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Review

Aspects of Relevance of Hybrid Power Plants in Control and Stability of Weak Grids

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Abstract: This paper reviews the possible contributions of Hybrid Power Plants (HPPs) to support weak grids while maintaining the desired system stability. Moving towards a converter-dominant power system with less inherent inertia and distant connections to the nearest synchronous generator, frequency and voltage controls are becoming more critical to ensure the stability of the weak grid. In this regard, state-of-the-art literature is reviewed for frequency and voltage controllers in single-technology power plants, like wind and solar power plants. The contribution of this paper lies in providing a clear overview of available literature in terms of frequency and voltage control stages, regardless of the utilized control method. On the other hand, focus has been put on the increased utilization of HPPs to provide more flexibility, increased availability, and reduced variability through the combination of various sources, i.e., wind, solar, and storage. Furthermore, investigating the specific capabilities and challenges of HPPs, this review shows that very little literature has been conducted on voltage control using HPPs. Finally, the aspect of relevance of HPPs is discussed in the control and stability of modern power systems.

Keywords: frequency control; hybrid power plants; voltage control; weak grid

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1. Introduction

Prospects for clean energy production have profoundly changed the structure of modern power systems during the last decades [1]. With that in mind, renewable energy resources are clearly maintaining an increasing share of electricity generation due to environmental concerns and the maturity of the technological features as well as the improved economic aspects [2]. The EU climate and energy targets for 2030 are set to increase the share of renewables to at least 39% of EU energy use, while Denmark aims for at least a 55% share of renewables in the gross final consumption of energy use by 2030 [3].

This increased share of renewables will eventually lead to a more converter-dominant power system since the converter-connected generation is replacing conventional fossil fuel generators [4]. Therefore, since fewer conventional synchronous power plants are connected, the modern power system will be prone to frequency instabilities due to the lower inertia [5]. On the other hand, most of the potential installation sites to exploit clean energy are usually dominated by far locations with long and low-capacity connections to the nearest synchronous generator. This long and low-capacity connection to the nearest synchronous generator represents a high equivalent impedance which inevitably decreases the grid short-circuit current levels [6]. As a result, voltage stability assessments of such weak grids also become important since they face higher voltage sensitivity regarding reactive power compared to conventional strong grids [7].

Various solutions have been proposed in the literature to overcome the challenges regarding the lack of appropriate inertial response in the system [8–10]. The most recent research trends are focused on different methods of grid forming controls to improve the power system stability, e.g., droop-based controllers [11,12], the concept of the virtual synchronous generator (VSG) [13,14], synchronous power controller (SPC) [15], etc. The abovementioned methods have also been applied to different configurations of renewable energy resources (e.g., wind, solar, etc.) to demonstrate the different potentials and the provided capabilities [16]. Besides fast frequency control, the power system's need to maintain a steady frequency after an imbalance between generation and load asks for further frequency support through primary and secondary frequency controls, which will be discussed in detail in the following sections. Additionally, several solutions have been proposed considering reactive power and voltage control in the presence of wind and solar integrations; however, most of the present literature is focused on renewable single-technology power plants [17–20]. Voltage stability demonstrates the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. This can be further classified into small and large disturbance voltage stability [21]. Similar to frequency stability, voltage stability is categorized as short-term and long-term stability, depending on the time span of the controller action, and will be discussed in detail later on. It is also good to mention that several review papers have been published on frequency and voltage control in renewable single-technology power plants. To mention a few recent studies, papers [22,23] mainly focus on the definition and explanation of available frequency control strategies in wind and solar power plants while studying their impact on the stability of power systems. With a more generalized view concerning the massive integration of renewables, grid frequency stability challenges have been reviewed in [24], while [25] provides significant information about the models and parameters used in frequency control studies. Unlike frequency control, voltage stability issues in renewable-based networks have been less studied. Paper [26] classifies the implemented reactive power control techniques in solar power plants into fixed power factor, constant active power control, and constant reactive power control. Explaining the basics of each method, the paper shows that the simultaneous implementation of two control methods can improve the stability of the system. Also, the robustness of centralized, decentralized, and distributed voltage control strategies to variations in grid characteristics have been evaluated in [27]. Considering the abovementioned reviews, a clear overview of the available literature in terms of frequency and voltage control stages, regardless of the utilized control method, has been neglected and will be covered in this paper.

Despite the above-mentioned challenges due to the increasing share of renewables, converter-based renewable generation will also provide new opportunities. In this regard, the converters can provide a faster control response compared to synchronous generators. However, due to the variable wind speed and solar irradiation, renewable energy resources usually demonstrate less availability than conventional thermal power plants [28,29]. Thus, renewable energy resources usually represent inherent volatility and uncertainty with a high dependency on environmental conditions [30,31]. As a consequence, the focus has been put on the increased utilization of Hybrid Power Plant (HPP) configurations in order to provide more flexibility through the combination of various sources, i.e., wind, solar, storage, etc. [32]. This way, more capabilities can be provided through HPPs which can demonstrate reduced variability and increased availability as well.

Based on the document published by WindEurope [33], HPP can be defined as a power-generating facility that produces electrical energy through more than one power-generating module, which all share one connection point to the network. It is good to mention that this definition covers a wide range of primary energy resources; however, this paper only considers the combination of renewable-based generation (wind and solar) with or without storage while referring to the term HPP. Based on this, several configurations of wind, solar, and storage have been discussed for co-located hybrid power plants in [34] which also briefly introduces pilot HPP projects running by Vestas as the first utility-scale HPP in the world. It is also good to mention that there are different types of HPPs, considering how the various generating modules are integrated. In this regard, as shown in Figure 1a, we can have WPP and SPP layouts that share the same grid connection point, or otherwise, Photovoltaic (PV) panels can be individually integrated with the Wind Turbines (WTs) (Figure 1b) [33]. Generally, both configurations can increase the capacity factor of installation, and thus, maximize the grid connection capacity usage. In addition to that, sharing the grid connection point and substation in both topologies can lead to reduced CAPEX and permitting time. Joint project development and O&M services as well as the adaptability of HPP based on different site conditions and the easier optimization of the substation sizing are also among the common advantages of these two topologies. The first topology shown in Figure 1a is developed more than the other one since the configuration is simpler and more flexible to develop and size with storage integrated. The other topology is an alternative where solar inverters can be eliminated in certain cases, and therefore, the evacuation capacity of WTs can be used for solar power in this configuration. On the other hand, the connection and metering processes of these topologies are new to the authorities and standardization is yet needed. Furthermore, the second topology faces additional challenges, e.g., potential shading of PV panels from WT blades, limited PV capacity due to WT's power export capacity and space, and the limitation of the provision of ancillary services since the solar inverters are not interfaced with the grid [33].

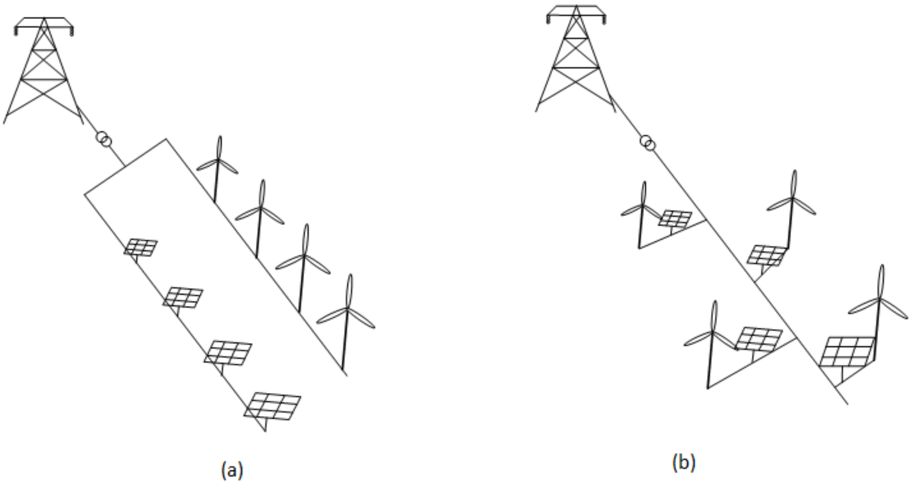

Figure 1. Different integration and operation configurations of various generating modules in HPPs, (**a**) WPP and SPP sharing the same grid connection, (**b**) PV panels integrated with the turbines.

The concept of HPPs has gained global attention lately due to the numerous advantages that come from combining renewable sources plus energy storage [35]. In this regard, a few advantages and benefits of HPPs can be mentioned as follows:

- A combination of wind and solar power enhances the system efficiency and power reliability since the variability and power fluctuations will be less here than in an individual RES due to the complementary nature of wind and solar energy. It is good to mention that as the negative correlation becomes stronger, the utilization of the grid connection will be better while the energy output will be more balanced [36].
- In addition to that, power curtailment in future power systems with a large integration of renewables will become more viable in the presence of the storage unit. While generating hydrogen for future use in a fuel cell can offer long-term storage solutions, battery stacks and supercapacitors are considered short-term storage options [37]. The literature shows an expanded interest in hydrogen energy storage systems during the past years which can improve operational efficiency as well as the environmental sustainability of this technology. By ensuring a reliable power supply, reducing costs, and increasing flexibility, the hydrogen energy storage industry has essential effects on HPPs [38]. Also, the flexibility of battery energy storage in providing both ramps up and down in active power output within short time responses can improve the HPP capability of frequency support [39]. In this regard, fast frequency support from HPPs has been proposed by [35] which considers integrating supercapacitors into the HPP configuration.

- Another important aspect of HPPs is the optimal utilization of the electrical infrastructure and its enhanced controllability. Since wind and solar plants have low-capacity factors, the electrical infrastructure remains unutilized most of the time in single-technology power plants. Therefore, combining these technologies together can increase the annual energy production and capacity factor while reducing the LCOE as well [36].

On the other hand, the hybridization of single-technology power plants can face some challenges. Coupling renewable energy with a battery behind the point of interconnection can reduce the operational flexibility of the battery since the charging and discharging cannot be conducted independently anymore [40]. In addition to that, there are only a few hybrid-specific policy schemes currently available since HPP is a new development. In this regard, if specific challenges of HPP are neglected, costs and uncertainty will arise. Also, it is good to mention that another aspect that needs to be standardized for HPPs is metering. Finally, in order to benefit from the complementarity of wind and solar generation, the total capacity of the installed HPP must be higher than the existing grid connection capacity. At the same time, developers need to be flexible in sizing requirements based on the optimized generation output of the HPP [33]. Overall, a summary of the pros and cons of hybrid power plant projects has been provided in Table 1.

Table 1. Overview of pros and cons of HPP projects [33,36].

pros	cons
Better grid utilization by increasing capacity factor	Reduced operational flexibility of the battery
Potential reduction in variability	Uncertainty related to future policy schemes
Potential increase in Net Present Value of investment (NPV/CAPEX)	Metering needs to be standardized
Increase in availability	Sizing the plant
Increase in ancillary service capability	

Considering the current literature, frequency and voltage control have been individually studied in a few papers concerning HPP-like configurations. However, there is an obvious gap in reviewing these methods and categorizing them for comparison purposes; this will be covered in this paper.

This paper studies the possible contributions of hybrid power plants in weak grid control architectures in order to maintain the desired stability criteria. Therefore, the contributions of this review paper can be listed as follows:

- State-of-the-art literature is reviewed for both frequency and voltage stability challenges in single-technology power plants in Section 2. The novelty of this paper compared to previous studies lies in providing an overview of available literature in terms of frequency and voltage control stages, regardless of the utilized control method.
- In Section 3, the current literature has been studied for frequency and voltage controls of hybrid power plants and the shortcomings have been mentioned. The novelty of this review shows that very little research has been conducted on voltage support and reactive power control using HPPs which highlights the need to contribute more studies to this field.
- Finally, in Section 4, the aspects of the relevance of HPPs will be discussed in the control and stability of modern power systems since this technology has been gaining more and more attention recently.

2. Control Approaches in Single-Technology Power Plants

In this section, various frequency and voltage control approaches are reviewed for single-technology power plants based on the existing literature.

2.1. Frequency Control

Following a major power imbalance, three main stages can be distinguished within the typical frequency response of the power system, as demonstrated in Figure 2: Fast Frequency Response (FFR), Frequency Containment Reserve (FCR), and Frequency Restoration Reserve (FRR) [41,42].

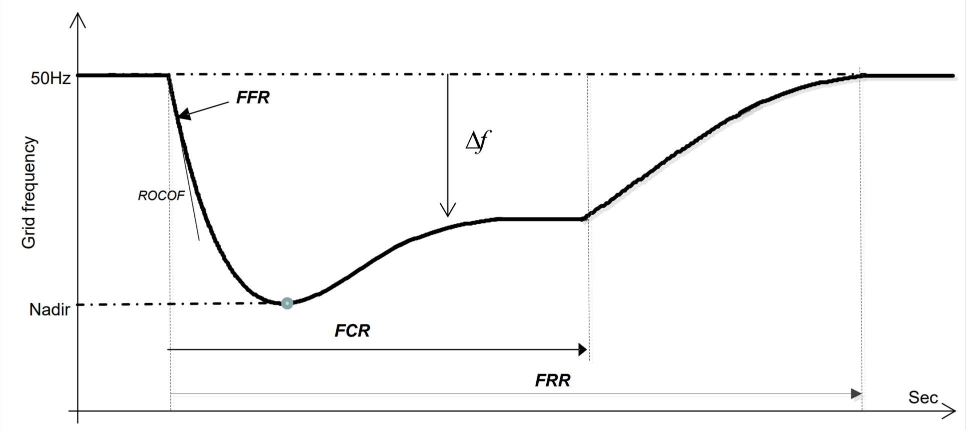

Figure 2. Frequency response contribution stages [41].

FFR is the fast reaction of the generators (or the converter-based generation units) to the active power and frequency dynamics of the power system. This stage has been traditionally named inertial response (IR) since it was associated with the natural uncontrollable inertial response of the synchronous generators in the power system [43,44]. It is good to mention that the most recent definitions distinguish between the two. As mentioned by [45], the synthetic inertia of a unit is its controlled contribution of electrical torque which is proportional to the Rate of Change of Frequency (ROCOF); FFR is defined as its controlled contribution of electrical torque, which is quickly responding to frequency changes to counteract the effect of a reduced inertial response. To clarify, the synthetic inertial response can be considered as a subset of FFR. The detection time for FFR including the frequency measurement is typically less than one second while the recovery time during this stage should be less than 10 s [41]. Following FFR, FCR refers to an automatically activated corrective measure for power balancing and bringing the frequency to a steady state in a generation unit while FRR adjusts the active power set points to recover the nominal frequency value of the generation units. It is good to mention that the last two stages are also called Primary Frequency Response (PFR) and Secondary Frequency Response (SFR) in the literature [46,47]. It is also good to mention that the full activation time for FCR lies over some seconds (typically less than 30 s) while FFR is expected to restore the system frequency to the nominal value within 15 min after the event occurrence [41].

Various control strategies have been proposed in the literature in order to support the active power and frequency dynamics of the power system, considering single-technology power plants. The importance of frequency control as a critical component of power system stability arises as the share of conventional synchronous generation decreases while integrating renewables into the power system. In this regard, wind and solar power plants are required to provide frequency support with or without auxiliary devices. These control strategies can vary in complexity and performance and reduce the frequency oscillations, i.e., droop and de-loading, load frequency control, inertia emulation, etc. [48–50].

Without auxiliary devices, frequency control can be classified into three categories in wind power plants [51]:

- Wind turbine level control such as inertial control [52], droop control [53], and de-loading control [54,55]
- Wind farm level control including central or local control methods [51,56,57]
- Power system level control such as wind-thermal coordination control.

Other than this, auxiliary devices including batteries [58,59], supercapacitors [60], flexible AC transmission systems (FACTS) devices [61], and superconducting magnetic energy storage (SMES) [62] can also be used to improve the frequency stability of wind power plants.

Similar to the above, for solar power plants, there are several frequency control methods that do not use any auxiliary devices, including the inertial response technique [63], de-loading technique [64], grid forming control techniques [65], artificial neural network [66–68], and other soft computing approaches [69]. This is while battery storage systems [70], flywheel energy storage [71,72], and superconducting storage devices [73,74] can also be used as auxiliary devices for frequency control in solar power plants.

Table 2 represents an overview of the proposed frequency control methods, considering Wind Power Plants (WPPs), Solar Power Plants (SPPs), and storage units. The above-mentioned approaches are further classified into fast frequency control (FFC), primary frequency control(PFC), and secondary frequency control (SFC) for each case. In addition to that, plant level controllers (P) and asset level controllers (A) have been distinguished for wind and solar power plants while the utilized storage technology has also been modified for each relevant case. The classification of the available literature in Table 2 shows that for frequency control in wind power plants, the controllers are applied at both the plant level and asset level (turbine level). This is while the majority of proposed frequency controllers using solar plants are employed at the plant level. It is also good to mention that based on the reviewed literature, storage technologies are mostly used for PFC and solar plants seem to be rarely used for SFC. This table demonstrates the contribution of each technology in various frequency control stages and the neglected potential in each case.

Table 2. Overview of proposed frequency control methods in single technology power plants.

Ref.	**FFC**	**PFC**	**SFC**	**Wind Power Plant**		**Solar Power Plant**		**Storage Technology**
				P	**A**	**P**	**A**	
[75]		✓			✓			
[76]	✓	✓		✓				
[77]	✓				✓			
[78]	✓			✓				
[79]		✓			✓			
[80]	✓	✓		✓	✓			
[81]			✓	✓				
[82]	✓				✓			
[83]		✓			✓			
[84]	✓					✓		
[85]		✓				✓		
[86]	✓					✓		
[87]		✓					✓	
[88]	✓	✓					✓	
[89]	✓					✓		
[90]		✓				✓		
[91]	✓					✓		
[92]		✓				✓		
[93]	✓						✓	
[94]	✓						✓	
[95]	✓							Battery
[96]			✓					Battery
[97]		✓						Battery
[98]		✓						Flywheel
[99]		✓						Battery
[100]	✓	✓						Distributed
[101]		✓						Compressed Air
[102]		✓						Battery
[103]		✓						Battery
[104]			✓					Battery
[105]		✓						Battery

Among various frequency control methods applied at different frequency dynamic stages, the concept of grid-forming control has attracted a lot of attention in recent years. The increased implementation of renewable energy sources in the grid results in weaker networks which highlights the importance of frequency control as early as the synchronization stage of the renewable with the connected grid. This is why grid-forming controllers are becoming more and more popular, and the current frequency control literature is mostly focused on these controllers. Considering the important and increasing role of grid-forming controllers in the frequency stability of weak grids, Subsection 2.1.1 is dedicated to analyzing current trends in grid-forming controllers.

2.1.1. Analysis of Recent Trends in Grid-Forming Controllers

As previously mentioned, Grid-Forming (GFM) controllers can provide inertia support for grids to improve system stability. Considering their crucial role in ensuring reliable grid performance, it is important to discuss various GFM control methods. Explaining the changing dynamics of the grid, ref. [106] classifies grid-connected inverter control to Grid-Following (GFL) and grid-forming methods. Explaining the fundamentals of each approach, it is mentioned that GFM can maintain a stiff voltage operation under step phase changes in voltage phasors, while GFL might face voltage violations before resynchronization with the grid. Various studies explain different GFM control approaches in detail which can be categorized as follows: droop control, Power Synchronization Control (PSC), synchronous machine emulation controllers (e.g., Virtual Synchronous Generator (VSG) Control and synchronverter), Virtual Oscillator Control (VOC), etc. Describing each method thoroughly, ref. [107] investigates different characteristics of each method while introducing their typical application scenarios in the power system. Considering the most recent commissioned projects in Australia, the UK and the US, the current challenges of adding the GFM trend into the existing power systems have been discussed in [108], i.e., small signal and transient stability, stand-alone and grid-connected mode transition, over-current protection, and Fault Ride-through (FRT). Research shows that most of the GFM control methodologies are communication-less, dispatchable, and employ overcurrent protection. Also, besides the droop-based controllers, other approaches have tunable and adaptive virtual inertia and damping parameters [108]. It is also good to mention that some of the most recent publications in 2024 focus on the leading role of GFMs in future power systems. In this regard, ref. [109] assesses GFM performance and robustness across various operational scenarios using frequency and time domain simulations. This evaluation of controllers can reveal their strengths and weaknesses to properly select the most appropriate controller for each desired practical application. In addition to that, ref. [110] explores the basic and advanced GFM control methods to interpret their ability to enhance the overall system stability. Thus, detailed analysis and performance comparisons have been provided for advanced control methods such as predictive control, model predictive control, and adaptive control which utilize innovative algorithms and real-time data to improve the overall system efficiency.

2.2. *Voltage Control*

Most renewable energy sites are located far from the synchronous generation centers, and therefore, connected to the weak end of the grid [111]. The increasing share of renewable energy sources can lead to a number of major challenges in the grid, e.g., voltage rise, voltage fluctuations, interactions with voltage regulating devices, and reverse power flow [112]. In order to overcome these issues, various devices have been utilized by wind farms to provide continuous and discrete voltage control support as follows:

- Wind turbine converters: the rotor-side converters in Double-Fed Induction Generator (DFIG) [113] and full-scale turbines [114] are used to support reactive power and maintain appropriate voltage. Traditionally, voltage control, reactive power control, and power factor control can be applied to the converter. It should be noted that voltage control faces limitations based on the reactive power capacity of the converter [115]. Paper [116] proposes a variable droop gain control method that can use the full capability of each wind turbine converter to mitigate voltage fluctuations.

- On load tap changing transformer (OLTC): Reference [117] performs a reactive power-based voltage support assessment for wind turbines under stressed voltage conditions. In this regard, the wind power plant's voltage support capability is increased by controlling the tap-changing transformer.
- Capacitors/inductors: These elements can be used to provide suitable reactive power and voltage interactions with the grid [111].
- Other shunt devices such as static var compensators (SVC) and static synchronous compensators (STATCOM): there are several papers studying various capabilities of SVC [118] and STATCOM [119–121] to improve the voltage stability of the power system.

However, combining several of these technologies requires coordination to avoid unintended or even destabilizing operations. Thus, coordinated controls have been proposed and studied in the literature. These control methods can be further categorized as centralized, decentralized, and distributed control [27]. It is also good to mention that considering the computational burden in the central control methods or the complexity of the communication network in the decentralized control strategies, a hybrid control method is proposed in [122] which uses the distributed consensus control and the central model predictive control together.

In addition to that, optimization-based voltage controllers have also been studied in recent years [123]. In this regard, paper [124] proposes a reactive power and voltage control scheme considering the stochastic deviation from baseline wind power, while [125] proposes an autonomous wind farm voltage control strategy considering the impact of voltage support ability from the integrated grid.

The converters in solar power plants can also be utilized to regulate grid voltage (mostly during nighttime) [112,126]. Similar coordinated controls and optimization methods are utilized here as well. It should be noted that the voltage control problem is becoming more challenging in bulk power systems. The coordination process becomes more detailed and sensitive due to the increasing complexity and dimensionality, together with the growing stochastic and dynamic behaviors of these systems [127]. To overcome these limitations, artificial intelligence and machine learning-based approaches have been introduced recently. In this regard, several studies address the novel contributions of these methods in solar or wind power plants [128–133].

Table 3 presents an overview of the proposed voltage control methods considering wind and solar power plants and energy storage. The abovementioned controllers are further classified into fault ride-through (FRT), primary voltage control (PrVC), and secondary voltage control (SeVC) for each studied case. In this regard, FRT is the capability of a generation unit to remain connected to the grid during faults while injecting reactive power to support transient voltage [134]. In addition to that, PrVC has a short response time (several seconds) and is responsible for the regulation of voltage at the inner loop of control [135]. As an example, droop control is mostly used at the primary control level. On the other hand, the operation time of the secondary control is longer than the primary control (several minutes) [136]. At this control level, reactive power sharing, coordinated control, voltage quality, etc., are considered as the main objectives [137]. Following this, as in Table 2, plant level controllers (P) and asset level controllers (A) have been distinguished for wind and solar power plants in Table 3 while the utilized storage technology has also been modified for each relevant case. It can be seen that voltage control is mostly embedded through plant-level controllers in wind and solar power plants. Table 3 also shows that wind power plants are capable of providing voltage support in all three stages of FRT, PrVC, and SeVC. This is while solar plants have less potential in voltage support and mostly provide short-term services like FRT. In addition to that, it can be seen that storage technologies are only utilized for primary and secondary voltage control stages since battery performance is not suitable for fast dynamics.

Table 3. Overview of proposed voltage control methods in single-technology power plants.

Ref.	FRT	PrVC	SeVC	Wind Power Plant		Solar Power Plant		Storage Technology
				P	A	P	A	
[138]	✓			✓				
[139]	✓				✓			
[140]	✓				✓			
[141]	✓			✓				
[142]	✓			✓				
[119]			✓	✓				
[111]	✓	✓		✓				
[115]		✓	✓		✓			
[116]		✓			✓			
[117]		✓		✓				
[27]		✓	✓	✓	✓			
[122]			✓	✓				
[123]			✓	✓				
[124]			✓	✓				
[125]			✓	✓				
[143]	✓					✓		
[144]	✓						✓	
[145]	✓					✓		
[146]	✓					✓		
[112]		✓				✓		
[126]			✓			✓		
[147]		✓	✓			✓	✓	
[148]		✓						Battery in SPP or WPP
[149]		✓						Battery in SPP
[150]			✓					Battery in SPP

3. Control Approaches in Hybrid Power Plants

Similar to what has been discussed in the previous sections, HPPs can be used for voltage and frequency control. The first thing to mention here is the superiority of HPPs compared to single-technology power plants in reassuring power generation stability through having a higher number of converters. Due to their stochastic nature, the usage of one of these renewable sources can lead to the potential reduction or loss of power supply; using a combination of them, especially in the presence of an energy storage device provides an energy capacity that is less dependent on changes in climate conditions [151]. Another point to mention here is the problems that arise as the grid becomes weak. This will be more deeply discussed in the next section; however, it should be mentioned that very few studies have addressed voltage control in the currently available literature on hybrid power plants. For example, ref. [152] demonstrates the role of battery energy storage in the mitigation of rapid voltage fluctuations due to variations in solar and wind generation. In addition to that, ref. [151] uses statistical indices of solar irradiations and wind speed data to model the power flow and study voltage fluctuations in microgrids with an HPP configuration. A droop-based frequency and voltage control method is also proposed in [153] which uses energy storage to balance the renewable generation and the load to maintain stability.

There are relatively more studies on the frequency control of hybrid configurations. Most studies do not mention the specific HPP definition but have more or less the same layout. The combination of wind, solar, and one or more types of storage has been used in [154,155] while others combine one renewable source with storage [156–158]. It is also good to mention that some studies focus on more simple approaches like PID controllers and droop control [155,159–161], while others propose more advanced methods like virtual inertia [46], model predictive control [55,162], and hierarchical control [163]. Table 4 presents an overview of the proposed control objectives in hybrid configurations. To the best knowledge of the authors, there is very little literature on voltage support and reactive power control using HPPs. This highlights the need to contribute more studies to this field, which will be further discussed in the next section.

Table 4. Overview of proposed frequency and voltage control objectives in hybrid power plants.

Ref.	Frequency Control			Voltage Control			Included Technologies
	FFC	PFC	SFC	FRT	PrVC	SeVC	
[164]						✓	Wind + solar + STATCOM
[165]				✓			Wind + solar
[151]					✓		Wind + solar +generalized energy storage
[152]					✓		Wind + solar + storage
[153]		✓			✓		Wind + solar + battery
[154]	✓	✓					Wind + solar+ fuel cell + biomass
[155]	✓	✓					Wind + solar + conventional energy sources
[156]	✓						Wind + diesel generator + aqua electrolyzer+ fuel cell + battery
[157]	✓				✓		Wind + battery
[158]	✓	✓					Wind + energy storage
[159]	✓						Wind + solar + biogas + biodiesel generators + flywheel + battery
[160]	✓						Wind + solar + battery + diesel generator
[161]	✓	✓					Wind + solar + energy storage
[46]	✓	✓					Wind + solar + energy storage
[162]		✓					Wind + thermal power system + battery + fuel cell +aqua electrolyzer + diesel generator
[163]	✓	✓	✓				Wind + solar + energy storage
[166]	✓	✓					Wind + solar + diesel generator + energy storage + Superconducting Magnetic Energy storage (SMES) + static synchronous series compensator (SSSC)

4. Relevance of Hybrid Power Plants in Control and Stability of Weak Grids

Frequency and voltage stability (as the two main stability factors) have been studied in this paper for renewable single technology and also hybrid power plants. Following that, this section will address the relevance of HPPs in the control and stability of weak grids. The term weak grid corresponds to the small short-circuit ratio of the grid which can happen in the presence of long low-capacity lines of renewable connection to the grid. There are several challenges associated with weak grids such as fragile voltage and frequency support, weak fault ride-through capabilities, etc. [167]. Therefore, some control approaches are superior to others in weak grid operation which can easily happen while integrating large amounts of renewables to the grid. In this regard, the grid-following control should generally be used in strong power systems since it uses a phase-locked loop (PLL) to follow the operating phase angle of the grid and cannot provide any frequency or voltage support [168]. Several methods are proposed to improve the performance of PLLs and grid-following controllers in case of weak grid operation [169]. On the contrary, grid-forming controllers are more suitable under weak grid conditions since they are able to support grid frequency and voltage during disturbances [170].

It is important to mention that considering a weak grid scenario, the utilization of hybrid power plants can improve schedulable power dispatch and provide a more reliable power supply [33]. However, there are various challenges which need to be addressed as follows:

- Various control layers: There are several controllers at different control levels in an HPP (one more control level in HPP than in single-technology power plants) which highlights the necessity of coordination. The hierarchical control of HPPs has been proposed in [171] to address this issue. As shown in Figure 3, there are three main control layers: the HPP control level, the technology plant control level, and the asset control level from top to bottom. Each of these control layers provides appropriate command and parameter references for the lower control level. This is while system states and measurements are sent backward to the higher control levels as feedback signals. It is important to mention that these control layers have different time scales. In this regard, the higher-level controller should respond slower than the lower-level controller and vice versa. The appropriate and efficient collaboration of these control layers is of high importance in HPPs.

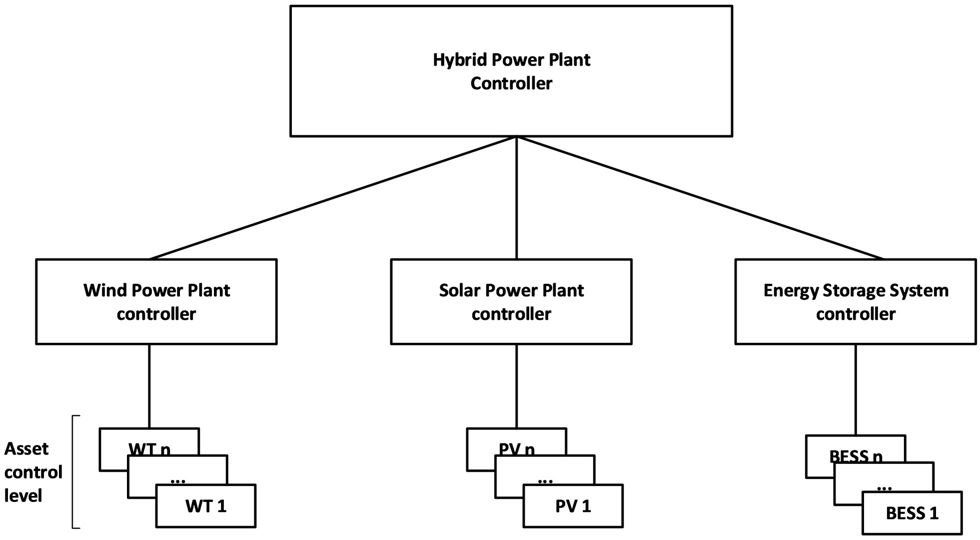

Figure 3. Generic structure of hierarchical HPP control.

- Oscillations: It is well known that a large gain in voltage control can lead to instability, especially when the grid is weak and the grid impedance is high [172]. Research shows that there are three main factors that can lead to the oscillations: communication delay between plant and asset level control, high volt/var sensitivity at a high power exporting level, and the volt/var feedback system consisting of plant and asset level controllers as well as the grid impact [173]. In this regard, we can see that lower grid strength and higher power exporting level can make the voltage more sensitive to reactive power, and the stability margin is reduced this way (because the grid is weak). Time delays regarding the various control levels and the interaction between them can be another source of oscillations and instability (because of the presence of HPP configuration). Other reasons for instability like insufficient damping in the PLL can be studied as well [174].
- Simulation study platforms: While some early studies show very few discrepancies (especially in the long-term stability of the system) between Electro-Magnetic Transient (EMT) and Root Mean Square (RMS) simulations [175], most recent studies emphasize the differences between the two. This is due to the shift in generation modules from synchronous generators to converter-based resources. In this regard, modeling challenges arise, including the need for EMT models and simulations since positive sequence simulators and phasor-based models are not adequate anymore to assess the transient stability issues [176]. The advantage of RMS over EMT simulation is that the simulation time will significantly reduce, and therefore, longer events and more complex systems can be simulated. However, this comes at the cost of losing fast electromagnetic transients. Therefore, it is important to consider the fact that numerous stability issues arise while integrating dominating amounts of converter-based generation that can only be accurately captured with EMT models [177].

In addition to the above, it should be mentioned that the large-scale integration of HPPs usually faces specific challenges and limitations. In this regard, several cases of large renewable integration around the world have shown stability challenges based on literature review and publicly available information. In Australia and Hawaii, a reduction in system strength due to the increased share of renewables has greatly limited the grid integration capacity of renewables. Also, in China and Texas, voltage oscillations at different frequencies have been reported. In these cases, the main reasons are believed to be the interactions between converter-based power plants in a weak grid, time delays in switching devices, and digital control. Various cases in Texas, Chile, and Nigeria show that as the sensitivity of dV/dQ grows in a weak grid, additional reactive power support is required to maintain voltage stability. Therefore, the connection of a reactive power supply has been proposed to improve the voltage control and reactive power support in such cases [178]. Considering the abovementioned challenges in this section together with the provided review of the available literature on HPP controllers in Section 3, the relevance of HPPs in the control and stability of weak grids remains almost untouched and requires further investigation in future studies.

5. Conclusions

This paper presents the aspects of the relevance of hybrid power plants in the control and stability of weak grids. In this regard, first, an overview of frequency and voltage control methods has been provided, considering renewable single-technology power plants (i.e., solar and wind power plants). These two main stability aspects have been discussed in detail since they are greatly affected by this reconfiguration of modern power systems due to the integration of renewables. To clarify, an increased share of renewables leads to a decrease in the inherent frequency support from synchronous generators, and therefore, various proposed approaches have been discussed and categorized to maintain appropriate frequency stability. At the same time, voltage stability sensitivity also increases since the renewable connection lines to the grid are long and low capacity, and thus, the grid becomes weaker. This issue makes voltage control strategies very important, and therefore, it has been discussed and categorized in detail for renewable-based power plants. The contribution of this review paper compared to the literature lies in providing a clear overview of the available literature in terms of frequency and voltage control stages, regardless of the utilized control method. Following that, the advantages and challenges of hybrid power plants have been discussed in detail since the technology has been gaining more and more attention recently. The current literature has been studied for frequency and voltage controls of hybrid power plants and the shortcomings have been mentioned. The novelty of this review shows that very little research has been conducted on voltage support and reactive power control using HPPs which highlights the need to contribute more studies to this field as mentioned in the last section. Finally, the current research questions and challenges of HPPs have been discussed, considering their relevance to the weak grid configuration.

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Abbreviations

CAPEX	Capital Expenditure
DFIG	Double-Fed Induction Generator
EMT	Electro-Magnetic Transient
EU	European Union
FACTS	Flexible AC Transmission Systems
FCR	Frequency Containment Reserve
FFC	Fast Frequency Control
FFR	Fast Frequency Response

FRR	Frequency Restoration Reserve
FRT	Fault Ride-Through
GFL	Grid-Following
GFM	Grid-Forming
HPP	Hybrid Power Plant
IR	Inertial Response
LCOE	Levelized Cost of Energy
OLTC	On Load Tap Changing transformers
O&M	Operation and Maintenance
PFC	Primary Frequency Control
PFR	Primary Frequency Response
PID	Proportional – Integral – Derivative
PLL	Phase-Locked Loop
PrVC	Primary Voltage Control
PSC	Power Synchronization Control
PV	Photovoltaic
RES	Renewable Energy Source
RMS	Root Mean Square
ROCOF	Rate of Change of Frequency
SeVC	Secondary Voltage Control
SFC	Secondary Frequency Control
SFR	Secondary Frequency Response
SPC	Synchronous Power Controller
SMES	Superconducting Magnetic Energy Storage
SPP	Solar Power Plant
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensators
VOC	Virtual Oscillator Control
VSG	Virtual Synchronous Generator
WPP	Wind Power Plant
WT	Wind Turbine

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