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Abstract

Idaho Falls Power (IFP) utility has local generation portfolio comprising of 56.3MVA of run-of-the-river (ROR) hydropower that can serve typically 25%-30% of the total load demand. The remaining load is served by importing power from Bonneville Power Administration through two Pacificorp transmission interconnections. In case of emergencies (power disruption or directed load reduction), the capability to island from transmission grid and stably serve critical loads in the IFP distribution grid can be a huge advantage. In this direction, the capability to black start with ROR is an essential requirement, and a challenge due to limited dispatchability and requires re-tuning of hydro-governor and excitation system controls. This paper presents the field experience from the testing done for black start of 8.9MW ROR hydro plant in the IFP distribution grid using an adjustable load bank in December 2017. The lessons from the successful black start testing is presented along with test results to establish the potential value and requirements to develop black start capability with a ROR hydro plant.

Keywords – black start, distribution grid, hydropower, phasor measurement units, reliability.

Introduction

Black start testing for one 8.9MVA run-of-the-river hydropower plant was performed at Idaho Falls Power in December 2017. The Lower Bulb plant was isolated from the medium voltage grid at 46kV at the Rack substation for black start. A controllable resistive load bank of 4MW capacity was connected to the 12.47kV bus as shown in Fig. 1.

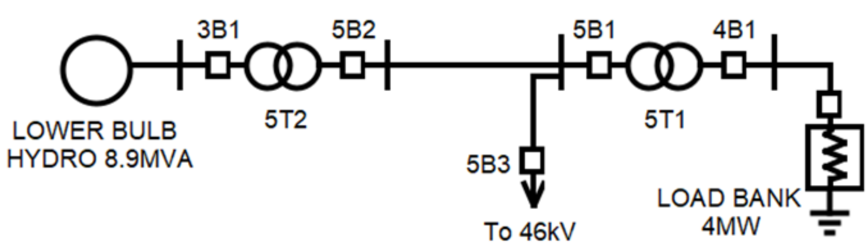


Fig. 1 Schematic of 8.9MVA Lower Bulb hydro and 4MW load bank setup for black start testing

As part of the United States Department of Energy funded Grid Modernization Lab Consortium project – GMLC 1.3.09, the plant was instrumented using micro-phasor measurement units (micro-PMUs) to record high-resolution black start data at two locations – one at the generator protection relay, and the other 12.47kV Rack substation bus where the load bank was also connected. The micro-PMUs collected GPS time-stamped phasor information for all three phases of voltage and current, i.e., magnitudes, phase angles, frequency and rate-of-change-of-frequency, along with some associated data and time quality information. The resolution of the data capture is 120samples per second, i.e. two estimates per fundamental power cycle of 60Hz.

System Description

Idaho Falls Power is a municipal utility located in Idaho Falls, Idaho that owns and operates local hydropower generation at the distribution level with an installed capacity of 56.3MVA (3x8.9MVA, 1x26MVA, 2x1.8MVA). IFP serves about 28000 customers in the Southeast region of Idaho. The total summer and winter load demand is around 130-140MW. The local generation supplies a portion of the total system load demand, and the balance is imported from Bonneville Power Administration. The distribution system has three voltage levels: 161kV transmission, 46kV sub-transmission, and 12.47kV distribution. Generator bus voltages range from 2.4kV to 13.8kV and step up to 46kV or 161kV. There are two transmission substations at Sugarmill and Westside where voltage steps down from 161kV to 46kV. Sugarmill has two 161kV/46kV transformers and carries about two-thirds of the power import, while Westside carries about one-third of the power imports. There are nine other substations at 46kV that step down to primary feeder voltage of 12.47kV.

The run-of-the-river hydropower plants are distributed around the city of Idaho Falls at four locations on the Snake River: City Bulb, Upper Bulb, and Lower Bulb are 8.9MVA each and are a horizontal Kaplan turbine type design and connected to the 46kVsystem. Old Lower Plant is a vertical Kaplan turbine type design with two units at 1.8 MVA each and connected to the 46kV system. Gemstate plant is a vertical Kaplan turbine type design with electrical generation capacity of 26MVA and connected to the 161kVsystem.

Table 1. Run-of-the-river hydropower plants in Idaho Falls Power distribution grid

Plant Name	Capacity (MVA)	Turbine	Substation
City Bulb	8.9	Kaplan	City
Upper Bulb	8.9	Kaplan	North Boulevard
Lower Bulb	8.9	Kaplan	Rack
Gemstate	26	Kaplan	Westside
Old Lower	3.6	Kaplan	Rack

Black Start Field Test Description

The black start field test was conducted on two days – December 5th and 6th, 2017, at the 8.9MVA Lower Bulb plant which is located at the Rack substation. The timeframe was chosen due to estimated flow and load demand being low in order to minimize system disruption and cost of lost generation. The Lower Bulb plant was chosen because its ability to electrically isolate from the system. It also had the physical space needed for the load bank and other testing equipment. The team at Idaho Falls Power prepared the isolation of the lower bulb plant for about two weeks considering the safety and adequacy of the generation in case required. The hydro-governor controls are provided by American Governor Company, and excitation system is provided by Bassler. Both manufacturers were consulted before the tests, and their field services teams visited and tuned controls for potential response during black start of the lower bulb plant in grid-islanded condition.

Micro-PMUs were installed at the generator protection relay of the Lower Bulb plant, and Rack substation feeder protection relay, in the end of November by INL team by help of Idaho Falls Power team. Signal, network, GPS, and data collection was established to configure and test data collection before the field testing. On the first day (December 5, 2017), the load bank was connected at 12.47kV below the main breaker. The load bank had two voltage taps: 4.16kV and 13.8kV and load step resolution at 13.8kV were 500kW, 1000kW, 1500kW, 2000kW with total load up to 5MW. Since, the substation load bus was at 12.47kV, the connection at 13.8kV end was chosen. The resistive load bank was energized, and step loads of 500kW were applied at a time. As a result of this, the resistive coils cut-in for step loads of 500kW were reflected as lower power step load of 408kW as shown in (1).

$$P_{load}^{act} = \left(V_{bus}^{act}/V_{load}^{rated}\right)^2 \times P_{load}^{rated} \quad (1)$$

The initial conditions and system parameters during the first day of the test were as follows:
River flow ~ 5900cfs; Temperature 12^0F – 26^0F; Wind Speed 0.3 – 3.8 mph; 5T1 (substation transformer) tapped at 45kV with LTC locked. 5T2 (generator step-up transformer) tapped at 46.2kV.

Test Plan

In preparation of the test, the substation and sub-transmission bus work were isolated from the city distribution network. A 4MW load bank was rented and connected in the substation at our distribution voltage of 12,470V. Modifications to the Automatic Voltage Regulator (AVR) and governor systems to optimize island mode performance, were made prior to and also adjusted during this test. The following are the steps that were intended to be used for this test:

Test Step 1: Demonstrate Asynchronous Capability

- Update controller settings for asynchronous operations.
- Start Lower Plant in asynchronous mode using plant black start procedure.
- Switch over to normal station service (about 200kW).

Test Step 2: Demonstrate Steady Load Stability

- Add 500kw load to Lower Plant.
- Run minimum one half hour and monitor for stability.

Test Step 3: Demonstrate Changing Load Stability

- Add 500kw loads incrementally at 15 min intervals to 2MW load.
- Decrease loads incrementally at 15 min intervals to 500kW load.
- Repeat, if needed, after adjusting PID/Droop to improve generator response.

Test Step 4: Demonstrate Ability to Follow Scaled Worst Case Load

- Follow load charted from 4B2-13 at 15 min intervals between load steps.
- 1500,1000,1500,3000,3500,2500,3500,2000,2500,3500,3000,2000,1500,1000

Test Step 5: Identify Maximum Load Rejection

- Increase load to 4MW
- Drop 2MW

- Increase load back to 4MW
- Incrementally increase dropped load by 500kW each test until 4MW load drop is achieved

Note: During the test the fourth and fifth steps exceed system stability capabilities and were not able to be performed. Test Step 3 was expanded to increase loading past 2MW in order to find the maximum stable load.

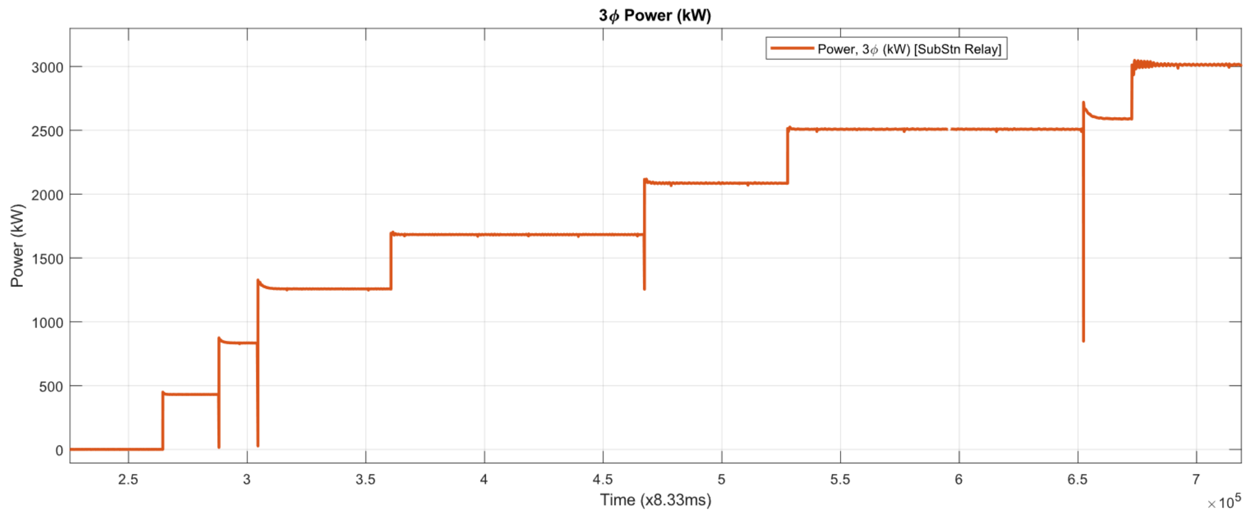
Table 2. Calculations for Rack substation micro-PMU data for December 6, 2017 field test

Time stamp	**Step Load (3ph, kW)**		**Frequency (Hz)**			**Governor**	
	Applied	**Measured, Substation**	**Start**	**Settled**	**Nadir, Zenith**	**P, I, D**	**1/R**
-	0		60.13	-	-	2,18,0.75	2%
0901	500	Trip, UF	60.13	-	58.42	2,18,0.75	2%
0922	500	*426**	*60.5*	-	-	2,18,0.75	2%
0941	1000	*831*	60.67	60.5	58.27	2,18,0.75	2%
1029	1500	*1250*	*60.58*			2,18,0.75	2%
1036	2000	Trip, UF	*60.58*	-	*< 57.0*	2,18,0.75	2%
1049	0	Plant reset	-	-	-	2,18,0.75	2%
1113	500	431	60.57	60.38	58.9	2,18,0.75	2%
1115	1000	835	60.61	60.49	58.46	2,18,0.75	2%
1118	1500	1198	60.54	60.48	57.73	2,18,0.75	2%
1126	1500+500	1684	60.53	57.77	60.45	2,18,0.75	2%
1154	2000	1576	60.21	60.09	59.64	2,18,0.75	2%
1250	1500	Trip, OF	60.01	-	65.31	2,18,0.75	1%
1253	0	Plant reset	-	-	-	2,18,0.75	1%
1311	500	429	60.31	60.17-60.2	58.55	2,18,0.75	1%
1316	0	0.6	60.25	60.4	61.94	2,12,0.75	0%
1320	500	429	60.34	60.3	58.59	2,12,0.75	0%
1323	1000	831	60.32	60.25	58.29	2,10,0.75	0%
1329	1500	1253	60.23	60.23	57.65	2,12,0.75	0%
1333	2000	Trip, UF	60.25	-	56.39	2,12,0.75	0%
1335	0	Plant reset	-	-	-	2,12,0.75	0%
1341	500	431	60.01	60.02	58.47	2,12,0.75	0%
1344	1000	833	60.06	60.07	58.06	2,12,0.75	0%
1347	1500	1258	60.03	60.08	57.48	2,12,0.75	0%
1355	1500+500	1683	60.02	60.02	57.32	2,12,0.75	0%
1410	1500+1000	2083	60.02	59.93-60.4	57.34	2,12,0.75	0%
1418	1500+1000+500	2509	59.95	59.84-60.3	56.47	1.5,20,0.75	0%
1435	1000+2000	2592	59.65-60.34	58.6	59.8-60.4	1.5,20,0.75	0%
1438	2000+1500	3015	60.15	59.49-60.6	55.58	1.5,20,0.75	0%
1518	2000+1000	2590	59.7-60.4	59.65-60.3	64.33	1.5,20,0.75	0%
1525	2000+500	2189	60.19	59.50-60.4	63.45	1.5,20,0.75	0%
1529	2000	1763	59.5-60.4	59.95-60.1	63.29	1.5,20,0.75	0%
1533	1500	1257	59.97	60.02	63.05	1.5,20,0.75	0%
1536	1000	834	59.94	59.98	62.26	2,18,0.6	0%
1538	0	0	60.05	60.02	63.43	2,18,0.6	0%

**observed from feeder protection relay*

Test Summary and Results

The load bank was connected on Monday December 4th, 2017. The capability of the load bank was to provide a resistive load up to 4MW in 500kW steps. Test step 1 was successfully completed on Tuesday December 5th, 2017 when the generator was started and station service (about 200kW) was switched in. Of note, all tests steps after test step 1 were performed with the station service switched in before any additional load was added. Test step 2 was attempted Tuesday until it was found that the load bank was tapped to the wrong voltage. After adjustment of the load bank to the correct voltage settings, test step 2 was attempted at the end of the day on Tuesday. The generator tripped offline, but it was found that the protection system was erroneously set with insufficient time delay on the under-voltage protection.



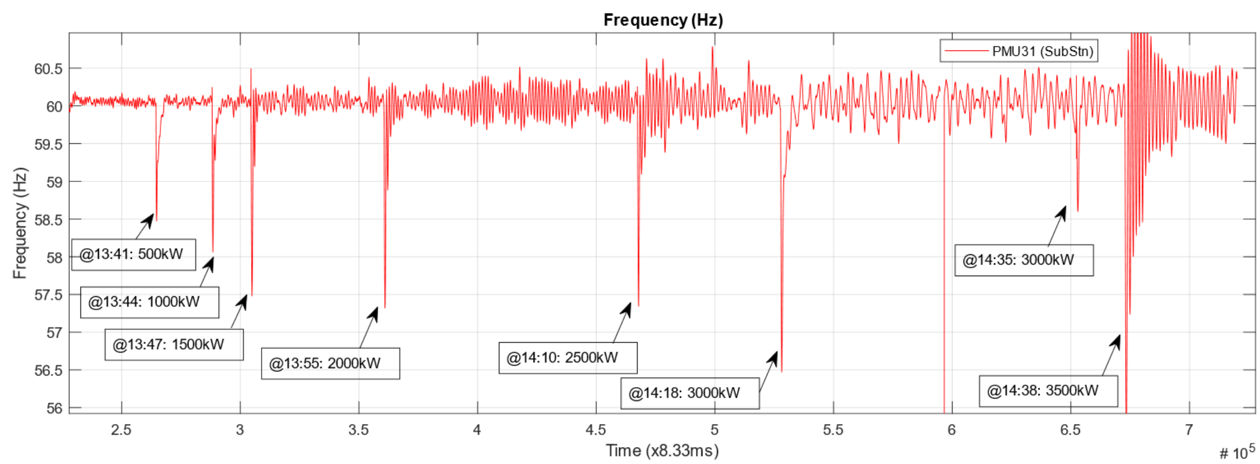
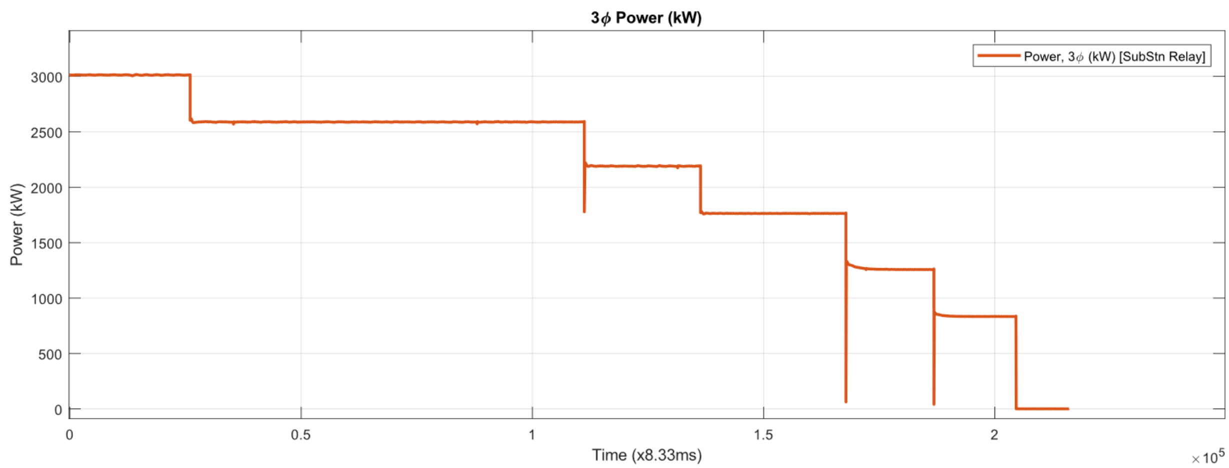


Fig. 2a (top): Power calculated based on micro-PMU measurements at the Rack substation for the step load applied by the load bank; and 2b (bottom): Frequency deviations for the step load in islanded mode operation of Lower Bulb plant. Annotations show timestamp and load applied in kW[1].

[1] Due to software application issues in the field during data collection, some data is missing in the above plot appearing around 14:28 hrs and shows as missing data in power and a large dip appears in frequency.

On Wednesday December 6th, 2017, test step 2 was attempted again and after a few adjustments 500kW was switched onto the generator successfully. Test step 3 was started. Adjustments were made as governor reactions were noted. Once 2MW was achieved 500kW was removed the generator tripped on over frequency. It was found that the protection was set over sensitive. Adjustments were made and several loading and offloading tests were performed. It was identified that test steps 4 and 5 would not be possible to be performed within the stability range of the generator. It was decided to modify test step 3 to increase load to find the maximum stable load. The load was increased to about 3.2MW. At this point the generator frequency and gate/blade position went into oscillation. Adjustments made to the control gains were found to be able to dampen the effect but only at the cost of undesirable governor reaction times. Load was reduced in 500kW steps until 1MW was left. As the stability at lower loads were greatly improved throughout the testing, it was decided to try to remove the last 1MW in one step. The attempt was successful. Fig. 1 and 2 show power and frequency plots for final test based on highlighted rows in Table 2.



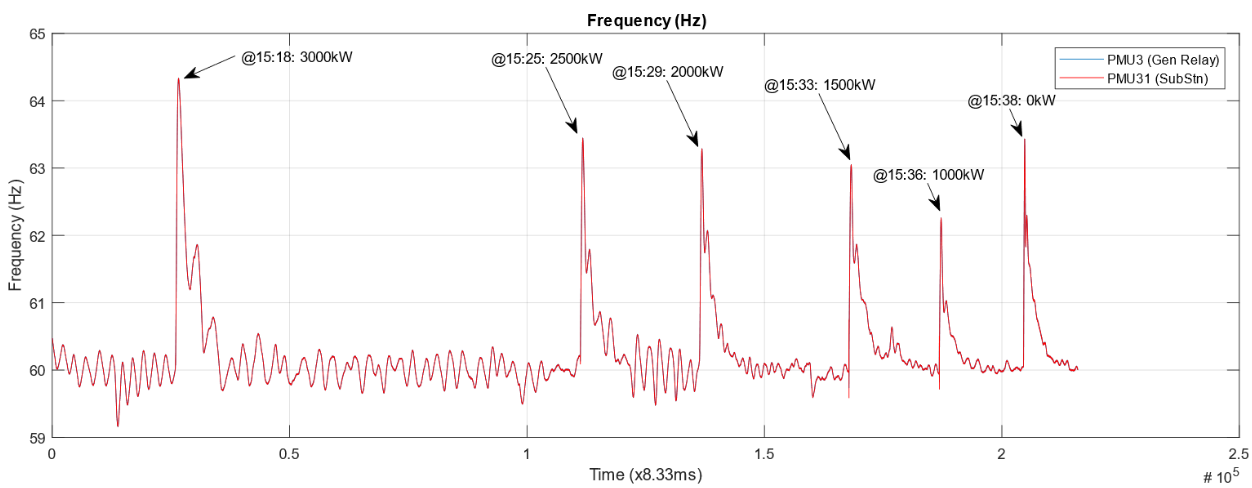


Fig. 1a (top): Power calculated based on micro-PMU measurements at the Rack substation; and 1b (bottom): Frequency deviations for the step load input in islanded mode operation of Lower Bulb plant. Annotations show timestamp and load applied in kW. Both micro-PMU data plots overlap.

Conclusion

The black start field test was successfully completed with the Upper Bulb ROR plant and generator in an islanded mode. This demonstrated the feasibility of the black start using a hydropower plant and provides a strong potential for existing hydro plants as a black start resource in the IFP distribution grid. Some observations and learnings from the field-testing experience is listed below.

Salient Points

1. The black start was successful for regulated load pickup and rejection without compromising stability, albeit for smaller capacity resistive load steps.
2. Load bank connectivity proved to be an issue in the initial tests and was rectified by proper connections. The load cut-in was also not consistent with the rating. But this did not affect the overall response much.

Key Learnings

1. Tuning of controls and direct coordination with vendors and manufacturers of governors and excitation controls was required, including manual controls adjustment and operational suggestions from the technical staff.
2. The initial testing proceeded with incremental improvements by adjusting droop settings, controller gains, protection settings adjustment and resulted in tripping the plant in some cases due to under- and over-frequency events. Later a feasible setting was achieved to successfully demonstrate load pick-up and load rejection in steps of 500kW.
3. Based on the experiences from this field testing, an opportunity lies for hydropower to become a major black start resource provided the plant response can be enhanced by secondary source of power injection to improve the frequency response, such as battery or supercapacitor energy storage. This will also require an autonomous or coordinated control to be developed for ensure stability.

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