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Utility-Scale Wind-Based Hybrid Power Plants and Control Strategy

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Abstract This study focuses on the control strategy for active power management in utility-scale co-located hybrid power plants (HPPs) comprising wind, solar, and battery storage system. With the increasing importance of environmental impacts and incentives for renewable energy, hybrid power plants have become an attractive option for plant developers. However, there is a lack of research on the control strategies and framework of these HPPs, particularly at the utility-scale when multiple sub-technologies are involved. The proposed control strategy incorporates a supervisory control framework with a focus on establishing oversight of active power among hybrid power plants and enhanced interaction with different technologies. Using MATLAB simulations and a dynamic model, the performance of the suggested control is tested under different operational and weather conditions. The proposed control strategy for active power management can contribute to bridging the gap in knowledge and improving the controllability and efficiency of utility-scale co-located HPPs.

Keywords: *Battery energy storage system, control strategy, hybrid power plant, solar power plant, wind power plant*

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1. Introduction

1.1. Background

Renewable energy has been gaining increasing attention as a solution to mitigate environmental challenges and reduce dependence on fossil fuels [1-2]. In addition, renewable energy is becoming more cost competitive with conventional fossil fuels due to the advancements in technology, economies of large scale, and government incentives and policies [3-6]. This contributed to increasing interest among the energy industry and researchers in utility-scale co-located wind and solar parks, also known as hybrid power plants (HPPs). Therefore, HPPs that consist of wind, solar, and energy have been proposed in research to overcome these problems [7-9]. There are different ways to set up an HPP [9] depending on factors such as available energy sources, local energy demand, control strategy, and the regulatory framework. This study proposed an AC- coupled topology consisting of a wind power plant (WPP), solar power plant (SPP), and a battery energy storage system (BESS) to create a hybrid power plant [10] as shown in Figure 1.

According to the studies [8-10], HPP offers several benefits. HPPs can provide i) a more stable and reliable power compared to standalone renewables, ii) reduced infrastructure costs by sharing transmission lines, substations, and control systems, iii) power fluctuations from one source can be offset by the other, iv) reduce the need for additional infrastructure, v) high annual energy production and capacity factor, vi) generate high revenue, vii) site and owner-specific power demand.

In a grid-connected HPP, the plant developer or owner typically holds the controllability of the entire HPP assets [11]. Effective energy management is crucial for ensuring the optimal performance of the HPP and maximizing its economic benefits [12]. However, to fully realize the potential of utility-scale HPPs requires further research on technology selection, sizing, operation, and control [5] [10]. The interaction and coordination among different dynamic technologies in HPPs are complex and require additional research. There are many studies that oversight individual technologies, however, there are limited published studies on the performance of co-located HPPs in utility-scale environments. Therefore, a control strategy is essential for the effective operation and energy management of HPPs and for managing the interactions between these different technologies. Few studies have also incorporated HPP controllers and plant controllers with dispatch functions to manage energy flow, with exact functionality depending on specific HPP requirements such as primary frequency control, power control, ramp limitation, voltage control, and battery utilization [11-15]. The control strategy involving BESS to smooth out the fluctuations in the power output of WPP and SPP has been studied in [15-17].

The studies highlighted that BESS could absorb excess power when the WPP and SPP generate more than the demand and release the stored power when the demand exceeds the generation. This helps to stabilize the output power and improve the predictability of the WPP and SPP. Some studies implemented a hierarchical control structure that consists of multiple levels, each with its own set of objectives such as active power [12] [17-20] and frequency control [12-13] [19], reactive power, and voltage control [12] [19]. Dynamic models and control algorithms for different HPP topologies, including AC and DC-coupled wind-solar-storage have been developed to maximize power generation, balance control, and delta control [11]. Similarly [14] developed a dynamic model for HPP control functions such as active and reactive power, frequency, and voltage control to minimize the complexity and computation effort. The study also validated the performance of the model through field measurement.

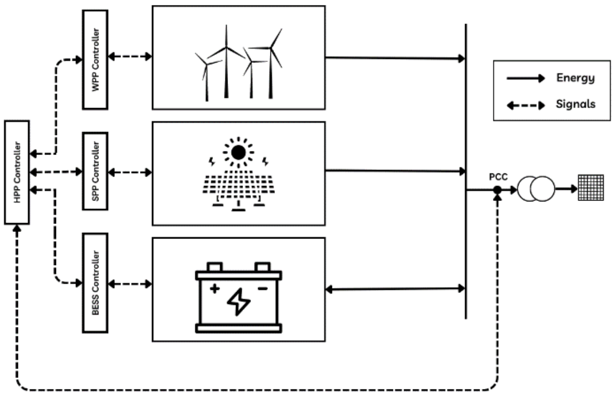

Figure 1. Co-located hybrid power plant

1.2. Objectives and Contributions

There are several components to a control strategy for an HPP. However, this study focuses on the control strategy and architectural framework for the HPPs, particularly at the utility-scale. The study aims to contribute to the development of a control framework for the HPPs that can interact with various asset levels within the HPP. In addition, the study focuses only on active power control and uses a dynamic model for each technology to evaluate the control strategy's performance through MATLAB simulations. The dynamic model design is not the scope of this study so detail was not included in this paper. The control framework consists of a control algorithm and controller designed considering the BESS contribution and its state of charge (SOC). The proposed control strategy can aid HPP developers in increasing renewable energy utilization, reducing wind and solar power curtailment, and meeting power demand. It will also facilitate future enhanced optimization functions such as ancillary services, market functions and requirements, and grid code. The study attempts to fill the knowledge gap in HPP control strategies, particularly at the utility-scale.

2. Methodology

2.1. Control Framework Development

A schematic diagram of the proposed control framework consisting of WPP, SPP, and BESS is shown in Figure 2. The control framework consists of four different control levels such as HPP energy management system (EMS), HPP control, plant control, and assets control to assist the efficient operation and integration of HPP. The inputs of the controller components are the total active power production measured in the point of common coupling and a reference value for the production. Each level is administrated according to a specified hierarchy. In Figure 2, the red color illustrates the signals from a higher level to a lower level and the blue is from a lower level to a higher level. Similarly, solid black represents the power flow. The framework for the HPP control strategy is developed using the concept implemented in [11-12] [14] [18]. The following notations have been used for the control framework.

EMS Energy management system
P_{HPP}^{EMS} Power reference from EMS to HPP controller
P_{WPP}^{AV} WPP power available
P_{SPP}^{AV} SPP power available
P_{BESS}^{AV} BESS power available
P_{WPP}^{ref} WPP power reference
P_{SPP}^{ref} SPP power reference
P_{BESS}^{ref} BESS power reference
$P_{WT_i}^{ref}$ Power reference for wind turbines (i=1: n)
$P_{\Sigma WT_i}^{AV}$ Power available from wind turbines (i=1: n)
$P_{\Sigma SPV_i}^{ref}$ Power reference for solar PVs (i=1: n)
$P_{nSPV_i}^{AV}$ Power available from solar PVs (i=1: n)
WT_i wind Turbines (i=1: n)
PV_i Photovoltaic (i=1: n)
P_{WPP} WPP power output
P_{SPP} SPP power output
P_{BESS} BESS power output
P_{HPP} HPP power output

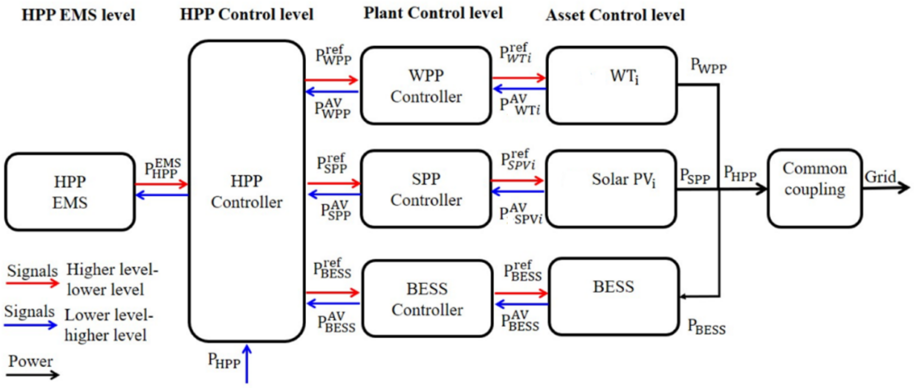

Figure 2. Hybrid power plant control framework

2.1. HPP Energy Management System (EMS) Level

The HPP EMS plays a crucial role in improving the controllability of HPPs and facilitating connections with the market operators and the central HPP control level. The EMS receives energy demands and communicates them to the HPP controller, which generates additional plant-level reference signals. How the EMS incorporates with the market operators is beyond the scope of this study. The EMS and HPP controller will ensure that the HPP behaves as a conventional power plant and performs active power control functions in response to power demand.

2.1.1. HPP Control Level

The HPP control level also known as the supervisory central control level or HPP controller is responsible for regulating the active power generation of HPP and coordinating the energy management of the different technologies within the HPP. It operates as a single central control system that provides active power reference commands to the various technologies in accordance with the set points. The HPP controller incorporates a proportional-integral (PI) controller and a power control algorithm block as shown in Figure 3.

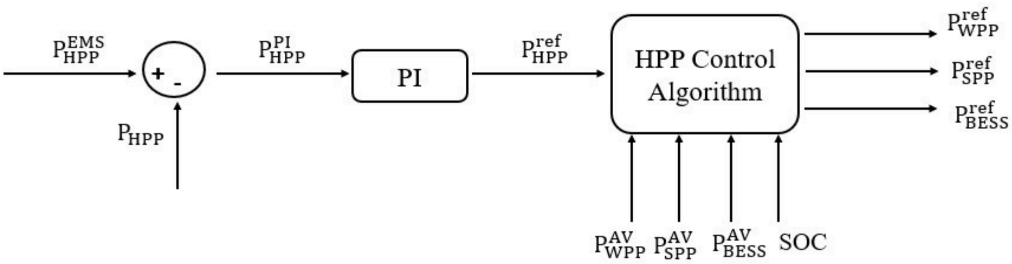

Figure 3. Components of HPP central level

2.1.2. HPP Plant Control Level

The third control level of this control framework is the plant control level, which consists of the controller for the WPP, SPP, and BESS as shown in Figure 4. The controller for each technology is responsible for regulating the active power output of the respective technology by transmitting active power references to the corresponding technology. The power references are generated at the plant control level using a PI controller and are allocated to individual technologies via proportional distribution as detailed in Hansen et al.'s research [21]. An example of proportional dispatch for WPP is shown below.

$$P_{WT_i}^{ref} = \frac{P_{WT_i}^{AV}}{P_{WPP}^{AV}} \cdot P_{WPP} \tag{1}$$

Where, $P_{WT_i}^{ref}$ and $P_{WT_i}^{AV}$ are power signal and available for each Wind Turbines (i=1: n) (WTs) and n is the number of WTs. $P_{WT_i}^{ref}, P_{WPP}^{AV}$, and P_{WPP} are available power for each WTS, WPP, and output power from the WPP respectively.

The available power of the WPP is expressed as

$$\sum_{i=1}^{n} P_{WT_i}^{AV} \tag{2}$$

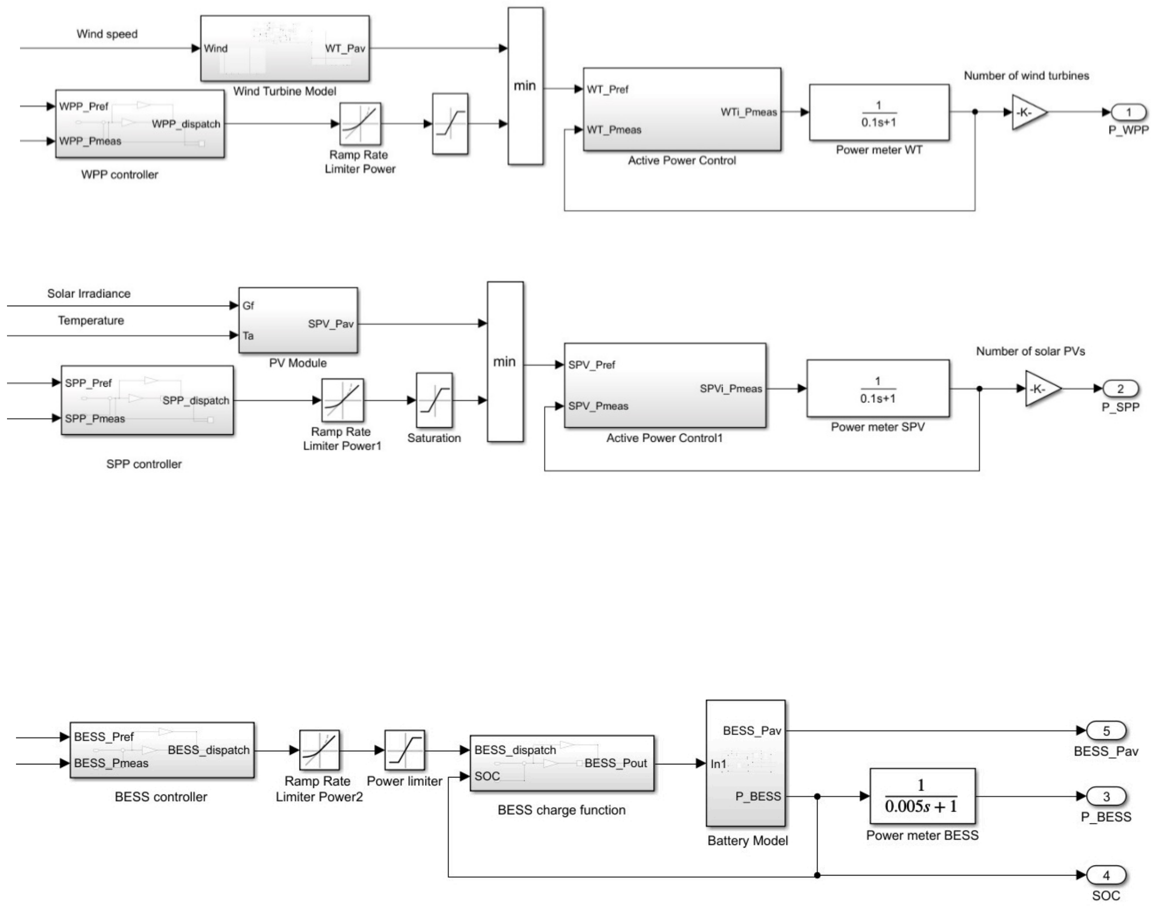

Figure 4. Plant control level: top (WPP control level), Middle (SPP control level), bottom (BESS control level)

2.1.3. Asset Control Level

The assets level plays a vital role in regulating the power output of wind turbines, solar PVs and battery as per the requirements set at the plant control level. To achieve this, dynamic models for each technology are employed based on [11]. The wind controller comprises a converter, aerodynamic, and pitch controls to meet the power demand. The PV controller is equipped with active power regulation and maximum power tracking to ensure the maximum power output from the solar panel. The battery model and charge controller make up the last component of the battery controller.

2.2. HPP Control Algorithm

The study examines active power control as a major control function. The HPP controller's control algorithm is designed to prioritize the maximum power production from the WPP and SPP to meet the power demand. When the power demand of the power system is equal to the total available power from both the WPP and SPP, each sub-plant contributes its maximum available power. This ensures the efficient use of all available energy resources. However, if the active power demand is less than the total available power from both the WPP and SPP, the surplus electricity is directed to charge the BESS. This enables the BESS to store excess electricity for later use when demand grows or when the WPP and SPP are unable to generate sufficient energy. The curtailment method begins once the BESS is fully charged and there is still excess available power from the WPP and SPP. During this procedure, the extra power that cannot be stored in the BESS is curtailed. Overall, this control algorithm assists in achieving a balance between power generation and demand and ensures the HPP operates smoothly and stably by considering the power demand, total available electricity from the assets, and the BESS charge level. As depicted in Figure 5, the control algorithm can be separated into six states and respective regulation functions are listed in Table 1. For simplicity, the power curtailment is done proportionally between WPP and SPP. Here, the control mechanism is implemented as a mode that follows the power reference. The mathematical description of the control algorithm comprises three cases, each with two states based on BESS's SOC. Some of the notations that have not mentioned previously are:

P_{BESS}^{max}	BESS maximum power available
SOC_{min}	BESS minimum state of charge

SOC_{max}	BESS maximum state of charge	PRF	Power reference following
K	Participation factor for curtailment	MPPT	Maximum power point tracking

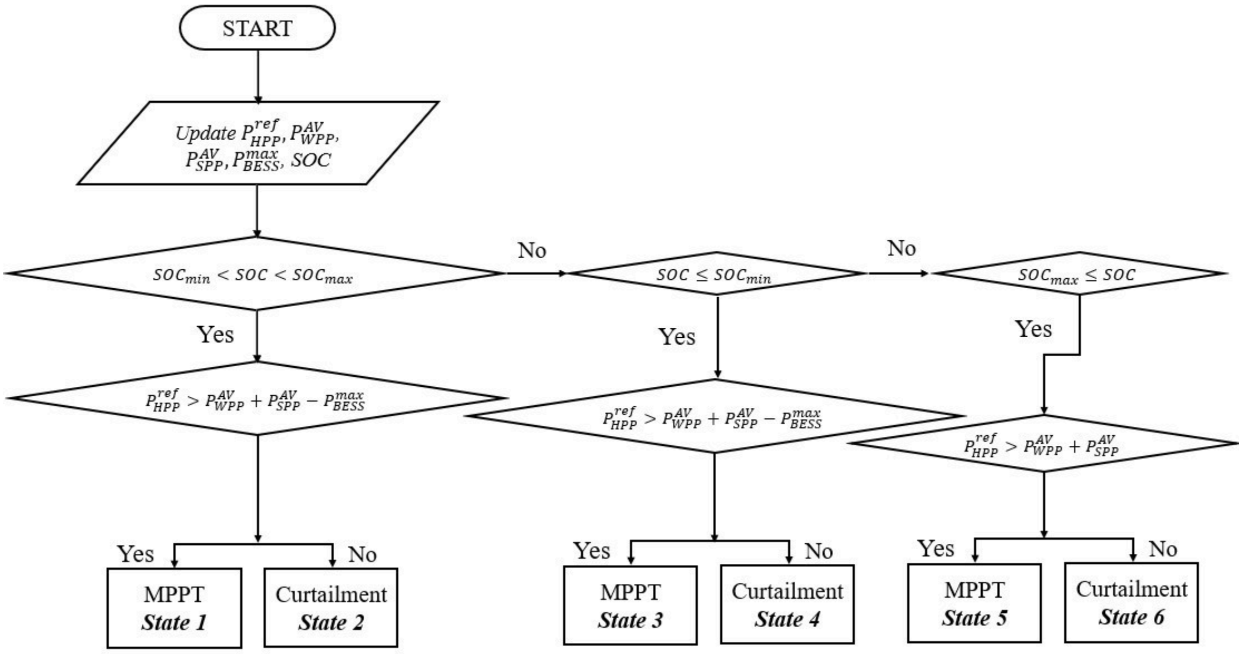

Figure 5. Control algorithm flowchart [18]

2.2.1. Case I: $SOC_{min} < SOC < SOC_{max}$

The control strategy operates in two different states depending on the state of charge of the BESS, i.e. when is between a minimum value (SOC_{min}) and a maximum value (SOC_{max}). In State 1,the control algorithm permits the WPP and SPP to operate at their MPPT to generate power, while the BESS follows a power reference to complement WPP and SPP and fulfill the overall power demand. Mathematically state 1 can be expressed as:

If $\quad P_{HPP}^{ref} > \left(P_{WPP}^{AV} + P_{SPP}^{AV} - P_{BESS}^{max}\right)$

$$P_{WPP} = P_{WPP}^{AV} \tag{3}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{4}$$

$$P_{BESS} = \min\left(P_{BESS}^{max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right) \tag{5}$$

State 2 represents the curtailment state. In this state, surplus power is used to charge the BESS as much as possible, and the remaining surplus power is curtailed proportionally among WPP and SPP. The active power dispatch references for state 2 are formulated as:

If $P_{HPP}^{ref} < \left(P_{WPP}^{AV} + P_{SPP}^{AV} - P_{BESS}^{max}\right)$

$$P_{WPP} = KP_{WPP}^{AV} \tag{6}$$

$$P_{SPP} = KP_{SPP}^{AV} \tag{7}$$

$$P_{BESS} = -P_{BESS}^{max} \tag{8}$$

2.2.2. Case II: $SOC \le SOC_{min}$

When the BESS SOC reaches the minimum level, the control algorithm operates in two states either MPPT or curtailed depending on the set points. State 3 represents similar to state 1 where WPP and SPP operate at their MPPT to generate power, while the BESS remains charging condition. This illustrates that the BESS is not needed to complement the WPP and SPP generation to meet the set points. Mathematically state 3 can be represented as:

If $\quad P_{HPP}^{ref} > \left(P_{WPP}^{AV} + P_{SPP}^{AV} - P_{BESS}^{max}\right)$

$$P_{WPP} = P_{WPP}^{AV} \tag{9}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{10}$$

$$P_{BESS} = \min\left(0, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right) \tag{11}$$

State 4 represents a situation where production is higher than the power demand. The control algorithm allows the BESS to charge first, and any excess power is curtailed. The equation representing this state is:

If $\quad P_{HPP}^{ref} < \left(P_{WPP}^{AV} + P_{SPP}^{AV} - P_{BESS}^{max}\right)$

$$P_{WPP} = KP_{WPP}^{AV} \tag{12}$$

$$P_{SPP} = KP_{SPP}^{AV} \tag{13}$$

$$P_{BESS} = -P_{BESS}^{max} \tag{14}$$

2.2.3. Case III: $SOC_{max} \le SOC$

When the BESS SOC reaches the maximum point, the algorithm operates in two states. In State 5, the power set point is greater than the available power from the WPP and SPP. Therefore, the algorithm initiates the WPP and SPP to operate in MPPT. In this state, the HPP may not be generating power as the power demand and initiates the BESS to discharge to meet the deficit power. The equation can be expressed as:

If $\quad P_{HPP}^{ref} > \left(P_{WPP}^{AV} + P_{SPP}^{AV}\right)$

$$P_{WPP} = P_{WPP}^{AV} \tag{15}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{16}$$

$$P_{BESS} = \min\left(P_{BESS}^{max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right) \tag{17}$$

In State 6 the WPP and SPP are generating more power than what is required to meet the set point, and there is no need space for the BESS to charge so it enters the standby mode, As a result, the control algorithm initiates power curtailments. Mathematically it is represented as:

If $P_{HPP}^{ref} < \left(P_{WPP}^{AV} + P_{SPP}^{AV}\right)$

$$P_{WPP} = KP_{WPP}^{AV} \tag{18}$$

$$P_{SPP} = KP_{SPP}^{AV} \tag{19}$$

$$P_{BESS} = 0 \tag{20}$$

The control strategy proposed above can be considered a base for other control functions such as reactive power, frequency control, market engagements, and so on.

Table 1. Hybrid Power Plant Regulation Function for Active Power [18]

Regulation	Control States			Power Reference		
	WPP	SPP	BESS	WPP	SPP	BESS
State 1	MPPT	MPPT	PRF	$\mathbf{P_{WPP}^{AV}}$	$\mathbf{P_{SPP}^{AV}}$	$\mathbf{min\left(P_{BESS}^{max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right)}$
State 2	Curtail	Curtail	Charge	$\mathbf{KP_{WPP}^{AV}}$	$\mathbf{KP_{SPP}^{AV}}$	$\mathbf{-P_{BESS}^{max}}$
State 3	MPPT	MPPT	Charge	$\mathbf{P_{WPP}^{AV}}$	$\mathbf{P_{SPP}^{AV}}$	$\mathbf{min\left(0, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right)}$
State 4	Curtail	Curtail	Charge	$\mathbf{KP_{WPP}^{AV}}$	$\mathbf{KP_{SPP}^{AV}}$	$\mathbf{-P_{BESS}^{max}}$
State 5	MPPT	MPPT	Discharge	$\mathbf{P_{WPP}^{AV}}$	$\mathbf{P_{SPP}^{AV}}$	$\mathbf{min\left(P_{BESS}^{max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right)}$
State 6	Curtail	Curtail	Standby	$\mathbf{KP_{WPP}^{AV}}$	$\mathbf{KP_{SPP}^{AV}}$	0

3. Assumptions and Sizing of HPP

3.1. Assumptions

To simplify the complexity of the simulation and achieve a balance between simulation time and accuracy the following assumptions are considered [18].

- To deal with utility -scale HPPS containing multiple wind turbines and numerous PV units, the study utilized an aggregated modelling technique. This approach aims to represent the whole farm by a single equivalent unit with a re-scaled power capacity, which simplifies the system's complexity and reduces computation time significantly.
- Solar irradiance and wind speed are assumed to be consistent for all PV modules and wind turbines respectively.
- The effect of temperature is not considered in models of PV modules and battery.
- Market forecasting and economic variables are left out of the simulation.
- The maximum quantity of energy that HPP can inject into the grid cannot exceed the total amount of energy available from WPP, SPP, and BESS.

3.2. Sizing of HPP

The size of an HPP and its components are influenced by several factors, such as geographical location, economics, plant functionality and market requirement and grid code. Since the sizing of the HPP plant and its assets is not within the scope of this work, the authors have selected design parameters similar to those used in Vattenfall's renewable

controller [20] for the size of the HPP and its assets, as presented in Table 2.

Table 2. Sizing of HPP with Its Asset

Technologies	Sizing [MW]
Wind power plant	120
Solar power plant	40
Battery energy storage system	10

3.3. Controller Parameters

To evaluate the performance of the HPP controller, the HPPs model is required to simulate the closed-loop performance. As detailed in above section every controller such as HPP control level or plant control level incorporates a PI controller. The primary role of PI controller is to achieve a precise tracking of the setpoint provided by the EMS at the PCC. The controller is designed using the s-domain and its transfer function is applied in the same domain as follows:

$$G_{pi}(s) = K_{pi}\frac{T_{pi}s+1}{T_{pi}S} \tag{21}$$

Where, G_{pi}, K_{pi} and T_{pi} are transfer functions, proportional gain and time constants of the PI controller respectively [13]. Table 3 illustrates the parameters of the implemented PI controller used in HPP controller and plant control level.

Table 3. Controller Parameters

Plant	K_{pi}	T_{pi}
HPP	0.95[20]	0.9[20]
WPP	1.008[13]	1[13]
SPP	0.3106 [13]	0.3 [13]
BESS	0.005 [13]	0.005 [13]

4. Simulation and Results

To assess the performance of the HPP model and control algorithm, a sequence of simulations was executed on a system consisting of 24 x 5 MW of type IV wind turbines, 166667 x 240 watts of fixed PV panels, and 10 MW of BESS. The simulations were performed with a constant wind speed of 12 m/s and a solar irradiance of 1000 W/m^2. The BESS is assumed to have sufficient capacity for charging or discharging, and its SOC set to 0.5 per unit (pu). The minimum and maximum value of the SOC is set at 0.1 pu and 0.9 pu to ensure that the BESS is not completely discharged or fully charged to avoid potential damage to the BESS.

4.1. Normal Operation

Figure 6 depicts the active power output of the HPP and its assets at the point of common coupling (PCC) during normal operation. During this period the WPP and SPP operate in maximum power point tracking mode, while BESS remains standby, neither charging nor discharging.

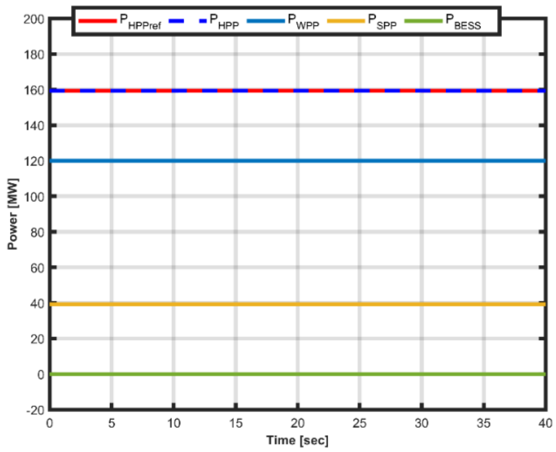

Figure 6. HPP and its assets' active power response at the PCC during normal operation

4.2. Shifting load (Step change in set points)

Figure 7 shows the performance of the HPP and its assets during a simulated period under a shifting load scenario. During the first and last 10 seconds, the system operates under normal conditions. At 10 seconds mark, the load is shifted from 160 MW to 170 MW. The BESS meets the increased load change as the WPP and SPP continue operating in MPPT mode. At 20 seconds, the load is reduced to 150 MW, causing the control system to let the BESS charge.

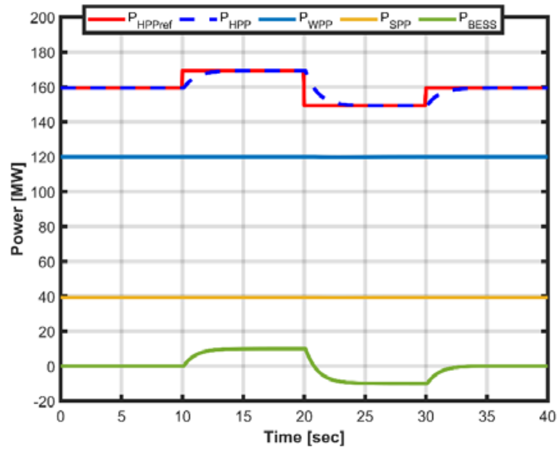

Figure 7. HPP and its assets' active power response at the PCC at shifting load scenario

4.3. Curtailment

Figure 8 depicts a scenario in which power curtailment is applied to the HPP's asset. During the initial 10 seconds and last 10 seconds of the simulation, the system operates at normal conditions with the WPP and SPP Operate at MPPT and the BESS neither charging nor discharging. At the 10 seconds mark, the active power setpoint is decreased in two steps and then restored to its original value at 40 seconds. The figure shows that the sum of the power generation from the WPP and SPP exceeds the setpoints. In response 10 MW power is employed to charge the BESS, while remaining excess power is curtailed from the WPP and SPP.

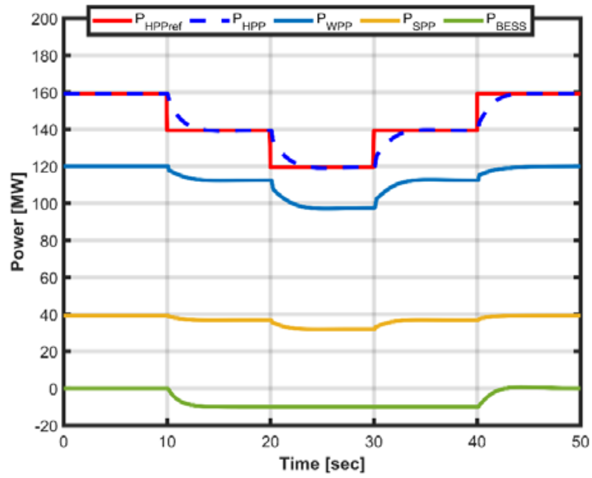

Figure 8. HPP and its assets' active power response at the PCC during curtailment

4.4. Shadowing effect

In Figure 9, the effect of shadowing due to passing clouds on solar power generation is demonstrated. The simulation involves reducing the solar irradiance due to the passing clouds from 1000 to 900 and 800 W/m^2 over a 10 seconds period, followed by an increase to 900 and

1000 W/m^2, while the wind speed remains constant at 12 m/s and the BESS's SOC at 0.5 pu. The passing clouds cause fluctuations in the power output of the SPP, whereas WPP power remains same during entire simulations as shown in Figure 9. The simulation highlights that sudden changes in solar irradiation due to passing clouds can results in significant power fluctuations in SPP generation, and the BESS exhibits the necessary behavior throughout the simulation.

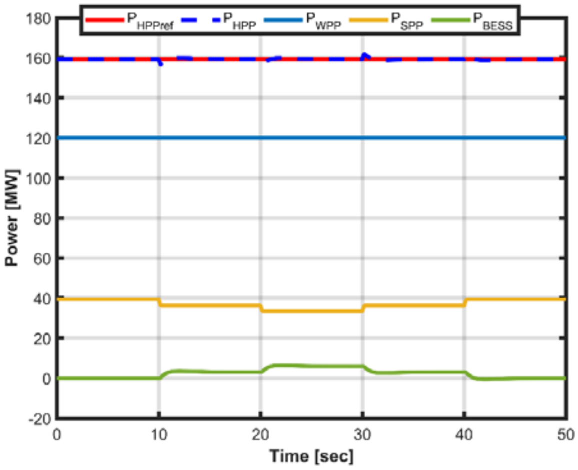

Figure 9. HPP and its assets' active power response at the PCC under shadowing effect

4.5. Change in BESS Size

In this scenario, the power response is investigated under the same power curtailment scenario explained in 4.3 with an increased capacity of BESS to 20 MW. Figure 100 demonstrates that increasing the BESS capacity from 10 MW to 20 MW enhances the performance of the WPP and SPP, leading to reduced power curtailment. With a larger BESS capacity, the BESS can also provide longer periods of backup power during power fluctuations. However, increasing the BESS capacity may increase the overall cost which is out of the scope of this study.

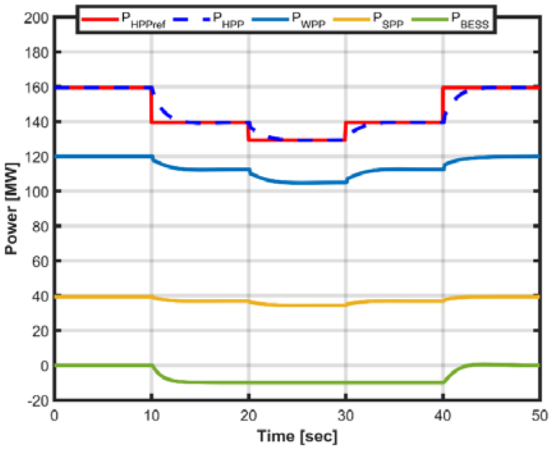

Figure 10. HPP and its assets' active power response at the PCC when BESS capacity increased from 10 to 20 MW

4.6. No wind and solar production

Figure 111 illustrates the condition where both wind and solar power generation are not viable due to inadequate wind speed and solar irradiance (2m/s and 2W/m^2 respectively). This could occur during periods of low wind and overcast skies, where there is not enough natural energy available to generate power from WPP and SPP. In such a circumstance, the BESS exhibits the required behavior throughout the simulation.

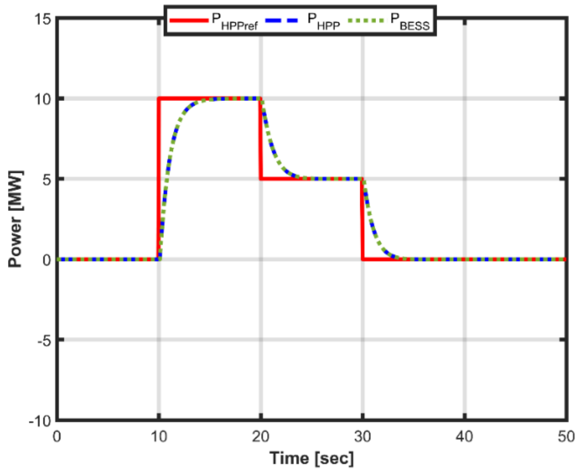

Figure 11. HPP and its assets' active power response at the PCC at zero wind and solar production

5. Conclusion

The present study has investigated the performance of a proposed control strategy for a HPP connected to a power system with renewable sources WPP, SPP, and a BESS during normal and different operating conditions using MATLAB simulations. The simulation results demonstrate that the proposed control strategy performs well and is able to meet the set points under various scenarios. The system also facilitates interaction between the sub-technology controllers. The findings contribute to the development of more efficient and effective control strategies for HPPs, particularly at the utility scale, filling a knowledge gap in the field.

6. Recommendation

Future research can focus on exploring additional control capabilities that support grid code, converter control for improved level interactions, techno-economic criteria and weather forecast uncertainty. In order to make broad statements regarding the viability of co-locating HPP, future research should be comparative. This means comparing the performance of HPPs with other types of power plants under different scenarios. Additionally, the size of WPP, SPP, and BESs should be optimized, and the impact of communication delays on HPP's capability to provide ancillary services should be investigated.

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