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# Enhancing the Flexibility of Generation of Run-Of-the-River Hydro Power Plants

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**Abstract:** Run-Of-the-River Hydro Power Plants (ROR HPPs) have been excluded from participating in Ancillary Services (AS) market for decades due to lack of flexible power adjustment. With cutting edge power electronics devices and energy storages, ROR HPPs can be equipped with greater inertia capability and hence contributing to frequency stability. In this paper, an optimal operational strategy is presented. It can coordinate output from various types of energy storages. Test results show combining coordinated output from energy storages can ensure rapid and sustainable supply of AS. Therefore the revenue source of ROR HPPs can be expanded, by participating in the AS market that was traditionally not feasible.

## 1 Introduction

Hydro power plants convert kinetic energy of water flow to electrical energy using a turbine-generator assembly. In the mid-west area of United States, Run-Of-the-River Hydro Power Plants (ROR HPPs) have a significant untapped potential and is approximately estimated 55 GW based on prior research. Unlike conventional hydro power plants, ROR HPPs do not require the construction of reservoir, therefore they are deemed to have lower impact on the surrounding ecosystem and environment [1]. Traditionally, due to the lack of water storage, generation output from ROR HPPs depends on the natural water flow. Therefore traditionally ROR HPPs cannot provide frequency stability which requires fast and accurate adjustment of power generation according to the dynamical load changes. ROR HPPs are only able to participate in the low-profit fundamental energy market, in which ROR-HPP operators sell forecasted generation at a fixed amount in advance. In the past two decades, research work showed that applying advanced power electronics technique such as Doubly-Fed-Induction-Generator (DFIG) to ROR HPP can maximize the efficiency of converting hydropower to electricity power with low upgrade cost. Furthermore, inertia capability of HPPs can also be enhanced by coupling with energy storage. HPP adds significant rotational inertia to the grids that enables stability and resilience of the power grids. However, the challenge of relatively flat revenue source for ROR HPP is unaltered, since the drawback of insufficient flexibility of generation still exists in DFIG. For the past few years, due to the increased penetration of Renewable Energy Sources (RESs) in power grid, total equivalent inertia has decreased[2]. Maintaining frequency stability has become a more severe challenge. RESs are being expected to provide frequency support as observed in numerous instances. A promising solution to enable ROR HPPs support frequency stability is to integrate Energy Storages (ES) with ROR HPPs [3]. ES functions as synthetic energy reservoirs that can be utilized based on grid needs. ES discharges can be programmed and controlled according to the command of system operators maintaining system stability.

In order to enable ROR HPPs participation in the Ancillary Service (AS) market, where energy is procured to provide frequency stability, integrated ES must be capable of providing flexible and durable power supply. Based on the electrical characteristics, ES are divided into two types: power density type and energy density type [4]. Power dense type of ES feature fast ramping rate and short-term high power output. Energy dense type of ES can store much more energy than former, however they cannot rapidly adjust their output. Researchers have conducted work to characterize ES using respective hardware prototypes and commercial products, to accurately understand their electrical behavior. In [4-6], supercapacitors are labeled as power density typed energy storage whereas high capacity batteries are labeled as ES with high energy density. Flywheels ES are designed and capable of striking a desired balance between power and energy density based on requirements [4]. Methodologies for controlling various types of ES are presented. In [7], model predictive controllers are applied to control the charging/discharging of supercapacitors in supporting frequency stability. In [8], batteries are used to provide long term power supply to islanded microgrid. Based on these past research inferences, this paper proposes a holistic solution for operating Hybrid Energy Storage System (HESS) proposed in [3] in order to enable ROR HPPs the capability to participate in typical AS market.

The proposed HESS is formed by both power and energy dense ES. The power dense ES serve the purpose of rapidly responding to the generation adjustment command. Whereas the energy dense ES insure the sustainable fulfillment of energy demands over longer durations. Critical challenges in HESS development are deciding the assignment to each type of ES and coordinating output from them. It is expected to provide sufficient power supply at the minimum cost as a function of the installed capacity of ES. Six operational scenarios covering all operation conditions by the integration of ROR HPP and the HESS are presented and discussed. In each operational scenario, the expected operation mode for each type of ES is elaborated and results are presented. Multiple ROR HPPs integrated with HESS controlled by the proposed strategy, are demonstrated to cohesively provide support to frequency stability similar to that of a conventional hydro power plant.

## 2 System Description

Figure 1 shows the framework of the system within which integrated ROR HPPs and HESS are operated. Generation units within the ROR HPP include power electronics interfaced hydro generator driven by water turbine, ES such as supercapacitors, flywheels, and batteries. The total output is expressed in Eq. (1):

$$P_{ror} = P_{gen} + P_{sc} + P_{bt} + P_{fw} \tag{1}$$

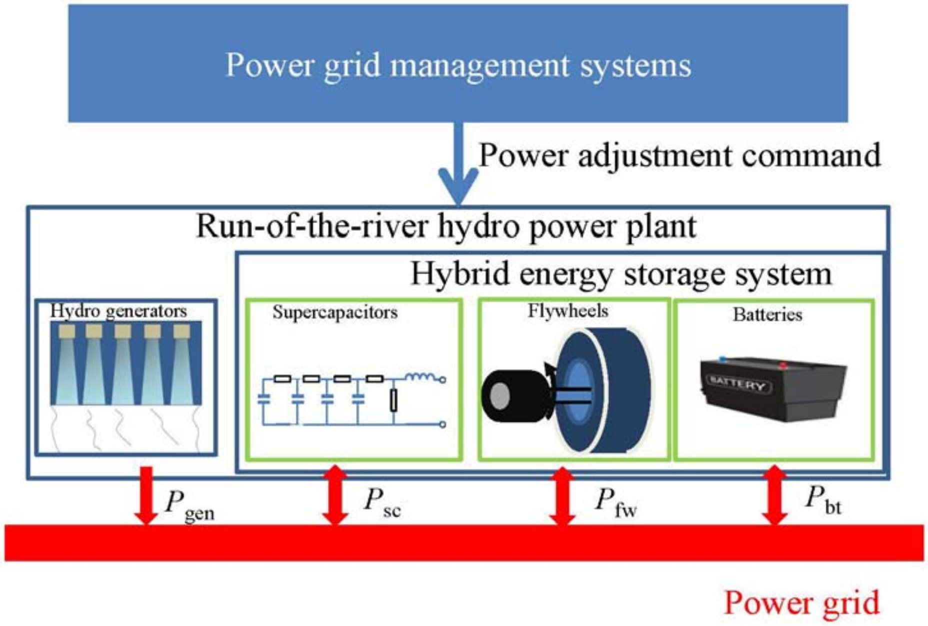


**Figure 1 System framework with the integrated ROR HPP and HESS to demonstrate the AS market participation**

Where $P_{ror}$ is the total generation output from ROR HPP. It is expected to closely track the generation command signal sent from system operators. $P_{gen}$ is the output from induction generator and is always positive. $P_{sc}$, $P_{bt}$, and $P_{fw}$ represents the output from supercapacitors, batteries, and flywheels respectively. They can be either positive or negative. Positive means discharging and negative means charging their aggregated power output is the performance of HESS. When ROR HPPs participate in both energy market and AS market, the generation reference signal $P_{ref}$ tracked by $P_{ror}$ can be divided into two parts: demand from energy market $P_{em}$ and fulfillment of demand AS market $P_{asm}$, as shown in Eq. (2):

$$P_{ref} = P_{em} + P_{asm} \tag{2}$$

The former is decided based on the forecasting of water flow and agreement with customer in advance. The latter is computed by system operators according to the real time condition of system frequency and balance between generation supply and load demand. Since ROR HPPs have participated in energy market for decades, scheduling and controlling of generation to serve the energy market have been maturely developed. In this work, we focus on the optimization of contribution from ROR HPPs integrated with HESS to participate in the AS market. System operators managing AS market send commands to generation unit in the form of generation adjustment $\Delta P$ in every four seconds. The adjustment from generation units is expected to reach this reference adjustment as quickly as possible. The ramping rate of generation units is critical to meet this requirement. Eq. (3) shows the mathematical expression for this problem:

$$t_{settle} = \frac{\Delta P}{r} \tag{3}$$

$t_{settle}$ is the longest time allowed for AS provider to reach the desired adjustment, $r$ is the ramping rate of a generation unit. The faster the $r$, the shorter time the generation unit take to adjust generation. In the proposed solution, we employ energy storage to enable the rapid power adjustment needs. Each type of ES inside the HESS can provide generation adjustment as shown in Eq. (4):

$$P_{asm} = \Delta P = \Delta P_{sc} + \Delta P_{bt} + \Delta P_{fw} \tag{4}$$

$\Delta P_{sc}$, $\Delta P_{bt}$, $\Delta P_{fw}$ are the adjustments of output from supercapacitors, batteries, and flywheels respectively. The ramping capability of the integrated ROR HPPs and HESS quickly tracking the reference depends on supercapacitors, which have as they are power dense. However, since the energy stored in supercapacitors cannot support long term high power discharging, after the total power output reaching reference signal, the control gradually shifts discharge to batteries and flywheels, which have large energy density. A holistic optimization strategy is developed to decide the optimal dispatch among various ESs under diverse operation conditions.

# 3 Optimal Operational Strategies of the HESS Integrated with ROR

## 3.1 Assumptions for developing optimal operation strategy

The rapid ramping capability is mainly provided from supercapacitors, therefore keeping the energy stored in supercapacitors close to a desired level is critical to ensure ROR HPPs sustainably participate in AS market. In this paper, an optimal operation strategy is proposed for optimally controlling charging/discharging of supercapacitors, flywheel, and battery comprising the HESS. We have used three reasonable assumptions to perform the proposed strategy:

1. Power output of the induction generator driven by hydro turbine can be accurately forecasted with tolerable error.
2. Batteries and flywheels have high energy density. With optimal sizing, their stored energy will not be depleted during the hours when AS is frequently requested from

system operators. They will recharge energy from the ROR HPP output when no AS is needed.

3. The size and maximum allowed ramping rate is properly selected. The maximum allowed energy charged/discharged from supercapacitors within a 4-second cycle can change increase the State-Of-the-Charge (SOC) up to 10%, SOC is calculated by:

$$SOC_{ES} = \frac{E_{ES}}{C_{ES}}. \tag{5}$$

$E_{ES}$ is the current amount of energy stored in ES. $C_{ES}$ is the capacity of ES. It is the maximum amount of energy that can be stored in ES.

## 3.2 Operational Guidelines and Control Aspects

Following operational guidelines were established set as the scheme for ROR HPP and HES integration:

1. ROR HPPs schedule *a %* of the total energy generated by induction generator to the energy market.
2. The difference of total forecasted generation of the ROR HPPs minus total actual generation is *b* %.
3. ROR HPPs reserve *c* % of the total generation from induction generator for charging batteries, flywheels, and supercapacitors.
4. Under all circumstances, the law of conservation of energy is followed, i.e., *a*+*b*+*c*=100%.
5. There is an optimal value for the energy stored in supercapacitors that enables significant flexibility of charging/discharging.
6. Since capability of charging/discharging supercapacitors is critical to provide AS, the energy stored in supercapacitors is expected to keep close to the optimal value.
7. According to the real time stock of energy in supercapacitors, the output from batteries and flywheels must be precisely computed. An optimal operation strategy is developed to prevent energy stored in supercapacitors from being much small/larger than optimal value and ensure the demand from AS market is fulfilled.

### 3.3 Potential Scenarios and Description

According to the initial energy storage of supercapacitors and the amount of power adjustment requested from the market, six operation scenarios are categorized. In each operational scenario, we derive an optimal operational procedure to manage each type of energy storage.

- *Scenario 1: Energy stored by supercapacitors is much higher than expected optimal value, and system operators require a power increase from the previous set point of ROR HPP. However, the required increase of power output is larger than the maximum allowed power increase from supercapacitors.*

  In this scenario, the proposed controllers of ROR HPPs and HESS have the opportunity to release energy stored in supercapacitors. The market condition coincidently offers such opportunity. In order to avoid unsupervised change of energy stored in supercapacitors, we specify for all 6 scenarios, at the beginning and ending of each operation cycle, power output of supercapacitors must be zero. In the light of this statement, there is a maximum change of the power output from supercapacitors in one cycle. In this scenario, supercapacitors discharge the maximum allowed energy. Batteries and flywheels provide the rest of the power adjustment. In order to maximize the energy discharged from supercapacitors, supercapacitors first ramp up power at the highest rate from 0. Due to the constraint that power of supercapacitors must be reduced to zero, a transition point must be computed. A transition point in this context implies an instance of ramping rate changes. For the transition point in this scenario, ramping rate change from positive constant to zero. This computation of the maximum power output duration of cycling of supercapacitors is performed during this cycle. Batteries and flywheels make up the rest part of power adjustment demand from system operator. When power output of supercapacitors reaches peak value, the discharge cycle of supercapacitors is started. The power output from batteries and flywheels continues to increase. The reduced power from supercapacitors is compensated by simultaneously increasing the power output from batteries and flywheels. Supercapacitors reduce the power at the maximum possible rate, and the power output of batteries and flywheels increasing. At the time power of supercapacitors drops to zero, total adjustment of batteries and flywheels reaches the maximum power of supercapacitors in this operation cycle.

- *Scenario 2: Energy stored by supercapacitors is much higher than expected optimal value, while system operators require a small power increase from ROR HPP, which can be accomplished by discharging of supercapacitors solely.*

  In this scenario, controllers of integrated ROR HPPs and HES are seeking opportunity to release energy from supercapacitors as well. However, since the required power increase is relatively low, supercapacitors will not adjust power to the maximum allowed value. At the beginning, only power from supercapacitors starts to ramp up. There is no change with power output from batteries and flywheels at this moment. Power from supercapacitors continues to increase till time reaches the transition point, which is the point, that the ramping rate of supercapacitors power change. Then power curve of supercapacitors becomes a flat line. Another transition point needs to be computed. When time reaches the second transition point, the supercapacitors must discharge. Meanwhile power output from batteries and flywheels starts to increase at their peak rate. The ramp up rate of combined power output from batteries and flywheels is reverse to the change rate of power from supercapacitors. When power of supercapacitors becomes zero, power from batteries and flywheels reaches the final value in this cycle.

- *Scenario 3: Supercapacitors stored energy with the amount close to optimal value, while system operators require ROR HPPs to increase power output. Batteries and flywheels are capable of fulfill the assigned task.*

  In this scenario, control system for the ROR-HPP will avoid charging or discharging the supercapacitors. If adjustment of power from batteries and flywheels can be accomplished by specified settle time mentioned in Eq. (3), power output from supercapacitors will remain at zero throughout the whole cycle. Batteries and flywheels increase output at the desired ramping rate from the beginning of this cycle. Once the combined output reaches the required set point, power output remains constant till the end of the cycle.

- *Scenario 4: Energy stored in supercapacitors is significantly below the optimal value, while system operators issue a power increase command. Batteries and flywheels are capable of fulfill the assigned task.*

In this scenario, controllers of ROR HPP and HESS are seeking opportunity to restore energy to supercapacitors. However, fulfilling task assigned by system operators gains top priority. Power output from supercapacitors is kept to zero till the combined power output from batteries and flywheels reach the required set point. Then, batteries and flywheel continue increase their output, the surplus power is absorbed by supercapacitors. The power curve of supercapacitors is triangular, because the power value must satisfy the zero value constraint at the end of this operation cycle. The power curves of batteries and flywheels during period of charging supercapacitors are also of a triangular shape.

- *Scenario 5: Energy stored in supercapacitors is close to the optimal value, while system operators issue a power increase command. Sole use of batteries and flywheel cannot fulfill the task within a required settle time.*

  In this scenario, although controllers of ROR HPP and HESS attempt to avoid charging/discharging supercapacitors, they must fulfill the power output assignment. Supercapacitors, batteries, and flywheels all start to increase their respective power output from the beginning of the cycle. Controllers of ROR HPP and HESS increase power from batteries and flywheels at the maximum ramping rate. The ramp rate of power from supercapacitors will be computed to ensure that by adding power increase from supercapacitors, total power adjustment will reach the desired set point within the computed settle time. Once the total power adjustment reaches the set point, supercapacitors start to decrease power output. This reduced rate follows the same amplitude of the maximum increase rate of the combined power output from batteries and flywheels. Once power of supercapacitors decreases to zero, combined power of flywheels and batteries remains constant as the final value of this cycle.

- *Scenario 6: Energy stored in supercapacitors is much less than the optimal value, while system operators issue a power increase command. Simply using batteries and flywheel cannot fulfill the task within a required settle time.*

  Same as scenario 5, total power adjustment must reach the assigned value within this settle time. Supercapacitors, batteries, and flywheels all start to increase power from the beginning of the cycle. Controllers of ROR HPP and HESS increase power from batteries and flywheels at the maximum ramping rate. The ramp rate of power from supercapacitors will be computed to ensure that by adding power increase from supercapacitors, total power adjustment will reach set point within the computed settle time. Once the total power adjustment reaches the set point, supercapacitors start to decrease power output. This reduced rate follows the same amplitude of the maximum increase rate of the combined power output from batteries and flywheels. If there is still sufficient time left before the end of cycle, ROR-HPPs operators inject energy to supercapacitors from batteries and flywheels. The power curves of each type of energy storages follow the triangular shape mentioned in the scenario 4.

In all of the above six scenarios, several analogous scenarios can be formulated with varying operation conditions.

## 4 Real-time Simulations and Results

Simulation for each scenario in Digital Real Time Simulation (DRTS) environment was performed and results were obtained. The capacities for supercapacitors, batteries, and flywheels are 10 kWh, 1 MWh, and 500 kWh respectively. Induction generator outputs 500 kW power to energy market. The maximum ramping rates for supercapacitors, batteries, and flywheels are set to 0.75 kW/second, 0.1 kW/second, and 0.15 kW/second respectively. Initial energy of batteries and flywheels are set to 0.8 MWh and 400 kWh. The optimal value of energy for supercapacitors is set to 6 kWh. If energy of supercapacitors is between 4 kWh and 8 kWh, it will be considered as close to optimal value. If it is above this range, it will be considered as too high. If it is below this range, it would be considered as low energy. We set for every operation cycle of 4 seconds, the proposed controller needs 0.4 second to select the best operation strategy. Therefore, the actual operation time for each type of ES is 3.6 seconds with the settle time set to 0.9 seconds.

Figure 2 shows simulation results of scenario 1. Supercapacitors have an initial energy of 8.5 kWh. System operator requests a power increase of 0.79 kW. Following the operational strategy, controller of HESS first increases the power output of supercapacitors with the maximum ramping rate of 0.75 kW/second. Batteries and flywheels increase their output at 0.05 kW/second and 0.08 kW/second, respectively. The transition point is 1.3 seconds in this cycle, which is 0.9 seconds needed for charging operation after 0.4 seconds for the controller decision-making.

Supercapacitors start to reduce output power at another transition point when it is peaked at 0.675 kW.

In all of the figures of simulation results, the first plot displays $\Delta P_{es}$, the adjustment of the power output from each type of energy storages. Eq. (6) shows the combination of instantaneous $\Delta P_{es}$ and $P_{es,ini}$, the initial power output of energy storages in this cycle is the instantaneous value of power output from energy storages.

$$P_{es} = \Delta P_{es} + P_{es,ini} \tag{6}$$

The second plot displays the total cohesive adjustment of output from HESS.

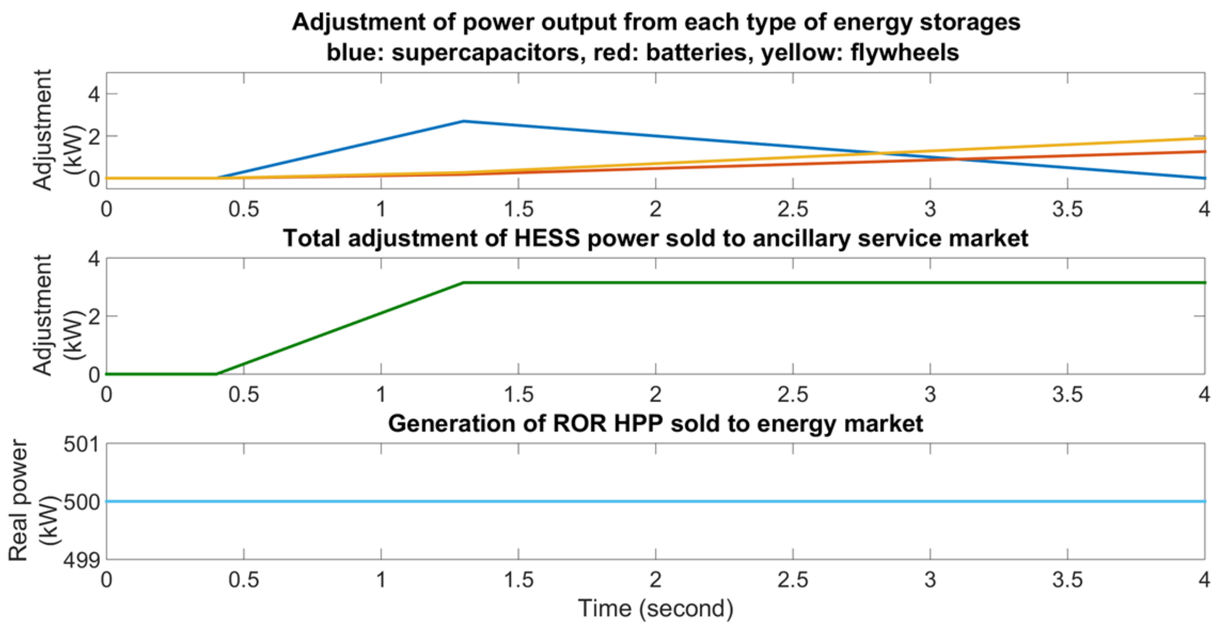


Figure 2 Simulation results of scenario 1

Figure 3 shows result for simulation of scenario 2. Supercapacitors have an initial energy of 8.5 kWh. System operator requests a power increase of 0.45 kW. Supercapacitors raise power output to 0.45 kW at 1 second. Then supercapacitors keep output at 0.45 kW for 1.2 seconds. At 2.2 second, supercapacitor reduces power output and simultaneously batteries and flywheels start to increase power output at the same instant. At the end of this cycle, power transfer from supercapacitors to batteries and flywheels are accomplished.

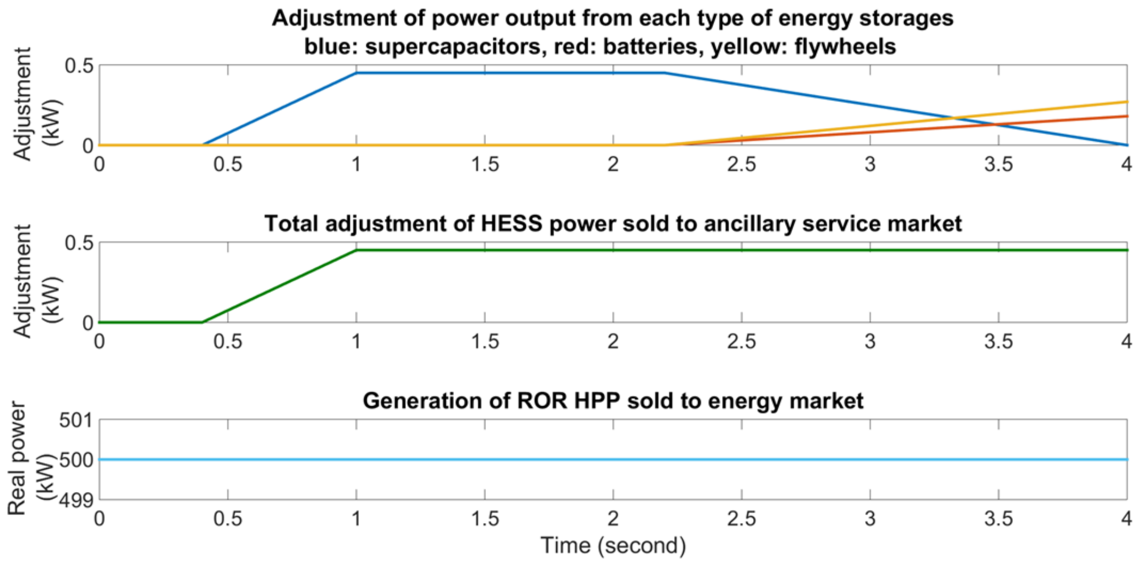


**Figure 3 Simulation results of scenario 2**

Figure 4 shows simulation results of scenario 3. Supercapacitors have an initial energy 5.5 kWh. System operator issues a power adjustment command of 0.2 kW. Supercapacitors do not function in this case. Batteries and flywheels start to raise their power at their maximum ramping rate. At 1.2 second of this cycle, the adjustment task is fulfilled.

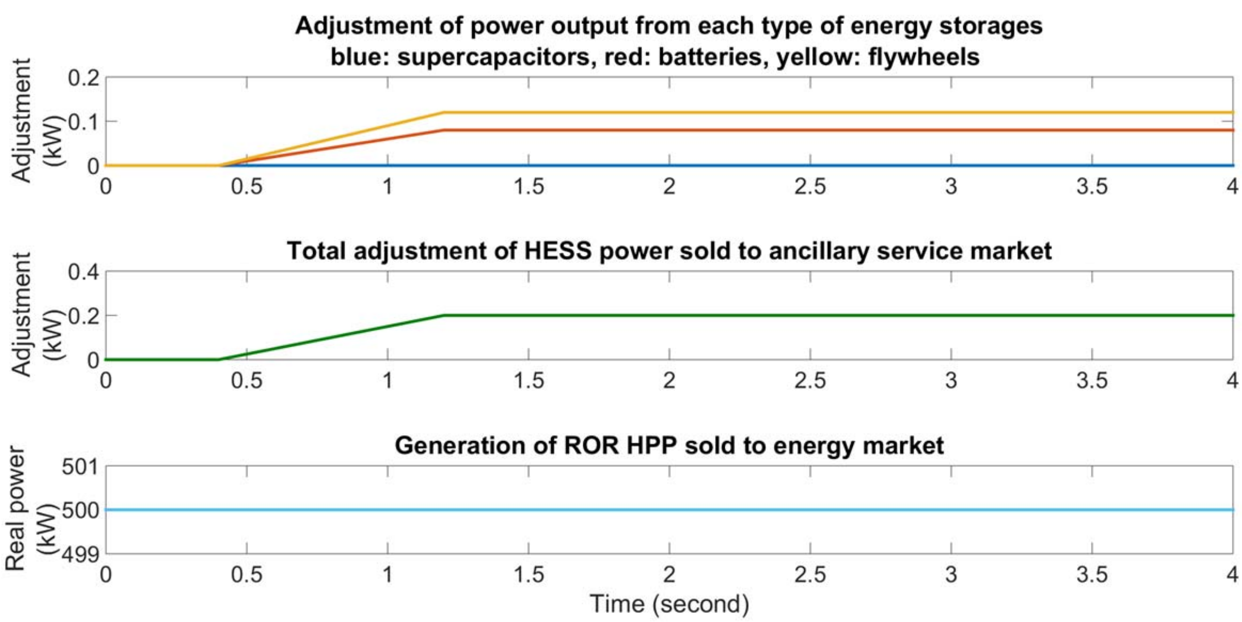


**Figure 4 Simulation results of scenario 3**

Figure 5 shows the simulation results of scenario 4. Supercapacitors have an initial energy of 4.8 kWh. System operator issues a power-adjustment command of 0.2 kW. Batteries and flywheels raise their power at their maximum ramping rate till 1.2 second in this cycle. Then HES controller starts to drain energy from batteries and flywheels. The charging of supercapacitors lasts for 2.8 seconds. The maximum power of charging supercapacitors appears at 2.6 seconds with a value of 0.35 kWh.

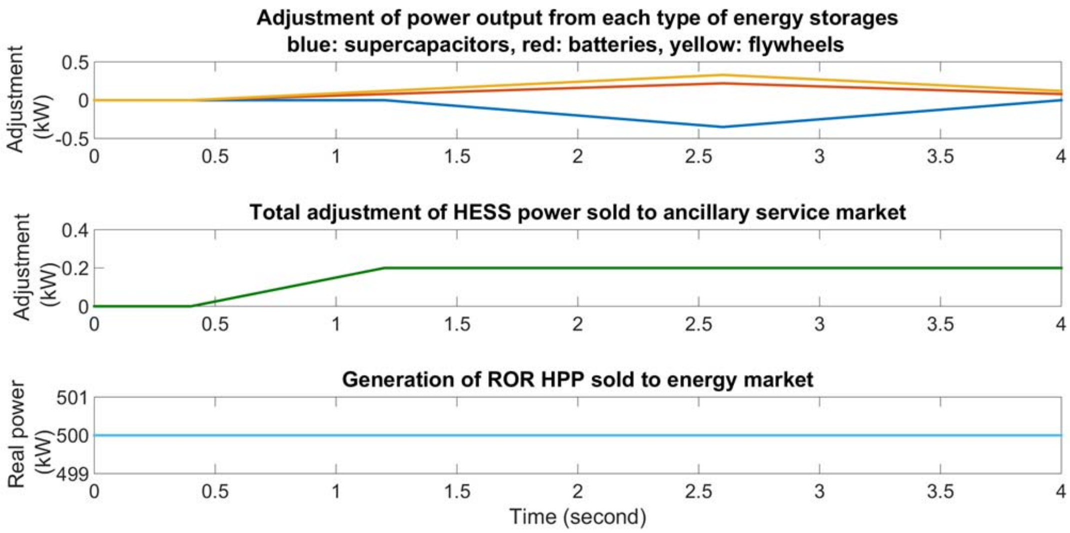


**Figure 5 Simulation results of scenario 4**

Figure 6 shows the simulation results of scenario 5. Supercapacitors have an initial energy 5.5 kWh. System operators issue a power adjustment command of 0.88 kW. Controllers of ROR HPP and HESS expect demanded power adjustment can be reached at 1.3 seconds, 0.9 seconds after command received by controllers of ROR HPP. Batteries and flywheels all increase their output at the maximum ramping rate from the beginning. Supercapacitors increase power output at a rate of 0.72 KW/second. The requested adjustment is reached at 1.3 seconds. Then the Controllers of ROR HPP start to shift power output between supercapacitors the other ESs. All types of ESs reach the final value at 3.9 seconds.

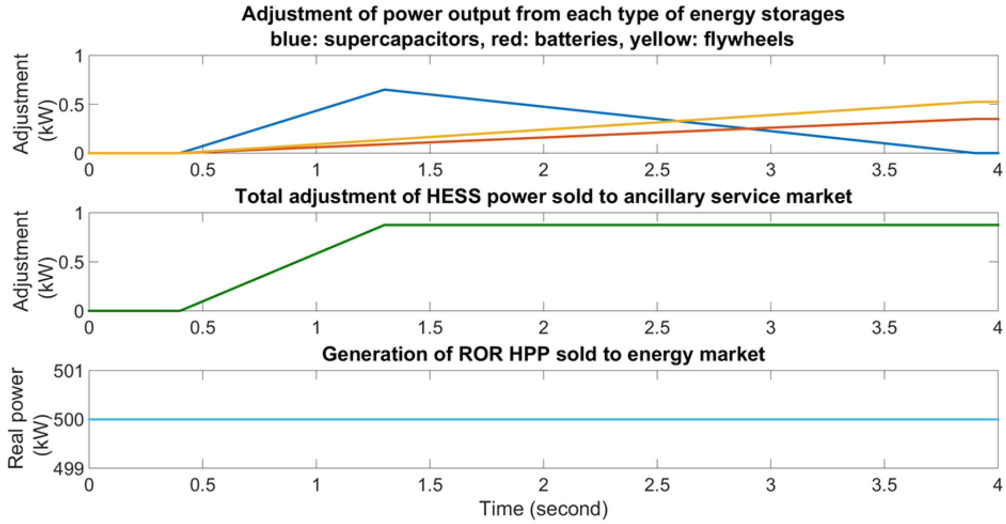


Figure 6 Simulation results of scenario 5

Figure 7 shows the simulation results of scenario 6. Supercapacitors have an initial energy 4.8 kWh. System operators issue a power-adjustment command of 0.675 kW. Batteries and flywheels raise their power at their maximum ramping rate from the beginning. Supercapacitor increase power at 0.5 kW/second. At 1.3 seconds, total power adjustment is 0.675. Then power of supercapacitors starts to decrease. From 3.1 seconds, supercapacitors start to charge from batteries and flywheels. The maximum charging power is 0.1125 kW at 3.55 seconds.

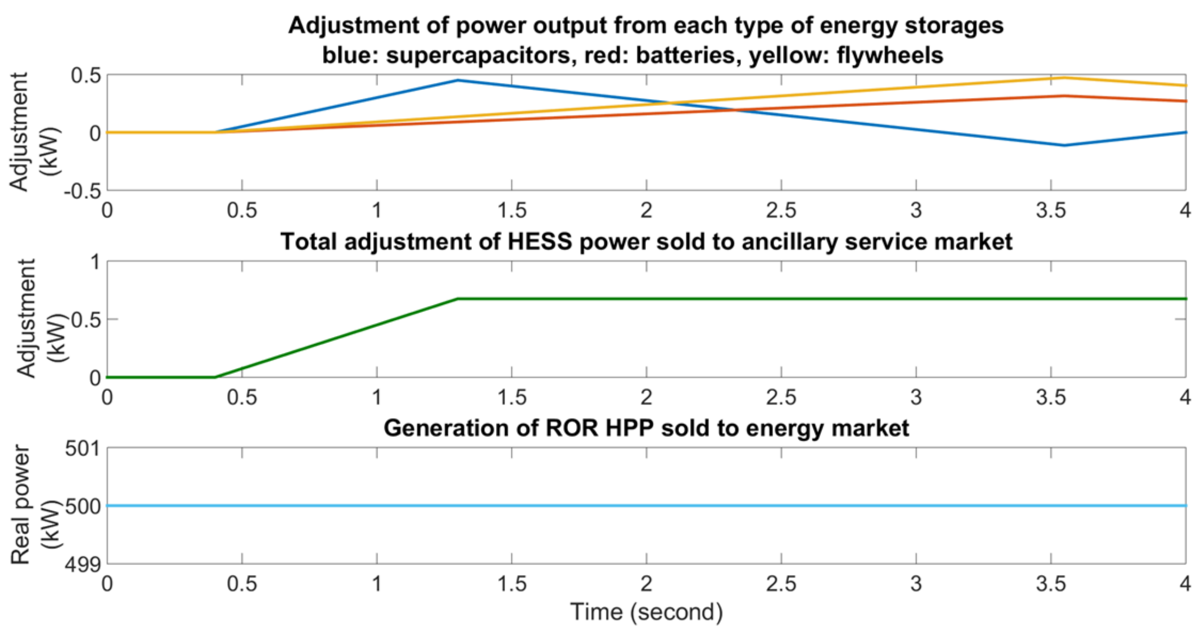


Figure 7 Simulation results of scenario 6

## 5 Conclusion

In this paper, an optimal operation strategy with a suitable controller environment is proposed to enable ROR HPP participate AS market by integration of HESS. It can ensure the economical use of energy from supercapacitors for the fulfillment of selling generation to AS market. If we can combine multiple upgraded ROR HPPs to cohesively participate in AS market, their contribution can approach that from a conventional hydro power plant with large reservoir. In the next stage of this research, analytical method for deciding the parameter of this optimal strategy will be developed. The optimal size of each type of ES will also be analyzed.

## 6 Acknowledgement

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