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Abstract: Electricity generated by Hydropower Plants (HPPs) contributes a considerable portion of bulk electricity generation and delivers it with a low carbon footprint. In fact, HPP electricity generation provides the largest share from renewable energy resources, which includes solar and wind energy. The increasing penetration of wind and solar penetration leads to a lowered inertia in the grid and hence poses stability challenges. In recent years, breakthrough in energy storage technologies have demonstrated the economic and technical feasibility of extensive deployments in power grids. Multiple ROR HPPs if integrated with scalable, multi time-step energy storage so that the total output can be controlled. Although, the size of a single energy storage is far smaller than that of a typical reservoir, cohesively managing multiple sets of energy storage distributed in different locations is proposed. The ratings of storages and multiple ROR HPPs approximately equals the rating of a large, conventional HPP. The challenges associated with the system architecture and operation are described. Energy storage technologies such as supercapacitors, flywheels, batteries etc. can function as a dispatchable synthetic reservoir with a scalable size of energy storage will be integrated. Supercapacitors, flywheels, and battery are chosen to provide fast, medium, and slow responses to support grid requirements. Various dynamic and transient power grid conditions are simulated and performances of integrated ROR HPPs with energy storage is provided. The end goal of this research is to investigate the inertial equivalence of a large, conventional HPP with a unique set of multiple ROR HPPs and optimally rated energy storage systems.

Keywords: Hydroelectric generation, Run-Of-the-River, Energy Storage Systems,

I. Introduction

The technology and deployment of Run-Of-the-River (ROR) Hydropower Plants (HPP) is gaining interest rapidly. Categorization of HPPs is typically done based on the installed capacity, head, flow, and machinery type. One of the preferred criteria being installed capacity as it holistically determines most other independent factors that contribute to the design of the HPPs. There is no internationally agreed ranges of what qualifies as micro, hydro, and large HPPs. The typical rating ranges of micro HPPs is less than 1 MW, of small ROR HPPs is less than 5 MW, and large hydro are rated larger than 5 MW [1]. A hydropower market report from 2014, indicates that for 2011 through 2013, approximately 7.1% of electricity generation in the United States came from utilizing hydro resources. Additionally, 65,500 MW of untapped hydro resources exist in the U.S., indicating the scope of future HPP development and deployment. In Europe and Asia, there are comparable untapped hydro resources that have mini and small hydropower characteristics.

The growth rate of constructing HPPs as observed in Asian countries is much higher as compared to the U.S. and Europe.

HPPs have several advantages that can be classified as technical, social, and environmental benefits. A specific type of hydropower technology - small ROR HPPs can be defined in several different configurations. One of the most commonly used definition is that small ROR HPPs have small to no water storage and civil construction, if any, works to simply route water from the river into the plant itself. There is no dam-like structure to hold and store water that can utilized for providing varying and controlled input to the generator based on load demands [2], [3]. This implies very limited to no scope for speed and frequency control. The ratings of small hydropower are typically in the range of 10 MW and lower. With other subcategories of mini hydro (less than 2 MW) and micro hydro (less than 500 kW) [4]. This makes interconnections of the ROR HPPs with electric grids an interesting challenge. ROR HPPs are typically located and intended to be connected to remote community grids. Such type of grids can be typically classified as 'weak grids' as they do not have large robust generators to provide typical stiffness. This serves as one of the important design consideration to determine the configuration of the hydropower plant to enhance the suitability of the application. Advantages of small ROR HPPs are low maintenance, robust design and structures, long life, rural electrification, and low environmental impacts.

The turbines utilized for different HPP projects can be classified using numerous criteria. One of the commonly used classification is based on the water head required for optimal operation. The types of turbines under this can be: high-head, medium-head, and low-head. Another classification of turbines is based on the principle of operation and design i.e., Pelton, Francis, Axial Flow, and Crossflow. These turbine types are suitable for application in certain ranges of head and flow at the site that can be assessed through site inspections and designs [3]. These turbines are currently used in innovative ways individually or in combinations to generate electricity. A critical gap that still exists in small HPPs is the optimal sizing of turbine ratings for any site. In fact, this is rigorously treated as a site specific assessment and tends to be a time consuming process. Without a formal technique to determine combinations of turbines and its ratings this is identified as a critical gap. In [3], the authors have given a very unique perspective that differential in the power rating of turbines for small HPPs has a wider and far-reaching advantages. Authors have demonstrated that these advantages are in terms of both economics and energy production within a given set of practical set of constraints. They have also demonstrated that the size ratio of the different turbines at the same site can provide an optimal technical and economical return if their ratings are in the ratio of 0.4 to 0.5.

One of the biggest challenges facing the widespread adoption of small and micro HPPs is the low degree of standardization in configurations, equipment, designs, civil works, etc. This leads to higher costs of HPP related projects as each one is treated as unique project. Although, it should be noted that not all instances of new HPPs under the small stream development are accounted as non-powered dams without any standardization. However, a significant level of standardization can be targeted and achieved with the small ROR HPPs. Second challenge regarding the technical abilities of small, mini, and micro HPPs is the configurations that are based on synchronous machines. This allows a fixed speed operation corresponding to either 50 or 60 Hz power output. In the current scenarios of increasing variability of renewable energy in the power grids, fixed speed operation of generators is not always the most optimal way of operating generators [5]. Especially HPPs with their unique resource with advanced control systems can provide support and assimilate this variability [6]–[8]. Additionally, there has been a tremendous change in the magnitude and pattern of load consumption. These factors have necessitated studies that are necessary for the determination of changes in ramping reserves requirements [9], [10]. Another technique, for providing support to the grid on account of such dynamic conditions of renewable generation and loads, is by deploying extensive storage systems [11]–[14].

In [15], for a small ROR HPP an adaptive design of a proportional-integration controller and parameterization is discussed. The authors provide an optimization of design parameters based on practical constraints of a small ROR HPP that has a controlled diversion to control water input. The typical control strategy adopted by the ROR HPP designs is to track optimally the water head, due to lack of speed control. A typical technique of managing power output from small ROR HPPs is the utilization of dump loads or controlled loads. Excess power is dumped into these to avoid over-frequency type situations. A novel technique of including automatic generation control for isolated small RORs based on servo motor controls to manage inlet water is discussed in [16]. However, this technique involves the operation of control valves that manage inlet water which may not be the cases with all HPPs. The authors have provided dynamic and transient and responses of this proposed control systems of the small ROR HPP.

The basic reason that small and micro ROR HPPs need a sophistication in controls is the lack of communication between grid management systems and lack of controls to respond to any signals thereof. In this paper, we propose to integrate a diverse set of storage systems with small ROR HPPs in order to provide an enhanced response to grid events. The selection of the storage systems is provided in the next section. In section 3, real-time simulations and integration of storage systems with the operation of ROR HPPs is explained. Section 4 summarizes the real-time simulation results and the transient and dynamic response of the coordinated operation of the ROR HPP and storage units. Concluding remarks and future work is the final section.

II. Integration of Run-Of-the-River and Energy Storage

Proposed architecture and controls are novel with multiple ROR HPPs integrated with Energy Storage Systems (ESS). The assessments and results provided here based on a generic set of energy storage technologies i.e., supercapacitors, flywheels, and batteries with heuristically assumed ratings. The device characteristics and capabilities form the logical reasoning of choosing them for integration with the ROR HPP [14]. This will provide the audience a better insight regarding the proposed system architecture. Commonly observed dynamic and transient events in power grids are presented with the responses of conventional generators.

The ultimate goal of this project is to investigate the possibility of integrating the small non-powered dams in an area to cohesively operate as a single large HPP and provide the typical grid services of a large HPP to the power grid. The infrastructure of interconnected ROR HPPs offers a scalable, cost-effective, and environment-friendly technological pathway to implement the benefits of a large hydropower plant. ROR HPPs are designed to integrate a large number of smaller, cascading HPPs across multiple time scales and operational capacities. A control layer needs to be implemented to supervise the operation of the interconnected ROR HPPs and make them operate cohesively in synchronism. A schematic of the proposed architecture of the integration of ROR HPP and ESS is shown in Figure 1.

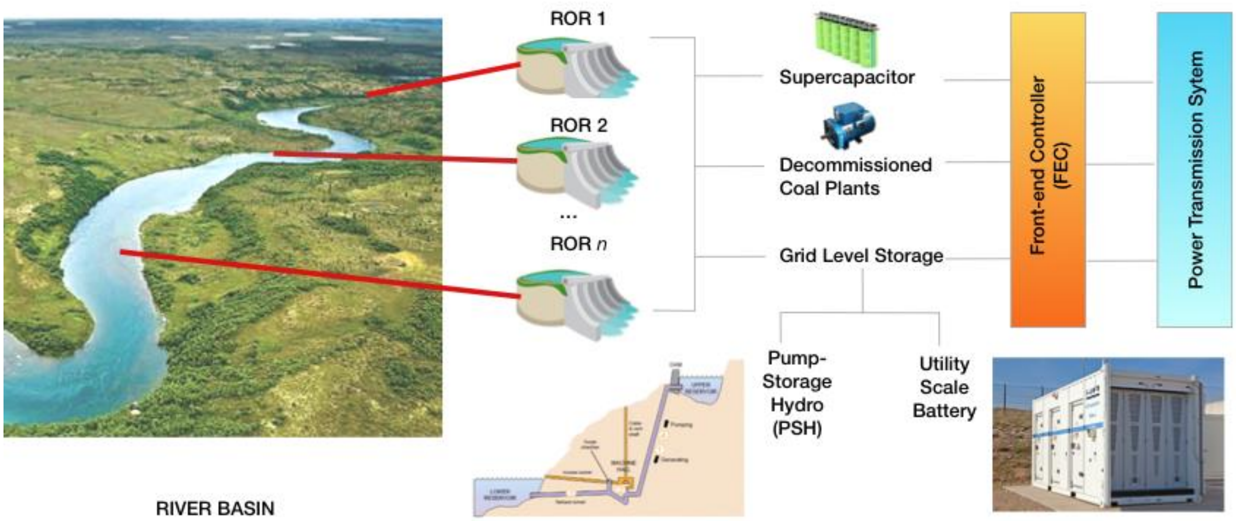

Figure 1 Proposed architecture to enhance the capabilities of ROR HPPs to provide grid services

This manuscript summarizes a part of the effort of a project that approaches the problem by developing an ESS with an interface with the electric grid using power electronics-based advanced controls. This advanced controls will interact with the multiple ROR HPPs and the individual ESS components to optimize their individual operation, leading to an optimal cumulative performance. The ESS comprises of a supercapacitor and flywheel for providing fast response to stabilize the grid with battery for a longer response. The advanced controls will serve as an interface between utility signals and control systems of the power grid equipment. Proximally located rotating machinery of decommissioned coal-fired plants can be integrated with the ESS for injecting additional inertia in the power system to provide the flywheel effect. The addition of flywheel effect leads to increased inertia in the grid, which helps assimilation of greater renewable energy penetration. Additionally, the cost of refurbishing existing, decommissioned coal plants may be an economically optimal solution over connecting new flywheel projects. This paper leverages the Digital Real Time Simulators (DRTS) infrastructure in multiple national laboratories connected via a high-fidelity communication link and advanced technologies in control systems and systems integration to demonstrate the combined operation of ROR HPP and ESS. When successfully implemented, the outcomes of the project will serve to advance the state of the art, by expanding the range of applications of ROR HPPs in the ancillary services market. Proposed approach here deals with augmenting the existing speed control capabilities or adding it in cases of lack of it. Figures 2 through 4 show the typical responses of battery, flywheel, and supercapacitor in real-time simulations. This provides us with an insight into the individual ramping capabilities of these energy storage technologies. In essence, the battery is regarded as an energy dense technology that can provide energy for a prolonged time. Supercapacitors and flywheels are considered as power dense technologies that can provide quick bursts of energy.

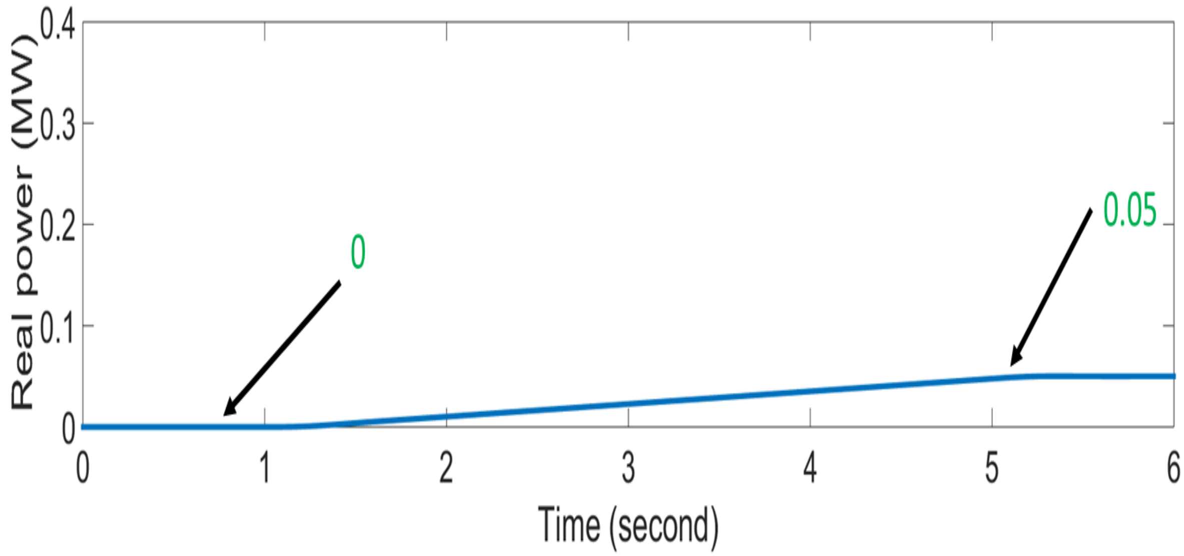

Figure 2: Sample battery power output in real time simulations

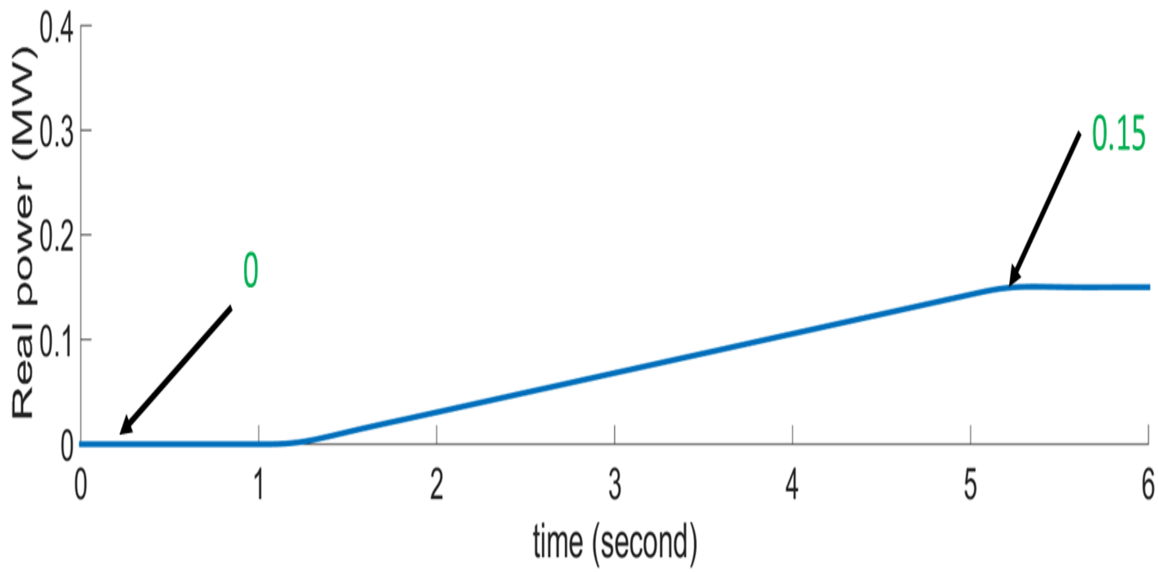

Figure 3 Sample flywheel power output in real time simulations

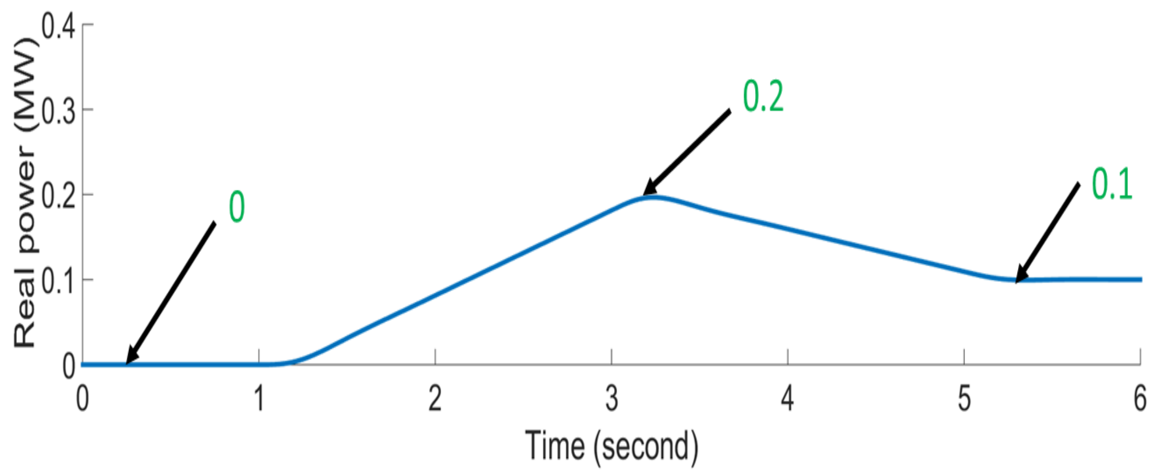

Figure 4 Sample supercapcitor power output in real time simulations

III. Real-time Simulations and Results

A real-time simulation is used as the test set up with the simulation time step of 50 microseconds. DRTS are used for performing real-time simulations of power and energy systems to understand the dynamics and transients. At the core of the DRTS is an electromagnetic transient program that performs the majority of simulations and provides system level rseponses. A circuit breaker at the Point of Common Coupling (PCC) connects local distribution system integrated with ROR to the transmission bus. This connection represents the connection with the rest of the power grid. Within the distribution system, there is a 30 MW diesel generator that provides for a significant portion of the loads. It can provide sufficient inertia to the system during islanded mode at a high cost. An ROR HPP with 15 MW capacity is also connected to this distribution system. With the ROR HPP, ESS is also installed to provide added source of instantaneous capacity and ramping capability. In the distribution network, a maximum load consumption of 20 MW is modeled. A 69 kV distribution bus connects diesel generation, ROR HPP, load and PCC circuit breaker (PCC CB) together as shown in Figure 5. Following test case scenarios are simulated:

Test case 1: Typical operation of the ROR HPP without any external integration with ESS is simulated. Power output of the ROR HPP is shown in Figure 6.

Test cases 2 and 3: A three phase balance fault is simulated in the system for the duration of 0.088 seconds, which is typical of a real world event. ESS rapidly discharges to provide extra power to the system to ensure stability. An integrated power output of ROR HPP and ESS is shown in Figure 7. Comparisons of frequency response of ROR HPP and ROR HPP with ESS are shown in Figure 8. The power output of the ESS for this event in the power grid is shown in Figure 9.

Test cases 4 and 5: A step load of 0.5 MW is applied to the system abruptly. At the beginning, ESS quickly discharges to provide inertia to the system, then its generation stays at 0.12 MW to share part of the power supply for the newly added load. Results of the real-time simulation results of power output of ESS are shown in Figure 12 to stabilize the grid.

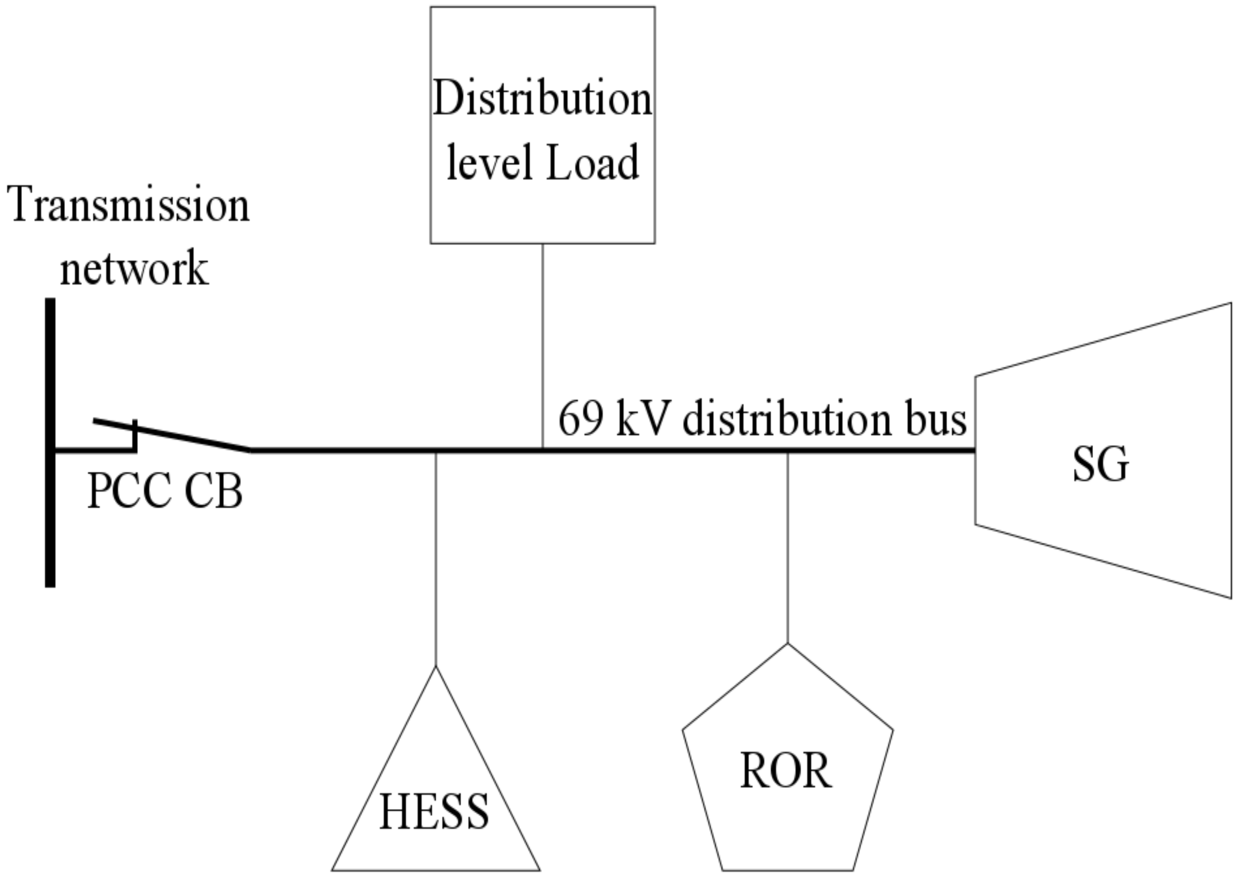

Figure 5 Schematic of the connection of ROR HPP and HESS in a distribution bus to serve loads

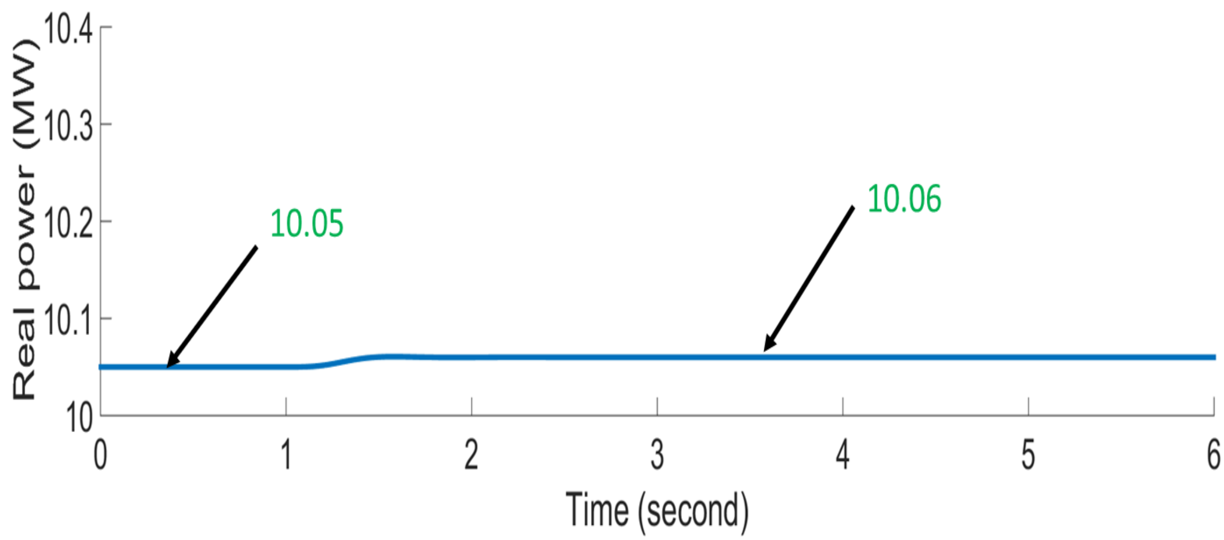

Figure 6: Typical output of ROR HPP described as case 1

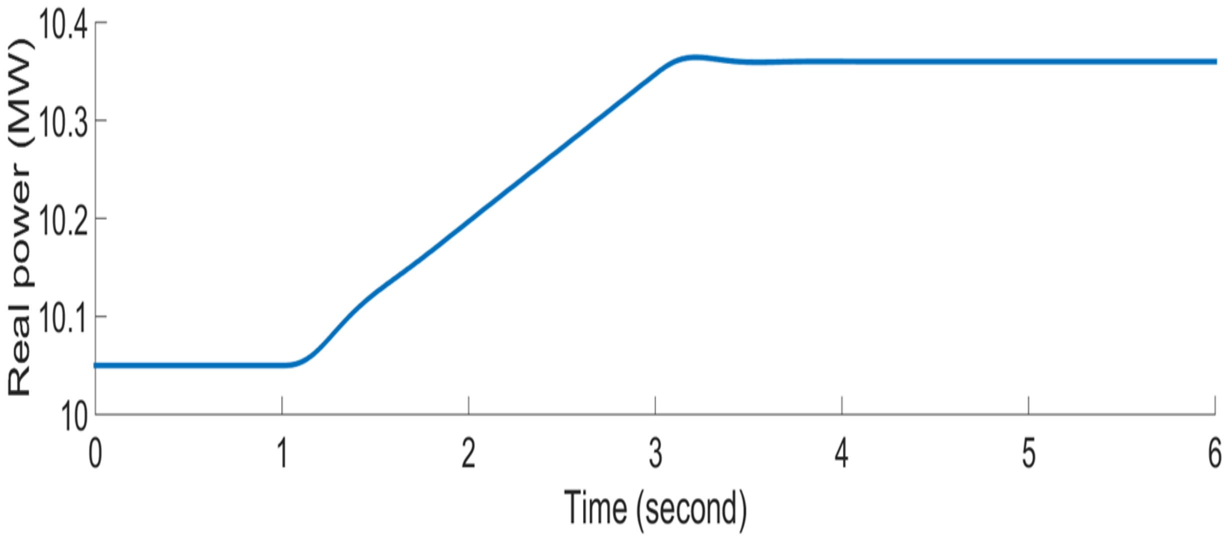

Figure 7 Total combined generation of ROR HPP and ESS for case 2

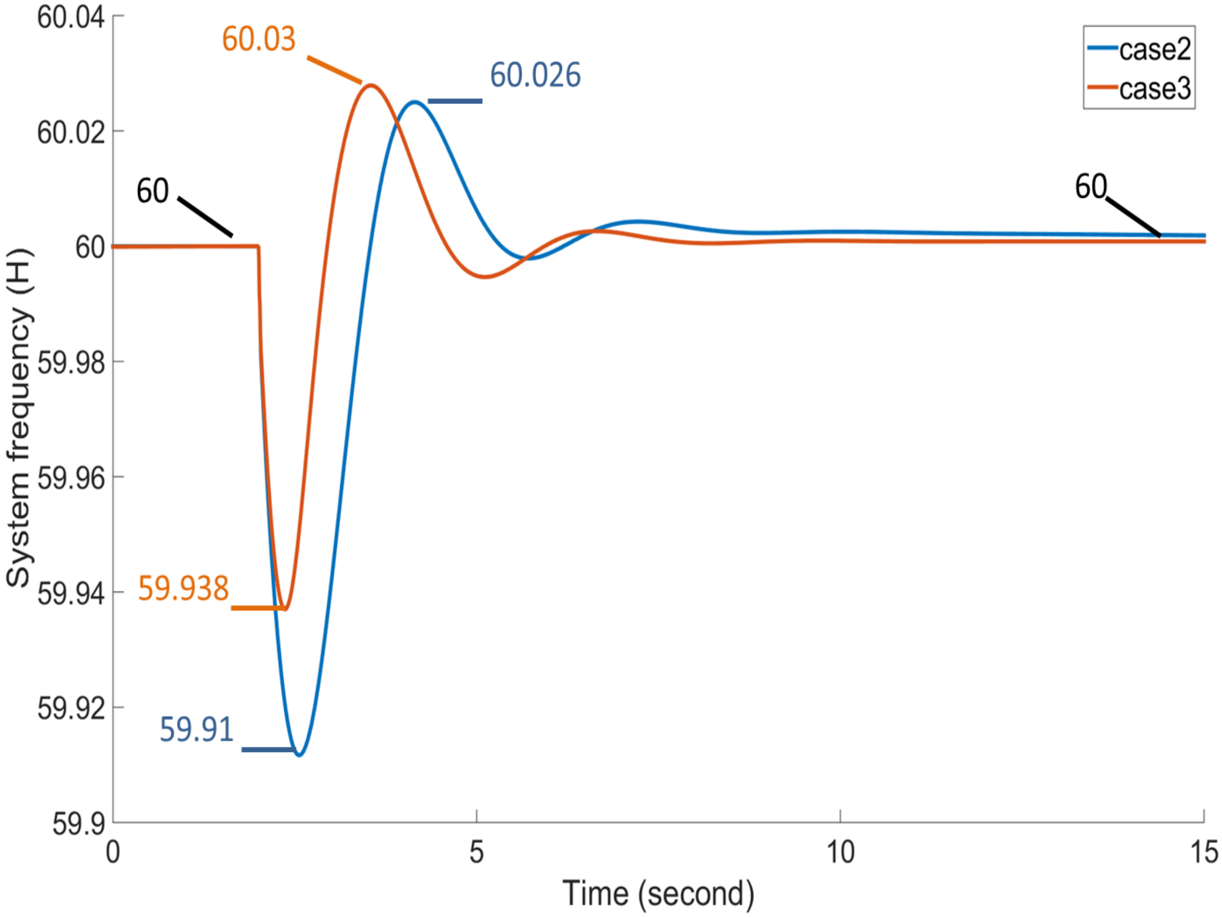

Figure 8 Frequency comparison between case 2 of ROR output without ESS and case 3 of ROR output with ESS for the three-phase fault

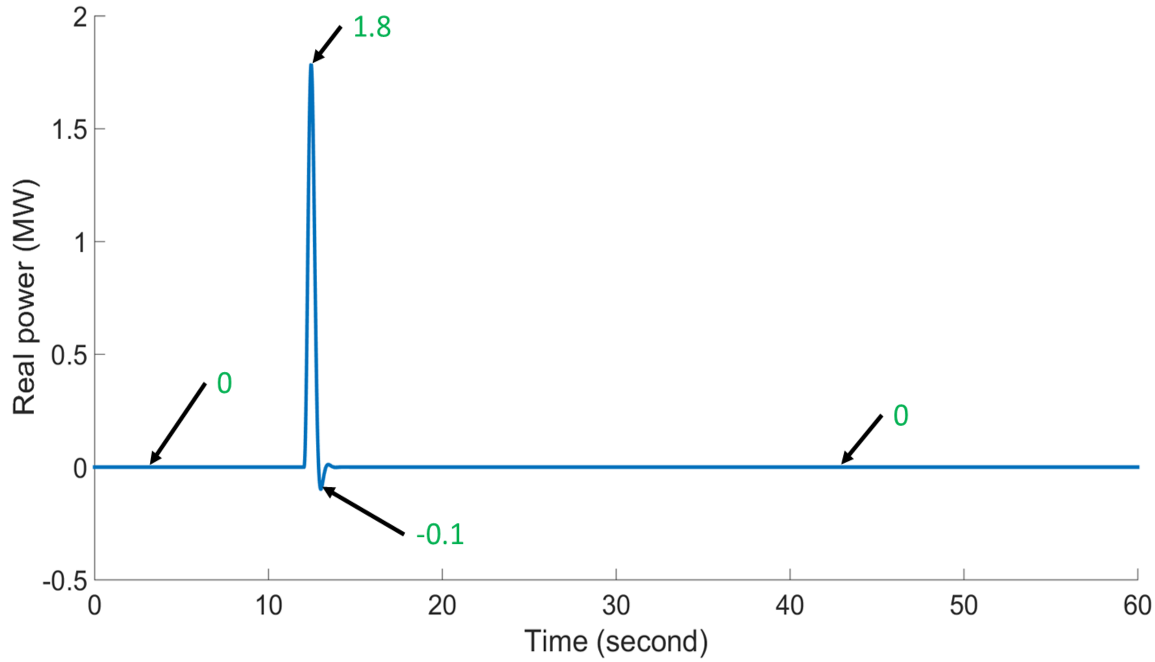

Figure 9 ESS power output for the simulation case 3 of fault in the distribution network

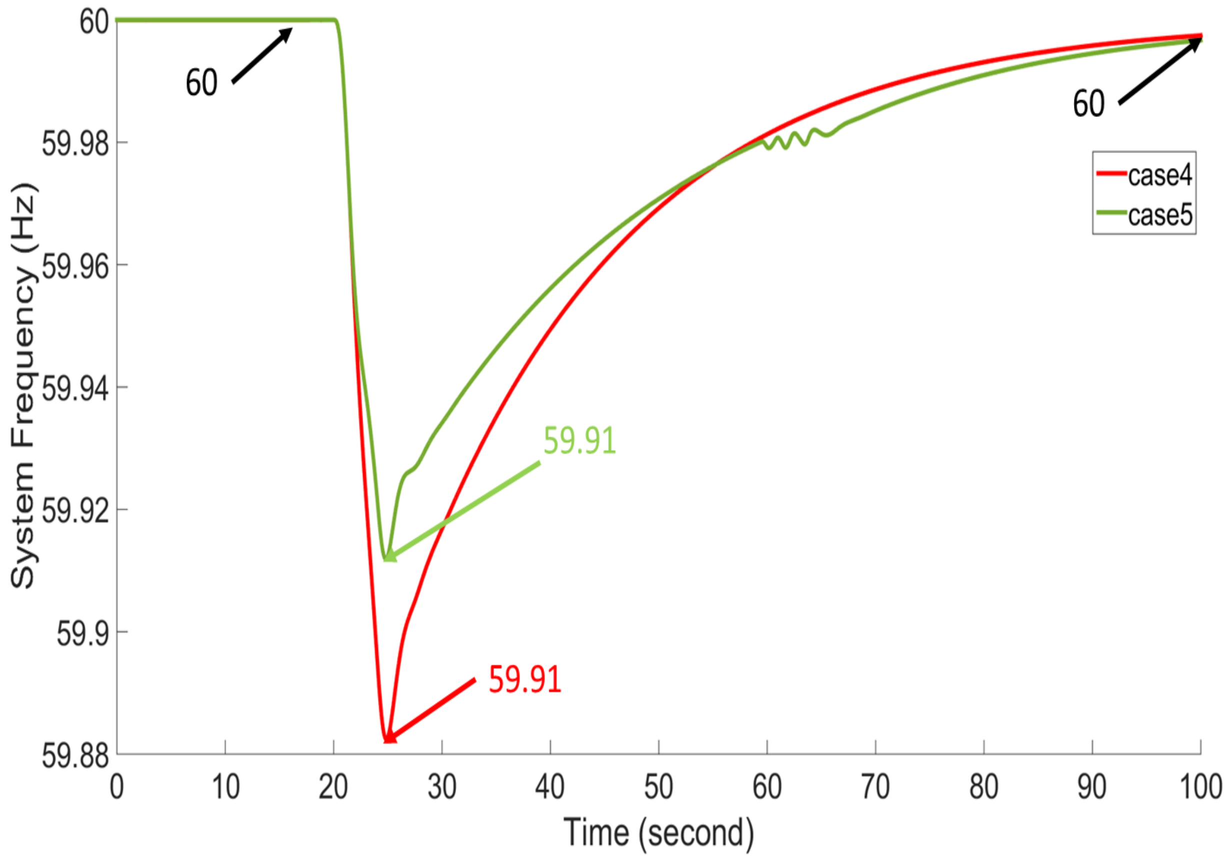

Figure 10 Frequency comparison between case 3 add load without ESS and case 4 add load with ESS

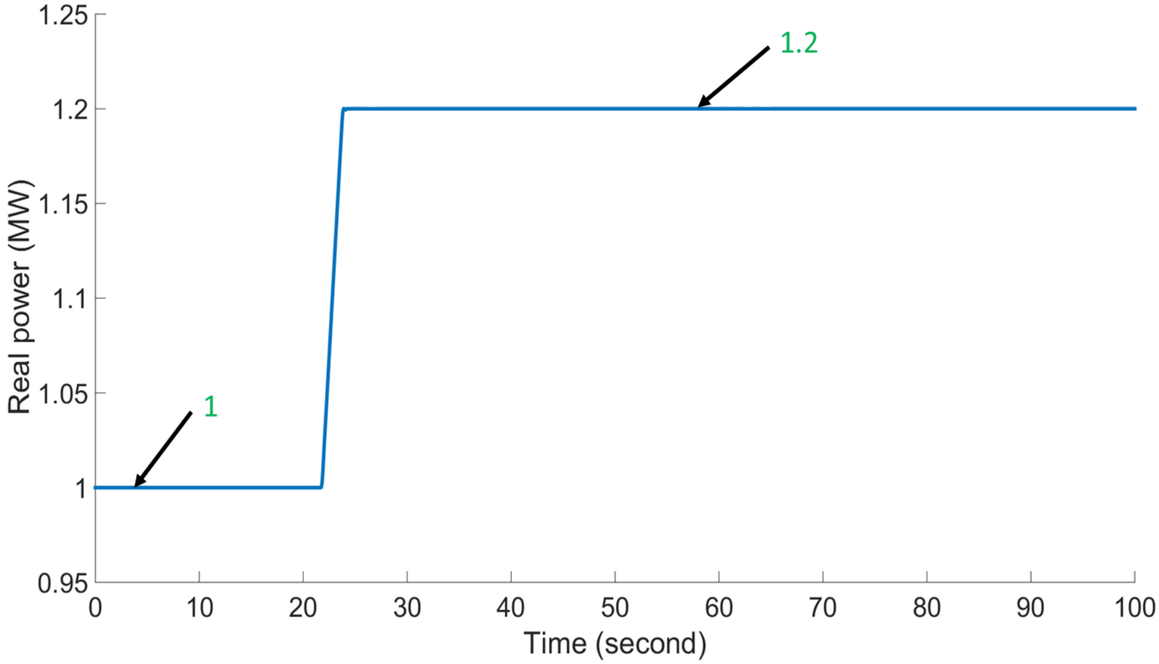

Figure 11 ROR turbine output in case 3 and 4

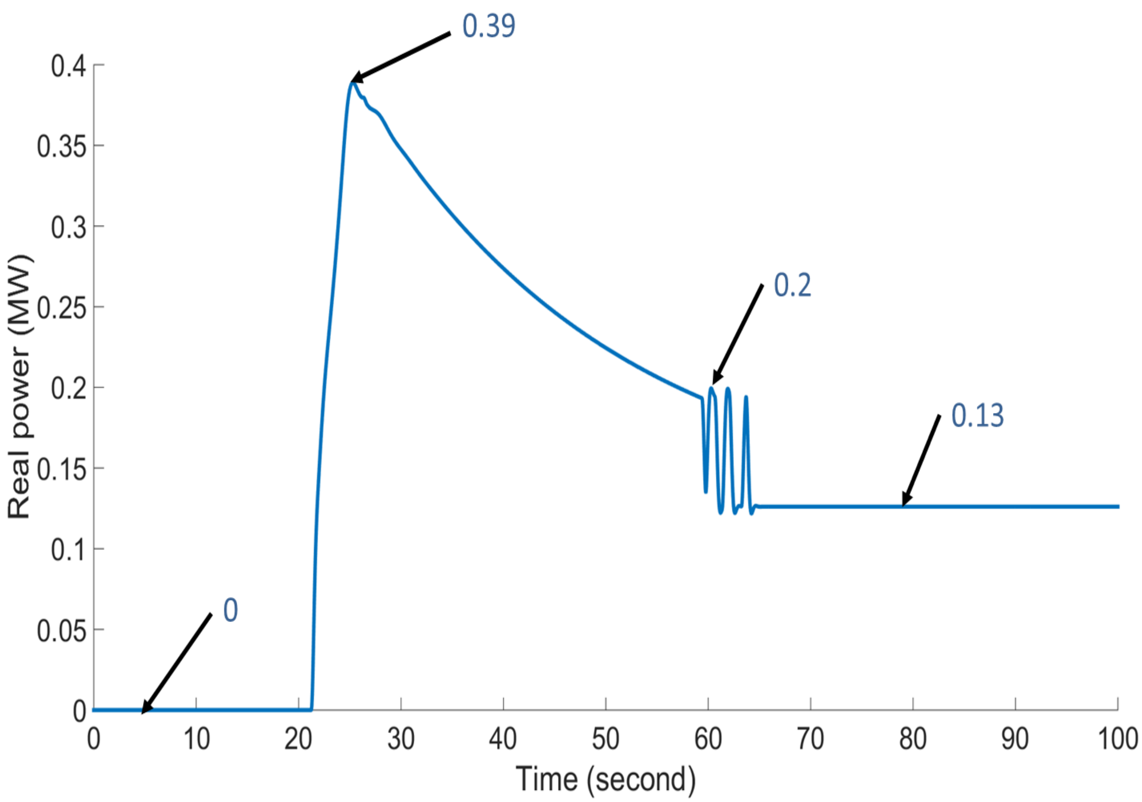

Figure 12 ESS power output for the case 4 of adding the step load to provide stability

IV. Concluding Remarks and Future Work

A unique application of integrating energy storage technologies of varying characteristics with run-of-the-river hydropower plants is proposed in this paper. Results demonstrating the usefulness of the proposed approach with ROR and ESS integration based on several grid scenarios is verified in real-time simulations. Without the loss of any energy, as in the case of dump loads for speed control, desired power output variations from the ROR can be ensured. The dynamic and transient response of the coordinated output of the ROR and ESS is also shown to have a stable impact in the system. Cases simulated include step load changes and typical faults in power grids to assess the performance of the ROR integrated with ESS. A superior performance and enhanced system stability is observed with integrated ROR and ESS. Future work involves the integration and coordination of multiple ROR HPPs on a single basin, real-time simulation of flows, and cohesive operation with performance assessment for the next level study. To ensure higher accuracy, controller-hardware-in-the-loop of the control systems that ensure the coordinated response of ROR and ESS will also be performed. Cases of lowered inertia in power grids with renewable energy will be highlighted to foster the importance of the proposed work. This paper provides a systematic overview of managing power grids under such challenging conditions.

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VI. Appendix

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