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Beyond 50 Hz, Unlocking Voltage and Frequency for More Flexible Grids

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ABSTRACT

The future grid needs to accommodate variable generation from a high share of renewables, together with frequent and large power variations from modern loads, such as massive charging stations and data centers. The grid therefore, needs to evolve to manage increasing uncertainty and intermittency through greater flexibility and controllability, particularly at the distribution level. This paper presents a vision of a clustered grid architecture enabled by power-electronic interfaces, which partition the grid into clusters comprising loads, generation, and storage systems. In the vision, power flexibility is unlocked by exploiting the dependency of power on voltage and frequency, enabling power regulation by adjusting these variables. As a result, each cluster functions as an active unit that supports bidirectional and controllable power exchange. The unlocked power flexibility enables clusters to provide a wide range of grid services, such as frequency and voltage support, power flow regulation, balancing services, while its power-electronic interface further supports fault isolation and disturbance buffering. This clustered structure enables a more robust and resilient power system. The proposed vision also discusses future market design, where price signals reflect grid conditions and service performance, thereby guiding and incentivizing cluster participation.

1 | Introduction

Electricity is considered the primary and most efficient energy carrier for achieving ambitious global plans for a fully carbon-neutral future [1]. Global renewable electricity capacity expansion between 2025 and 2030 is expected to be twice that of the 2019 to 2024 period, reaching approximately 4600 GW. This is equivalent to the combined current power generation capacity of China, the European Union, and Japan [2]. However, the phase-out of fossil-fuel power plants, coupled with the increasing penetration of renewable energy sources (RES) and electrification in transportation and industry, introduces critical challenges, including higher power uncertainty and variability, reduced system inertia, and the need for rapid and cost-effective capacity expansion. Addressing these challenges requires improved controllability and flexibility of the power system, particularly at the distribution level.

RES integration and electrification have already caused radical changes in the distribution system architecture. For instance, in Germany, over 50% of total solar energy capacity is installed at the low voltage (LV) level [3], thereby increasing bidirectional power flows within the distribution grid. However, as illustrated in Figure 1a, current grid infrastructures and operating principles are still largely designed for a synchronous machine-dominated and predominantly unidirectional power flow with limited automation and power controllability at the distribution level. Meanwhile, most loads are nonresponsive, and inverter-based resources (IBRs) are primarily operated to maximize energy output rather than support grid operation

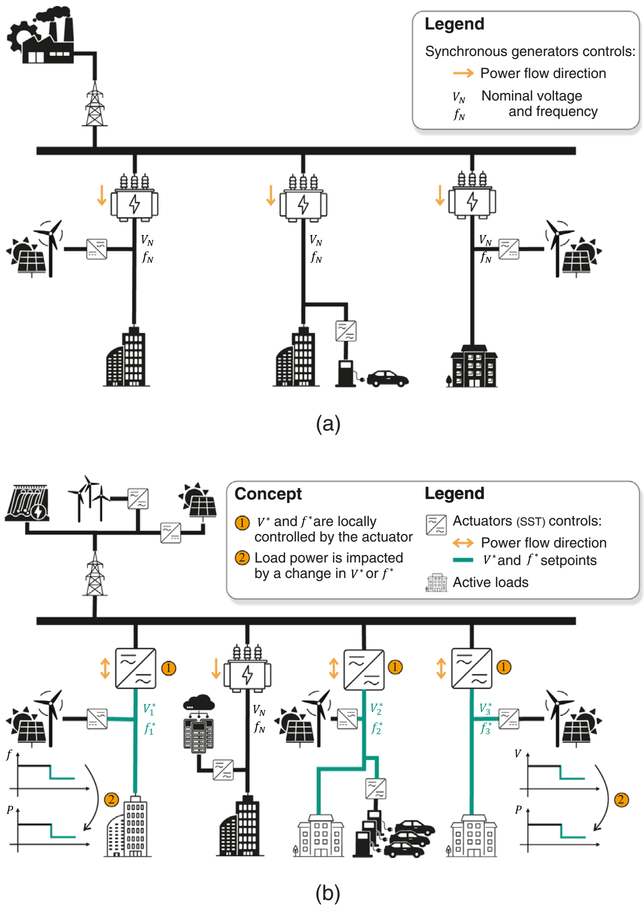


FIGURE 1 | Evolution of power system from (a) the current configuration: passive substations designed for a stiff synchronous grid dominated by synchronous machines, to (b) the proposed vision: flexible asynchronous clusters enabled by voltage and frequency control.

(except during severe disturbances). As a result, distribution grids exhibit limited controllability and flexibility creating bottlenecks for reliably and economically integrating higher share of RES and electrified loads.

At the same time, the need for power flexibility rises dramatically. Historically, power flexibility has been predominantly supplied by fossil-fuel power plants [4], most of which are expected to be phased out by 2050. Currently, dispatchable RES such as hydropower plants are increasingly taking over this role. However, relying solely on dedicated large generation units for flexibility is costly and inflexible, calling for new sources of flexibility.

To address this, are increasingly turning to decentralized distributed resources for flexibility. In many countries, a broader set of distribution-level devices, such as IBRs, electric vehicles (EVs), controllable loads, and DC systems (typically energy storage systems), are required to implement volt-watt [5], volt-var [6], and frequency response functions [7]. While these controls adjust active and reactive power to support voltage and frequency, the same coupling can also be leveraged in reverse to control active and reactive power by adjusting voltage and frequency, as illustrated in Figure 1b.

This principle enables a new pathway for unlocking power flexibility from existing grid and has already been applied in practice. For example, in the UK, voltage is adjusted at substations via on-load tap changers (OLTCs) to control power and participate in balancing services. Following the initial trial at sixty primary substations, the control scheme was subsequently expanded to an additional two hundred substations due to its significant economic benefits by unlocking power flexibility from the existing grid [8]. In this way, the power of a large number of devices can be controlled from a single point without communication, the dependency of power on voltage and frequency becomes a source of power flexibility, and the allowable operating ranges of voltage and frequency become a degree of freedom for power control.

This work extends this power control principle to a vision of a decentralized clustered grid architecture, in which power-electronic (PE) interfaces, such as solid-state transformers (SSTs), partition the grid into clusters comprising loads, generation units, and storage units, or subsets thereof. Each cluster can exchange bidirectional power and regulate its power by controlling voltage and frequency within the cluster. These controllable clusters can jointly provide various grid services, such as frequency and voltage support, power flow control, and balancing services, while PE interfaces enable additionally grid functionalities. This work aims to demonstrates how this clustered structure significantly enhances the flexibility and controllability of the grid, thereby enabling further RES integration and electrification.

The rest of the paper is organized as follows. Section 2 reviews the potential power flexibility that can be unlocked from voltage and frequency control and reviews existing works that deploy this control concept. Section 3 presents a vision of the clustered network, outlines the grid services enabled by the active clusters, and provides insights into market concepts to encourage and manage cluster participation. Section 4 presents candidate PE interfaces with a representative control framework. Section 5 discusses key challenges and future research directions to realize the vision, and Section 6 concludes the paper.

2 | Unlocking Power Flexibility Through Voltage and Frequency Modification

2.1 | Source of Flexibility: Power Sensitivity to Voltage and Frequency

The power sensitivity is defined as the dependency of power to voltage and frequency. The active power sensitivities to voltage, n_{pv}, and to frequency, n_{pf}, are expressed as:

$$n_{pv} = \frac{\Delta P \,/\, P_{\text{base}}}{\Delta V \,/\, V_{\text{base}}} = \frac{\Delta P(\%)}{\Delta V(\%)} \tag{1}$$

$$n_{pf} = \frac{\Delta P \,/\, P_{\text{base}}}{\Delta f \,/\, f_{\text{base}}} = \frac{\Delta P(\%)}{\Delta f(\%)} \tag{2}$$

where all variations are normalized to the corresponding base values P_{base}, V_{base}, and f_{base}. The same definitions apply to reactive power sensitivities to voltage n_{qv}, and to frequency n_{qf}. A positive sign indicates that a reduction in voltage or frequency leads to a reduction in power consumption. The power sensitivity varies

TABLE 1 | Representative devices that provide power sensitivity in distribution grids.

Power sensitivity	Representative devices
$P-V$	• Voltage-dependent loads (e.g., constant impedance, constant current)
	• IBRs with volt-watt control (e.g., PVs, storage systems, active distribution grid, DC microgrids)
$P-f$	• Frequency-dependent loads (e.g., electric motors)
	• IBRs with frequency response
$Q-V$	• Reactive power compensators (e.g., SVC, STATCOM, shunt capacitor/reactor bank)
	• IBRs with volt-var control (e.g., PV and/or wind systems)
$Q-f$	• Grid-connected inverters with Q–f droop (relatively fewer)

over time and can be identified online [9] by measuring power responses to small perturbations in voltage or frequency [10].

Table 1 categorizes representative devices in the distribution grid, providing the four types of power sensitivity. Active power sensitivity to voltage ($P-V$) mainly arises from the response of voltage-dependent loads [11] or volt-watt control of IBRs [12]. Among all sensitivity types, it has been the most extensively investigated in prior works, particularly in load modeling at both the device level [13] and the system level [14], as well as in demand control studies such as conservation voltage reduction (CVR) [15] and voltage-led demand management [8]. The reported results consistently demonstrate sufficient active power sensitivity to voltage across diverse regions, load types (residential, commercial, industrial) [13], and at temporal conditions (seasonal, weekday, and weekend variations) [16]. Moreover, the trend of requiring such power sensitivity from IBRs is becoming increasingly prevalent, as evidenced by various recent reports [17].

Regarding active power sensitivity to frequency ($P-f$), this behavior stems from frequency-dependent loads, such as directly connected motors, and IBRs equipped with frequency response capabilities [18]. For instance, the German grid code VDE-AR-N 4105 [19] requires generation units to reduce active power at a droop of 40% of P_{ref} per hertz above 50.2 Hz, where P_{ref} is the active power at 50.2 Hz. Similar active power to frequency droop requirements are adopted in many countries with comparable droop values [20]. The frequency response requirement is expanding to a broader set of devices and countries. For instance, ENTSO-E recommends default under-frequency support settings for EVs, electrolyzers, and heat pumps in Continental Europe to be added in future grid code updates [7].

The reactive power sensitivity to voltage ($Q-V$) behavior is provided by reactive power compensators, such as static var compensator (SVC) and STATCOM [21], as well as by IBRs equipped with volt-var control, such as photovoltaic (PV) and

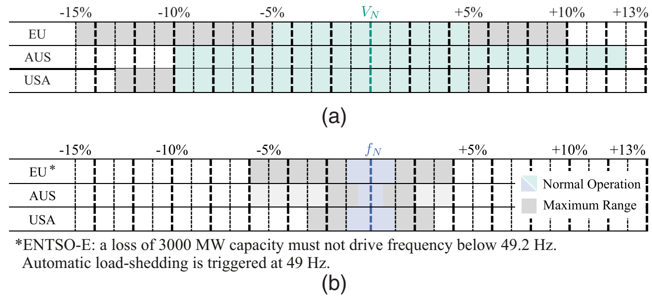


FIGURE 2 | Grid regulations on allowable (a) voltage and (b) frequency operation ranges.

wind systems [22]. Arising either from the physical impedance of connected devices or their internal voltage-dependent control schemes, distribution grids exhibit distinctive reactive power sensitivity to voltage. In contrast, distribution grids typically possess weak reactive power sensitivity to frequency ($Q-f$), as few devices are designed to adjust reactive power according to frequency deviations. Exceptions exist only in special cases, such as resistive microgrids that employ $Q-f$ droop control for grid-connected inverters [23].

Overall, these power sensitivities describe how active and reactive power respond to voltage and frequency variations. By leveraging these relationships, voltage and frequency can be maintained by adjusting active or reactive power. Conversely, voltage and frequency can be adjusted to regulate active and reactive power. This duality of voltage and frequency is discussed in detail in the following subsection and serves as the fundamental basis of our vision on the clustered grid.

2.2 | Allowable Voltage and Frequency Ranges: Control Requirement or Degree of Freedom?

Internationally, each region defines its own grid regulations on voltage and frequency tolerance band around the nominal values (V_N, f_N). Figure 2 summarizes specifications in representative regions: Europe (EU: German adoption (DIN) of the European standard EN 50160 [24]), Australia (AUS: Essential Services Commission AS 61000.3.100 [25]), and the United States (US: American National Standards Institute ANSI C84.1 [26]). Despite differences in how these limits are defined, all regulations clearly specify that the system may vary within small ranges (colored areas) during normal operation and within an extended range for limited durations (gray areas). While devices are designed to operate within the maximum allowable range, protection schemes are triggered before this limit. For instance, in synchronous area of Continental Europe, load shedding is triggered at 49 Hz [27]. Thus, the feasible voltage and frequency ranges must be coordinated with the thresholds of protection schemes.

These grid regulations may evolve towards greater flexibility. For example, Australia widened the allowed voltage range in the 2018 update of AS 61000.3.100 [25]. Moreover, experimental studies demonstrate that many loads can safely operate across a wider frequency range than specified in current grid regulations, particularly given the increasing prevalence of PE interfaces in both domestic and industrial loads [28]. The strict frequency regulation is primarily driven by the mechanical constraints (danger of mechanical resonances) of directly connected turbine-generator systems in large conventional power plants. As large synchronous machines fade out and parts of distribution grids decouple from transmission grid frequency constraints, frequency limits can be more relaxed in the future.

Even while complying with these regulations, voltage and frequency can be modified to control active and reactive power, and this concept is not entirely new. Existing field implementations and laboratory experiments have already demonstrated the feasibility of using the allowable voltage and frequency ranges as degrees of freedom, rather than treating them only as constraints to be maintained.

For instance, CVR exploits the active power sensitivity to voltage and reduces the voltage, typically toward the lowest permissible level, via OLTC over long durations (hours) to save energy and cut the demand peak. A national report in the US concludes that deploying CVR on only heavily loaded distribution feeders (40% of all feeders) achieves a 2.4% reduction in annual energy consumption [29]. Similarly, as mentioned in the introduction, the CLASS project in the UK reduces the voltage with OLTC to a desired value (not necessarily the lowest) in a short time frame of minutes for power balancing [30] and estimated that applying voltage control to 1/15 of total UK demand could reduce balancing service costs by approximately $244 million (across a 24 year period).

Furthermore, PE actuators enable more effective utilization of power flexibility. In [31], active power–frequency sensitivity is used to avoid reverse power flow by reducing downstream generation through frequency adjustment. In [32], the downstream active power is adjusted proportionally to upstream frequency variations, thereby supporting upstream frequency. Even when the apparent power capacity of the downstream controlled grid is only 5% of the upstream grid, the upstream RoCoF is reduced by nearly 50% and the frequency nadir is improved by 14%. In [33], the SST regulates downstream active power consumption to emulate inertia and provide frequency support, while the remaining converter capacity is utilized for reactive power compensation to support upstream voltage. Simulation results on the all-island Irish transmission system show that this coordinated control can increase allowable wind penetration by approximately 10% without additional storage.

These works showed that using voltage and frequency range as degrees of freedom, even within a small deviation (e.g., 3% [34]) and over a limited part of the grid [32], can already deliver significant benefits. However, most existing studies treat the distribution grid as a support for the transmission system. As the distribution grid grows in size and importance, coordinated operation and cooperative support among multiple distribution grids should be studied in the future.

3 | Vision: Redefining Roles of Voltage and Frequency in the Grid Design, Control, and Market Operations

3.1 | Dual Role of Voltage and Frequency in Clustered Grids

In our vision, as illustrated in Figure 3, the grid is partitioned into clusters (green circles) through PE interfaces. A cluster comprises the PE interface together with loads, generation units, and storage systems, or a subset thereof. Each cluster can control its voltage and frequency independently, while the remaining parts of the grid outside the clusters continue to operate synchronously. Power can flow into or out of a cluster (orange arrows), and its magnitude can be adjusted within a limited range by modifying the voltage and/or frequency of the cluster according to its power

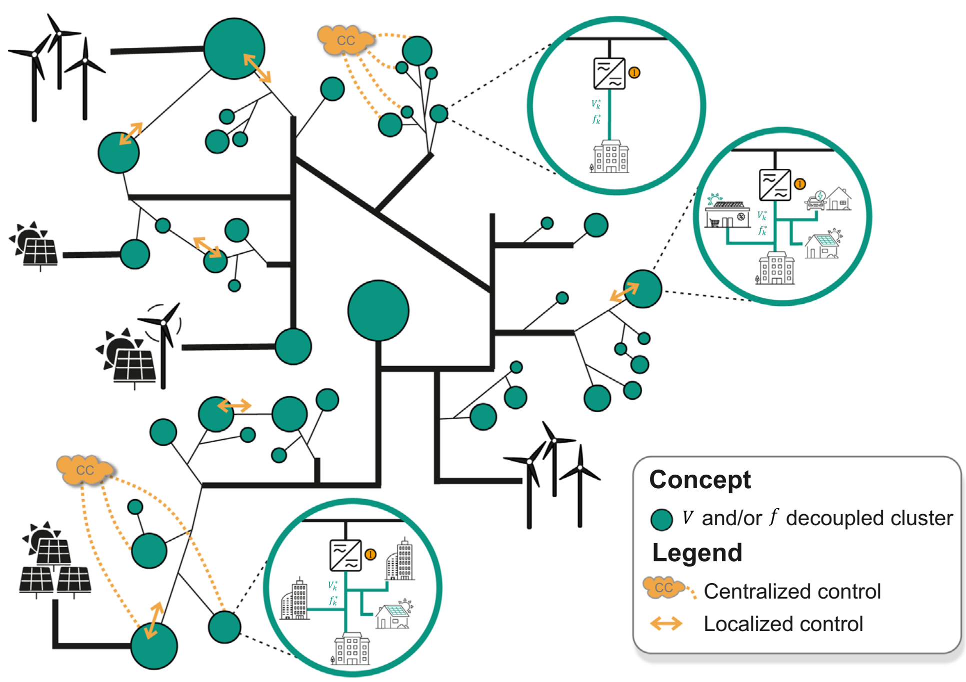
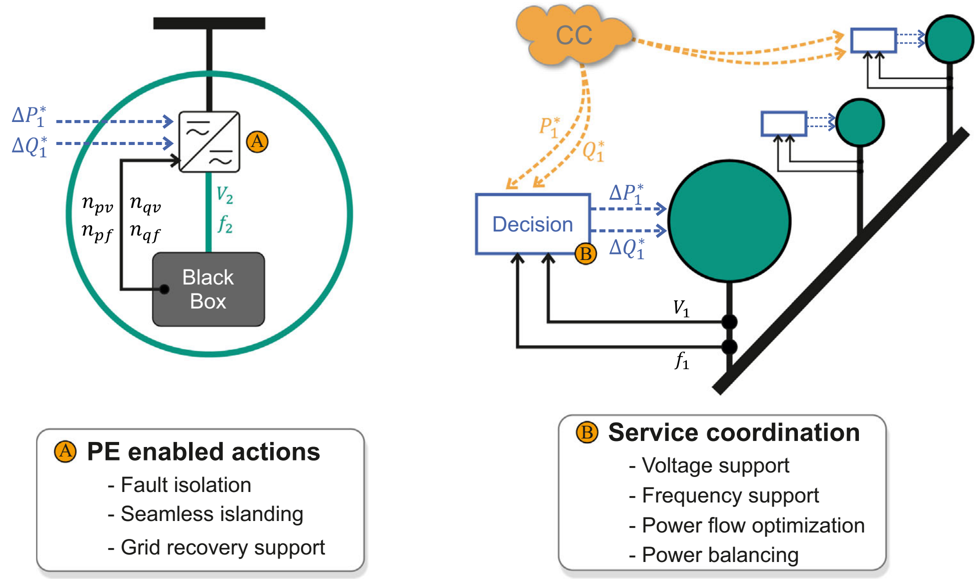


FIGURE 3 | Vision of a flexible grid enabled by PE interfaced clusters with decoupled voltage magnitude and/or frequency.



(a) Inside cluster (b) Outside cluster

FIGURE 4 | Cluster operation concept: (a) Inside cluster: voltage and frequency control for power regulation. (b) Outside cluster: grid services using cluster power flexibility.

TABLE 2 | Key shifts from the current grid to the vision grid.

Aspect	Current grid	Vision grid
Role of V and f	Control *targets* maintained near nominal.	Also control *means*: adjusted to regulate cluster power.
Flexibility source	Dedicated large generation units.	Clusters with bidirectional and controllable power flow.
Power control	Thousands of responsive devices.	A single PE interface per cluster.
Resilience	Faults and fluctuations propagate across the synchronous network.	Faults isolated and fluctuations buffered by the PE interface.
Market logic	Pay for energy.	Pay for performance and services.

sensitivity. Thus, each cluster can be viewed as an operational unit with its own voltage and frequency, capable of bidirectional power flow and active and reactive power control. Clusters can work coordinately to reach local objectives or a global optimum, following local measurements or control signals from a central controller (CC). The main shifts from the current grid to the future grid in our vision are summarized in Table 2 and discussed in detail in the following subsections.

Figure 4a shows the power control logic inside the cluster. The downstream network of the PE interface is treated as a "black box," which is characterized by its aggregated power sensitivity. The PE interface controls the power following the reference variations ($\Delta P_1^*, \Delta Q_1^*$) by modifying voltage and frequency according to the power sensitivity. In this way, the problem of controlling thousands of devices is reduced to controlling a single point (the PE interface). This approach efficiently obtains power flexibility from existing devices without communication and avoids accessing user-level devices, thereby preserving user privacy. It also decouples the control logic from the cluster topology and composition, demonstrating strong scalability.

In this framework, inside the cluster, voltage and frequency are adjusted to regulate power, while outside the cluster, the unlocked power flexibility is used to provide grid services, such as frequency and voltage support and balancing services, as illustrated in Figure 4b. The role of voltage and frequency shifts from solely control objectives to both control objectives and control means. This role shift significantly improves grid controllability and flexibility, enabling reliable and economical system operation under increasing power stochasticity and variability.

3.2 | Coordinated Cluster Operation for Grid Services

While clusters can provide various grid services, the contribution of a single cluster is limited. Therefore, coordinated operation of multiple clusters is required to provide sufficient support.

Clusters can be widely distributed across the grid; however, they can still provide some grid services jointly based solely on local measurements. For instance, as multiple clusters are connected to a common synchronous grid, the grid frequency (f_1 in Figure 4b) can serve as a shared control signal to trigger fast frequency response across clusters. Each cluster can adjust the active power proportionally to the grid frequency variation and eventually contribute to mitigating this deviation [32]. Similarly, clusters can adjust their reactive power output based on local voltage measurements (V_1 in Figure 4b), providing voltage support.

Clusters can also be coordinated by a CC that dispatches active and reactive power setpoints (P_1^*, Q_1^* in Figure 4b) to regulate power flows, optimize power dispatch, and mitigate network congestion [35]. The CC can also use the power flexibility of clusters as a cost-efficient reserve and trade it in short-period balancing services [36]. However, implementing dedicated communication for every cluster will add significant costs. Technologies like talkative power [37, 38], spike talk [39, 40], and energy packets [41] can address this issue by enabling PE interfaces to transform both energy and data.

Beyond power coordination among clusters, the advanced control capabilities of PE interfaces can conduct additional grid functionalities (Figure 4a). For instance, PE interfaces can isolate faults and buffer fluctuations between the synchronous network and clusters, preventing their propagation in both directions. In a main grid failure, clusters equipped with sufficient local generation and storage can execute seamless islanding to survive global blackouts and support system recovery. As a result, PE-interfaced clusters build a more robust, resilient, and self-healing system.

3.3 | From Consumption-Based to Performance-Based Market

Although clusters are technically capable of providing various grid services, delivering these services requires investment in PE interfaces and may also involve reducing generation or increasing consumption, all of which lead to economic trade-offs. Therefore, economic incentives are essential to reward and guide clusters to participate in both energy provision and ancillary services.

Distributed participants typically have limited capacity and duration of flexibility, making it difficult to meet existing bidding requirements. Electricity markets must evolve to enable distributed flexibility. For instance, the 2024 EU electricity market design reform [42] lowers minimum bid sizes in day-ahead and intraday energy markets from 500 kW to 100 kW or less and introduces peak-shaving products with bids up to 100 kW. It also enables non-fossil flexibility support schemes, improves transparency, promotes aggregation, and allows alternative measurement solutions for small participants. These measures demonstrate how market design can support distributed participation.

Beyond enabling participation, market mechanisms should also guide and reward cluster behavior through appropriate price signals. The overall increase in variable renewable energy curtailment [43] indicates that the key challenge is shifting from energy production to optimal power dispatch and delivery. Therefore, markets should evolve from energy-based to performance-based, rewarding not only steady energy provision but also the capability of dynamic power variation. For example, the Pennsylvania-New Jersey-Maryland interconnection RegD signal sends power adjustment requirements, and the price of providing the service depends on how much, how accurately, and how quickly the power follows the signal [36]. The price can also reflect local grid conditions and the urgency of required services. For example, under locational marginal pricing [44], if exporting power from a cluster causes line congestion, the local price may decrease (even becoming negative) to discourage further power export. In this way, physical constraints are managed through economic signals.

4 | PE Interfaces Enabling Future Grid Vision

4.1 | Capabilities of Potential PE Interfaces

Candidate PE interfaces for advanced grid services can be classified into two groups: synchronous and asynchronous. Synchronous interfaces can control output voltage magnitude but not frequency independently of the input, whereas asynchronous interfaces can regulate both output voltage and frequency independently. Their capabilities are summarized in Table 3.

Hybrid Transformers (HTs) are representative synchronous interfaces. As shown in Figure 5a, a HT can adjust its output voltage V_2 independently of the input voltage V_1 through the superposition of a fractionally rated back-to-back (B2B) converter output and the series-connected winding. However, due to the frequency coupling across windings, the output frequency f_2 cannot be controlled independently of the input frequency f_1. Thus, the synchronous interface has voltage flexibility but not frequency flexibility, and only the power sensitivity to voltage can be utilized. Moreover, they lack DC connectivity and cannot interface with DC grids. This also implies the absence of an alternative path to buffer the power imbalance between the input and output. The output power P_2 cannot differ significantly from the input power P_1, and thus adjusting P_1 requires adjusting P_2.

TABLE 3 | Capabilities of synchronous and asynchronous interfaces for grid services.

Group	Synchronous	Asynchronous
PE interfaces	HT	B2B, SST
Voltage flexibility ($V_1 \neq V_2$)	+	+
Frequency flexibility ($f_1 \neq f_2$)	—	+
DC connectivity	—	+
Power decoupling ($P_1 \neq P_2$)	—	+

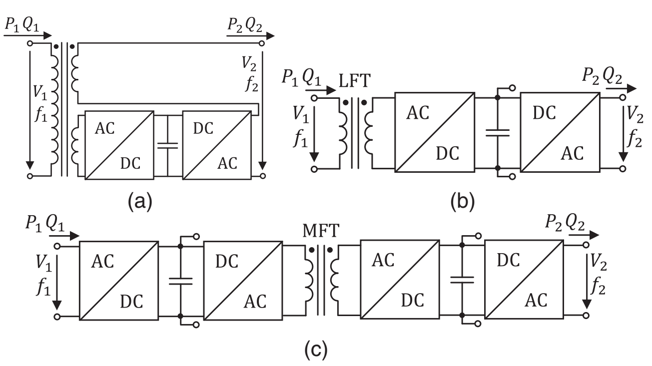


FIGURE 5 | Circuit diagrams of PE Interfaces actuators: (a) hybrid transformer (HT), (b) back-to-back (B2B) converter, and (c) solid-state transformer (SST).

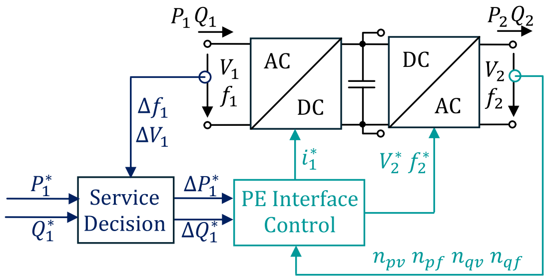


FIGURE 6 | A representative control framework of the actuator for advanced grid services.

The asynchronous interfaces exhibit comprehensive capabilities for advanced grid services, as presented in Table 3. The asynchronous interface group includes B2B converters shown in Figure 5b and SSTs in Figure 5c. A B2B converter is constructed by connecting a line frequency transformer (LFT) with two AC-DC converters in a back-to-back configuration [32], [45], enabling both voltage and frequency flexibility. These flexibilities provide the necessary degrees of freedom to regulate both active and reactive power independently. Moreover, the DC-link in the back-to-back configuration can be used to interface with a DC grid and serves as an alternative path for power decoupling. This path can enable a wider variation range of P_1 by facilitating power flow in addition to the AC power path.

Likewise, SSTs possess similar capabilities but with enhanced flexibility. A typical SST structure comprises a medium-voltage (MV) rectifier, a DC-DC converter based on a medium-frequency transformer (MFT), and a low-voltage (LV) inverter [46]. Since the SST can offer both MVDC and LVDC ports, unlike a B2B converter, this enhanced DC connectivity offers greater power flexibility across AC and DC terminals.

4.2 | PE Interface Control for Cluster Operation

A representative control framework for PE interface is illustrated in Figure 6. Since this framework depicts a typical structure, numerous variations can be applied depending on the specific grid services required. The B2B converter is selected as the target actuator to demonstrate these broad services, since asynchronous actuators encompass the capabilities of synchronous actuators, and the SST encompasses B2B converter features. In this setup, the MV rectifier and inverter are initially assumed to operate in grid-following and grid-forming modes, respectively, [47], [48]; each control mode can be reconfigured according to the desired services.

As explained in Section 3, the required grid service decides the input power variations references, ΔP_1^* and ΔQ_1^*, depending on the setpoints from the central control, P_1^* and Q_1^*, or local measurements, ΔV_1 and Δf_1. To achieve the desired power variations, the inverter adjusts the output setpoints, f_2^* and V_2^*, in accordance with the power sensitivities, n_{pv}, n_{pf}, n_{qv}, and n_{qf}. Based on this adjustment, P_2 is varied in accordance with ΔP_1^*.

Concurrently, to maintain the DC-link voltage, the rectifier adjusts the current control setpoint, i_1^*. Given that this current setpoint consists of active and reactive components, the active component of i_1^* is varied to compensate for P_2. On the other hand, to achieve ΔQ_1^* for the service, the reactive component of i_1^* is adjusted. In summary, the B2B converter mainly adjusts P_1 through the voltage and frequency control of the inverter, and primarily varies Q_1 through the current control of the rectifier. Furthermore, beyond this specific control framework, numerous modified versions can be designed to vary P_1 and Q_1 of the PE interfaces.

5 | Challenges and Future Research Directions

The transition toward a cluster-based grid architecture brings significant opportunities, but also faces many challenges that need to be addressed.

Implementing clustered grids first faces challenges related to the use of PE interfaces, particularly in protection schemes. Conventional relays require high fault currents (5–10 times nominal) to trigger reliably, whereas PE interfaces withstand only 1.1–1.5 times the nominal current. Semiconductor oversizing can increase overcurrent capability, but it is economically suboptimal. Therefore, novel protection strategies exploiting the advantages of PE interfaces, such as early detection [49] and current limiting schemes [50], are required.

Clusters enhance grid controllability and flexibility yet increase system complexity. A key challenge is to coordinate and prioritize multiple services within a cluster, while enabling inter-cluster collaboration for the shared services. Clusters should meet system-level optimality while respecting local constraints and priorities. This calls for advanced hierarchical or distributed control strategies [51], as well as market mechanisms [52] to resolve conflicts between service requests.

In addition, studies on grid architecture design, regulation, and market systems suitable for decentralized operation are needed. Clear regulatory frameworks are required to define the roles of clusters, how they should respond to control signals, and how their performance is evaluated and rewarded. For instance, if PE interfaces are intended to handle grid service power flows rather than full power transfer, their size can be designed significantly smaller than the total capacity of the cluster. Looking further ahead, as more generation and loads become interfaced through PE devices, voltage and frequency nominal values and operating ranges may shift from physical constraints to agreements among controllers, requiring new definitions of operating rules and limits.

6 | Conclusion

This work presents a vision of a clustered, decentralized grid architecture where PE interfaces transform passive network segments into controllable clusters. These clusters leverage the dependence of power on voltage and frequency to regulate their aggregated power through voltage and frequency control via a single PE interface, making voltage and frequency not only control objectives but also control means. This approach unlocks new sources of power flexibility and enhances system controllability. Clusters can provide multiple grid services jointly, while PE interfaces additionally enable advanced control actions. To guide and reward cluster participation, the market must evolve to reflect grid conditions and service quality. Realizing this vision requires further investigation into challenges of deploying PE interfaces, inter-cluster coordination strategies, and market and regulatory frameworks.

Author Contributions

Qiucen Tao: conceptualization, methodology, visualization, writing – original draft. **Maëva Courcelle:** conceptualization, methodology, visualization, writing – review & editing. **Felix Wald:** formal analysis, writing – review & editing. **Jonghun Yun:** conceptualization, project administration, supervision, writing – original draft. **Johanna Geis-Schroer:** conceptualization, writing – review & editing. **Michael Suriyah:** funding acquisition, supervision. **Thomas Leibfried:** funding acquisition, supervision. **Giovanni De Carne:** conceptualization, funding acquisition, project administration, supervision.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article, as no datasets were generated or analysed during the current study.

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