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Comprehensive Review About The Control Architecture Of Co-located Utility-scale Hybrid Power Plants: State-of-the-art And Future Directions

Soheil Pouraltafi-Kheljan[1], Moataz El-Sied[2], Mustapha-Amine Rahmani[2], Kaushik Das[1], Poul Ejnar Sorensen[1]

[1]: Department of Wind and Energy Systems, DTU

[2]: TotalEnergies

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26–28 SEPT ´23
COPENHAGEN DENMARK
organized by energynautics

Outline

- Introduction
- HPP Controller (HPPC)
- In the scope of this review
- Observations
- Hierarchical Control Architecture
- Challenges and Future Directions
- Conclusion

Introduction

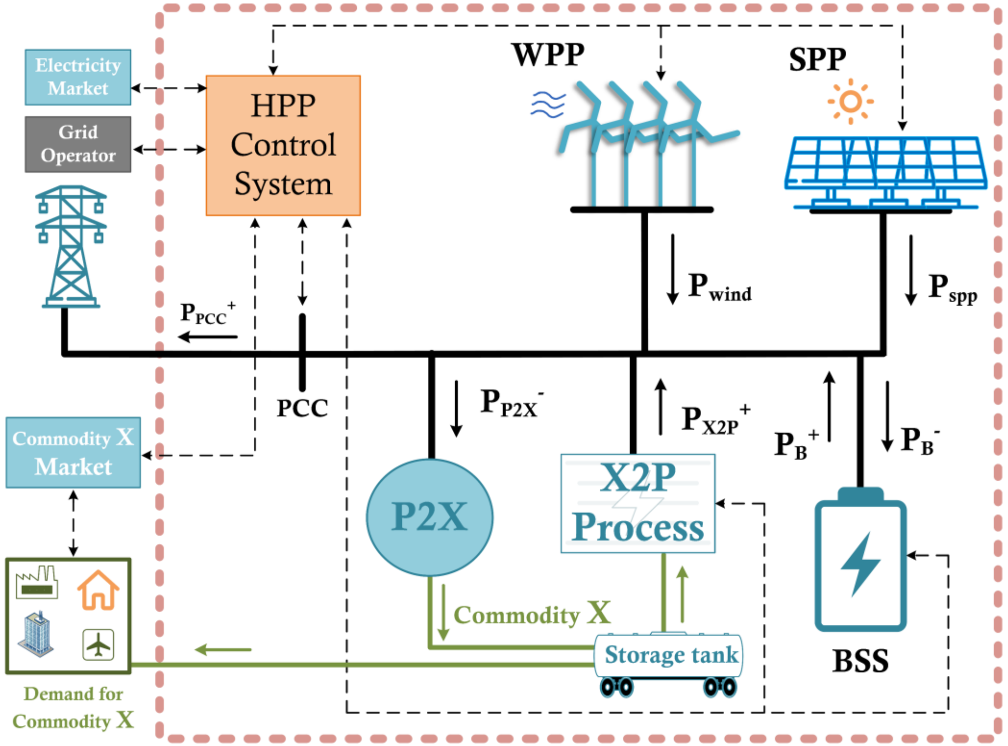
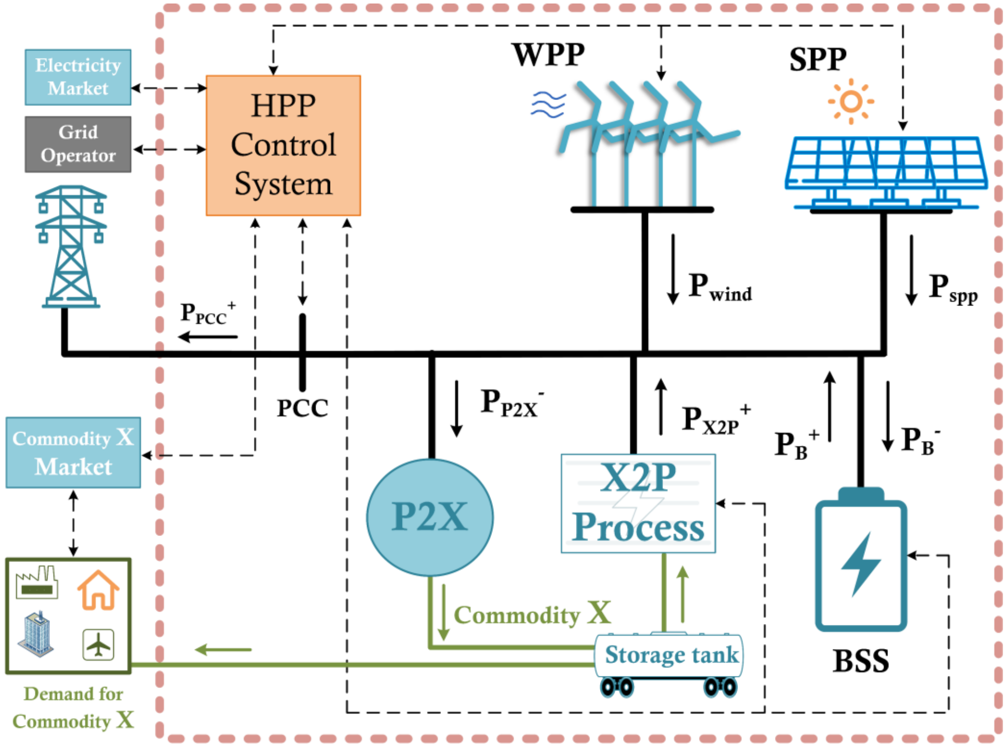


Fig. 1: Generalized illustration of hybrid power plants, where P, PCC, BSS, PV, WPP, and SPP stand for active power, point of common coupling battery storage system, wind power plant, and Solar power plant

- Hybrid Power Plants
  - *"The term HPP refers to a power-generating facility that converts primary energy into electrical energy and which consists of more than one power-generating module connected to a network at one connection point"[1]*
  - *"Co-Located Clusters of Inverter-Based Resources"* [2]

[1] WindEurope. 'Renewable hybrid power plants: Benefits and market opportunities', 2019.
[2] Haines,et al. 'The Impact of Co-Located Clusters of Inverter Based Resources on a Performance-Based Regulation Market Metric', 2022. 2022 North American Power Symposium (NAPS)

Introduction

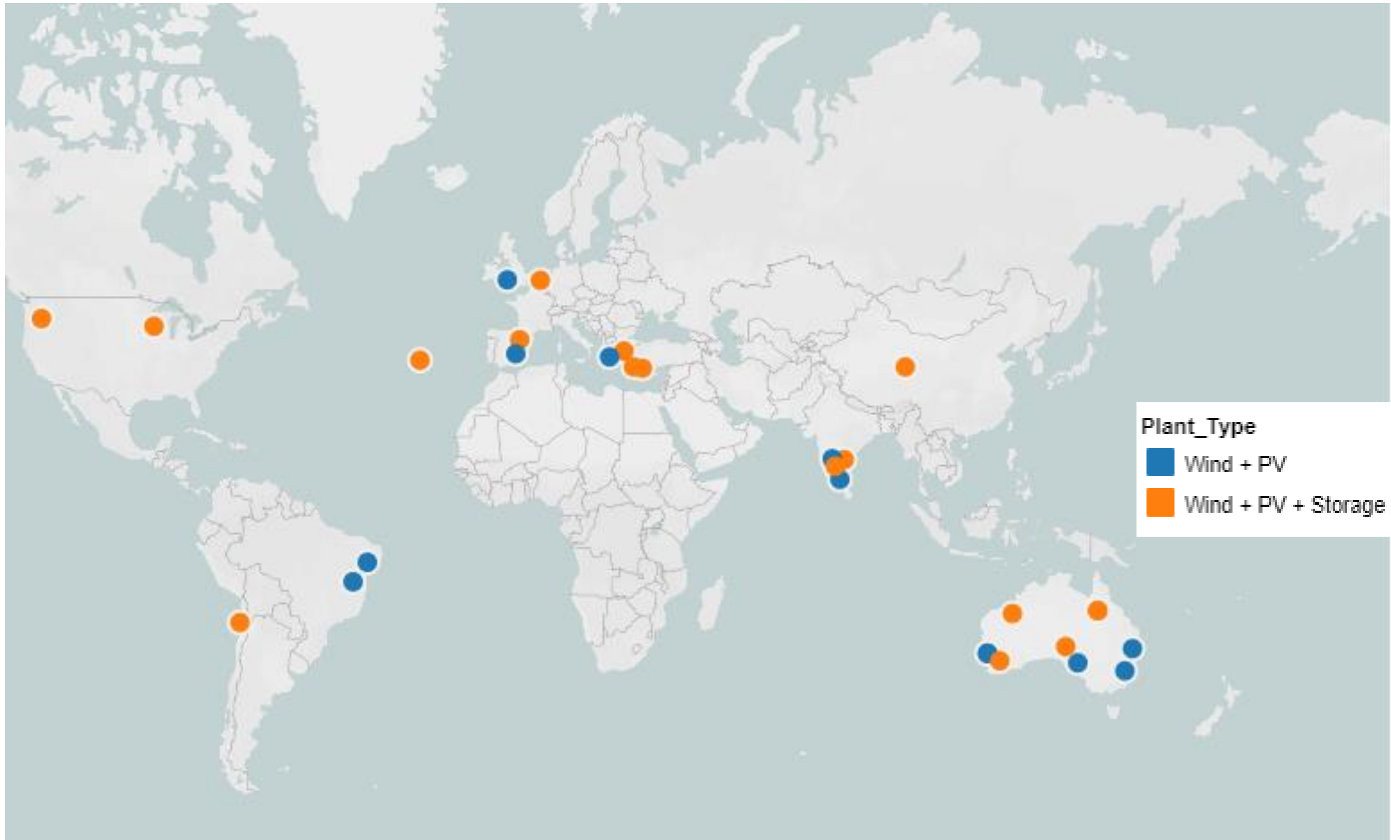


Generalized illustration of hybrid power plants, where P, PCC, BSS, PV, WPP, and SPP stand for active power, point of common coupling battery storage system, wind power plant, and Solar power plant

- Advantages [1,2]:
  – Optimized network use
  – Higher capacity factor
  – More dispatchable and stable power
  – Eased fulfillment of stakeholder demand
  – Reduced infrastructure expenses reduced electricity balancing costs

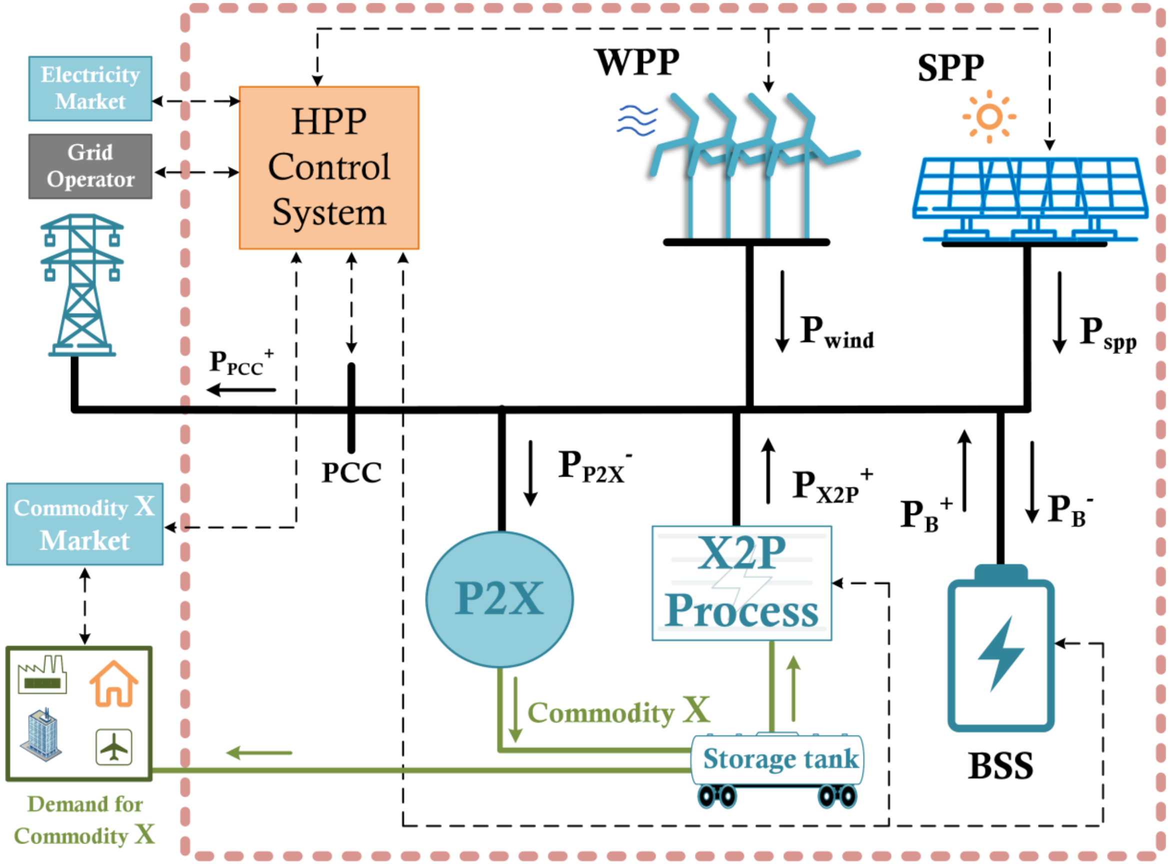
[1] WindEurope. 'Renewable hybrid power plants: Benefits and market opportunities', 2019.
[2] Clark, C., Barker, A., King, J., et al. 'Wind and Solar Hybrid Power Plants for Energy Resilience', 2022. NREL/TP-5R00-80415, 1842446, MainId:42618

- The number of such HPPs under development or already operating around the globe is limited and their business case is still under development or evaluation



Source: https://windeurope.org/about-wind/database-for-wind-and-storage-colocated-projects/

Introduction



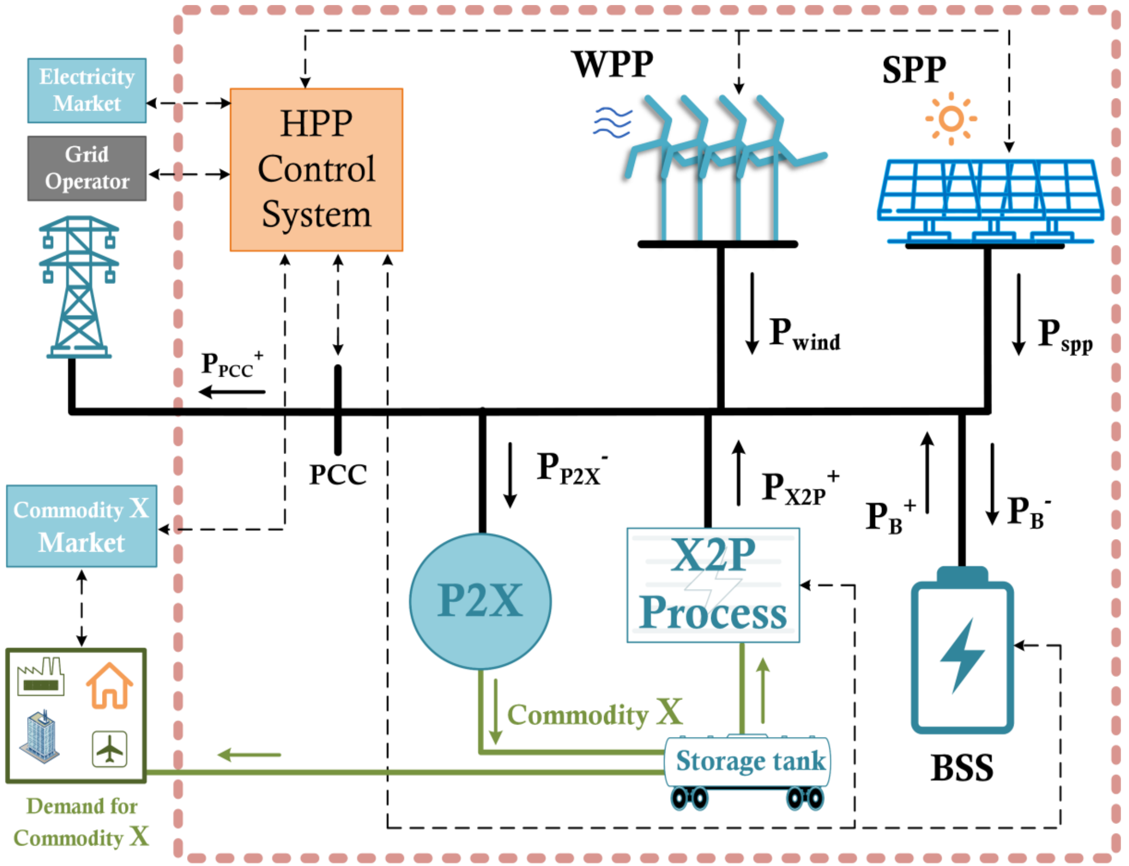
1. Co-Location [1]

2. Coordinated Control [1]

Dual Defining Characteristics

[1] U.S. Department of Energy (DOE). 2021. Hybrid Energy Systems: Opportunities for Coordinated Research.

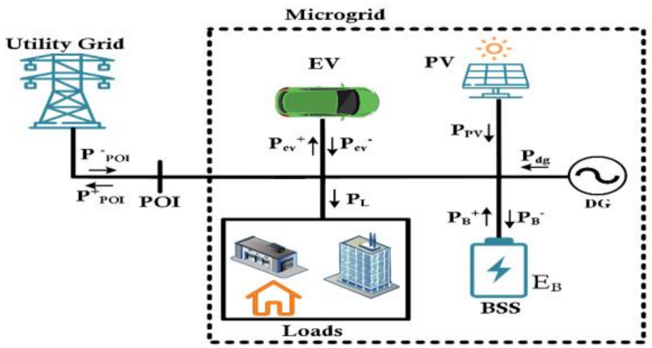
HPP Controller (HPPC)



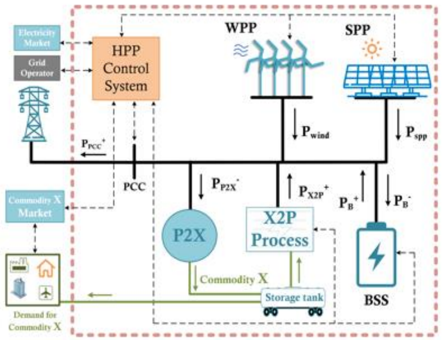
- Handling the interplay between disparate technologies.
- Robust against uncertainties
- Reliable for the dedicated services
- Represents the HPP as a single power-generating entity to the interconnected grid
- Contradictory to individual technologies, there is a notable scarcity of published integrated HPPC

In the scope of this review:

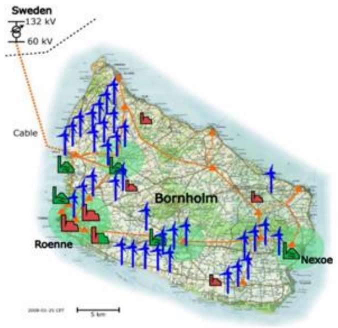
1. Stakeholders
2. Objectives
3. Structural attributes



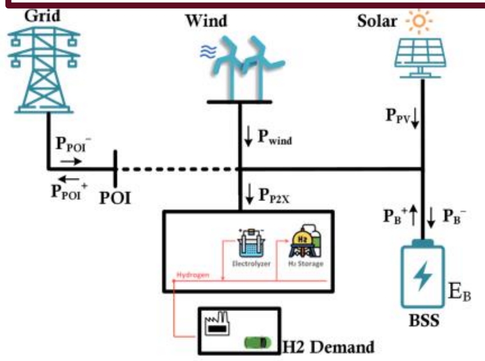
Microgrids (MG)



Hybrid Power Plant (HPP)

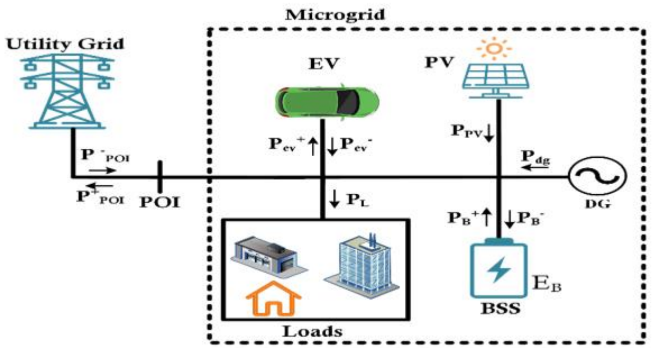


Hybrid Power Systems (HPS)

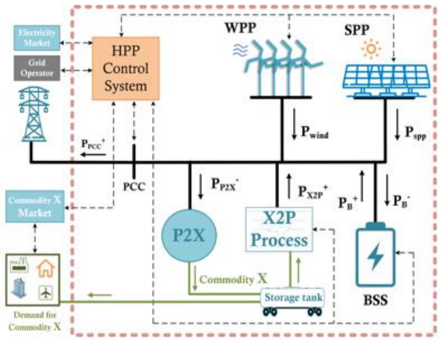


Hybrid Energy Systems(HES)

In the scope of this review:



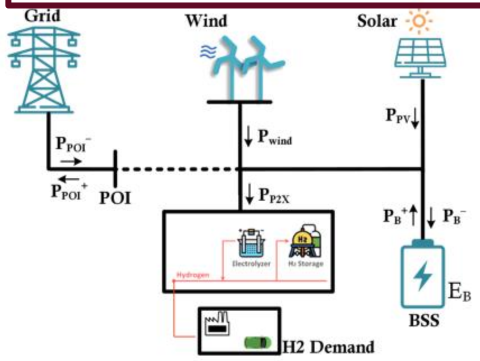
Microgrids (MG)



Hybrid Power Plant (HPP)

1. Co-Located
2. Coordinated Control
3. Grid-Connected
4. Utility-Scale
   - ➢ Several MW to a few GW

Hybrid Power Systems (HPS)



Hybrid Energy Systems(HES)

In the scope of this review:

1. Co-Located

2. Coordinated Control

3. Grid-Connected

4. Utility-Scale

[1] Raducu, A.G., Styliaras, N., Funkquist, J., et al. 'Design and Implementation of a Hybrid Power Plant Controller'. Third International Hybrid Power Systems Workshop, 2018.

[2] Das, K., Hansen, A.D., Adamou, P., et al. 'Dynamic Modelling of Wind-Solar-Storage Based Hybrid Power Plant'. 18th International Wind Integration Workshop, 2019.

[3] Wilches.Bernal, F., Haines, T., Darbali.Zamora, R., et al. 'A Resource Aware Droop Control Strategy for a PV, Wind, and Energy Storage Flexible Power (Flexpower) Plant'. In: 2022 IEEE Kansas Power and Energy Conference (KPEC), 2022. pp. 1–5

[4] Haines, T., Darbali.Zamora, R., Jiménez.Aparicio, M., et al. 'The Impact of Co-Located Clusters of Inverter Based Resources on a Performance-Based Regulation Market Metric', 2022. 2022 North American Power Symposium (NAPS)

[5] Haines, T., Wilches.Bernal, F., Darbali.Zamora, R., et al. 'Flexible Control of Synthetic Inertia in Co-Located Clusters of Inverter-Based Resources'. In: 2022 IEEE Power and Energy Conference at Illinois (PECI), 2022. pp. 1–6

[6] Sahin, O., Alahmad, B., Raducu, A.G., et al. 'New Frequency Control Philosophy for Future Hybrid Power Plants', 2023.

[7] Alahmad, B., Sahin, O., Cassamo, N., et al. 'Coordinated control of hydrogen production based on wind power generation', 2023. 7th Hybrid Power Plants and Systems Workshop

[8] Ionita, C., Raducu, A.G., Styliaras, N., et al. 'Online Optimization and Control for Renewable Hybrid Power Plants', 2019.

[9] Long, Q., Das, K., Pombo, D.V., et al.: 'Hierarchical control architecture of co-located hybrid power plants', International Journal of Electrical Power & Energy Systems, 2022, 143, pp. 108407

[10] Attya, A.B., Vickers, A.: 'Operation and Control of a Hybrid Power Plant with the Capability of Grid Services Provision', Energies, 2021, 14, (13), pp. 3928

[11] Bakhtvar, M., Al.Hinai, A.: 'Robust Operation of Hybrid Solar–Wind Power Plant with Battery Energy Storage System', Energies, 2021, 14, (13), pp. 3781

[12] Vázquez.Pombo, D., Iov, F., Stroe, D.I.: 'A Novel Control Architecture for Hybrid Power Plants to Provide Coordinated Frequency Reserves', Energies, 2019, 12, (5), pp. 919

[13] Long, Q., Zhu, R., Das, K., et al. 'Interfacing energy management with supervisory control for hybrid power plants', 2021. pp. 347–351

[14] Long, Q., Das, K., Sorensen, P.: 'Hierarchical Frequency Control of Hybrid Power Plants Using Frequency Response Observer', IEEE Transactions on Sustainable Energy, 2023, 14, (1), pp. 504–515

[15] Pombo, D., Raducu, A., Styliaras, N., et al. 'The First Utility Scale Hybrid Plant in Europe, The Case of Haringvliet', 2021.

[16] Long, Q., Celna, A., Das, K., et al.: 'Fast Frequency Support from Hybrid Wind Power Plants Using Supercapacitors', Energies, 2021, 14, (12), pp. 3495

Table 1 Summary of reviewed literature regarding the included technology, topology, control, and ancillary service provision. In this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power storage system, grid support, optimized generation, output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and optimization, respectively.

Reference	Technologies					Topology		Control											Ancillary Services Provision	
								Objective			Type		Architecture		Strategies					
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	*P*	*Q*	Cen.	Distr.	Dymc.	Rule-based	Opt.	EMS	Frequency	Other
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓		✓	✓			Primary	
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓				Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓			Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓						Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓	✓				SI	
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓		✓	✓			FCR	
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓			mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓		FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓					SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓							
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

Observations

Table 1 Summary of reviewed literature regarding the included technology, topology, control, and ancillary service provision. In this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power storage system, grid support, optimized generation, output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and optimization, respectively.

Reference	Technologies					Topology		Control											Ancillary Services Provision	
								Objective			Type		Architecture		Strategies					
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	*P*	*Q*	Cen.	Dis	[illegible]	[illegible]	[illegible]	EMS	[illegible]	[illegible]
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓							
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓							
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓							
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓							
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓						
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓							
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓			mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓		FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓					SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓							
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

WPP, SPP, BSS technologies have been considered, except for two studies also have H2 electrolyzer or supercapacitor

Observations

Table 1 Summary of reviewed literature regarding the included technology, topology, control, and ancillary service provision. In this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power storage system, grid support, optimized generation, output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and optimization, respectively.

Reference	Technologies					Topology		Control											Ancillary Services Provision	
								Objective			Type		Architecture		Strategies					
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	*P*	*Q*	Cen.	Distr.	Dymc.	Rule-based	Opt.	EMS	Frequency	Other
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓		✓	✓			Primary	
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓				Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓			Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓						Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓									
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓								
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓									
Ionita et al. [8]	✓	✓	✓			✓		✓												
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓								FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓									
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓									
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

AC-coupled topology is addressed in all papers

AC/DC-coupled considered by only two of them

Observations

The active power control is included in all studies, however, the reactive power control loop has been considered in Three papers

Table 1 Summary of reviewed literature regarding the included technology, to . In this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power s on, output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and

Reference	Technologies					Topology		Objective			Type		Architecture			Strategies			Ancillary Services Provision	
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	P	Q	Cen.	Distr.	Dymc.	Rule-based	Opt.	EMS	Frequency	Other
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓		✓	✓			Primary	
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓				Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓			Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓						Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓	✓				SI	
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓		✓	✓			FCR	
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓			mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓		FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓					SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓							
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

Observations

All dynamic controller is PI(D).
rule-based controllers are for SOC-following, curtailment dispatch, etc.

Table 1 Summary of reviewed literature regarding the included technology, topolog
this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power storag
output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and optimization, respectively.

Reference	Technologies					Topology		Control												Ancillary Services Provision	
								Objective			Type		Architecture		Strategies						
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	P	Q	Cen.	Distr.	Dymc.	Rule-based	Opt.	EMS		Frequency	Other
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓		✓	✓				Primary	
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓					Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓				Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓							Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓	✓					SI	
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓		✓	✓				FCR	
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓				mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓			FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓				FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓						SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓								
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓					FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓		FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓				FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓				FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓				FFR, FCR, FRR	

Observations

The frequency services has been considered almost in every study

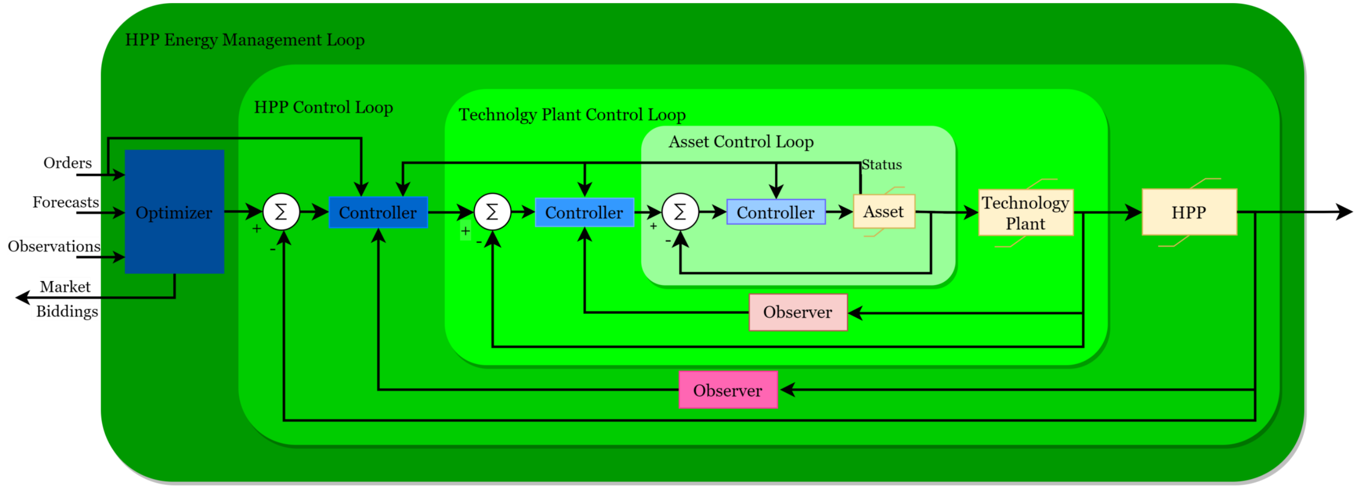
Table 1 Summary of reviewed literature regarding the included technology, topolog
this table, PSS, GS, OG, OS, Cen. , Distr., Dymc. , SI, and Opt. stand power storag
output smoothing, centralized, Distributed, dynamical, Synthetic Inertia, and optimization, respectively.

Reference	Technologies					Topology		Control											Ancillary Services Provision	
								Objective			Type		Architecture			Strategies				
	WPP	SPP	BSS	PSS	Other	AC	AC/DC	GS	OG	OS	*P*	*Q*	Cen.	Distr.	Dymc.	Rule-based	Opt.	EMS	Frequency	Other
Raducu et al. [1]	✓	✓	✓			✓		✓		✓	✓		✓		✓	✓			Primary	
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓				Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓			Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓						Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓	✓				SI	
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓		✓	✓			FCR	
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓			mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓		FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓					SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓							
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

Hierarchical Control Architecture

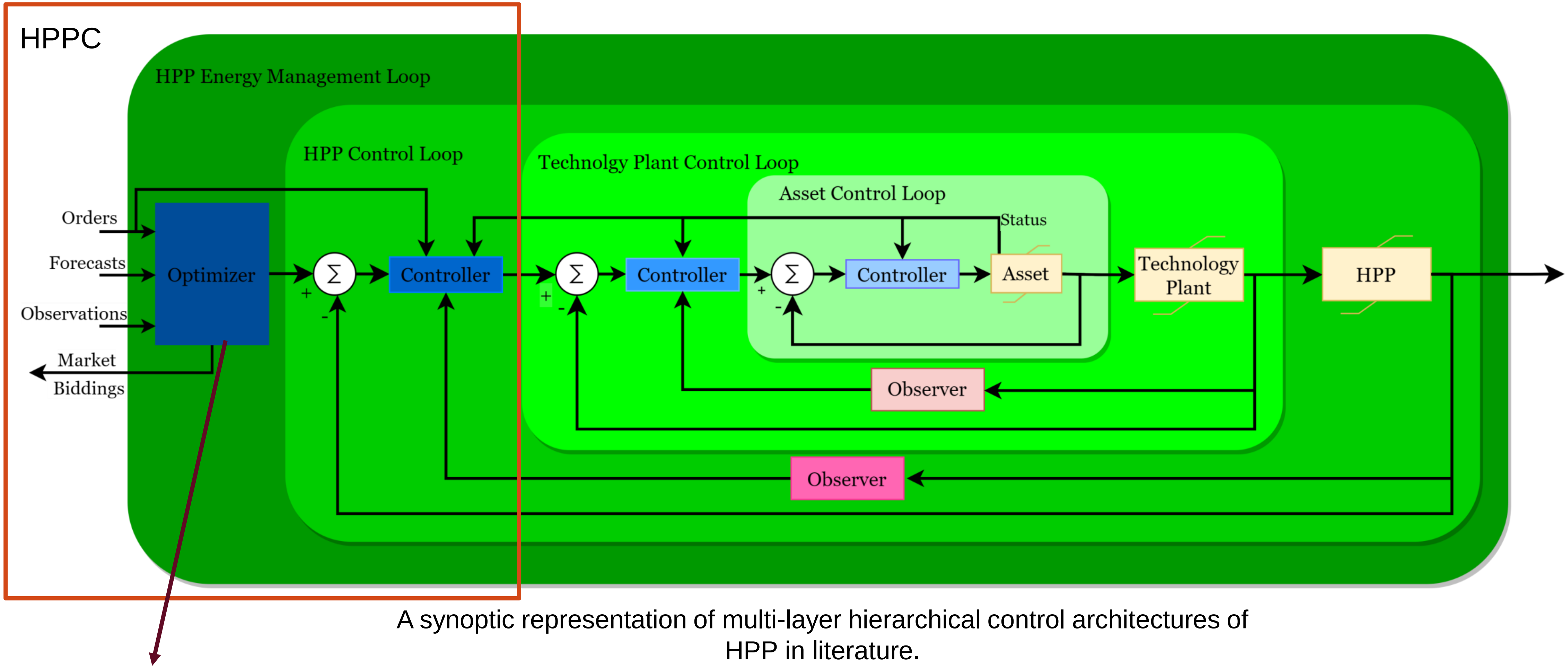
- Based on the presented literature review and common practice in the industry
  - Grid code compliance
  - Profitability: Optimal operation

- The benefits of hierarchical control include:
  - Increased scalability
  - Improved robustness
  - Reduced complexity



A synoptic representation of multi-layer hierarchical control architectures of HPP in literature.

Hierarchical Control Architecture



A synoptic representation of multi-layer hierarchical control architectures of HPP in literature.

Energy management System

A distributed approach is adopted for the implementation of frequency control at asset level (FFR, SI, FCR)

The centralized approach is adopted in the majority.

Table 1 Summary of reviewed lit… lo…
this table, PSS, GS, OG, OS, Cen… ag…
output smoothing, centralized, Di… im…

Reference	Technologies					Topology		Control											Ancillary Services Provision	
								Objective			Type		Architecture		Strategies					
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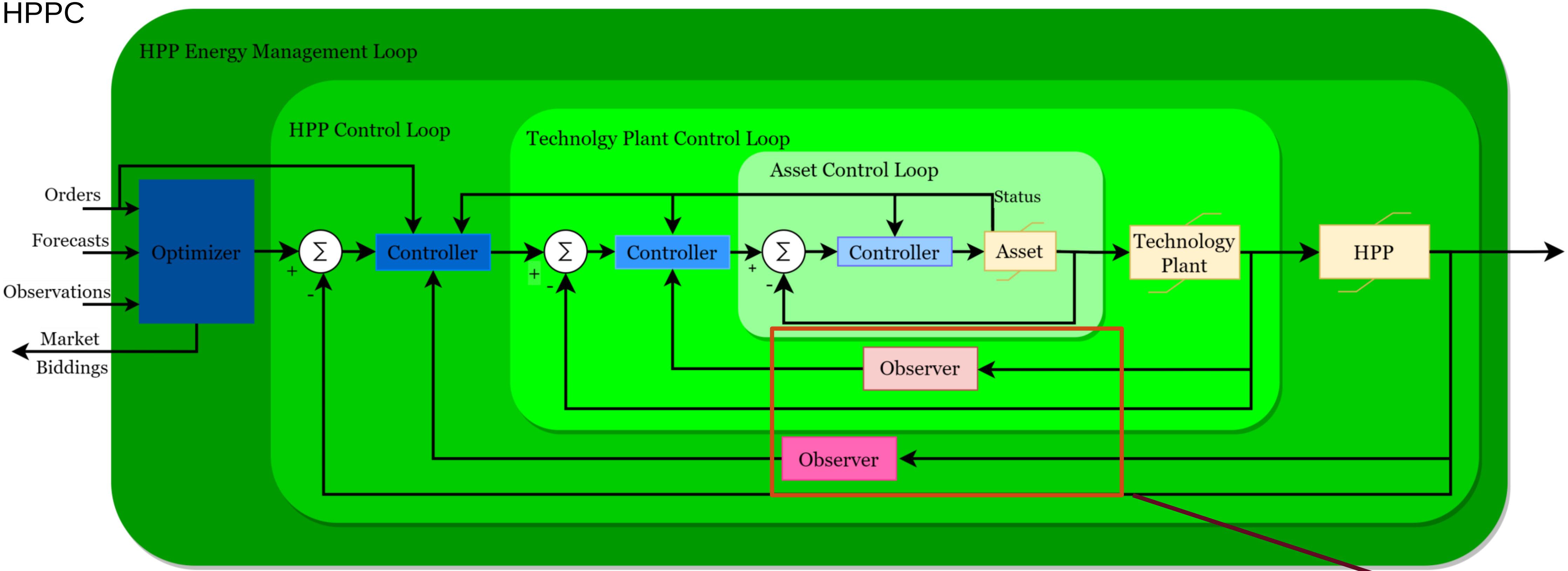
Das et al. [2]	✓	✓	✓			✓	✓	✓	✓		✓		✓		✓				Primary	LVRT
Wilches-Bernal et al. [3]	✓	✓	✓			✓		✓			✓		✓			✓			Primary	
Haines et al. [4]	✓	✓	✓			✓		✓			✓		✓						Secondary	
Haines et al. [5]	✓	✓	✓			✓		✓			✓		✓	✓	✓				SI	
Sahin et al. [6]	✓	✓	✓			✓		✓			✓	✓	✓		✓	✓			FCR	
Alahmad et al. [7]	✓				H2S	✓		✓	✓		✓		✓		✓	✓			mFRR	
Ionita et al. [8]	✓	✓	✓			✓		✓					✓				✓		FCR	
Long et al. [9]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR, FRR, FFR	FRT
Attya et al. [10]	✓	✓	✓			✓		✓			✓			✓					SI, Primary	
Bakhtvaret al. [11]	✓	✓	✓			✓		✓	✓		✓		✓							
Pombo et al. [12]	✓	✓	✓			✓		✓			✓		✓		✓				FCR, FFR	
Long et al. [13]	✓	✓	✓			✓		✓	✓		✓				✓	✓		✓	FCR, FRR, FFR	
Long et al. [14]	✓	✓	✓			✓		✓	✓		✓			✓	✓	✓			FCR, FFR	
Pombo et al. [15]	✓	✓	✓			✓		✓	✓		✓	✓	✓		✓	✓			FCR	
Long et al. [16]	✓	✓	✓	✓			✓	✓			✓			✓	✓	✓			FFR, FCR, FRR	

Hierarchical Control Architecture

HPPC



To estimate asset behavior and avoid the counteract from the higher levels [1]

[1] Long, Q., Das, K., Sorensen, P.: 'Hierarchical Frequency Control of Hybrid Power Plants Using Frequency Response Observer', IEEE Transactions on Sustainable Energy, 2023, 14, (1), pp. 504–515

Challenges and Future Directions

1. **Interaction of multi-layer and multi-vendor controllers**
   – the interaction between the voltage control at the technology plant level and asset level can cause oscillations in voltage and reactive power output [1]
2. **Service Stacking**
   1. At different levels and different time intervals
   2. a contraction between the services such that the realization of one specific objective could impede the achievement of another: Fault-ride-through [2]
   3. P2X: inaccurately capturing the dynamic behavior and its possible interactions with other assets effects delivery of the service [3].

[1] Fan, L., Miao, Z., Ramasubramanian, D., et al.: 'Operational Challenges of Solar PV Plus Storage Power Plants and Modeling Recommendations', IEEE Open Access Journal of Power and Energy, 2023.
[2] Long, Q., Das, K., Pombo, D.V., et al.: 'Hierarchical control architecture of co-located hybrid power plants', International Journal of Electrical Power & Energy Systems, 2022, 143, pp. 108407
[3] ozein, M.G., De.Corato, A.M., Mancarella, P.: 'Virtual Inertia Response and Frequency Control Ancillary Services From Hydrogen Electrolyzers', IEEE Transactions on Power Systems, 2023, 38, (3), pp. 2447–2459.

Challenges and Future Directions

3. **Black-start Capability**
   - shorter starting time of renewables + incorporation of ESS [1] shows good potential for HPP black-start capability
   - This will present a multi-stage procedure in which different control architectures might be adopted at each stage

[1] Zhao, C., Andersen, P.B., Træholt, C., et al.: 'Gridconnected battery energy storage system: a review on application and integration', Renewable and Sustainable Energy Reviews, 2023, 182, pp. 113400[2] Long, Q., Das, K., Pombo, D.V., et al.: 'Hierarchical control architecture of co-located hybrid power plants', International Journal of Electrical Power & Energy Systems, 2022, 143, pp. 108407.

[2] Kölle, K., Göçmen, T., Garcia.Rosa, P.B., et al.: 'Towards integrated wind farm control: Interfacing farm flow and power plant controls', Advanced Control for Applications, 2022, 4, (2), pp. e105 2447–2459.

[3]Dykes, K., et al.: 'Wind farm flow control: prospects and challenges', Wind Energy Science, 2022, 7, (6), pp. 2271–2306. publisher: Copernicus GmbH

4. Artificial intelligence (AI)-Driven Uncertainty Mitigation

1. Uncertainties pertaining to the power grid, such as faults and frequency disturbances
2. Weather and environmental-related uncertainties like wind speed and solar irradiance
3. Uncertainties associated with modeling parameters of BSS, P2X, storage tank, and re-electrification assets
4. Uncertainties connected with Electricity and commodity X markets, including variations in pricing and demand dynamic

- Identification of different sources of uncertainty and development of advanced dynamic modeling [1]
- controlling uncertain parameters via AI-driven model-free approaches [2].

[1] Shen, S., Sadoughi, M., Chen, X., et al.: 'A deep learning method for online capacity estimation of lithium-ion batteries', Journal of Energy Storage, 2019, 25, pp. 100817
[2] Liew, J., Göçmen, T., Lio, W.H., et al.: 'Model-free closed-loop wind farm control using reinforcement learning with recursive least squares', Wind Energy, 2023,

Challenges and Future Directions

5. Exposure to Communication Failure and Risk of Cyber-Attacks

- latency, reliability, and security of communication impact the operation and service quality, for example, communication delays may cause negative resistance, oscillations, and damping [1].
- Tightiz et al. [2] have applied the IEC 61850 information model to enable the Microgrid central controller to support the frequency restoration
- Developing new HHPs with new standards and their interconnection is easier but hybridizing already operating plants may require an update in the communication layer.

[1] an, L., Miao, Z., Ramasubramanian, D., et al.: 'Operational Challenges of Solar PV Plus Storage Power Plants and Modeling Recommendations', IEEE Open Access Journal of Power and Energy, 2023, PP, pp. 1–1

[2] Tightiz, L., Yang, H., Bevrani, H.: 'An Interoperable Communication Framework for Grid Frequency Regulation Support from Microgrids', Sensors, 2021, 21, (13), pp. 4555

Conclusion

- This study delves into the pivotal realm of control architecture for HPPs with a focus on co-located utility-scale grid-connected installations.
- The predominant architecture for HPPs is hierarchical control, known for scalability, robustness, and simplifying complex control systems.
- The control objectives have been achieved both in a centralized and distributed manner.
- The noted challenges encompass the need to further investigation of the matter

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