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Mitigating the Effect of Wind Ramp Events on Local Run-of-River Hydropower Plants Using Cooperative Control

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***Abstract*—This paper focuses on the challenges of frequency response from run-of-river (ROR) plants and potential solutions, especially considering the effect of wind ramp events in a low inertia power system. Due to sudden increases in instantaneous wind power, the system frequency can increase, causing excessive reduction in the ROR system's power. Considering their small pondage, this can result in damage to the physical structure due to water level violations which are also penalized by stakeholders. To prevent excessive ROR power deviations, ROR governor wear and tear, and to prevent tie-line deviations, a centralized coordination scheme with a balancing layer of distributed control has been developed for coordinating the response from a cluster of ROR plants. Results indicate that the centralized scheme both, with and without the balancing distributed control layer can reduce frequency peaks. However, the inclusion of distributed cooperative controls leads to reduced governor actions from fast-acting plants while enhancing net response from the hydropower cluster, and faster damping of tie-line power oscillations.**

***Index Terms*—Hydropower, Run of river, Frequency control, Wind energy, Cooperative control**

I. Introduction

Increasing penetrations of non-dispatchable renewables can create challenges and opportunities for hydropower resources. When there is a frequency deviation in the power system connected hosting the ROR systems, they respond to these deviations due to their speed feedback and primary frequency response (PFR) control. As power system inertia decreases, the effect of renewable power fluctuations cause excessive hydrogovernor action, thereby increasing governor wear and tear [1], [2], [3]. This is more severe for hydropower units with fast governors which causes unequal response and governor wear among a hydropower fleet. A case study in Australia presented in [4], showed that large-scale wind generation in low-inertia systems (those with up to 50% wind:hydro capacity ratio) would result result in a high-rate of change of the frequency during disturbances, such as wind ramping, incurring on operational impacts in the hydropower system. These impacts on ROR plants becomes a very sensitive subject, specially in the U.S, because maintaining river flows to meet downstream stakeholder needs takes a higher priority than power production.

Recent studies have shown that power system inertia [5] and frequency response has been declining during the last several years [6], [7]. Excessive frequency excursions can lead to load shedding, instability, machine damage, and even blackouts. Therefore, increased flexibility and ancillary service requirements such as frequency response from small hydropower units plays an important role for the stability of a power network with high penetration of renewable energy resources. Some of the problems mentioned above (unequal wear and tear, pondage water level deviation) can be solved by reducing the response of the governors. However, this would reduce the contribution of these plants to frequency support and tie-line error minimization. Also note that, the change in plant control parameters opposes downstream stakeholders interest.

To cater to this set of problems, an external real power reference control scheme is designed by implementing a centralized control (CC). The response from the CC scheme is then balanced and redistributed among the units using a decentralized control (DC) approach implementing a consensus protocol. The centralized control (CC) strategy uses a power distribution scheme similar to conventional automatic generation control (AGC) [8]. The decentralized control (DC) strategy uses a real power utilization ratio consensus protocol-based cooperative control scheme [9], [10]. Two configurations of the balancing DC layer are tested, a) leader follower free (DC1), and b) with leader follower DC2. A similar application in literature can be found in [11]. The details of each configuration is presented in later sections.

II. Methods

A. System Model

The power network of Idaho Falls (IFP) consists of 94.5 MW of load and 52.9 MW of ROR hydro generation [12]. The IFP network has a ring bus topology at 46 kV and is connected to the WECC system at 161 kV. Fed by the Snake River, there are four ROR plants (three having identical Kaplan bulb turbines) distributed across this power network.

In [13], the H6E governor and turbine models used for three of the ROR systems in this work, have been described and matched with field data. A larger unit was reported to have a PID governor [14] with a similar turbine model.

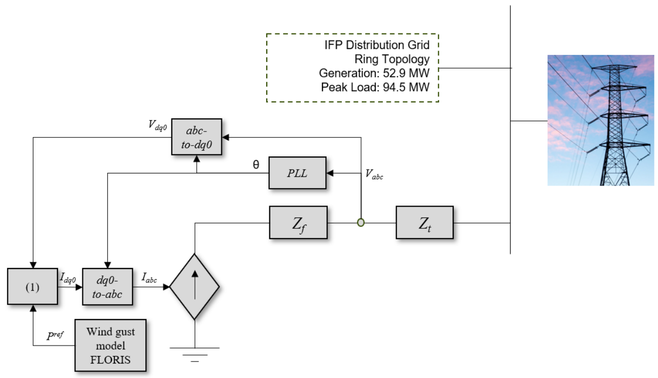


Fig. 1: Aggregated wind farm with IFP distribution system (Detailed topology can be found in [12])

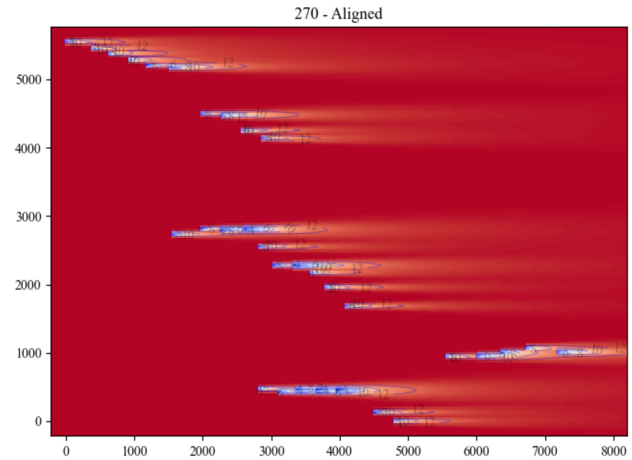


Fig. 2: FLORIS snapshot of the wind farm wake interactions with a wind direction of 270^o and a wind speed of 14 m/s.

B. Wind Farm Modeling

In the foothills of Idaho Falls, approximately 12 miles east from the city center, four wind farms with a total capacity of 366 MW have been operational since 2005 (see table I). While these wind farms are not part of IFP's jurisdiction, nor Idaho Falls receives electricity from them, their power is routed through the Goshen substation, south of Idaho Falls. The hydropower plants from IFP are also interacting with the WECC network through Goshen. This means both generation types, hydropower and wind, are interacting electrically through the point of interconnection.

TABLE I: High-level information of the wind farms in the vicinity of IFP.

Wind Farm	Capacity MW	Number of Turbines	Year
Meadow Creek	119.7	57	2012
Horse Butte	57.6	32	2012
Goshen North	124.5	83	2010
Wolverine Creek	64.5	43	2005

Among these farms, IFP has a revenue share with the Horse Butte farm, and hence we focus on the impact this farm may have on IFP's electrically co-located hydropower generation [15]. The Horse Butte farm is modeled using the open-source code FLORIS [16], which is a python package to model wake and controls in wind farms. The inputs to the package is a time series of wind speed and direction. The model output is the aggregated and individual wind turbine power time series. By considering wake effects in the simulation, the aggregated output will show variations in the real power, rather than a laminar value (2). The output power time series is then used as an input in the Simulink model.

A current source-based aggregate model is used to model the wind farm in Simulink, where the injected current is calculated as:

$$i_{dq}{}^{r} = \begin{bmatrix} i_d^r \\ i_q^r \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix}^{-1} \begin{bmatrix} P^r \\ Q^r \end{bmatrix}. \quad (1)$$

Here P^r and Q^r represent real and reactive power references for the farm, v and i represent instantaneous voltage and currents and subscripts d, and q represent dq-axis components. The injected currents are synchronized using a phase-locked-loop (PLL) driven by the terminal voltage. The current source based model greatly reduced computational burden.

C. Generation coordination scheme - Centralized control (CC)

As mentioned before, modification of parameters of the existing system governor for these ROR plants would not be feasible due to stakeholder engagement and other risk factors. Consequently, to meet flexibility needs, a second layer of power reference control (CC) is applied. The CC scheme employs the traditional centralized automatic generation control scheme which is a function of both, the tie-line error and the frequency error.

$$\Delta P_{pu}^{'} = \frac{\gamma_1}{\Sigma_i \overline{P}_i} \int (\gamma_t (P^*{}_t - P_t) + \gamma_f (60 - f)) dt. \quad (2)$$

Here, $\overline{P}_i, P_t, P^*{}_t, f, \gamma_t$ and γ_f, represent the rated power of the i^{th} ROR unit, tie-line power-flow, reference value of tie-line power-flow, frequency and gains for tie-line power-flow and frequency control, respectively. The above scheme ensures capacity proportional sharing of response by sharing $\Delta P_{pu}^{'}$ among units. However, it does not consider feedback from individual unit. This scheme deploys a one - way communication scheme which is modeled as [17]:

$$S_{ij} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (3)$$

Equation (3) is a binary matrix representing the on/off status of communication between two ROR plants participating in the scheme. If every generator and the inter-connecting substation can be considered as a participant, each row (a communication vector) in the S matrix in (3) is dedicated to one participant.

TABLE II: Qualitative Comparison of Control Strategies

	Centralized approach (CC)	**Decentralized control approach 1 (DC1)**	**Decentralized control approach 2 (DC2)**
Brief Description	Based on local frequency and local tie-line power measurement. Divides and distributes the power reference changes for each participating unit in a capacity proportional manner.	DC1 acts a balancing layer between the CC and the units. Considers $\Delta P'_{pu}$ from the CC scheme as an external input, where CC output is channeled to every participating unit.	DC2 also acts a balancing layer between the CC and the units. However, DC2 involves a leader, and the CC output is channeled only to the leader. The other units are followers.
Strengths	Individual plant feedback-free (based on local measurements) and hence has low communication requirements. Lower computational burden and easier maintenance and debugging.	Enhances plant behavior through consensus of slow and fast plants. DC1 scheme employs consensus protocol which prevents saturation of lower reserve plants. DC1 not only balances CC response but also droop based primary frequency response.	Includes the strengths of the DC1 scheme. Only peer-to-peer communication is required.
Weaknesses	The individual plant feedback free aspect prevents CC from being aware of each plant reserve and response. This can cause saturation and added oscillations.	Additional Communication network requirements to enable peer-to-peer communication.	Initial choice of leader is important. If leader fails or is sabotaged, the central command has an additional responsibility to detect the same and choose a new leader.

Also, each participant is only aware of its own communication vector (row in (3)). Additionally, when varied from 0 to 1, the elements of the S matrix also represent weight factors of the influence of a peer. In (3), the top row represents the inter-connecting substation that would measure, calculate and distribute signals to other generators.

D. Generation coordination scheme - Decentralized control DC (DC1 and DC2)

Separate ROR plants respond differently to the same disturbance due to different governor and plant control parameters as vendors may not be the same, or year of installation may be different. Therefore, wear and tear is comparatively greater for faster units. Also, many ROR plants have small ponds which might be endangered due to rapid changes in water levels, which is most probable for fast-acting plants. However, the differences between the units can be exploited to realize benefits through a distributed cooperative control framework. For this, we first define utilization α_i factor as

$$\alpha_i(t) = \frac{p_i(t)}{\overline{P}_i}, \tag{4}$$

where p_i is the real power injection of the i^{th} ROR unit. The DC protocol is simply expressed as

$$\Delta P''_{pu,i} = \begin{cases} \text{sign}(A_i) \times \overline{P}_i, & \text{if } |A_i| \geq \overline{P}_i \\ A_i & \text{otherwise} \end{cases}, \tag{5}$$

where

$$A_i = -\gamma_2 \int S_{ij}(\alpha_i - \alpha_j)\text{DZ}_\alpha dt.$$

and

$$\text{DZ}_\alpha = \begin{cases} 1, & \text{if } |\alpha_i \text{ - } \alpha_j| \geq \epsilon_\alpha \\ 0 & \text{otherwise} \end{cases}. \tag{6}$$

Equation (5) can be used as a supplementary control with the power reference to the H6E or PIDGOV governor. The saturation in (5) and dead-zone (DZ_α as in (6)) functionalities are built into equation (5) to allow traditional control functionalities like PFR and CC to dominate. DZ_α is implemented if complete consensus among neighbors is not preferred and other objectives (such as dispatch or contracts) are to be prioritized after the neighbors are close to each other under normal operating conditions. The saturation in (5) is implemented for two purposes, a) to increase plant capacity awareness of the consensus control and b) to limit the action of the consensus control to prioritize restorative action. For DC1 the communication matrix in (3) is modified to represent peer - to - peer communication scheme as:

$$S_{ij} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & S_{12} & 0 & S_{14} \\ 0 & S_{21} & 1 & S_{23} & 0 \\ 0 & 0 & S_{32} & 1 & S_{34} \\ 0 & S_{41} & 0 & S_{43} & 1 \end{bmatrix} \tag{7}$$

Here, as the distribution network under consideration has a ring bus topology, each ROR generator has two peer generators. When using (7), note that there are no leaders or followers.

To eliminate the communication burden a partially decentralized scheme for implementing (5) was examined by setting $[S_{01}, S_{02}, S_{03}, S_{04}, S_{10}, S_{20}, S_{30}, S_{40}] = [1, 0, 0, 0, 0, 0, 0, 0]$ showing that the CC scheme at the substation communicates with plant #1. This is an alternative to (7) (and forms DC2) where, one chosen ROR plant (say plant #1) is the leader, while other units are followers. A qualitative comparison of CC, DC1 and DC2 relevant to this work is provided in table II.

The adjacent wind farm has not been considered in the CC or DC schemes as the ownership of the wind farms and ROR units is different. Also, to have consensus between controllable and uncontrollable resources will need further investigation.

However, the impacts of its participation of the wind farm with PFR has been examined in the following section.

III. Results

The system in Fig. 1 is simulated with a wind ramp as produced by section II-B. In simulation 1 we look at the effects of combining governor PFR with DC, while in simulation 2 we look at the effect of combining governor PFR with DC1 and CC. The wind ramp is applied at 10s for both simulations. Also, the wind farm does not participate in CC or DC1 (only PFR).

A. Simulation 1: Effect of combining hydrogovernor PFR response with cooperative control (PFR+DC1)

The results of this case are shown in Fig. 3. Here, baseline represents without DC1. Three identical slower units are naturally in consensus, given similar initialization and capacity, and are represented by the bold solid line on Fig. 3. It can be clearly seen that, the DC strategy reduces frequency peak with or without PFR response from the wind farm (WF). Additionally, the following observations can be made:

- Without WF PFR: Initially during t ∈ [0 25] there is strong consensus which helps arrest the frequency peak at a lower value. However, at t=25s, DC1 saturates and allows the PFR to dominate. Around 60s, DC1 is reactivated and redistributes the response of the generators to form consensus while a larger frequency error exists due to the prevented gate movement.
- With WF PFR: PFR response from the WF is characterized to be much faster than that from the hydrogovernors. With WF participating in frequency response, required response from the hydro plants is reduced, thereby preventing DC1 from saturating and consensus is maintained throughout. With DC1 the frequency peak is lower. Including DC1 reduces gate movement from faster hydro units.

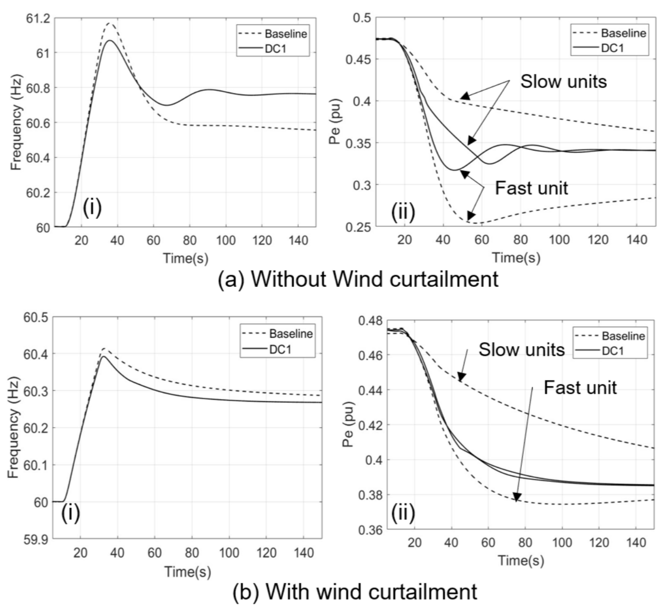


Fig. 3: Simulation results displaying baseline (PFR only) and the effect of DC1 (or PFR + DC1) from (a) ROR hydropower plants only (b) wind farm (PFR only) and hydrogovernors

B. Simulation 2: Effect of combining hydro PFR response and centralized control with cooperative control (PFR+CC+DC1) and (PFR+CC+DC2)

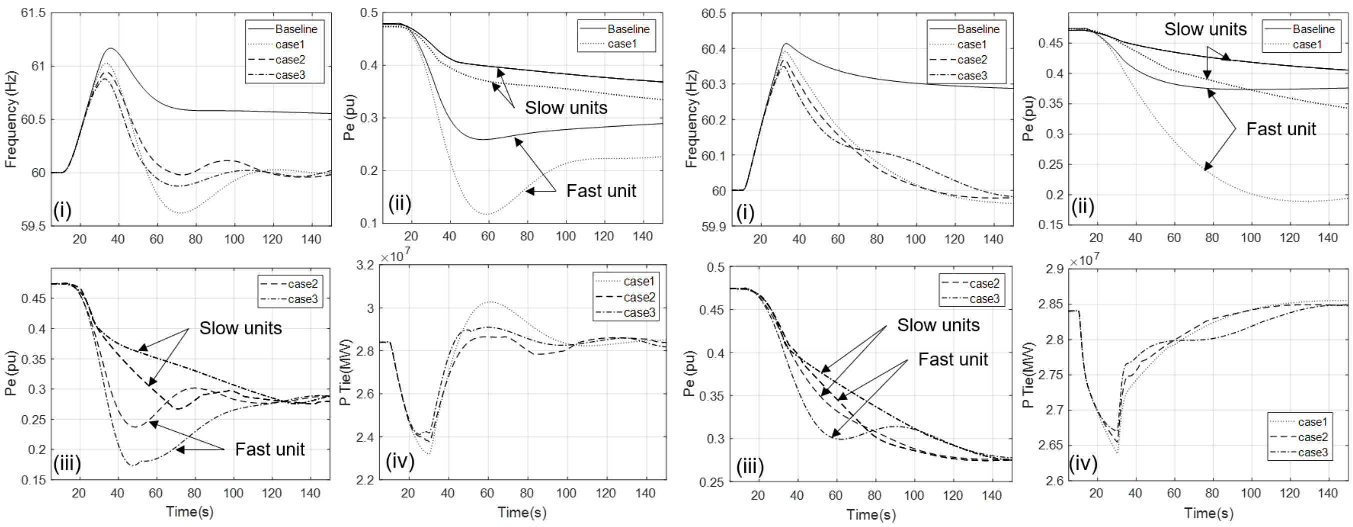
To understand the effectiveness of combining PFR, CC, and DC, four cases are constructed as follows; baseline: PFR only, case1: PFR + CC, case2: PFR + CC + DC1, and finally, case3: PFR + CC + DC2. Case 3 considers unit4 as the leader and receiving CC communication. To view the effect of primary control of the wind farm, all 4 cases are repeated with wind and without wind. The main observations in the simulation results as shown in fig. 4 can be described as follows:

- Without WF PFR: With the application of every layer of additional control (CC, CC+DC), frequency peak is reduced as can be seen in Fig. 4(a)(i). This clearly shows that with external control, the response of existing plants can be enhanced to support system frequency. Additionally, the DC strategies aid in distributing the CC response by assimilating the behavior of 4 units for the CC, which reduces the need for individual plant feedback for the CC scheme.

  The CC as expected would bring down the steady-state frequency. However, the inclusion of the CC also demands extra response which produces frequency oscillations, and excessive gate movement especially for the faster unit. When the DC1 or DC2 strategy is used alongside the CC, the oscillations are reduced, frequency peak is reduced and governor action of the faster unit is reduced. The inclusion of DC also results in smoother tie-line power flow profile. In case2 and case3, the DC algorithm reduces gate movement of fast units as in Fig. 4(a)(iii).
- With wind farm PFR: With PFR response from the wind farm the frequency peak is reduced further as expected for every case. Similar to without wind, here we see the reduced governor action from the faster unit. The response to case3 is different compared to that for case2. The stronger response from unit4 in case3 is mostly because CC is connected to unit4 only and the frequency and tie-line deviation is severe that CC dominates DC. However, compared to case1, the governor action is lower.

IV. Conclusions

As renewable penetration increases, frequency response from hydropower units gains even more importance. This paper investigates the ability of external controls to improve frequency response of a hydro unit cluster while reducing governor action (in turn reducing governor wear and sudden water level deviation). It was observed that with the help of an external centralized control strategy (similar to commonly used AGC), frequency response could be improved but the faster



(a) Without Wind curtailment (b) With wind curtailment

Fig. 4: Simulation results displaying baseline: PFR only, case1: PFR + CC, case2: PFR + CC + DC1, case3: PFR + CC + DC2 where only unit4 is the leader and receives the CC commands.

units would absorb most of the generated power command. This mainly arises from the fact that this centralized scheme is unaware of whether the divided power signals are being followed accurately by the participating plants or not. As such, another consensus protocol based distributed control scheme is used to allow balance the real power sharing between slow and fast units during dynamic response periods. It was observed that this unifies the behavior of units. As a result, this allows the decrease and increase in response of faster and slower units, respectively, if the communication weights are properly selected. Further, it was observed that the leader follower scheme could also effectively reduce the frequency peak but since the leader was chosen to be the faster unit, the action of the faster unit is greatly increased.

References

[1] D. Valentín, A. Presas, M. Egusquiza, J.-L. Drommi, and C. Valero, "Benefits of battery hybridization in hydraulic turbines. wear and tear evaluation in a kaplan prototype," *Renewable Energy*, vol. 199, pp. 35–43, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148122012927

[2] A. Juslin, "Complementing a kaplan hydropower turbine with a battery energy storage," 2021.

[3] W. Yang, P. Norrlund, L. Saarinen, J. Yang, W. Guo, and W. Zeng, "Wear and tear on hydro power turbines – influence from primary frequency control," *Renewable Energy*, vol. 87, pp. 88–95, 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148115303621

[4] T. Acker, "Iea wind task 24 integration of wind and hydropower systems; volume 1: Issues, impacts, and economics of wind and hydropower integration." [Online]. Available: https://www.osti.gov/biblio/1033033

[5] A. Fernández-Guillamón, E. Gómez-Lázaro, E. Muljadi, and Ángel Molina-García, "Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time," *Renewable and Sustainable Energy Reviews*, vol. 115, p. 109369, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032119305775

[6] N. A. E. R. Corporation, "Industry advisory: Reliability risk—interconnection frequency response (revision 1)," 2 2010.

[7] V. Gevorgian and Y. Zhang, "Wind generation participation in power system frequency response: Preprint." [Online]. Available: https://www.osti.gov/biblio/1339349

[8] J. D. Glover, M. S. Sarma, and T. Overbye, *Power system analysis & design, SI version*. Cengage Learning, 2012.

[9] M. Zeraati, M. E. Hamedani Golshan, and J. M. Guerrero, "A consensus-based cooperative control of pev battery and pv active power curtailment for voltage regulation in distribution networks," *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 670–680, 2019.

[10] G. Marasini, Z. Qu, S. Nag, and Y. Xu, "Distributed secondary control of grid-forming inverters and ac microgrids: Impacts of voltage feedback choices," in *2022 North American Power Symposium (NAPS)*, 2022, pp. 1–6.

[11] T. Kovaltchouk, A. Blavette, J. Aubry, H. B. Ahmed, and B. Multon, "Comparison between centralized and decentralized storage energy management for direct wave energy converter farm," *IEEE Transactions on Energy Conversion*, vol. 31, no. 3, pp. 1051–1058, 2016.

[12] S. Shafiul Alam, R. Bhattarai, T. Hussain, V. Gevorgian, S. Shah, Y. Velaga, M. Roberts, T. Mosier, J. Alzamora, B. Jenkins, and P. Koralewicz, "Enhancing Local Grid Resilience with Small Hydropower Hybrids: Proving the concept through demonstration, simulation, and analysis with Idaho Falls Power," Tech. Rep. INL/RPT-22-69038-Rev000, 1891110, Sep. 2022. [Online]. Available: https://www.osti.gov/servlets/purl/1891110/

[13] A. Banerjee, S. M. S. Alam, T. M. Mosier, and J. Undrill, "Modeling a Bulb-Style Kaplan Unit Hydrogovernor and Turbine in Mathworks-Simulink and RTDS-RSCAD," in *2022 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*. New Orleans, LA, USA: IEEE, Apr. 2022, pp. 1–5. [Online]. Available: https://ieeexplore.ieee.org/document/9816952/

[14] Powerworld. Governor model: Pidgov and pidgovd. [Online]. Available: https://www.powerworld.com

[15] I. F. Power. Generation power statistics. [Online]. Available: https://www.ifpower.org/about-us/generation-power-statistics

[16] "Floris wake modeling wind farm controls — floris." [Online]. Available: https://nrel.github.io/floris/intro.html

[17] Z. Qu, "Cooperative Control of Linear Systems," in *Cooperative Control of Dynamical Systems: Applications to Autonomous Vehicles*. London: Springer London, 2009, pp. 195–252. [Online]. Available: https://doi.org/10.1007/978-1-84882-325-9_5