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Battery Uses for Regulating Active Power in Utility-scale Wind-based Hybrid Power Plant

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Abstract Growing demands for renewable energy sources have resulted in the integration of wind and solar power in utility-scale power plants and the building of a hybrid power plant. This requires a deep understanding of the interactions between the different technologies. To overcome the inherent intermittency of these sources, batteries are often used as energy storage. However, the proper utilization of batteries in these hybrid power plants remains a challenge because of the dynamic nature of renewable energy sources. Additional research is required to investigate how different dynamic technologies interact and perform dispatch energy as a single convenient unit. This research provides a battery contribution control approach for utility-scale wind-solar hybrid power systems. The proposed control strategy incorporates a supervisory control framework with a focus on establishing oversight of active power and enhanced interaction with different technologies involving the battery's state of charge. Using MATLAB simulations and dynamic modelling, the effectiveness of the suggested control approach is tested. The results indicate that the control technique improves battery use, and minimizes wind and solar power curtailment to fulfill the power demand. This research offers a promising solution for the battery contribution in utility-scale wind-solar-battery hybrid power plants thereby contributing to grid stability and the integration of renewable energy sources.

Keywords: *utility-scale hybrid power plant, wind power plant, solar power plant, battery energy storage, control strategy*

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1. Introduction

1.1. Background

Renewable energy sources like wind and solar are gaining popularity due to their ability to reduce greenhouse gas (GHG) levels and prevent global warming [1]. In addition, the price declines of wind turbines and solar panels over the past few years [2,3] and the flexibility with policy have led to an increase in renewable sources and make it an attractive option for the plant developers to implement the energy mix in the power system [4,5]. However, the transition to 100% renewable is hindered by the variable nature of these sources [6,7]. Additionally, renewable technologies replace traditional power plants in a way that reduces dispatchable capacity and introduces variable generation, making the power system more unpredictable. Hybrid power plants (HPP) that mix wind, solar, and battery storage technologies have been proposed to overcome these problems [7]. This will give plant developers to operate HPP more like conventional power plants in terms of dispatchability and reliability of the power system.

There are a few ways that HPP solutions can be set up, depending on factors like the business case and the available energy sources. Petersen et al. [8] presented in detail various HPP topologies for alternate current (AC) and direct current (DC). However, this study considered a grid connected HPP topology for AC configuration consisting of WPP, SPP, and BESS and is illustrated in Figure 1.

In the AC-coupled HPP approach, each asset has its own point of connection to the external grid, which is connected via a single transformer [8,9]. The utility-scale HPP has several advantages [8,10], such as (i) Enhancement of annual energy production (AEP) and capacity factor, (ii) Reduced variations and unpredictability and enhanced power profile at the PCC, (iii) Decreased power forecast error, (iv) Better usage of electrical infrastructure, (v) Increased revenue, (vi) Enhanced provision of auxiliary services.

The most frequent forms of energy storage systems (ESS) include battery storage systems (BESS) such as Lead acid and Lithium-ion, Sodium Sulphur, Nickel Cadmium, Vanadium etc., fuel cells, supercapacitors, and flywheel-based energy storage [11], pumped hydro storage, super conducting magnetic energy storage (SMES) [12] as shown in Figure 2. However, flow batteries, SMES, ultracapacitor are still in R&D stages with few commercial applications [12]. It can be noticed that most of the technologies used are characterized based on energy density or power density [13].

Wandhare and Agarwal [14] recommended using ultracapacitors as a second smoothing control to smooth the output. Li et al. [15] suggests power smoothing management to reduce wind and solar power output fluctuations and preserve the state of charge (SOC) of a battery. As a technique for minimizing the intermittent nature of renewable energy sources, the battery energy storage system (BESS) can be characterized by high power density, long lifetime and no maintenance [15]. Typical characteristics of some ESS that can be integrated with renewables are given in Table 1.

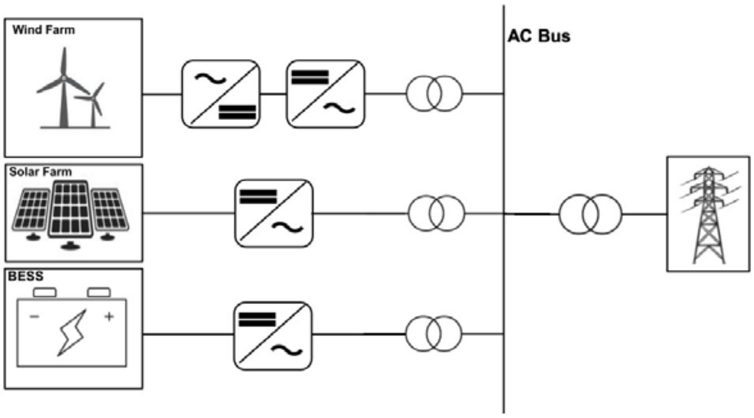


Figure 1. Co-located AC coupled hybrid power plant

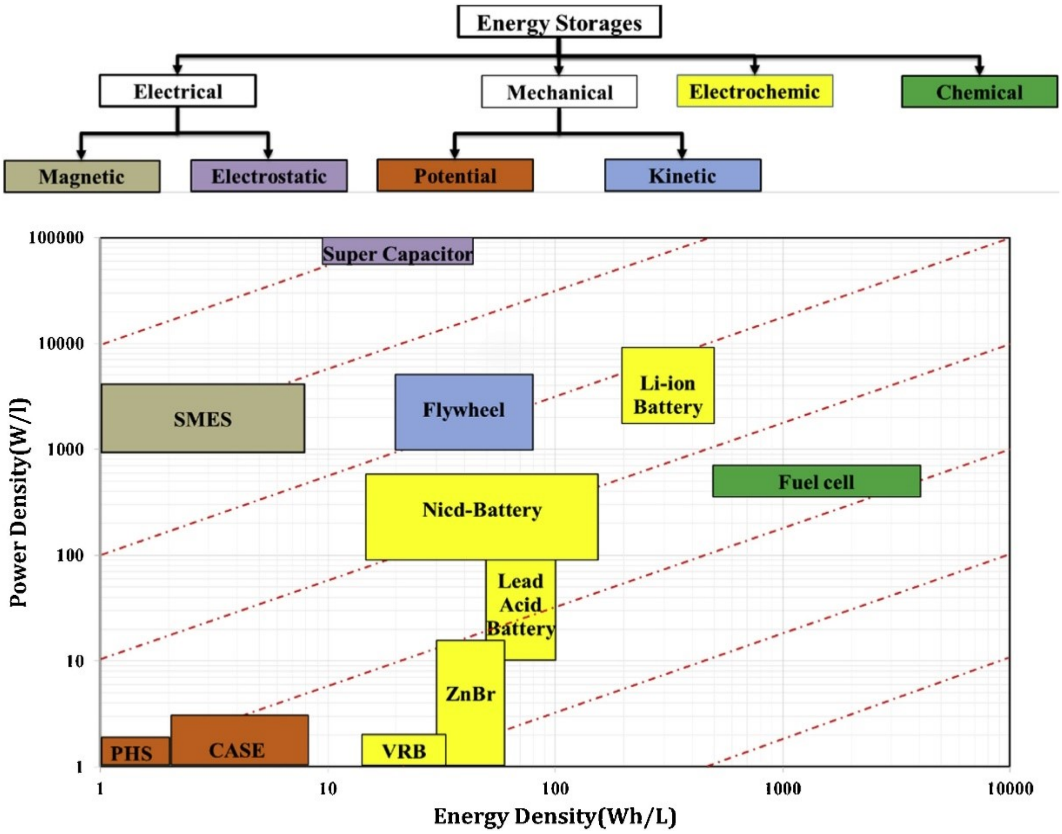


Figure 2. Commonly used storage technologies [13]

Table 1. Characteristics of energy storage systems suitable with renewable energy systems [12][17][18]*[7]**

ESS	Power rating MW	Energy rating MWh	Power density W/L	Energy Density Wh/L	Efficiency %	Lifetime	Response time**
Flywheel	0.1-10	0.01-5	1000-2000	20-80	85-87*	15-20	
Supercapacitors	0.001-10	0.000001-0.01	10000+	10-30	90-95	10-20	<S
Battery	0-50	100		~500	60-95*	5-20	<S
SMES	0.01-10	0.0001-0.1	1000-4000	0.2-2.5	90-95	15-20	<S
Fuel cell	0-50			500-3000	~50	5-15	S-min
PHS	100-5000	1000+		0.5-1.5	70-85	50-60	min

PHS- Pumped hydro storage; SMES-Superconducting magnetic energy storage; S- Sec.

1.2. Literature Review

HPPs based on utilities that mix wind, solar, and battery storage are still in the early stages of development [9]. However, there are many studies that oversight the individual technologies. In recent years, numerous research studies on the utilization of BESSs in HPPs have been done. For example, the authors in [19] developed a reinforcement learning-based control technique to managing wind power and forecast uncertainty. Wu et al. [20] implemented a machine learning-based control technique to enable wind power plant frequency regulation. To provide frequency ancillary services, the proposed control approach included the SOC, charging rate, and discharging rate of BESS. Li et al. [21] introduced a BESS to assist WPP in achieving energy balancing dispatch capability. Wang et al. [22] create a -novel active power coordinating control approach for wind, solar, and energy storage systems that enhance frequency stability. Similarly, [16] investigated dual-battery energy storage systems to improve the dispatch ability and power quality of WPP. Taghvaei et al. [23] suggested a fuzzy logic-based control approach for wind storage systems to offer the major frequency response to grid disturbances. The suggested control technique incorporates both converter-level control loops and dynamic models for wind farms and batteries. Dozein and Mancarella [24] modeled utility-connected BESS for frequency/active power and voltage/reactive power control. By utilizing a thorough BESS dynamic model, the proposed control approach responded to system contingencies. The outcomes demonstrated that the model can effectively provide dynamic integrated services. Li et al. [16] established forecast-based control techniques for BESS. Wu et al. [25] describe a coordination strategy for photovoltaic (PV) and BESS frequency management and employed a system using bus signaling, the BESS is never overcharged or undercharged. Lin et al. [26] proposed an intelligent control method for a recurrent fuzzy neural network to smooth wind power. The recommended model monitored the references, and BESS charging/discharging handled differences between the actual and the response.

Similarly, Altin and Eyamaya [27] proposed a hybrid algorithm for smoothing wind power and energy management with BESS. Syed and Khalid [28] developed a neutral network predictive control method to reduce fluctuations in PV power. The recommended control method employs BESS's SOC. Vázquez Pombo et al. [29] designed a control architecture for frequency management using HPPs consisting of wind farms, solar farms, and BESS. The suggested control architecture integrates the most recent European Network of Transmission System Operators for Electricity laws and recommendations (ENSTO-E). Raducu et al. [30] designed a controller and dispatch function for WPP, SPP, and BESS to integrate new generating/BESS with old systems. The proposed control technique regulates the BESSs' charging and discharging rates in accordance with the setpoint. Long et al. [31] presented a hierarchical control design for a co-located HPP consisting of WPP, SPP, and BESS.

1.3. Objectives and Contributions

The plant developers intend to operate the entire HPP assets and control power output as a single conventional plant, necessitating an optimized power output management strategy at the point of common coupling (PCC). However, there is a lack of research on the control strategies and architecture of these HPPs, particularly at the utility-scale. In the present study, a novel control strategy is provided for the battery's contribution to utility-scale wind-solar-hybrid power plants, and the performance of the proposed control strategy is evaluated using MATLAB simulations and a thorough dynamic model. The control system also permits the optimal interaction between the controllers of the sub-technologies. The technique integrates an active power control algorithm and BESS control using the SOC of the BESS. The study aims to contribute to the development of control framework for HPP and the integration of renewable energy technologies into the power grid. Developers of HPPs can utilize a control strategy to enhance battery usage, increase the utilization of renewable energy, and reduce wind and solar power curtailment to meet power demand. This also includes the advancement of the knowledge gap in HPP.

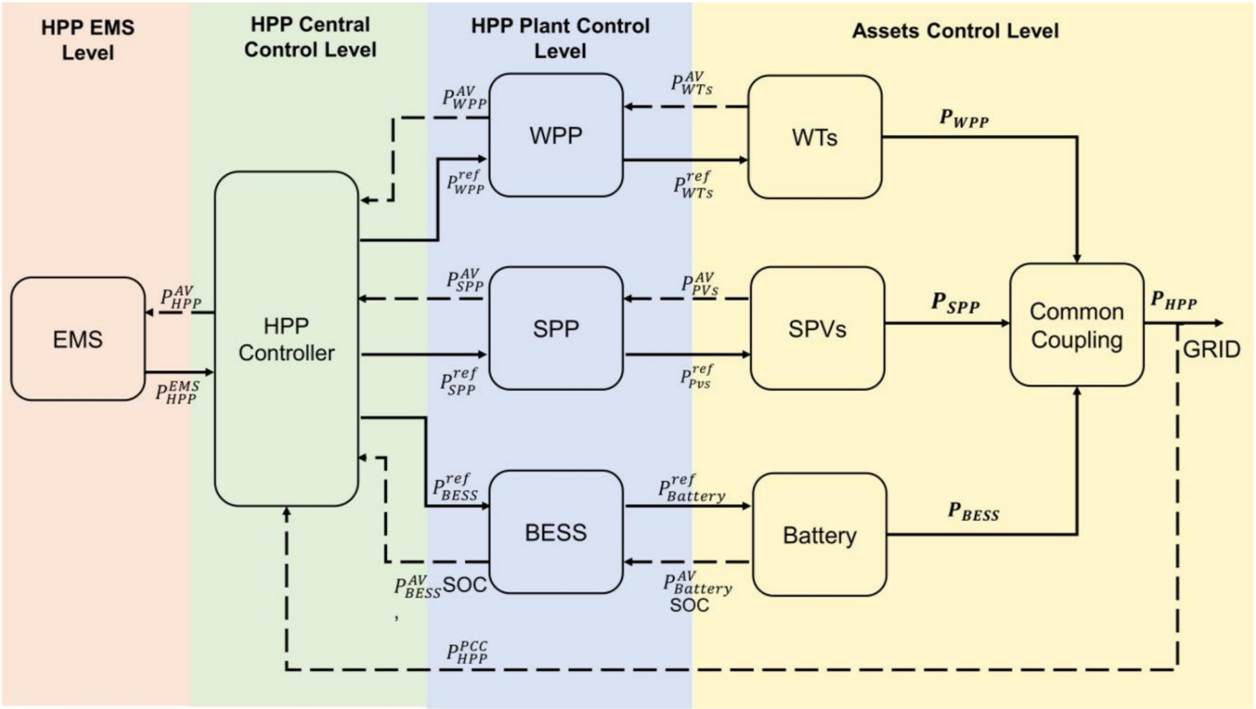
2. Methodology

2.1. Control Framework Development

The HPP control architecture is a collection of control levels designed to assist the efficient operation and integration of many power sources, such as wind, solar, and battery energy storage technologies. The concept of the HPP control framework draws from multiple sources [9,29,31]. Figure 3 demonstrates the design presented in this paper. A hierarchical control scheme for the HPP consists of four control levels, including the energy management system (EMS), the core supervisory HPP levels, the plant control level, and the asset control level. The solid black lines and arrows represent energy/power reference, whereas the dashed black lines with arrows represent feedback signals.

The EMS is responsible for enhancing the HPP's controllability and establishing connections with market operators and the central control level of the main HPP. Once the EMS receives the energy demands, it transmits them to the HPP controller, which then generates and transmits additional plant-level reference signals. The HPP control level, also known as the supervisory HPP controller, is the second primary control level and is solely accountable for coordinated control and energy management.

The HPP controller level contains the control algorithm that manages the HPP's active power generation by issuing an active reference power command to the various technologies. The EMS transmits power demands to the HPP controller, which continuously monitors the HPP power reference and regulates the active power that HPP integrates into the grid centrally. In addition to a control method, it incorporates a proportional-integral (PI) controller, as shown in Figure 4, to ensure that the HPP complies with the active power references defined by the EMS. Here, the control algorithm is developed considering the BESS's SOC as proposed by Syed and Khalid [28].



EMS- energy management system; WTs- wind turbines, SPVs- Solar PVs; P_{HPP}^{EMS} –HPP power reference from EMS; P_{WPP}^{ref} - WPP Power reference; P_{SPP}^{ref} – SPP power reference; P_{BESS}^{ref} – BESS power reference; P_{WTs}^{ref} – WTs power reference; P_{PVs}^{ref} – PVS power reference; $P_{Battery}^{ref}$ -Battery power reference; P_{WTs}^{AV} - WTs available power; P_{PVs}^{AV} – PVs available power; P_{WPP} – WPP power at PCC; P_{SPP} – SPP power at PCC; P_{BESS} – BESS power at PCC; P_{HPP} – HPP power to the grid ; PCC- point of common coupling

Figure 3. Hybrid power plant control framework

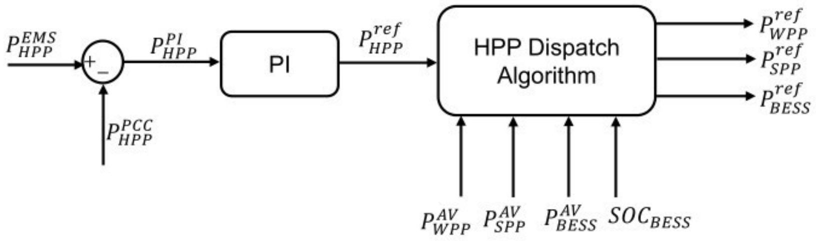


Figure 4. HPP Central control level with the PI dispatch function

The PI controller calculates the HPP power reference from the EMS, P_{HPP}^{EMS} and the power measured at PCC, P_{HPP}^{PCC} .The supervisory HPP controller can provide consistent power production or reduce excess power based on the BESS's SOC, thereby minimizing curtailments through BESS.

The third control level of this control framework is the HPP plant control level, which consists of the controller for the WPP, SPP, and BESS. Their major purpose is to regulate the active power output of these technologies by sending power references (P_{WPP}^{ref} , P_{SPP}^{ref} and P_{BESS}^{ref}). As described by Hansen et al. [33], the PI controller generates the power references at the plant control level, and the resulting outputs are proportionally allocated to the corresponding technologies employing the controllers. In addition, each power plant controller is equipped with a dispatch block that considers the available power, as depicted in Figure 5.

The assets control level is responsible for managing the power output of wind turbines, solar photovoltaic arrays, and batteries to fulfill the preferences established at the plant control level. The dynamic model for wind turbines may be found in [33], while the solar PV model is detailed in [34] and the BESS model in [35]. The controller for wind turbines consists of a converter, aerodynamic, and pitch controls to fulfill the power requirement [20]. The PV controller is equipped with active power regulation and maximum power point tracking (MPPT). The battery model and charge controller [9] constitute the last component of the battery controller. The wind turbine control level notifies the WPP controller of the individual power capacity of each wind turbine. Similar information is provided to the SPP and BESS controllers regarding the power capacity of the solar PV module and battery control, respectively. The battery control also refreshes the battery's charge level (SOC).

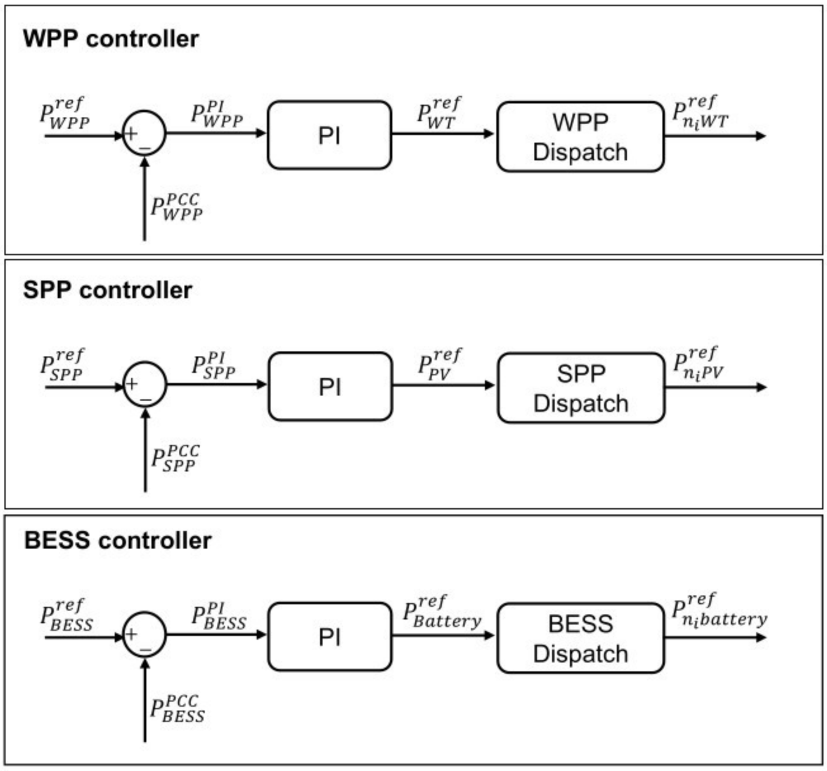


Figure 5. Plant control level

2.2. HPP Control Algorithm

One of the control functions explored in this work is active power control. The HPP controller's dispatch strategy is designed to prioritize the maximum usage of available power from the WPP and SPP to meet the power system's active power demand. When the active 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 wind farm and the solar photovoltaic plant, the surplus electricity is directed to charge the BESS. The curtailment method begins once the BESS is fully charged and there is still excess available power from the WPP and SPP. To implement active power control, the control strategy considers the BESS's SOC under three different conditions. As indicated in Figure 6, the control algorithm can be partitioned into six states, whose corresponding regulatory tasks are stated in Table 2.

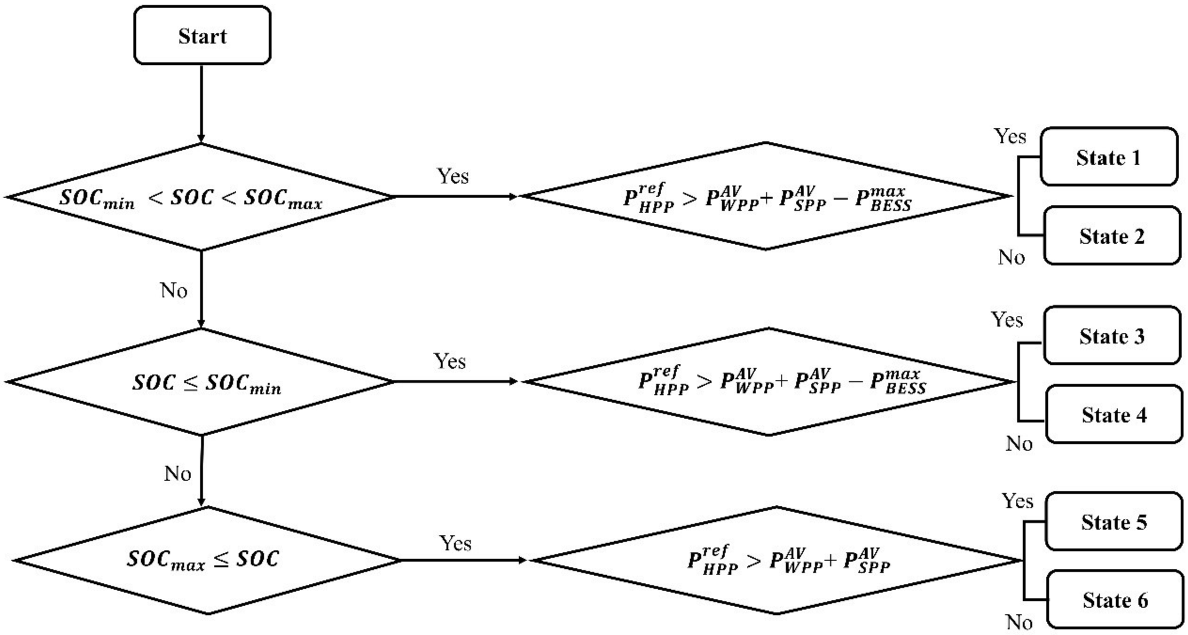


Figure 6. Hybrid power plant control algorithm for active power control (SOC- State of charge of BESS; SOC_{min} -BESS minimum state of charge; SOC_{max} -BESS maximum state of charge)

Table 2. Hybrid power plant dispatch

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

k-Participation factor for curtailment; PRF-Power reference following; MPPT- Maximum power point tracking.

When $SOC_{min} < SOC < SOC_{max}$

***State 1*:** Occurs when P_{HPP}^{ref} is more than the sum of the available power from WPP and SPP minus the maximum charging power of the BESS. In this situation, the supervisor HPP control strategy permits the WPP and SPP to operate at maximum power point tracking (MPPT), while the BESS follows a power reference to complement the WPP and SPP and fulfill the overall power requirement. The active power dispatch references in state 1 are defined as below.

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

$$P_{WPP} = P_{WPP}^{AV} \tag{1}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{2}$$

$$P_{BESS} = \min(P_{BESS}^{\max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}) \tag{3}$$

State 2: Occurs when the available power production from WPP and SPP exceeds the P_{HPP}^{ref}. First the HPP control checks the status of the battery and lets the BESS charge. When the BESS is fully charged, the HPP control strategy commences power curtailments proportionally if the HPP cannot inject all its power into the grid. The active power dispatch references in state 2 are defined as below.

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

$$P_{WPP} = kP_{WPP}^{AV} \tag{4}$$

$$P_{SPP} = kP_{SPP}^{AV} \tag{5}$$

$$P_{BESS} = -P_{BESS}^{\max} \tag{6}$$

When $SOC \leq SOC_{min}$

State 3: State 3 is like state 1, the supervisor HPP control strategy permits the WPP and SPP to operate at maximum power point tracking (MPPT), but the BESS remains in charging condition.

i.e.

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

$$P_{WPP} = P_{WPP}^{AV} \tag{7}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{8}$$

$$P_{BESS} = \min\left(0, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}\right) \tag{9}$$

State 4: Occurs when the available power production from WPP and SPP exceed P_{HPP}^{ref}. As HPP cannot inject all its power into the grid, when the BESS is fully charged, the HPP controller commences power curtailments.

i.e.

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

$$P_{WPP} = kP_{WPP}^{AV} \tag{10}$$

$$P_{SPP} = kP_{SPP}^{AV} \tag{11}$$

$$P_{BESS} = -P_{BESS}^{\max} \tag{12}$$

When $SOC_{max} \leq SOC$

State 5: If the power reference is greater than the available power from the wind and solar subsystems, the supervisor HPP control strategy permits the wind and solar plants to generate power at their maximum point, and the BESS can discharge if there is a difference between the reference and measured power.

***i.**e.*

If $P_{HPP}^{ref} > (P_{WPP}^{AV} + P_{SPP}^{AV})$

$$P_{WPP} = P_{WPP}^{AV} \tag{13}$$

$$P_{SPP} = P_{SPP}^{AV} \tag{14}$$

$$P_{BESS} = \min(P_{BESS}^{\max}, P_{HPP}^{ref} - P_{WPP}^{AV} - P_{SPP}^{AV}) \tag{15}$$

State 6: When the available power from WPP and SPP exceeds the power reference, the BESS enters standby mode and the supervisory HPP control strategy initiates power curtailments.

***i.**e.*

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

$$P_{WPP} = kP_{WPP}^{AV} \tag{16}$$

$$P_{SPP} = kP_{SPP}^{AV} \tag{17}$$

$$P_{BESS} = 0 \tag{18}$$

Here the main purpose of the HPP control framework and algorithm is regulate the active power and to ensure HPP output follow the power reference send by the HPP EMS.

3. Assumptions and Assets Data

In this study, various assumptions were made to establish a balance between simulation time and accuracy.

- For utility-scale HPPs comprised of several wind turbines and PV units, modeling is achieved by integrating these units into larger systems as used by [34] to increase simulation speed and decrease processing requirements.
- Solar irradiance and wind speed are assumed to be consistent for all PV modules and wind turbines; however, cloud movement and wind speed variations are probable for large SPP and WPP.
- Temperature is not considered in models of PV modules and batteries.
- WPP, SPP, and BESS losses are not assessed.
- Economic and marketing variables are left out of the simulation.
- The maximum quantity of energy that the HPP may inject into the grid cannot exceed the total amount of energy available from all technologies.

3.1. Wind Turbine

The electrical data [33] for the wind turbine (type IV) is illustrated in Table 3.

Table 3. Wind turbine data

Parameters	Value	Units
Nominal Power	5	MW
Type	VSWT	-
Gear ratio	99.2	-
Rotor diameter	63	M
Rotor interia	354440467	kgm^2
Generator interia	534	kgm^2
Pitch controller KP	2	-
Pitch controller KI	2.2	-

3.2. Solar PV Module

The 40 MW PV plant is considered to consist of a total of 1,666,67 numbers of fixed-type PV panels and the rated capacity of each of the PV panels is considered 240 watts. Table 4 illustrates the PV module parameters [34].

Table 4. PV module specifications

Parameters	Value	Units
Open circuit voltage	54.9	V
Short circuit current	5.45	A
MPP voltage	44.2	V
MPP current	5.1	A
PV array power	240	W
Nominal operating cell temperature	45	Degree
Reference temperature	25	Degree
Irradiance	1000	W/m^2
Constant a	0.00055	K^{-1}
Constant b	0.5	K^{-1}
Constant c	0.00288	K^{-1}

3.3. Battery System

A Lithium-ion battery is selected as an energy storage in this system. The battery capacity is assumed to be constant and equal to 10MW. Electrical parameters [35] of the battery is illustrated in the Table 5.

Table 5. Electrical parameters of a battery

Parameters	Value	Units
Cells in series	65	-
Cells in parallel	60	-
Internal resistance per cell	0.001	Ohms
Ah rating of battery	120	Ah
Maximum battery voltage	13.85	V
Minimum battery voltage	12	V
Minimum SOC	0.2	in %
Maximum SOC	0.9	in %

3.4. Sizing of HPP

Here the exact sizing of the HPP plant and its assets is not within the scope of this work. For simplicity, the authors selected close to Vattenfall's renewable controller design parameters [30] for the size of HPP and its asset, which is illustrated in Table 6.

Table 6. Sizing of hybrid power plant

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

4. Simulation and Results

To evaluate the performance of the supplied HPP model and control algorithm, a sequence of simulations is performed on HPP consisting of 24 X5 MW Type 4 WTs, 40 MW of PV, and 10 MW of battery storage. Simulations are conducted with a constant wind velocity (12 m/s) and solar irradiation of 1000 W/m^2. It is assumed that BESS has adequate capacity to be charged or discharged, and its SOC is set to 0.5 per unit.

4.1. Normal Operation

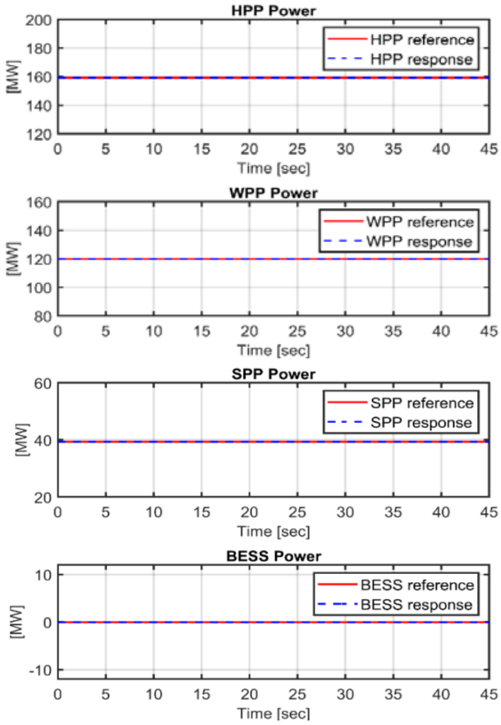


Figure 7. Active power response of the HPP and assets at the PCC during normal operation

Figure 7 illustrates the active power output of the entire HPP and its assets at PCC during normal operation. During normal operation, the WPP and SPP operate in MPPT mode, and the BESS remains on standby i.e., neither charge does not discharge. In Figure 7 during the whole simulation time the power requirement for HPP is provided by the WPP and SPP and BESS do not have to participate with any power.

4.2. Step Change in Active Power Set Points

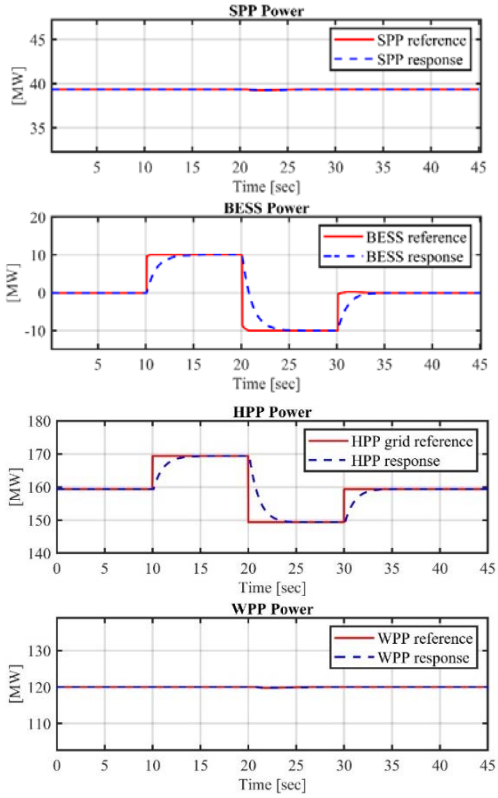


Figure 8. Active power response of the HPP and assets at the PCC at various power reference signals

As illustrated in Figure 8, it is observed that during the first 10 secs and the last 15 secs, it performs under normal operation where WPP and SPP produce maximum available power whereas, BESS is on standby. At 10 seconds the EMS system imposed the rise in demand from 160 MW to 170 MW. This increase in demand of 10 MW is met by the BESS, since WPP, and SPP is operating in MPPT mode. At 20 seconds, the HPP power is reduced to 150 MW. As a result, the control system lets the BESS charge otherwise; the excess must curtail. As expected, the power output responds a few seconds later as a communication lag exists between the two control levels. This is because the activation speed of the asset depends on how quickly it can communicate with the central controller.

5. Sensitivity Analysis

5.1. Power Curtailments

When there is more power generation and BESS is charged, the control strategy needs to curtail the excess power. Figure 9 illustrated the power curtailment scenario. During the first 10 secs and the last 25 secs, the WPP and SPP operate at MPPT. It should be noted that BESS neither charges nor discharges. At 10 secs there is a step change in HPP and the HPP output reduced from 160 to 140 MW. 10 MW is used to charge the BESS and remaining excess power is curtailed from the WPP and SPP. The curtailment is being done proportionally from both WPP and SPP.

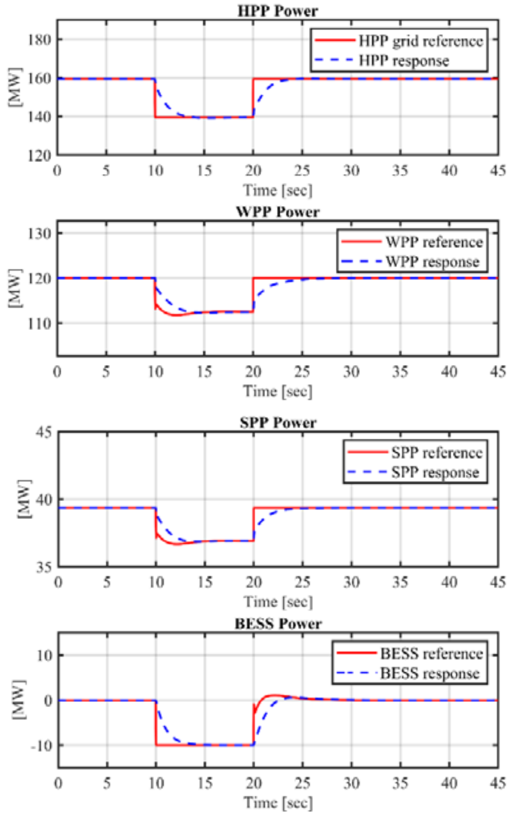


Figure 9. Active power response of the HPP and assets at the PCC during curtailment

5.2. Zero Wind Production (Highly Sunny)

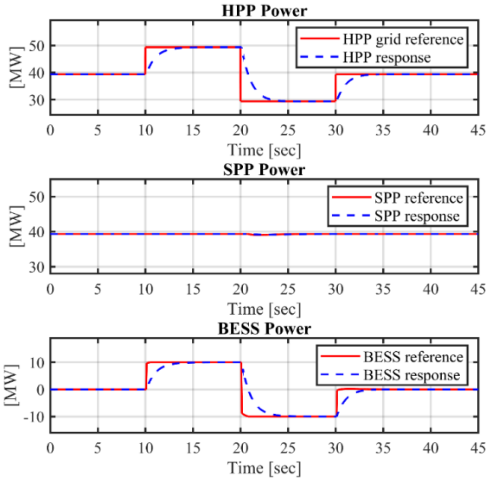


Figure 10. Active power response of the HPP and assets at the PCC during no wind production

In this case study, the power from the wind resource is deemed insufficient for wind production, as the wind speed is below the cut-in i.e., 2m/s speed. In contrast, solar radiation maximizes the generation of solar energy while BESS is assumed to have sufficient capacity to be either charged or discharged. Figure 10 shows the responses of both the entire HPP and the assets when there is no contribution from WPP.

5.3. Zero Solar Production (Night Time)

During the night, the solar resource produces no energy. In contrast, wind resources maximize wind energy production. The BESS responses i.e., discharging/charging as soon as it receives the reference power signal from the HPP controller. Figure 11 shows the responses of both the entire HPP and the assets when there is no contribution from SPP.

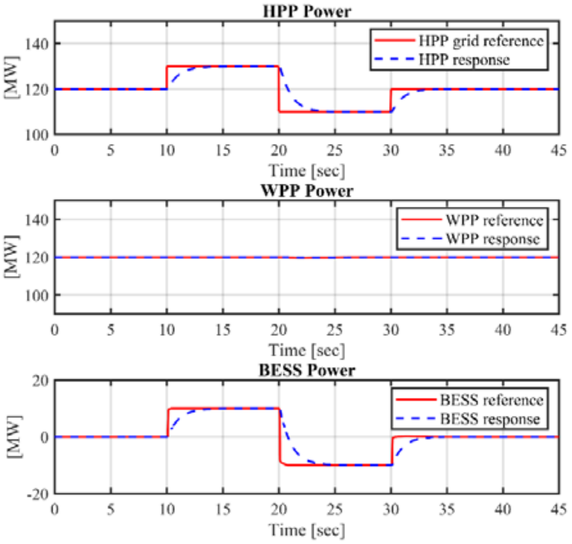


Figure 11. Active power response of the HPP and assets at the PCC during the night

5.4. Zero Wind and Solar Production

Figure 12 demonstrates that the power output of the BESS is equivalent to the total response of the HPP when wind and solar power outputs are both at zero. BESS exhibits the required behavior throughout the simulation.

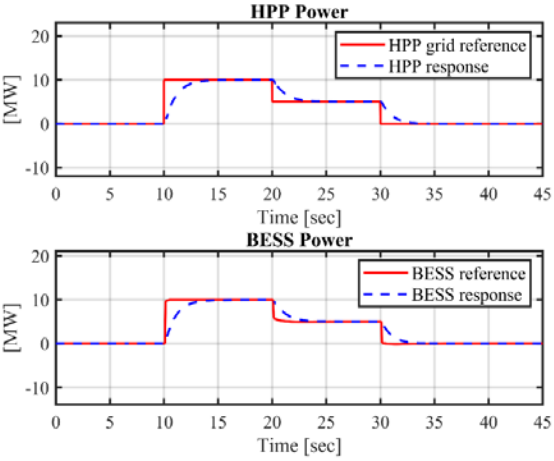


Figure 12. Active power response of the HPP and assets at the PCC at zero wind and solar production

5.5. Wind and Solar Irradiance Variability

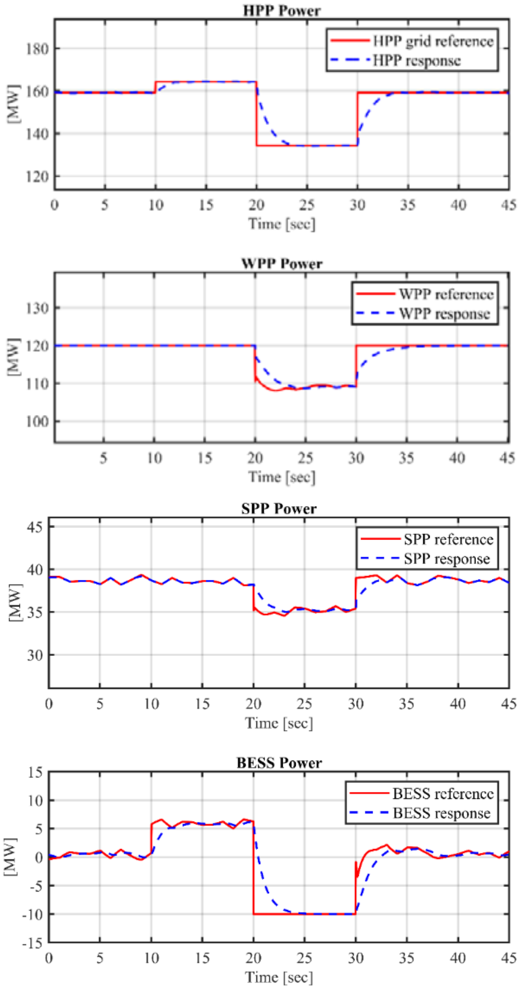


Figure 13. Active power response of the HPP and assets at the PCC under variable wind speed and solar irradiance

For the simulation tests described above, both wind speed and solar irradiance are constantly maintained. However, weather conditions fluctuate, hence it is necessary to analyze the power response of the HPP-developed model under turbulent conditions. The statistics for wind speed and solar irradiation fluctuated between 12.5-12.9 m/s and between 980 - 1000 W/m^2 respectively. The power response is evaluated using the same reference signal as in the above condition 4.2. Figure 13 demonstrates that the power output satisfies the ordered signal. Note that the applied variation has no noticeable effect on the response's settling time or its stability.

6. Conclusion

This study focused on the ability of the HPP control strategy to govern optimal use of battery for the active power generation at PCC. For this purpose, a control approach is provided for the battery's contribution to utility-scale wind-solar-hybrid power plants, and the performance of the proposed control strategy is evaluated using MATLAB simulations and a thorough dynamic model. The model enhances the interaction between the controllers of the sub-technologies. The active power injection of HPP into the grid has been evaluated and discussed using simulations of a created generic model. The simulation results show that the proposed control strategy performs well and can coordinate and combine the power generation from WPP, SPP, and BESS. Further the results show that the proposed control strategy uses battery can contributing in reducing wind and solar power curtailment to meet the specified set points set by the EMS. The outcomes of this research can give insight into HPP developers, and how the EMS can be made responsible for holding the HPP controller accountable for meeting its power commitments at the PCC.

7. Recommendations

In this paper the battery energy storage system-based control strategy has been successfully developed in the HPP for active power generation. Additionally, a different hybrid energy storage including super capacitors, flow battery can be investigated. Control capabilities, such as reactive power and grid support functions and market engagement will be the focus of future research. The proposed control strategy can be tested in a real system, to validate its control capabilities.

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Nomenclatures

GHG	Green house gas
HPP	Hybrid power plant
AC	Alternative current
DC	Direct current
WPP	Wind power plant
SPP	Solar power plant
BESS	Battery energy storage system
AEP	Annual energy production
ESS	Energy storage system
SMES	Super conducting magnetic energy storage
R&D	Research and development
SOC	State of charge
PHS	Pumped hydro storage
PV	Photovaltic
ENSTO-E	European network of transmission system operators for electricity
PCC	Point of common coupling
SO	System operator
EMS	Energy management system
WTs	Wind turbines
SPVs	Solar photovaltics
PI	Proportional integral
$\mathrm{P_{HPP}^{EMS}}$	HPP power reference from EMS
$\mathrm{P_{HPP}^{PCC}}$	HPP power measured at PCC
$\mathrm{P_{HPP}^{PI}}$	HPP power to PI controller
$\mathrm{P_{HPP}^{ref}}$	HPP power reference to HPP controller
$\mathrm{P_{WPP}^{ref}}$	WPP power reference
$\mathrm{P_{SPP}^{ref}}$	SPP power reference
$\mathrm{P_{BESS}^{ref}}$	BESS power reference
$\mathrm{P_{WPP}^{AV}}$	WPP power available
$\mathrm{P_{SPP}^{AV}}$	SPP power available
$\mathrm{P_{BESS}^{AV}}$	BESS power available
$\mathrm{P_{WTs}^{ref}}$	WTs power reference
$\mathrm{P_{PVs}^{ref}}$	Solar PVs power reference
$\mathrm{P_{Battery}^{ref}}$	Battery power reference
$\mathrm{P_{WTs}^{AV}}$	WTs power available
$\mathrm{P_{PVs}^{AV}}$	Solar PVs power available
$\mathrm{P_{Battery}^{AV}}$	BESS power available
$\mathrm{SOC_{BESS}}$	BESS State of charge
MPPT	Maximum power point tracking
PRF	Power reference following
$\mathrm{SOC_{min}}$	BESS min state of charge
$\mathrm{SOC_{max}}$	BESS max state of charge
Pu	Per unit
MW	Mega watt

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