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Power Hardware-In-the-Loop Hydropower and Ultracapacitor Hybrid Testbed

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Changing the World's Energy Future

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***Abstract*—Ultracapacitors are an effective energy storage system for providing short duration grid services such as frequency response. In this paper, we explain a closed-loop digital real time simulation testbed using RTDS with a simulated hydropower plant and ultracapacitors as power hardware-in-the-loop to refine the ultracapacitor controls and assess their performance for stabilizing frequency during an islanded black start test. This physical testbed includes RTDS, an UCAP, load banks, grid emulators, and 6-bridge VSC technology grid following inverter with hardware components connected using RTDS i/o functions. The paper focuses on calibration and validation of the testbed, which is then used to tune the hydropower-ultracapacitor hybrid system to support sudden changes in load consistent with the islanded black start. This work was conducted to de-risk a field demonstration in which the ultracapacitor and inverter components were connected to a real hydropower plant and tested for this operational mode.**

***Index Terms*—ultracapacitor, hydropower, hybrid plants, PHIL, RTDS testbed**

I. Introduction

The electric grid is undergoing rapid innovation with increasing deployment of wind, solar, and multiple types of energy storage. While often times this innovation is viewed as disruptive, it also holds the potential to enable new gird operational paradigms [1]. One example is with black starts. Typically, large generation units, such as hundred megawatt and greater hydropower plants, tied to the transmission are used for restoring the grid [2]. Smaller hydropower plants tied to the distribution system are not designed to support stability and therefore are not used for traditional black start. Yet, integrating them with energy storage systems (ESS) [3] can mitigate such stability issues through providing fast frequency response during the transients of load restoration. This has been demonstrated by integrating an ultracapacitor (UCAP) with a small hydropower plant to perform an islanded black start [4].

On-site power technology demonstration is expensive and risky because it requires temporarily isolating units and portions of the grid and reconfiguring them for testing purposes. Digital real-time simulation (DRTS) tools such as RTDS [5] can be used to model and simulate the range of real-world conditions in a controlled lab setting, reducing risk and cost associated with testing and tuning new technologies or equipment configurations prior to field demonstration.

This paper presents a DRTS testbed with PHIL of an ultracapacitor system and a high fidelity hydropower model that is used to simulate hybrid system performance. The content is designed to guide the reader regarding developing and calibrating the testbed. The testbed is used to prepare for a black start field demonstration [4] and can be applied to other types of PHIL tests. Section II gives an overview of the PHIL test setup. Section III characterizes the UCAP ESS for DRTS integration. Section IV describes the current injection model and associated calibration. Section V presents results. Section VI provides the conclusions.

II. The PHIL Test Setup

The overall PHIL testbed is designed to mimic integration of a run-of-river (ROR) hydropower plant (simulated) with an UCAP and inverter (physical hardware) (Fig. 1). DRTS is performed using RSCAD [5] with a 540 kVA AMETEK grid emulator [6] (interfaced to the *virtual* 480 VAC bus via Giga-Transceiver-Analog-Output (GTAO)) and the UCAP energy storage system (ESS) (interfaced to the Norton current source via Giga-Transceiver-Analog-put (GTAI)). The UCAP ESS includes a 1000 VDC, 8.9 F Maxwell Ultracapacitor (UCAP Power has acquired this grid energy solution in 2021 [7]) and 375 kVA EPC bidirectional DC-AC converter [8]. The "Lower Bulb" virtual plant includes an 8.9 MVA synchronous machine feeding a dynamic load bank at the 12.47 kV bus.

The Lower Bulb synchronous machine represents an ROR hydropower plant with bulb-style Kaplan turbine through a customized version of the H6E hydrogovernor model [9]. This customization is achieved through adjusting the power and blade versus gate curves according to field test of wicket gate response in grid connected mode [10]. The hydrogovernor model is cross validated between Simulink [11] and RTDS [5] and is publicly available at GitHub [12].

This grid following converter's nominal DC operating voltage is 710-1000 V to maintain a line-to-line voltage of 480 V on the AC side. The converter will trip if the DC side voltage

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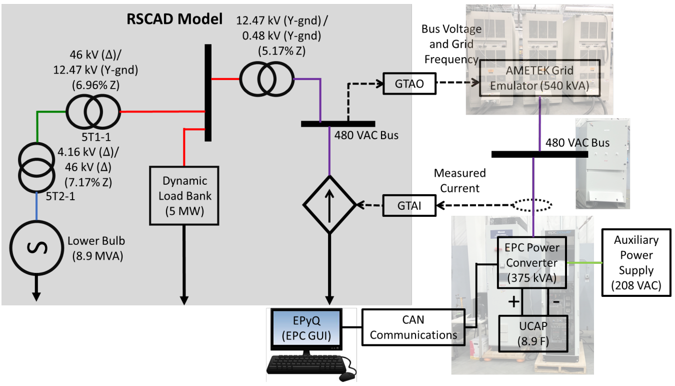

Fig. 1. Overall PHIL testbed.

goes below 650 VDC. The EPyQ (a graphical user interface (GUI)) from EPC Power Corporation that communicates with the EPC converter over the controller area network (CAN) is utilized for setting up frequency-Watt (hereafter referred to as “f-Watt”) droops and operational monitoring of UCAP DC voltage. Both the grid emulator and UCAP ESS are AC-coupled to the physical 480 VAC bus. The grid emulator acts as a dependent voltage source that modulates according to the instantaneous magnitude, phase, and frequency of the line-to-neutral kilo-Volts at virtual 480 VAC bus. The instantaneous current injected from UCAP ESS to grid emulator is captured using Tektronix current probe [13] (Fig. 2), sent to the virtual model, and fed to Norton current source via a current injection model. The closed-loop coupling of the virtual plant and the hardware assembly follows the voltage type ideal transformer interface [5], [14].

Fig. 2. Current probing assembly.

III. UCAP Characterization

Finding the UCAP capacitance as seen at the physical 480 VAC bus is important to set the active power injection rate on the f-Watt droop. High injection rate based on an optimistic capacitance assumption may drop the DC voltage rapidly-causing DC under-voltage trip of the converter during the PHIL test. For this characterization, the GTAO interface to grid emulator has been disabled and the *physical* 480 VAC bus is maintained at the nominal level. The equivalent capacitance is expressed as

$$C_{480\text{VAC}} = \frac{2 \times 1000}{N_{\text{c}}(950^2 - 750^2)} \sum_{n=1}^{N_{\text{c}}} P_n[\text{kW}] \times \Delta t_n \quad (1)$$

where Δt_n represents the UCAP discharge time (seconds) from 950 VDC to 750 VDC for the power discharge command of P_n kW and N_{c} is the number of power discharge commands issued through the EPyQ GUI. Before each power discharge command, the UCAP is recharged to 950 VDC. We have set $N_{\text{c}} = 8$ discharge commands from 35 kW to 70 kW in 5 kW increments with corresponding Δt_n are shown in Fig. 3.

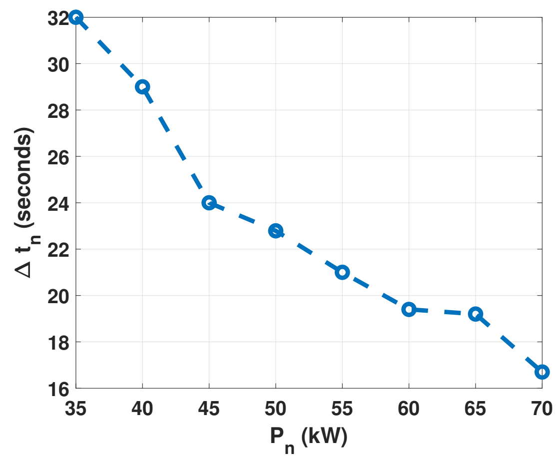

Fig. 3. Discharge time versus power discharge command.

Faster decrease of the DC voltage is expected because $C_{480\text{VAC}} = 6.7F$ from (1), indicating that the effective capacitance is less than the rated capacitance. Based on this, active power injection has been set at partial rate through the f-Watt droop curve. In particular, three f-Watt curves of real power injection has been developed with lower frequency deadband of 58 Hz (see Fig. 4). The deadband is introduced to reduce sensitivity to frequency oscillation and preserve more energy to improve frequency nadir.

f-Watt Setting 3, for example, has been utilized with the Simulink’s “Generic Supercapacitor Model” [11] and has shown the final DC voltage near 710 VDC after injecting real power in response to a 500 kW step load increase [4]. Based on this observation, the amount of step load change has been adjusted during the PHIL test to avoid DC under-voltage trip.

IV. The Current Injection Model

The current injection model depicted in Fig. 5 applies to each phase of the 3-phase system shown in Fig. 1. This model completes the closed-loop system and mimics the UCAP ESS’s response in real-time on the virtual platform. K_v presents the pre-scaling factor applied to the instantaneous line-to-neutral kilo-Volt signal being sent to grid emulator via GTAO and K_i represents the post-scaling factor applied to the instantaneous line current (A) signal being received

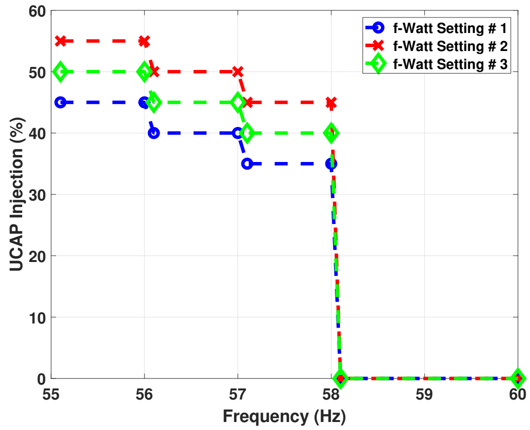

Fig. 4. Frequency-Watt settings.

from the Tektronix current probe via GTAI. The instantaneous phase of the *virtual* "480 VAC Bus" is captured through the "Phase Locked Loop" and sent to the "Sine Wave Generator". This generator utilizes the phase information and the peak value of the instantaneous current to synthesize instantaneous *virtual* current. The rate of change of this synthetic current is then limited within specified range using the "Dynamic Rate Limiter" (DRL). The Norton current source then utilizes this *virtual* current to inject into the *virtual* "480 VAC Bus". An additional division by a factor 1000 is used to match the electric current unit of Norton source in RSCAD. The next subsections explain how to set DRL, Kv, and K_i.

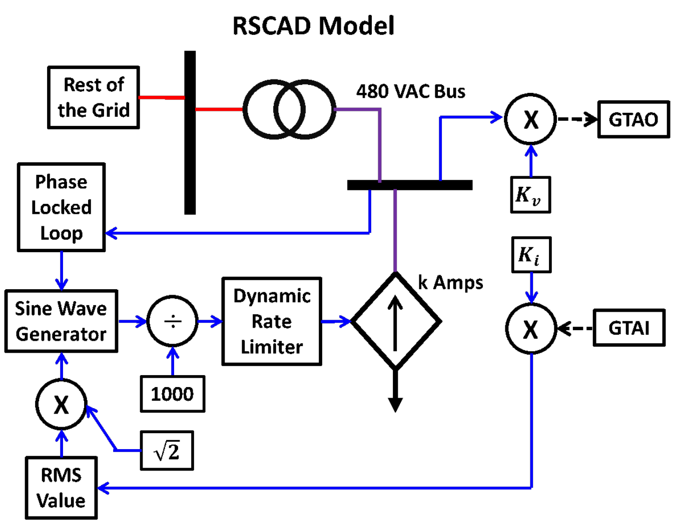

Fig. 5. Current injection model. RMS stands for root-mean-square.

A. Setting DRL

The range of the DRL plays a vital role in synthesizing the branch current on the virtual 480 VAC bus. Overestimation of the branch current can lead to over-voltage causing a trip of the grid emulator via GTAO. Hence, the magnitude of the DRL limits is pre-determined in the absence of the PHIL setup. This is achieved by providing a reference current from an f-Watt responsive current source and comparing it with the branch current. Fig. 6 shows such current source inside the dashed block. The "Sawtooth Wave Generator" provides the necessary phase to the "Sine Wave Generator". Given the frequency at the "Lower Bulb" unit, the % real power injection value is determined and appropriately scaled to provide the peak value of current to the "Sine Wave Generator". For the 375 kVA 480 VAC system, this scaling factor is determined as

$$\frac{375 \times \sqrt{2}}{0.48 \times \sqrt{3}} \approx 637.88$$

where I_{Ref} is the RMS value of the instantaneous current (A) input to the DRL. The RMS value of the instantaneous injected at the virtual 480 VAC bus is denoted as I_{Branch}. Both the upper (positive) and lower (negative) range of the DRL are specified by the same DRL magnitude. For a step load increase from 1.0 MW to 1.5 MW using a given DRL magnitude, the ratio score (RS) is calculated as

$$RS = 100 \times \left(1 - \frac{I_{\text{Ref}}}{I_{\text{Branch}}}\right) \tag{2}$$

Thus, the ideal value of RS is zero, while positive and negative values respectively indicate over and under estimation of the branch current. RS is calculated across different DRL magnitudes and a value of 33 is chosen to be the most appropriate (see Fig. 7).

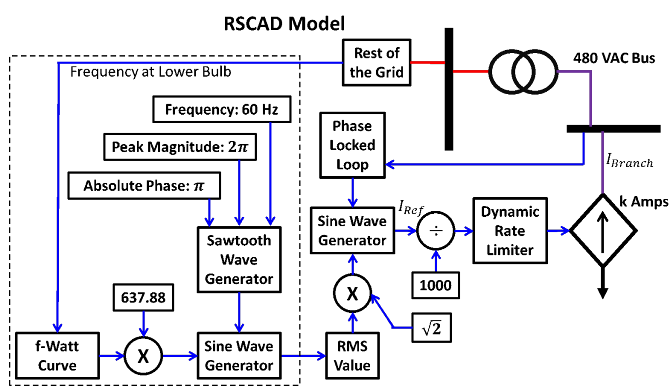

Fig. 6. RSCAD model showing the f-Watt responsive current synthesis inside the dashed block.

B. Calculating K_v

K_v is set based on grid emulator values as follows. The peak analog input to the AMETEK grid emulator is 10 V, which the emulator can amplify 40 times. Second, the "Peak value for 5 volts D/A out" for GTAO's "D/A Output Scaling" has been set as 5. Since, the line-to-neutral peak value for the 480 VAC bus is approximately 0.4 kV,

$$0.4 \times K_v = 10$$

Resulting in $K_v = 25$.

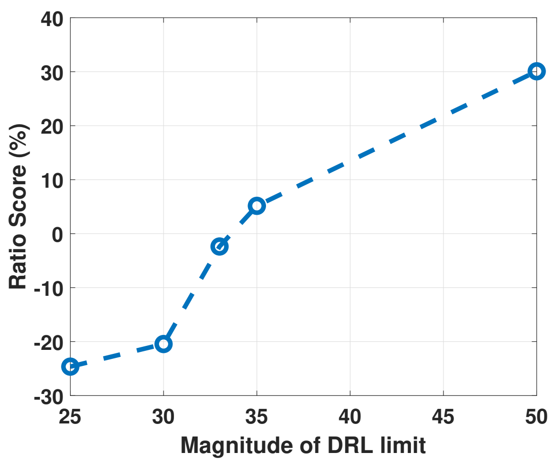

Fig. 7. Ratio score versus magnitude of DRL limits.

C. Calculating K_i

Setting K_i requires the observation of the actual and measured currents. For this reason, a 155 kW SIMPLEX dynaMITE load bank [15] has been connected to the physical 480 VAC bus, current injection model has been disabled, and a virtual ammeter has been placed to capture the measured currents (see Fig. 8). First, the "A/D Input Scaling (for each of the 3 phases)" of the GTAI has been set to 0.02, and K_i is initially set to 1. This implies just 50 times pre-amplification through the GTAI interface. The load bank has been set to different power levels and corresponding RMS currents are measured at the grid emulator display and on RSCAD ammeter. The value of K_i is then calculated as

$$K_i = \frac{1}{N_{\mathrm{L}}} \sum_{n=1}^{N_L} \frac{I_n^{\mathrm{Emulator}}}{I_n^{\mathrm{RSCAD}}} \quad (3)$$

where N_{L} is the total number of power levels set on the load bank, I_n^{Emulator} and I_n^{RSCAD} are the respective RMS currents on the grid emulator display and on RSCAD for the n^{th} power level on load bank. We have utilized $N_{\mathrm{L}} = 15$ load set points from 10 KW to 150 kW at 10 kW increments and have determined $K_i = 78$ from (3).

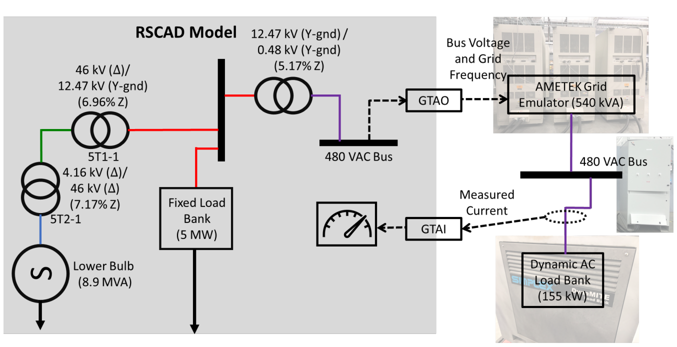

Fig. 8. Hardware test setup to calculate K_i.

The settings thus obtained have been utilized throughout the PHIL test. The entire RSCAD draft model along with all other parameters are now publicly available on GitHub [12].

V. RESULTS

The PHIL test involves investigating the frequency transients at the "Lower Bulb" unit as a result of step increases in load using different ultracapacitor f-Watt settings. The test is run in sequence of nine events (E1-E9) as denoted in Table I.

TABLE I
EVENT-WISE DESCRIPTION OF TEST SEQUENCE

Event Number	Event Description
E1	UCAP ESS: Disable inverter operation. Current injection model: 'Disable'
E2	"Lower Bulb" Unit: Set "Initial Mode of Lock/FreeSwitch" to "Lock" under "Mechanical Data and Con-figuration".
E3	Dynamic Load Bank": Set the desired value for steady-state load.
E4	Run load flow and initialize hydrgovernor turbine settings according to [10], [12]. This step must be repeated for each steady-state electric loading and prior to stepload change.
E5	Compile the draft file and load to RUNTIME.
E6	Start simulation and "unlock" the "Lower Bulb Unit" from E2.
E7	Apply a desired step load change on the "Dynamic Load Bank" and observe frequency and other variables of interest.
E8	Stop the simulation.
E9	EPC converter: Load the desired f-Watt setting via the EPyQ GUI. Enable inverter operation and current injection model from E1. Repeat E2 - E8.

Frequency transients are simulated with and without UCAP ESS integration following these nine steps. It is observed that over a range of conditions UCAP ESS integration improves the frequency nadir. For example see frequency transients corresponding to a load change from 3 MW to 3.375 MW in Fig. 9.

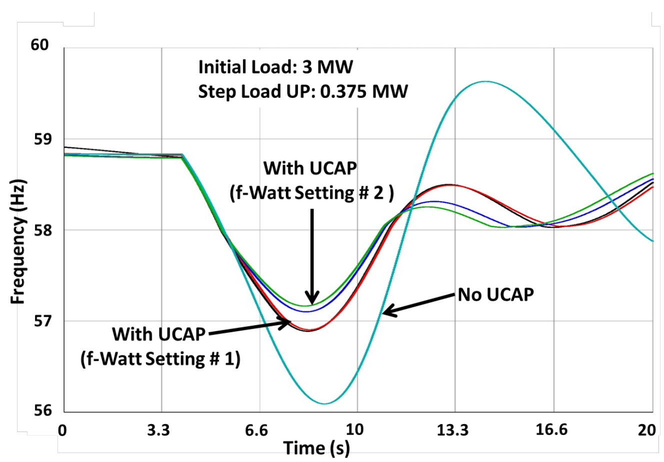

Fig. 9. Frequency excursion with and without UCAP power injection.

The corresponding envelopes of line currents and UCAP power for f-Watt setting 1 are shown in Fig. 10. The step load change is kept at 375 kW to compare improvement from f-Watt setting 1 to higher injection rate of setting 2. A higher step load change with setting 2 would cause DC under-voltage trip.

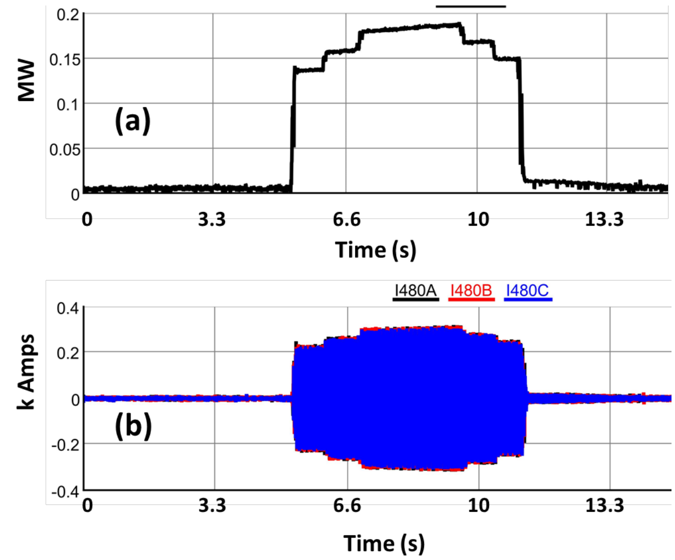

Fig. 10. UCAP response to step load increase from 3 MW to 3.375 MW: (a) power injection envelope, (b) line current envelope.

The PHIL testing also enables assessing the steady-state load carrying capability. For example, Fig. 11 demonstrates this for a 2 MW initial load. Here, the frequency nadir decreases gradually as the amount of step load is increased. This can recommend the maximum step load change that is advisable within the ROR unit's under frequency trip settings.

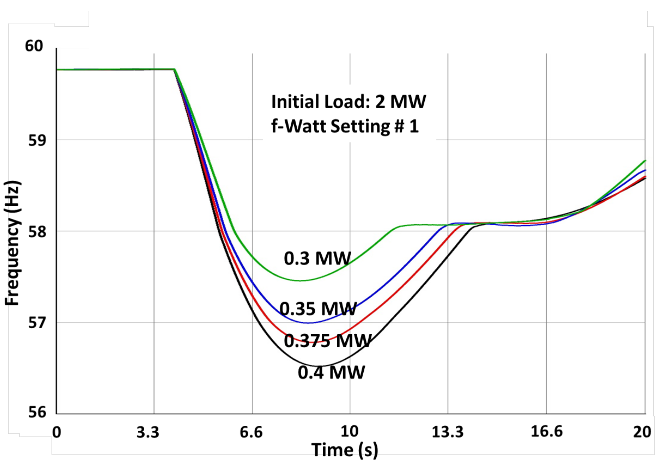

Fig. 11. Frequency excursion for different step load increase at 2 MW.

VI. Conclusion

We have presented a step-by-step process of storage characterization, current injection modeling, measurement calibration, and parameter tuning to develop a closed loop PHIL testbed. We have specifically designed this testbed to evaluate fast frequency response of an UCAP and inverter setup during black start involving an ROR hydropower unit. As expected, the UCAP ESS improved the frequency nadir during load step transients. The PHIL testing enabled tuning the f-Watt droop settings on the inverter to maximize response for various load conditions. Furthermore, the process enables assessing the integrated ROR unit and ultracapacitor's load carrying capability. Others can use this model [12] and methodology to investigate other technology innovations in the lab as well, prior to field demonstration or deployment. Overall, this paper shows an approach for advancing controls of hybrid energy systems to improve the grid services that they can provide, helping to realize the possibility of using distributed energy resources to change grid operational paradigms.

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