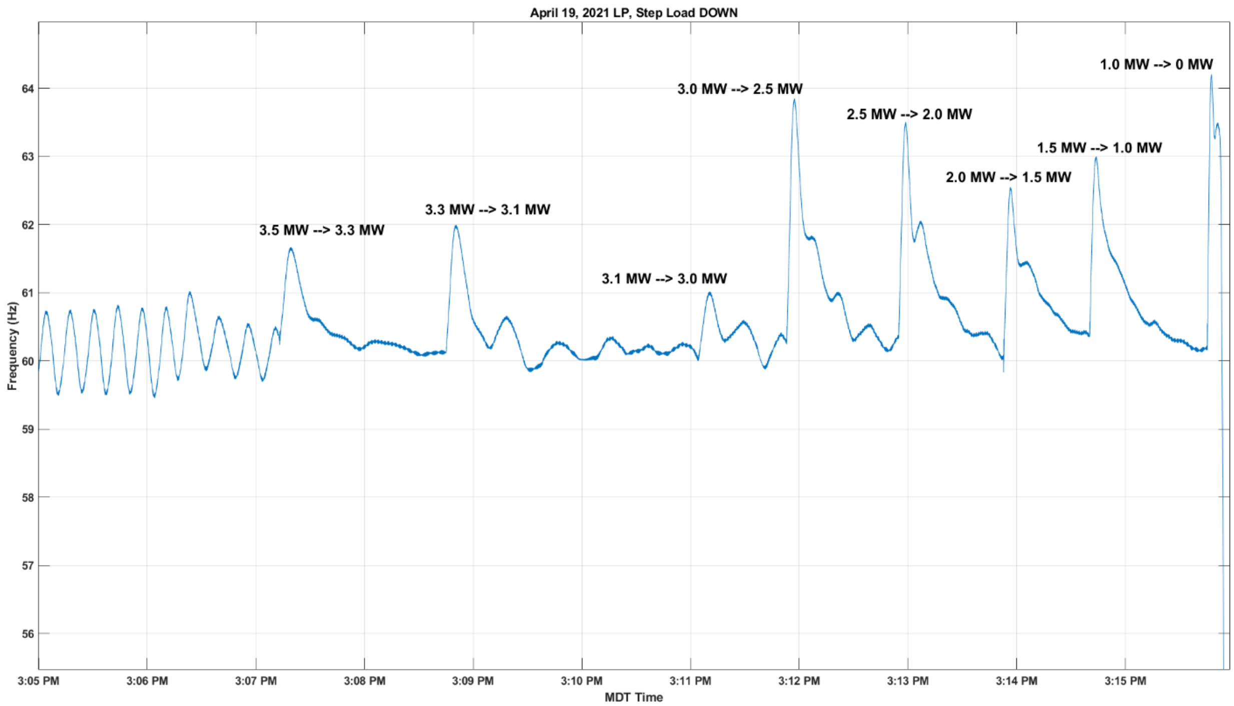

Figure 4. Islanded system frequency during step load DOWN (Scenario 1A).

Section 4.1.1–4.1.3 details the test's preparation and scenarios.

4.1.1 Loading test preparation

Following tasks were completed for the loading test preparation:

Time (MDT)	Activity
8:22 a.m.	Verify protection and PID/droop settings for islanded mode of operation.
8:59 a.m.	New settings for protection and PID/droop have been uploaded.
9:13–10:18 a.m.	UCAP ESS integration tested and no issues observed.
10:25 a.m.	46 kV line switched off. Alternate station service has been activated. HVAC has been switched off.

4.1.2 Scenario 1A: LP baseline

Loading test in the LP baseline scenario was conducted to replicate findings from the 2017 IFP Blackstart test. In 2017 IFP Blackstart test, generator instability was observed when the base load was increased from 3.0 MW to 3.5 MW. However, the generator protection settings back in 2017 were more rigid—causing several trips and hampering the continuity of the loading test. For the April 2021 field demonstration, more flexible settings were set for "islanded" mode generator protection (see Section 2). This ensured less intermittency to the loading test while capturing generator response (both stable and cease to be stable) to different loading.

The LP hydro-governor settings were P = 1.5, I = 0.08, D = 0.75, and droop = 0.

The following tasks were completed for Loading Test:

Time (MDT)	Activity
1:04 p.m.	Start LP in Isochronous mode. Pick up station service load (about 200 kW).
1:39 p.m.	LP tripped offline. MVAR control was turned OFF. Detected misleading alarm (flow alarm and PT alarm). These were resolved, and MVAR control was turned ON.
1:45–2:30 p.m.	Step load UP in 500 kW steps, from 0 MW to 3.5 MW, totaling in seven steps. Frequency excursions have been recorded for each step by the PMUs. Bad speeds have been recorded by hydro-governor PLCs during step load UP from 1 MW to 1.5 MW and 2 MW to 2.5 MW. For this reason, load was decreased from 1.5 MW to 1.0 MW and step load UP 1.0 MW → 1.5 MW was REPEATED.
2:30 p.m.	Step load DOWN: 3.5 MW → 3 MW. More unstable frequency response than in the case of 3 MW → 3.5 MW step load UP. LP tripped from over frequency.

4.1.3 Scenario 1B: LP + UCAP

The following tasks were completed for Loading Test:

Time (MDT)	Activity
2:45 p.m.	LP tripped offline due to oil pump control overloading. Restarted the LP.
2:48–3:00 p.m.	UCAP ESS was connected. F-watt Curve #1 (Real power injection only if frequency falls below 58 Hz) is programmed for fast frequency response. Step load UP in 500 kW steps, from 0 MW to 3.5 MW, totaling seven steps. Frequency excursions have been recorded for each step by the PMUs. UCAP ESS was disconnected when the load reached 3.5 MW.
3:08–3:15 p.m.	Load is reduced from 3.5 MW to 0 MW in variable steps (500 kW, 200 kW, and 100 KW). Corresponding frequency overshoots were recorded by the PMUs and shown in Figure 4.

Figure 3 shows the generator frequency recorded during Scenario 1A and 1B loading test. Frequency nadir improved due to the fast frequency response from UCAP ESS.

4.2 Scenario 2 Loading Test

We synchronized Lower Bulb and Old Lower Plant (a plant with two 1.8 MW Francis units) and conducted similar tests. The main objective of adding the smaller unit was to see if the extra inertia would help (by operating in manual mode) or additional contribution is needed from hydro-governor control. Qualitatively, the testing found the ultracapacitor bank we were using was about as effective as adding the extra inertia. With both the extra inertia and the ultracapacitor, there was some additional improvement, but analysis is needed to really assess how much additional improvement there was with both.

The day went slower than expected because of protection settings that caused the Old Lower Plant to trip offline and needed to be debugged. The good news is our testing helped the plant operators identify a few glitches in the protection settings, which IFP personnel corrected in the Balance of Plant PLC to resume the test. Figure 5 shows the islanded system frequency during the loading test in Scenario 2A and 2B.

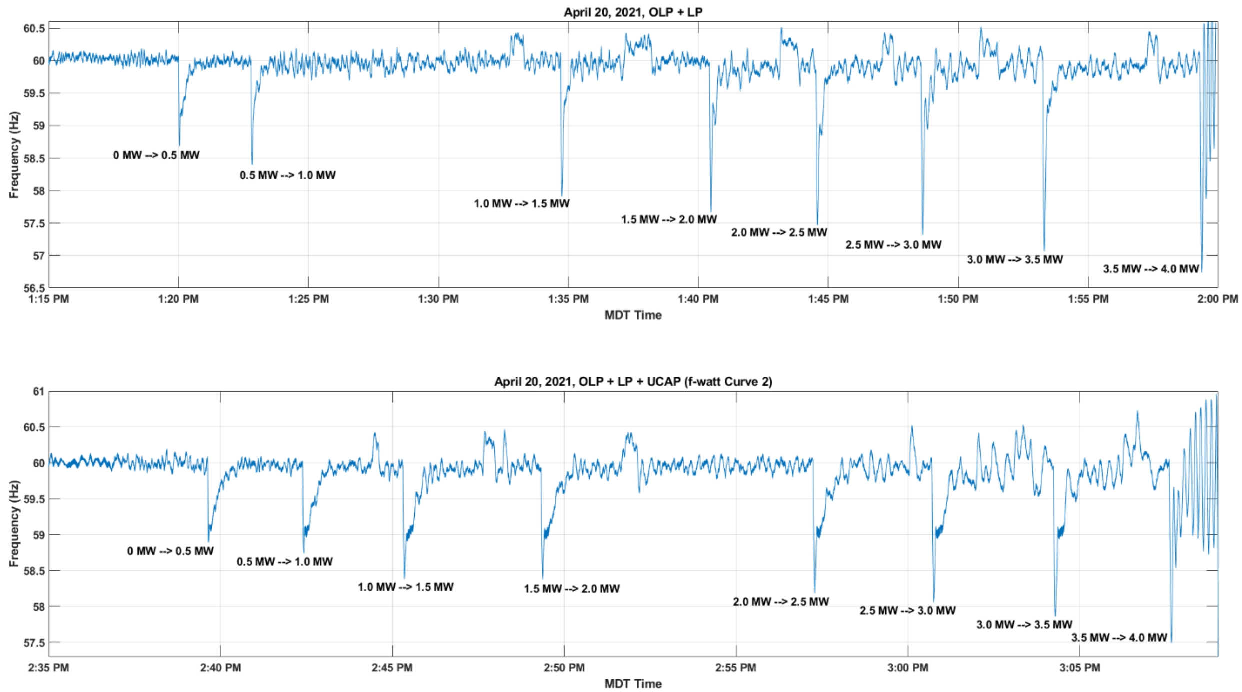

Figure 5. Islanded system frequency during Scenario 2A (top) and 2B (bottom) loading test.

Section 4.2.1–4.2.3 details the test's preparation and scenarios.

4.2.1 OLP synchronization with LP

LP hydro-governor settings: P = 1.5; I = 0.08; D = 0.75; droop = 0.

The following tasks were completed for synchronization:

Time (MDT)	Activity
8:30–8:36 a.m.	LP turned ON and breaker closed.
8:37–8:42 a.m.	OLP turned ON in manual mode (no frequency response). Breaker closed.
9:03 a.m.	0 MW → 0.5 MW. OLP was sharing 0.15 MW. Frequency dropped and OLP went out of manual mode.
9:14 a.m.	Frequency discursion was disabled for OLP, and load gain was re-based to push load back to LP. *OLP should only provide additional inertia.*
9:19 a.m.	OLP tripped offline. LP manually tripped. For OLP, 700G should not send over/under frequency trip command.
9:20 a.m.	OLP over and under frequency trip settings were changed -> Slot C -> Output 301: Remove under and over frequency trip.
9:57–10:06 a.m.	Step load UP in 500 kW steps, from 0 MW to 2.0 MW, totaling four steps. Frequency excursions have been recorded for each step by the PMUs.
10:10 a.m.	Step load UP 2.0 MW → 2.5 MW. OLP tripped offline (under frequency trip from 751 relay). Mechanical trip (86M). OLP tripped from mechanical vibration, and frequency oscillation observed on LP. Vibration probe was disabled.

10:41–10:43 a.m.	Step load DOWN from 2.5 MW to 2.0 MW in smaller load steps to avoid over frequency trips.
10:44 a.m.	REPEAT Step load UP 2.0 MW → 2.5 MW. OLP tripped offline (under frequency trip from 751 relay). 86M1 lockout relay trip. All vibration probes were disabled.
10:46–10:47 a.m.	Step load DOWN from 2.5 MW to 2.0 MW in smaller load steps to avoid over frequency trips.
11:16 a.m.	REPEAT Step load UP 2.0 MW → 2.5 MW. OLP tripped offline. 751 relay executed under frequency trip. 86M1 lockout relay tripped. Frequency oscillation observed on LP.
11:23–11:26 a.m.	Step load DOWN from 2.5 MW to 2.0 MW in smaller load steps to avoid over frequency trips.
12:30 p.m.	OLP settings changed -> Slot A -> Output 301: Remove SV09T/10T.
12:40 p.m.	OLP turned on and synchronized.
12:41 p.m.	Step load UP in 500 kW steps from 2.0 MW to 3.5 MW totaling three steps.
12:53 p.m.	Step load UP 3.5 MW → 4.0 MW. LP manually tripped due to excessive and unceasing oscillations.

4.2.2 Scenario 2A: OLP + LP

LP hydro-governor settings: P = 1.5; I = 0.08; D = 0.75; droop = 0. OLP hydro-governor settings: manual to speed control; speed reference: 100.9; droop: 2%.

The following tasks were completed for loading test:

Time (MDT)	Activity
1:19–1:58 p.m.	Step load UP in 500 kW steps, from 0 MW to 4.0 MW, totaling eight steps. Neither LP nor OLP tripped.

The top plot of Figure 5 shows the frequency excursions recorded in Scenario 2A loading test. Frequency nadir improved as compared to Scenario 1A and 1B. This is due to the inertia contribution from the OLP.

4.2.3 Scenario 2B: OLP + LP + UCAP

LP hydro-governor settings: P = 1.5; I = 0.08; D = 0.75; droop = 0.

The following tasks were completed for loading test:

Time (MDT)	Activity
2:39–3:07 p.m.	OLP hydro-governor droop settings: 2%. UCAP ESS was connected. F-watt Curve #2 (Real power injection only if frequency falls below 59 Hz. Real power absorption if frequency goes above 61 Hz.). Step load UP in 500 kW steps, from 0 MW to 4.0 MW, totaling eight steps. Frequency excursions were recorded by the PMUs.

The bottom plot of Figure 5 shows the frequency excursions recorded in Scenario 2B loading test. Frequency nadir improved as compared to Scenario 2A due to the fast frequency response from the UCAP ESS.

4.3 Scenario 3 Loading Test

We synchronized the Lower Bulb, Old Lower, and City Bulb Plants (City Bulb is identical to Lower Bulb). Adding City Bulb to the test was a big undertaking because IFP had to change the configuration of their system to isolate it along with Lower Bulb. It was definitely worth it because it yielded some useful results. We tested two configurations in this scenario: (1) CP at low load and (2) CP load matched to LP. In both cases CP governor was set for 2% droop. Loading test up to 4.5 MW was carried out in Configuration #1. It showed improvement in frequency nadir as compared to Scenario 2A. Configuration #2 more than doubled the load carrying capacity of the combined system. Our effective operational range for the load banks was 8 MW, and we reached that without tripping the plants offline. Eight MW is sufficient to cover the emergency infrastructure in Idaho Falls, such as the hospitals, fire stations, police stations, and emergency shelters that could be setup to address community needs, so this was a great benchmark to achieve.

Figure 6 and Figure 7 show the islanded system frequency response during the synchronization and loading test in Scenario 3.

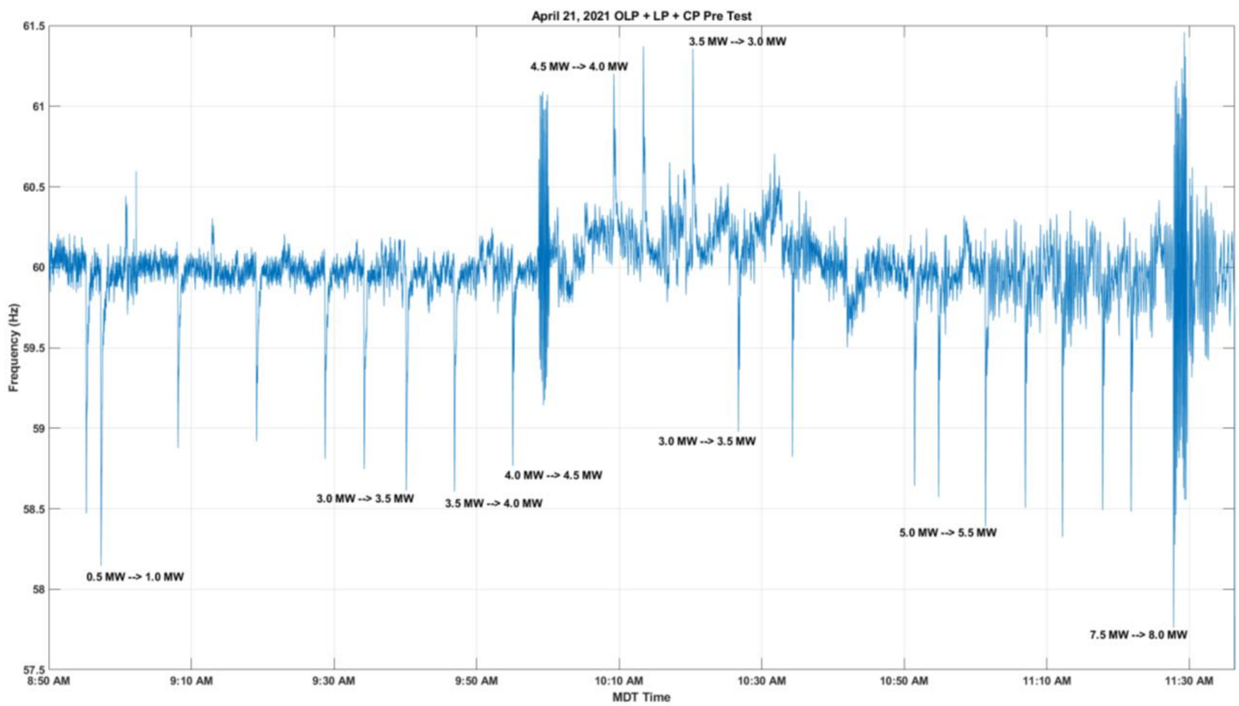

Figure 6. Islanded system frequency during speed reference adjustment for synchronization and load sharing. It captures Configuration #1 (CP at low load) and Configuration #2 (CP sharing load with LP).

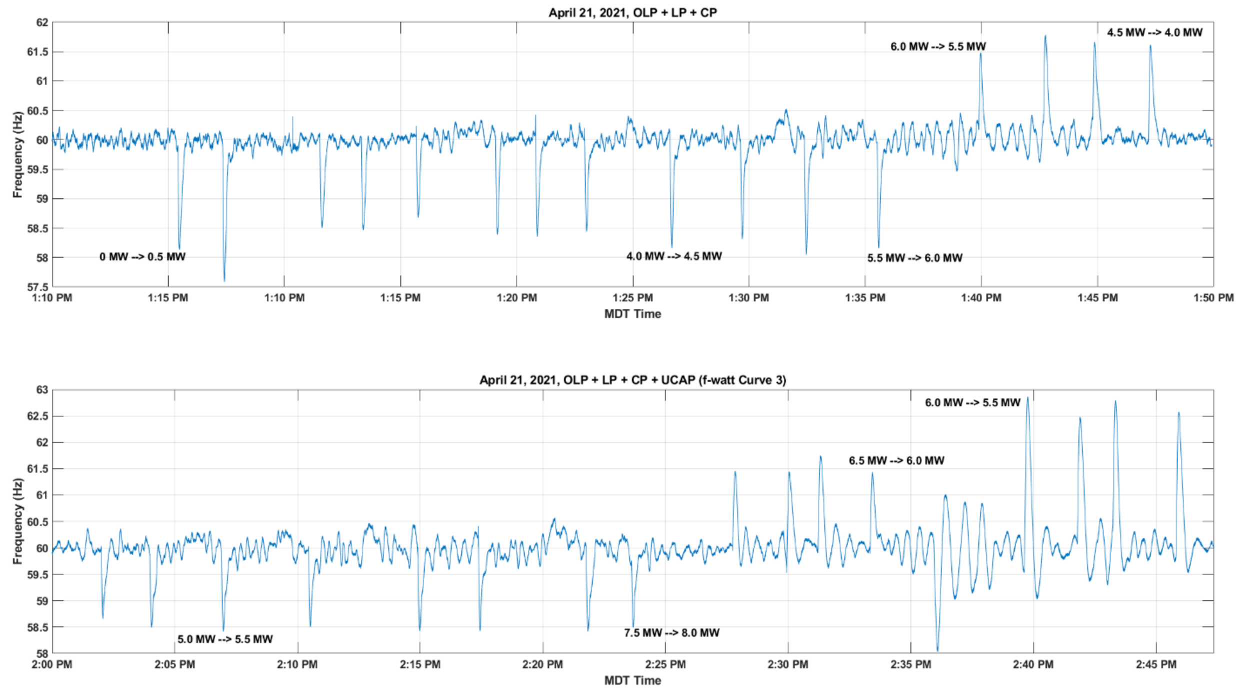

Figure 7. Islanded system frequency during Scenario 3A (top) and 3B (bottom) loading test.

Section 4.3.1–4.3.3 details the test's preparation, and scenarios.

4.3.1 OLP, LP, CP synchronization and load sharing

LP and CP hydro-governor settings: P = 1.5; I = 0.08; D = 0.75; LP droop = 0. CP droop = 2%. OLP droop = 2%.

The following tasks were completed for synchronization and Configuration #1 load sharing:

Time (MDT)	Activity
8:52–8:57 a.m.	Start LP. Start OLP and synchronize with LP. Step load UP in 500 kW steps from 0 MW to 1 MW totaling two steps.
9:00 a.m.	Start and synchronize CP with OLP, and LP. OLP and CP carrying 60 W, and 150 W, respectively. *Range of OLP and CP within 50–200 W*
9:07–9:46 a.m.	Step load UP in 500 kW step from 1.0 MW to 4.0 MW totaling six steps. All these loads were mostly carried by LP, while OLP and CP were synchronized with LP, and CP shared a small load.
9:54 a.m.	OLP settings were changed to carry load between 0.5 MW and 1.0 MW. Rest of the loads were shared between LP and CP. Step load UP 4.0 MW → 4.5 MW.
9:59 a.m.	Frequency oscillation were observed.

Table 1. Speed reference adjustment for Configuration #2 load sharing.

Time (MDT)	**Speed Reference**			**Load Change**
	LP	OLP	CP	
10:08–10:20 a.m.	100	101.25	100.9	Step load DOWN from 4.5 MW to 3.0 MW in 500 kW step totaling three steps.
10:26 a.m.	100	101.5	100.7	Step load UP 3.0 MW → 3.5 MW.
10:34–10:51 a.m.	100	101	100.6	Step load UP from 3.5 MW to 4.5 MW in 500 kW step totaling two steps.
10:54–11:00 a.m.	100	101	100.65	Step load UP from 4.5 MW to 5.5 MW in 500 kW step totaling two steps.
11:05 a.m.	100	101	100.7	Step load UP 5.5 MW → 6.0 MW.
11:11 a.m.	100	101	100.8	Step load UP 6.0 MW → 6.5 MW.
11:17 a.m.	100	101	100.9	Step load UP 6.5 MW → 7.0 MW.
11:21–11:27 a.m.	100	101	101	Step load UP from 7.0 MW to 8 MW in 500 kW step totaling two steps.

The islanded system frequency response recorded during this synchronization and load sharing task is shown in Figure 6.

4.3.2 Scenario 3A: OLP + LP + CP

LP, hydro-governor settings: P = 0.6; I = 0.08; D = 0.55; droop = 0. OLP droop = 2%. CP is sharing load with LP (Configuration #2).

The following tasks were completed for loading test:

Time (MDT)	**Activity**
1:15 p.m.	LP, OLP, and CP turned ON and synchronized. Step load UP 0 MW → 0.5 MW.

Load change for different speed reference is summarized in the table below.

Table 2. Loading test with speed reference adjustment.

Time (MDT)	**Speed Reference**			**Load Change**
	LP	OLP	CP	
1:16–1:21 p.m.	100	100.66	100.3	Step load UP from 0.5 MW to 1.5 MW in 500 kW step totaling two steps.
1:23 p.m.	100	101	100.4	Step load UP 1.5 MW→ 2.0 MW.
1:25 p.m.	100	101	100.5	Step load UP 2.0 MW → 2.5 MW.
1:28 p.m.	100	101	100.6	Step load UP 2.5 MW → 3.0 MW.
1:30 p.m.	100	101	100.7	Step load UP 3.0 MW → 3.5 MW.
1:32 p.m.	100	101	100.8	Step load UP 3.5 MW → 4.0 MW.
1:36 p.m.	100	101	100.9	Step load UP 4.0 MW → 4.5 MW.
1:39–1:45 p.m.	100	101	101	Step load UP from 4.5 MW to 6.0 MW in 500 kW step totaling three steps.
1:48–1:52 p.m.	100	101	100.8	Step load DOWN from 6.0 MW to 5.0 MW in 500 kW step totaling two steps.

1:54–1:57 p.m.	100	101	100.6	Step load DOWN from 5.0 MW to 4.0 MW in 500 kW step totaling two steps.

4.3.3 Scenario 3B: OLP + LP + CP + UCAP

The following tasks were completed for loading test:

Time (MDT)	Activity
1:58–2:03 p.m.	Connect UCAP ESS with F-watt Curve #3 (Real power injection only if frequency falls below 59 Hz. Real power absorption only if frequency goes above 60.5 Hz.). Step load UP from 4.0 MW to 5.0 MW in 500 kW step totaling two steps.
2:06 p.m.	New speed references (LP: 100; OLP: 101; CP: 100.7). Step load UP 5.0 MW→ 5.5 MW.
2:10–2:14 p.m.	New speed references (LP: 100; OLP: 101; CP: 100.8). Step load UP from 5.5 MW to 6.5 MW in 500 kW step totaling two steps.
2:17–2:23 p.m.	New speed references (LP: 100; OLP: 101; CP: 101). Step load UP from 6.5 MW to 8.0 MW in 500 kW step totaling three steps.
2:27–2:31 p.m.	Step load DOWN from 8.0 MW to 6.5 MW in 500 kW step totaling three steps.
2:33 p.m.	Step load DOWN 6.5 MW → 6.0 MW. Shutdown OLP on purpose.
2:36–2:45 p.m.	Step load DOWN from 6.0 MW to 4.0 MW in 500 kW step totaling four steps.

Figure 7 shows the islanded system frequency recorded in Scenario 3A and 3B. Frequency nadir improved in Scenario 3B due to the fast frequency response from UCAP ESS.

4.4 Scenario 4 Loading Test

We went back to just the Lower Bulb Plant to test new control settings and techniques. The two controls tweaks we made were (1) new PID settings, which effect how the plant responds to deviations in frequency (e.g. how quickly does it try to return to 60 HZ and how much damping does it perform) and (2) utilized a technique called "blade biasing" that to our knowledge has never been used in this type of plant. This technique pre-positions the angle of the blades so they don't have to move as much when the speed changes. This reduces plant efficiency but also potentially increases its stability. At small loads the impact was small, but this did have a measurable positive impact at higher loadings. With the improved controls and ultracapacitors, we were able to increase the plant load carrying capacity by at least 500 kW. The loading test with different settings for PID controller and blade biasing is summarized below. Droop was set to 0% throughout this loading test.

Table 3. Scenario 4 loading test summary.

Time (MDT)	Load Change	UCAP Integrated? (Y/N)	P	I	D	Blade Bias Null	Blade Bias Gain
8:18–8:44 a.m.	Step load UP/DOWN in 500 kW steps between 0 MW and 2 MW.	N	1.5	0.08	0.75	N/A	N/A

8:45–8:51 a.m.	1.5 MW→2.0 MW→ 1.5 MW	N	1.5	0.08	0.75	0.5	1.0
8:53 a.m.	1.5 MW → 2.0 MW	N	1.5	0.08	0.75	1.0	0.5
8:58 a.m.	2.0 MW → 2.5 MW	N	1.25	0.13	0.75		
9:03 a.m.	2.5 MW → 3.0 MW	N	0.6	0.08	0.55		
9:26 a.m.	0 MW → 0.5 MW	Y (F-watt Curve #3)	0.6	0.08	0.55		
9:28 a.m.	0.5 MW → 1.0 MW	Y (F-watt Curve #3)	1.5	0.08	0.75		
9:32–9:38 a.m.	1.0 MW → 1.5 MW → 2.0 MW	Y (F-watt Curve #3)	1.25	0.13	0.75	1.0	0.5
9:43–10:07 a.m.	Step load UP/DOWN in 500 kW steps between 1.5 MW and 2.5 MW.	Y (F-watt Curve #5)				1.0	0.5
10:12–10:23 a.m.	Step load UP in 500 kW steps from 2.5 MW to 4.0 MW.	Y (F-watt Curve #3)				1.0	0.5
1:25–1:39 p.m.	Step load UP in 500 kW steps from 2.0 MW to 4.5 MW.	Y (F-watt Curve #3)	0.9	0.09	0.75	1.0	0.5
1:56 p.m.	2.0 MW → 2.5 MW	Y (F-watt Curve #3)	1.0	0.1	0.6	1.0	0.5
1:58–2:02 p.m.	Step load UP in 500 kW steps from 2.5 MW to 3.5 MW.	Y (F-watt Curve #3)	0.9	0.09	0.75	N/A	N/A
2:13–2:21 p.m.	Step load UP/DOWN in 500 kW	N					

	steps between 0 MW and 2.5 MW.						

Based on the recorded data, we are currently investigating the impact of this new PID settings and blade biasing.

5. COMPANION SIMULATIONS

The UCAP is constrained to a DC voltage limit of 300V discharge based on the EPC inverter operation limitation. This section's main idea is to investigate the nature of the voltage decline from the energy storage. In the field test, it was not possible to analyze the response of the stored voltage, and it served as a motivation to actually understand the time scale of the voltage decline by running different simulations with various f-watt curves that were used in the field. UCAP sizing and configurations are also tested in the simulation environment to understand the question: if we had a larger invertor of more ultracapacitors, would that have made a notable impact?

5.1 UCAP Configurations Based on Scenario 1B

The configurations and PID gains for the lower-bulb hydro-governor and turbine used on Scenario 1B (April 19, 2021) have been replicated in the Simulink model for the inverter connected ultracapacitor test system. The simulation testbed has been designed as an inverter connected ultracapacitor AC coupled to the run-of-river (ROR) HPP. The UCAPs are set to different f-watt curves defined as scenarios as they were used during the field testing at IFP testing site.

The f-watt curves used in the field testing have been broadly classified into five categories (see Figure 2), and they have also been used in the simulations here. The main goal was to look into what-if situations with regard to UCAP sizing and the frequency response attained from the generator. Another important factor is the energy capacity in the UCAP and the DC voltage dip that is permissible for the black start operations. The Maxwell UCAP has a low-voltage rating of 650 VDC, and the max voltage potential at 950VDC making the operable range from 650-950 VDC. The aim is to understand the DC voltage decay and how sizing could help replenish the total available capacity in the energy storage device without tripping due to under-voltage.

5.1.1 Single UCAP with F-watt Curve #1

The critical loading point was identified at 3 MW stepping up to 3.5 MW with a local load of 0.5 MW on the test system. The cutoff point for the power injection was chosen at frequency of 58.1 Hz. It should be noted the rated capacity of the Maxwell UCAP is 375 kVA, and the power injection rate has been chosen as a percentage of the total capacity according to the low-DC voltage requirement. It has been noticed in the lab setup and in real-time digital simulator testing that such configuration for the percentage power injection allows a room of 10–20 s of current injection from the UCAP energy storage to improve the frequency nadir subject to sudden loading on the system. Table 4 contains the parameters of the UCAP used for the simulation studies. Even in the case of testing different UCAP topologies the same parameters have been used for the other devices connected in parallel.

Table 4. Parameters of the UCAP used for testing.

Parameters	**Values**
Rated capacitance (F)	6.5
Rated voltage (V)	950
Number of series capacitors	8
Number of parallel capacitors	1

Initial voltage (V)	945
Operating temperature (Celsius)	25

As it can be observed from Figure 8, the UCAP provides considerable support and lifts the frequency nadir from below 56 Hz to above 57 Hz in approx. ~4 s with a burst of real power injection. It should be noted the trip frequency at the Lower Bulb Plant is set at 55 Hz with a 5 s delay.

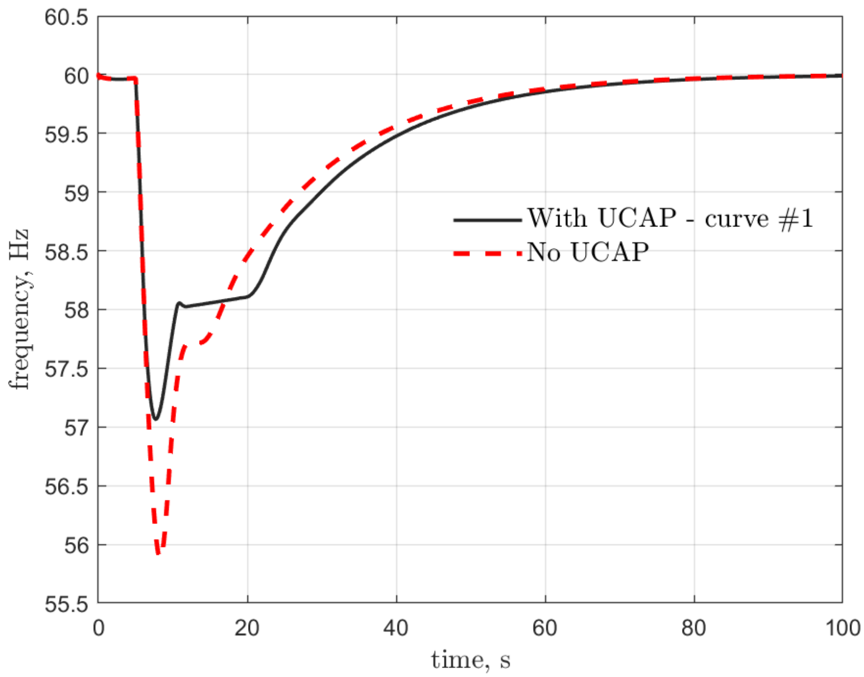

Figure 8. System frequency response: Scenario 1B, F-watt Curve #1.

The current, voltage, and SOC of the UCAP can be observed in Figure 9. The voltage dip as observed is just above 700VDC which is within the permissible range of the UCAP low-voltage limits.

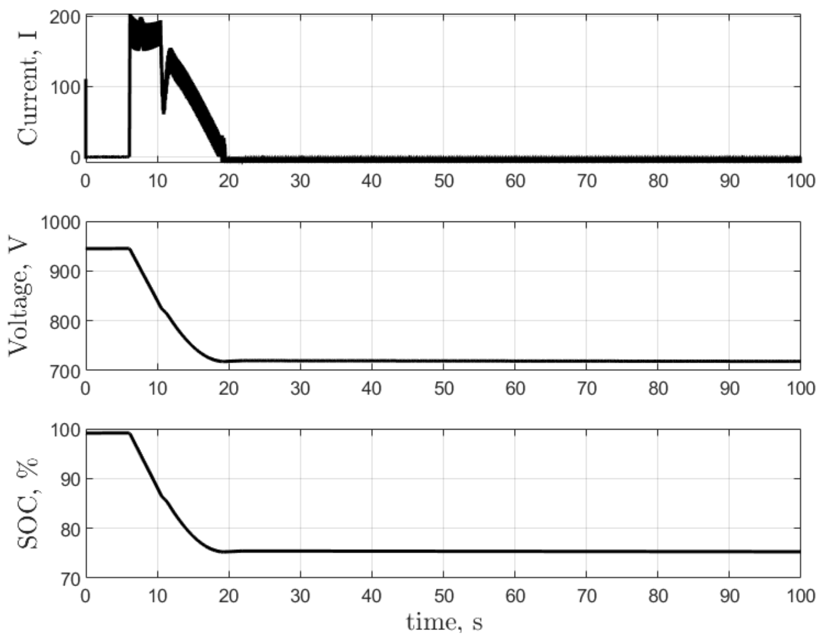

Figure 9. UCAP response in Scenario 1B, F-watt Curve #1.

5.1.2 Frequency response to different f-watt scenarios

The field tests were done considering other f-watt inverter curves as well that have been classified into Curves #1 through #5. The goal is to disseminate the effects of each scenario on the frequency nadir and DC voltage discharge subject to baseload of 3 MW and stepping up to 3.5 MW. The f-watt curves, namely Curves #2 and #4, each have different cutoff frequencies for the UCAP power injection.

The frequency response of the system based on the inverter f-watt curves is depicted in Figure 10. It can be observed Curves #1 and #4 have similar response where Curve #4 shows a slightly better performance in raising the frequency nadir. The cutoff frequencies for Curves #1 and #4 are 58.1 and 58.5 Hz, respectively. On the other hand, Curve #2 has a cutoff frequency set to 59.1 Hz, and it can be seen in Figure 10 the UCAP starts injecting power at 59.1 Hz and improves the frequency nadir significantly but at t = 24 s. The DC voltage of the device is completely drained, which results in a second dip in frequency response. The voltage profiles have been shown in Figure 11. It should be noted Curve #1 provides the most energy efficiency with a considerable improvement in frequency response whereas Curve #4 shows better frequency response but at the expense of significant DC voltage drainage from the UCAP.

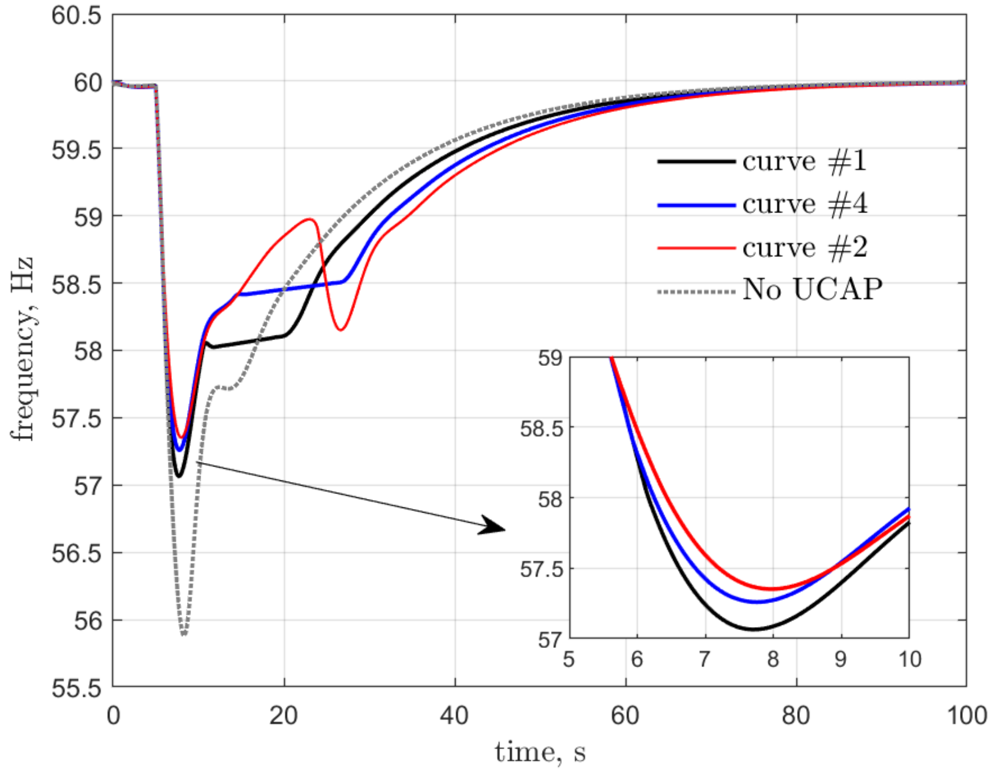

Figure 10. System frequency response based on different f-watt curves.

Curve #2 cutoff frequency is set at 59.1 Hz and starts injecting early but drains the voltage very quickly to zero thus rendering it undesirable since it reaches the low-voltage trip setting of the UCAP within ~10 s.

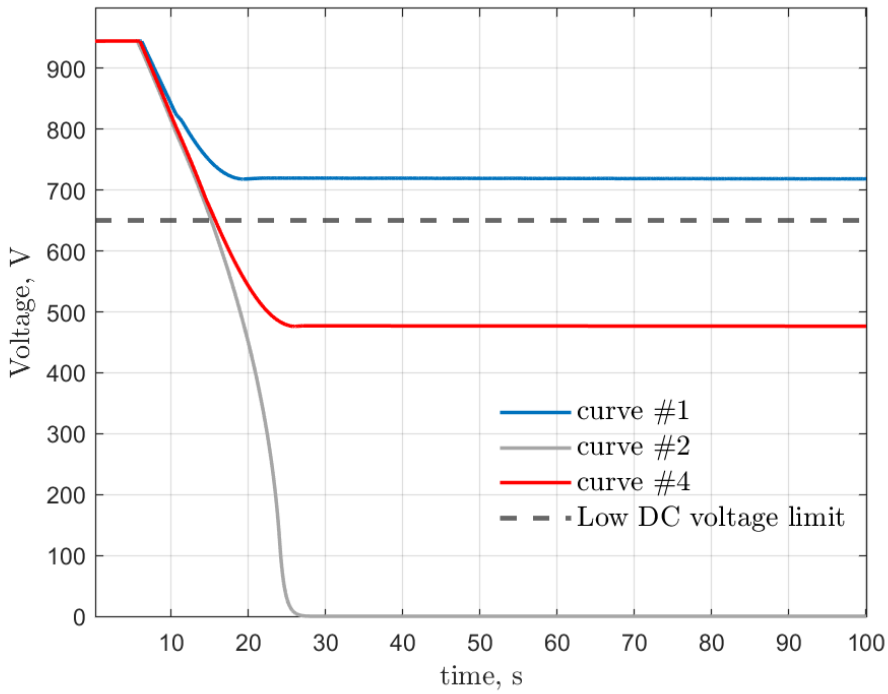

Figure 11. UCAP voltage profiles subject to different f-watt curves.

5.1.3 UCAP: configurations

In order to share voltage burden and to determine the use of sizing energy storage, two UCAPs were integrated into the test system in different configurations [2] and with the same ratings. The configurations tested are the a) parallel semi-active (pSA) and b) parallel full-active (pFA) as shown in Figure 12. The main difference between both is while pSA uses the same DC-DC buck/boost converter for both UCAPs, the pFA uses individual converters for each device thus decoupling their responses and adding the ability to define f-watt curves for each energy storage device.

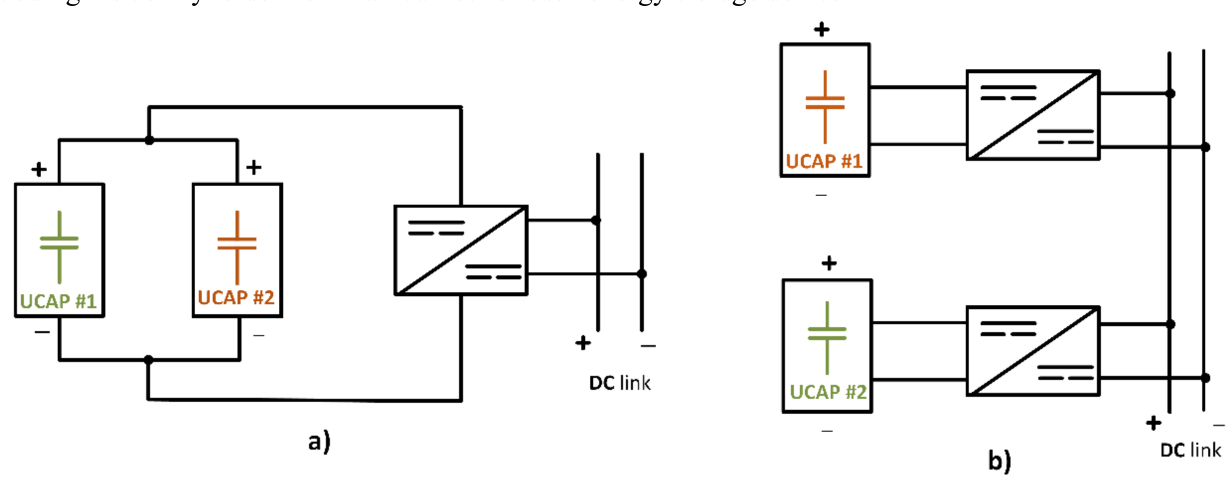

Figure 12. pSA and pFA topologies for UCAPs.

5.1.3.1 *Scenario 1B: F-watt Curve #1*

The frequency response of the plant for both configurations can be observed in Figure 13. It should be noted the pFA configuration is able to improve the frequency nadir better than the pSA configuration on expense of the different energy expenditures.

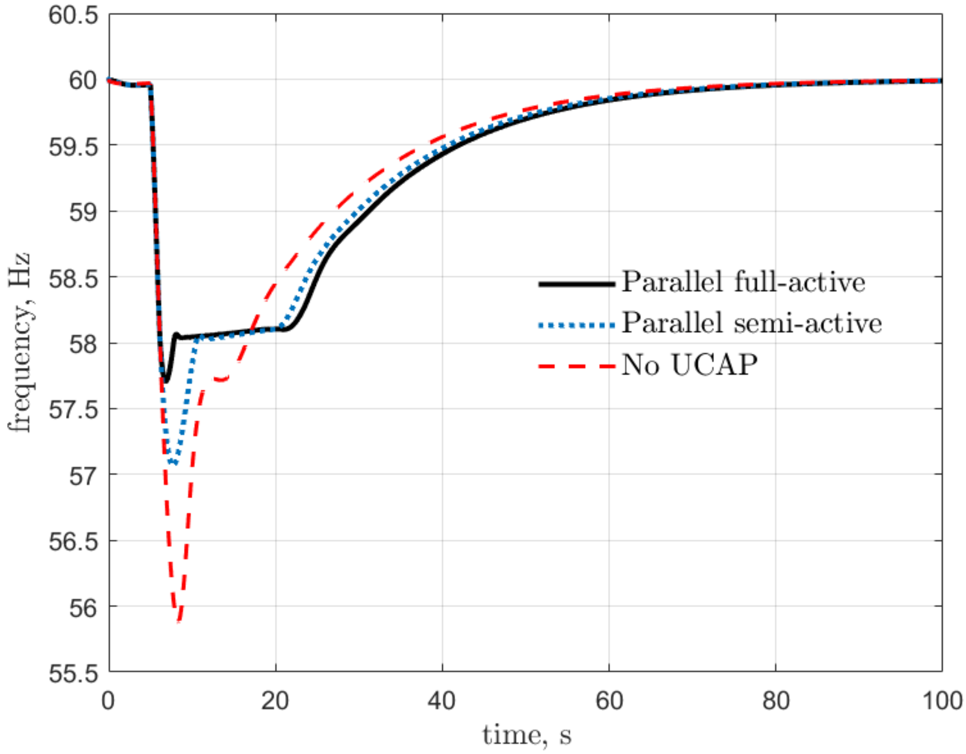

Figure 13. System frequency response for F-watt Curve #1.

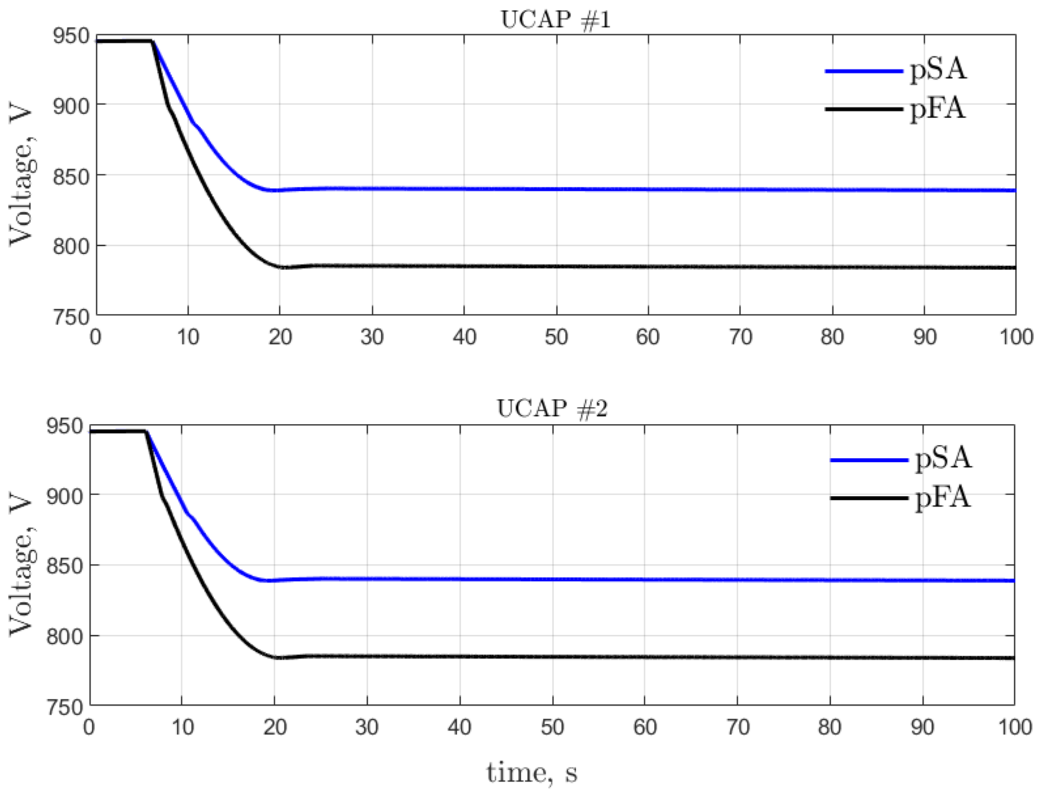

Figure 14. DC voltage profiles of UCAPs in the pSA and pFA topologies for F-watt Curve #1.

The pFA is able to recover the frequency nadir close to 58 Hz, whereas the pSA is around 57 Hz; however, the amount of DC voltage discharge from the pFA is around ~780 VDC. Whereas for the pSA, it is around ~840 VDC (see Figure 14). Both the discharge rates are within the admissible limit of 650 VDC; however, the improvement in frequency nadir for the pFA comes clearly on the expense of more energy discharge from the UCAP, given both configurations are using Curve #1 in their inverter f-watt curve.

5.1.3.2 Scenario 1B: F-watt Curve #2

To arrest the DC voltage decline in case of F-watt Curve #2, three UCAPs were connected in the pSA topology with the same parameters as mentioned in Table 4. The frequency response of the system subject to Curve #2 can be seen in Figure 15. The frequency nadir is significantly improved with the pSA topology as compared to the single UCAP integrated with the system.

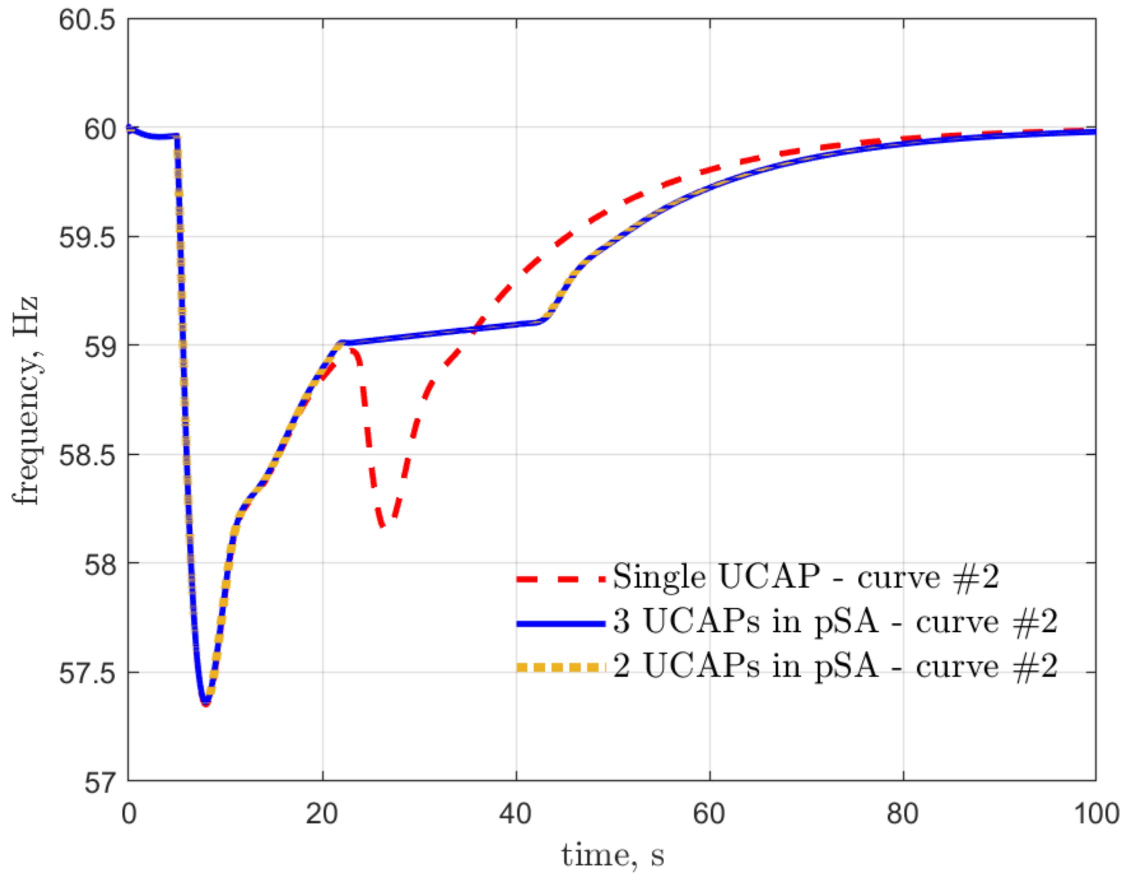

Figure 15. System frequency response subject to F-watt Curve #2.

The DC voltage decay in case of Curve #2 is very fast due to the very aggressive 59.1 Hz—low-frequency setting in the f-watt curve. This renders the device to expend more energy during recovery of the frequency nadir, and the behavior can be seen in Figure 16. With the addition of the other UCAPs, the DC voltage decline is significantly reduced to 700 VDC, which is well within the permissible limit for the low-voltage DC cutoff. Thus, to use Curve #2 as f-watt setting, the sizing of the UCAPs needs to be reconsidered to supplement the DC voltage when combined in parallel mode of operation.

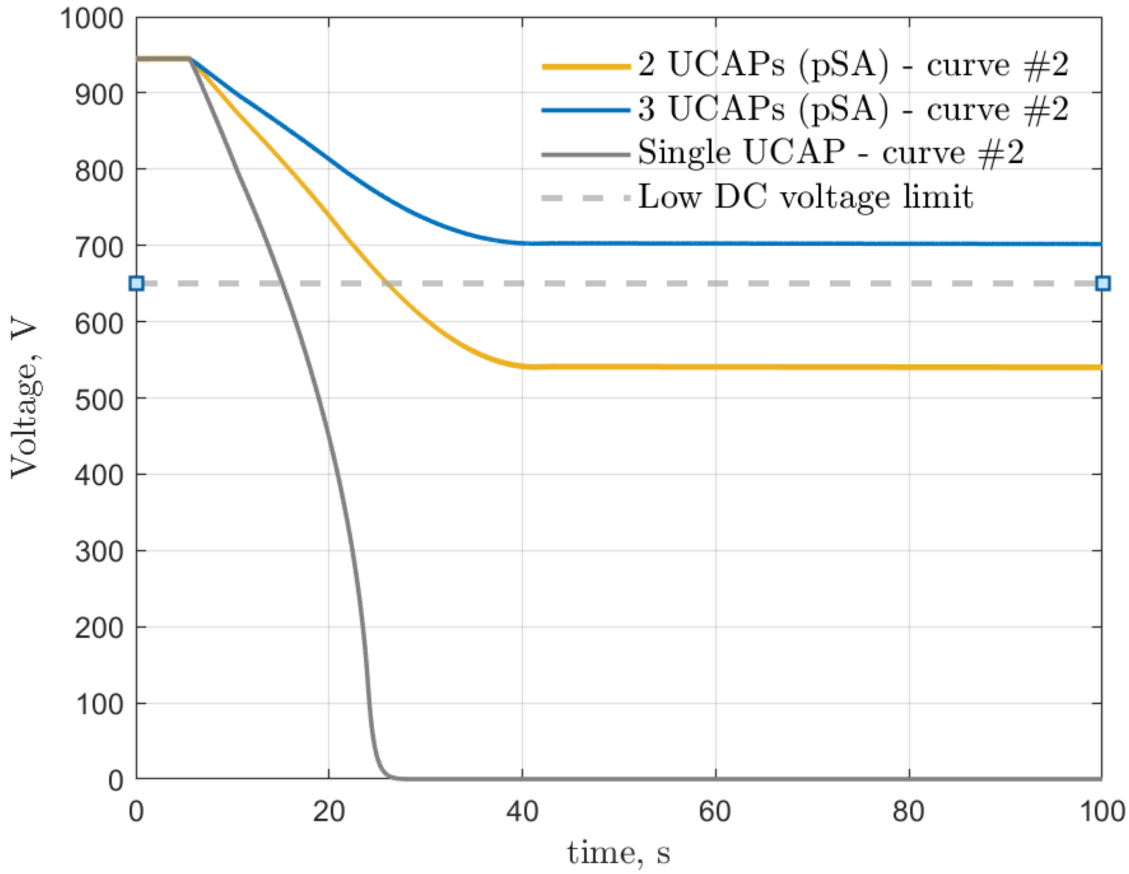

Figure 16. DC voltage profiles of UCAPs in pSA vs single UCAP for Curve #2.

5.1.4 UCAP: sizing

A larger energy capacity UCAP was modeled with ratings that are exactly double the ones used in the field testing. The newly sized UCAP is rated at 750 KVA with 13 F capacitance. As it can been from Figure 17, the frequency nadir notably improves with the sized UCAP, and the settling time to steady-state frequency is significantly reduced by ~52 s. It should be noted the F-watt Curve #1 has been used in this simulation run, and DC voltage discharge limits are set between 650–950 V.

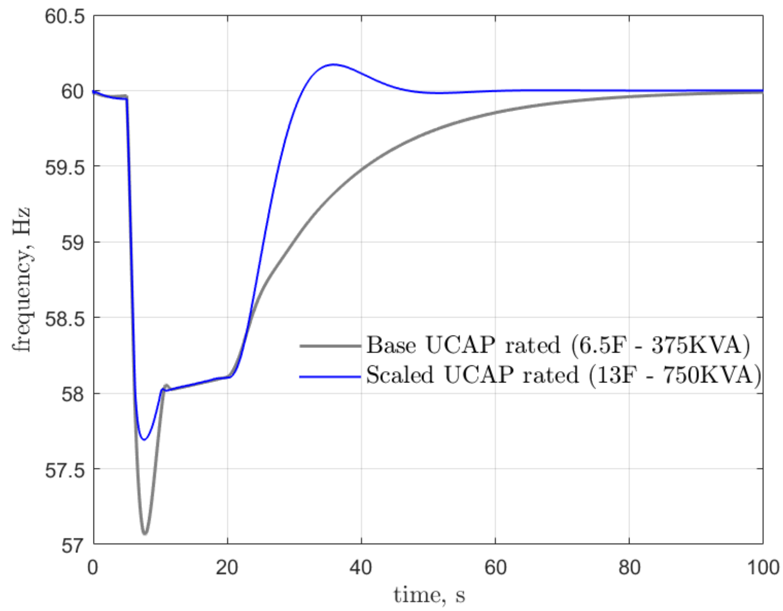

Figure 17. System frequency response to base UCAP vs. scaled UCAP.

Similarly, the DC voltage discharge has been shown in Figure 18, and it can be observed there is a marginal improvement in the DC discharge voltage with the scaled UCAP as compared to the base one.

Table 5. UCAP sizing with different configurations and for different f-watt curves.

S. no	**f-watt used**	**No. of UCAPs**	**Topology used**	**Frequency nadir (Hz)**	**DC voltage cutoff reached? (Y/N)**	**Minimum DC Voltage attained (V)**
1.	Curve #1	2	pSA	57.0	N	840
			pFA	57.7	N	785
2.	Curve #2	2	pSA	57.38	Y	540.7
		3	pSA	57.38	N	702.5

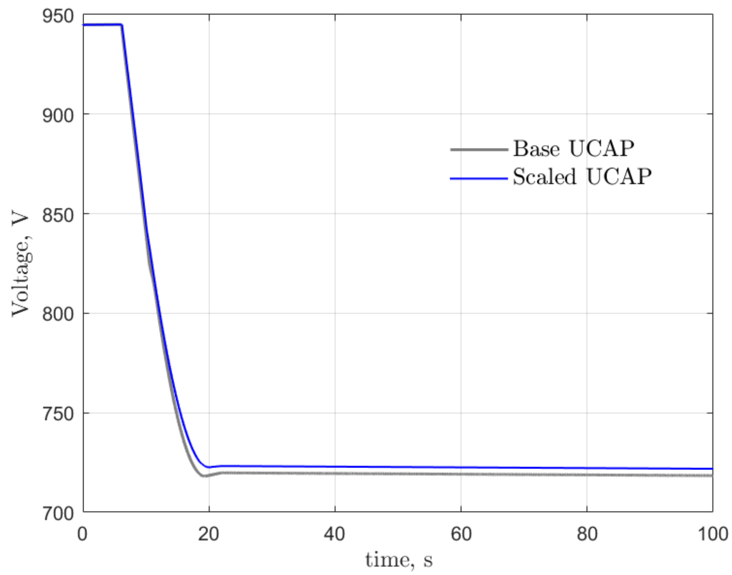

Figure 18. DC voltage profile for base UCAP vs. scaled UCAP.

Both scaling and configurations have their own benefits and offerings. The pFA configuration for F-watt Curve #1 in Figure 13 has a slightly raised frequency nadir as compared to Figure 17. However, the settling time for the scaled UCAP is the fastest as compared to anything else. Similarly, the DC voltage discharge profile for the pFA and pSA, shown in Figure 14, are slower than the sized UCAP as it can be seen in Figure 18. Table 5 depicts the details of the UCAP sizing with different configurations and for different f-watt curves. The choice between a larger sized UCAP or several UCAPs in different efficient configurations will depend on the outcomes from different energy storage strategies. If the main criterion is to arrest the frequency deviation significantly quicker, a sized UCAP might be the best solution. On the other hand, if improving the frequency nadir considerably (in the expense of significant draining the DC discharge voltage) is the main goal, the multi-UCAP configurations will provide better solution.

6. CONCLUSIONS AND EXPECTED ADDITIONAL ANALYSES

Based on the preliminary observations of the entire four-day filed demonstration, we present the following key takeaways:

- The City Bulb and Lower Bulb Plant running together were able to carry 8 MW load—the maximum capacity from the rented load bank. This demonstrated higher load carrying capability without violating frequency stability by running multiple ROR hydro units.
- Various control settings (e.g., P, I, D, and blade bias) and associated response from loading test, such as islanded system frequency, wicket gate position, and turbine blade position, can lead to further refinement to the associated hydro-governor model. This is motivated from the difference in response while simulating the loading test with the same f-watt curves. We hypothesize the hydro-governor model needs to be *adaptive* to the base load and water flow rate as well as available flow head to capture loading response (base load $\pm$ step load) as close to the field test as possible. Such refinement will lead to more accurate sizing and configuration for integrating an energy storage device. The recorded data is currently under investigation to lay path forward of such refinement of the existing hydro-governor model.
- The single UCAP ESS was able to arrest frequency deviation within the island mode protection settings—allowing the single and multiple hydro unit to support electrical loading at a different level. This was achieved through the UCAP's fast frequency response through a grid-following inverter.

Further investigation will answer whether the rate-of-change-frequency (ROCOF) can be improved by synthetic inertia (real power injection according to df/dt) response through a grid-following inverter.

- Commercial inverters are available with different level of controllability of the DC cutoff voltage. (It was 650 VDC for the field demonstration.) Thus, sizing and configuration of single/multiple energy storage device will be driven by the inverter under consideration and can be validated through simulation with a refined hydro-governor model.
- We further hypothesize integrating an energy storage device in grid forming mode would bring dampening to the frequency instability beside improving ROCOF and frequency nadir/zenith.
- Beside ROCOF, nadir, and zenith, we are currently integrating additional set of metrics for frequency stability assessment: settling time, the time when the frequency is above/below a certain value. All these metrics will guide to quantify performance of different sizing and configuration of integrated energy storage for a given inverter type as well as loading of the ROR unit.
- Unrelated to the field demonstration, but also interesting, was IFP's mention about the mere presence of a single wind farm on the same substation where they connect to the transmission system. Such integration is causing frequency disturbances to their HPPs during day-to-day operations (e.g., when the wind ramps up and down). Further investigation is needed to evaluate such disturbance with future projection of wind and solar capacity.

7. References

[1] "HydroWIRES Initiative," Water Power Technologies Office, Office of Energy Efficiency & Renewable Energy, U.S. Department of Energy, [Online]. Available: https://www.energy.gov/eere/water/hydrowires-initiative. [Accessed 25 August 2021].

[2] A. Banerjee, S. M. S. Alam and T. M. Mosier, "Impact of Hybrid Energy Storage System (HESS) Topologies on Performance: Exploration for Hydropower Hybrids," in *54th Hawaii International Conference on System Sciences (HICSS 2021)*, 2021.

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