Virtual Power Plant-based Grid Planning for Gigawatt-Scale Data Center Interconnection

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***Abstract*—The rapid expansion of gigawatt-scale data centers, driven by the growing artificial intelligence (AI) workloads, presents significant challenges to power system stability and infrastructure adequacy. This paper proposes a Virtual Power Plant (VPP) framework that integrates distributed energy resources (DERs), battery energy storage systems (BESS), and on-site facilities to support data center interconnections. A VPP controller is implemented to determine optimal dispatch strategies based on aggregated DERs and wholesale market dynamics. Using steady-state power flow simulations in PSS®E, we evaluate the VPP's ability to maintain voltage and thermal compliance under multiple contingency scenarios across two study cases. Results demonstrate that the VPP-enabled configuration effectively mitigates voltage/thermal violations and reduces costly network upgrades. This study highlights the potential of VPPs to enhance grid reliability and flexibility in accommodating large-scale data center loads. Moreover, the developed simulation workflow is adaptable to a variety of scenario studies, offering a scalable approach that can expedite the interconnection process for large-scale data centers.**

***Index Terms*—Gigawatt data center, virtual power plant, steady-state analysis, load interconnection.**

I. Introduction

The rapid growth of hyperscale data centers driven by AI workloads is straining the electricity sector , where power supply expansion lags significantly behind demand. According to the report from McKinsey & Company [1], the U.S. data center demand is projected to grow by nearly 10% annually, doubling from 17 gigawatts (GW) in 2023 to 35 GW by 2030. As shown in Fig. 1, this growth is shifting away from individual enterprise facilities toward hyperscale data centers. This poses challenges to grid generation and transmission infrastructures due to the long timelines of siting, permitting, and supply chains, typically several years to deliver a new grid facility. In fact, the use of renewable energy is a critical component of the hyperscalers' strategies. To reach carbon-free energy goals, data center owners are signing power purchase agreements (PPAs) with suppliers of renewable energy. Sufficient and reliable power supply under grid failure is a major concern in the data center industry. Reducing energy costs and critical load management is another concern.

Specifically, large load interconnection introduces the following challenges:

- Unpredictable demand patterns
- Imbalance between demand and supply
- Equipment upgrades and transmission reinforcements
- Frequency control and balancing reserves for sudden load drops.
- Dynamic voltage control difficulties due to converter-dominated interfaces.
- Restoration constraints under ramp rate limits.
- Power quality and harmonic emission concerns.
- Protection system coordination challenges.

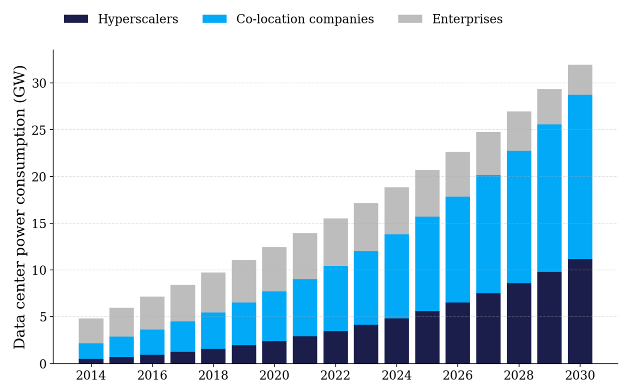

Fig. 1. Data center power consumption by 2030.

Microgrids have been proposed to support megawatt (MW) scale data centers; however, distributed energy resources (DERs) alone are insufficient for GW-scale facilities [2]. This gap has motivated research into Virtual Power Plant (VPP) concepts [3] as a scalable solution. Comprehensive reviews have examined VPP architectures, control strategies, and market participation mechanisms [4], highlighting their role in renewable integration and grid resilience [5]. More recent studies have explored the application of VPPs to large and flexible loads, including emerging work on gigawatt-scale AI data centers, which emphasizes multi-timescale control and stability under fast-varying demand profiles. Peivandizadeh in [6] proposed a theoretical framework for the integration of VPP with GW-scale AI data centers, introducing hierarchical multi-timescale control strategies. His findings indicate that VPP-enabled data centers provide peak reduction and grid service provisions. The U.S. Department of Energy emphasizes scaling VPP capacity to 80–160 GW by 2030 to address growing electrification and data center demand [7]. VPPs are positioned as non-wire alternatives to mitigate interconnection delays and reduce transmission congestion.

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Google, in collaboration with the Brattle Group, demonstrated that VPPs can deliver resource adequacy comparable to gas power plants and utility-scale batteries at 40–60% lower cost [8]. Their analysis suggested that deploying 60 GW of VPP capacity could save $15–35 billion over a decade compared to traditional power plants. Wood Mackenzie reports a 33% surge in VPP deployments in North America, driven by hyperscale data center growth in regions like ERCOT and PJM [9]. The literature consistently highlights VPPs as a cost-effective and flexible solution for large load interconnections. They enhance reliability, accelerate interconnection timelines, and support decarbonization goals by integrating renewable resources and distributed storage. However, research gaps remain in on-site generation allocation, large load modeling, market design and intelligent dispatch for VPP participation.

This paper focuses on long-term planning; therefore, day-ahead and real-time controls are beyond its scope. The main idea is to find a VPP-enabled solution for GW-scale data centers to meet growing demand while ensuring grid reliability and security. AC contingency analysis was performed on the pre-project and post-project cases. Thermal and voltage violations in the study cases with the data center loads were compared with the corresponding thermal loadings and bus voltages in the benchmark cases. The steady-state analysis results demonstrate that the proposed VPP framework effectively maintains grid constraints—such as thermal loading and bus voltage limits—without requiring infrastructure upgrades. The major contributions of this paper are summarized as follows:

1) Developed a scalable VPP-based interconnection framework for GW-scale data centers,
2) Established a coordinated optimization–simulation workflow linking DER dispatch with transmission contingency analysis,
3) Validated the effectiveness of the proposed VPP framework under two representative real-world planning scenarios using industry-standard simulation tools, offering valuable insights for transmission planning and large-load interconnection assessment.

The remainder of this paper is organized as follows: Section II outlines the methodology, covering the VPP-based framework, the optimization model, and the contingency simulation workflow. Section III details the power flow model development under two study scenarios and presents the corresponding analysis results. Finally, Section IV concludes the paper with key findings and future works.

II. METHODOLOGY

This section presents the proposed VPP framework for a GW-scale data center. Inspired by [2] and [3], we integrate the VPP platform with aggregated DERs and wholesale market to determine the optimal bidding strategy for data center owners. Furthermore, an automated simulation workflow is developed to facilitate complex contingency analysis, enhancing the robustness and scalability of the planning process.

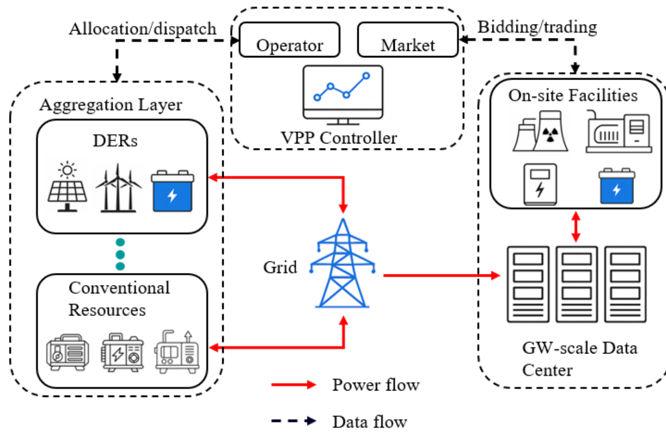

Fig. 2. VPP framework for GW-scale data center.

A. VPP-based Framework

Fig. 2 illustrates the proposed VPP architecture tailored for GW-scale data centers. The framework consists of three primary components: an aggregation layer, a VPP controller, and data center infrastructure with co-located generation and battery energy storage systems (BESS). The aggregation layer consolidates diverse resources, including distributed energy resources (DERs) such as solar and wind, alongside conventional resources. This integration not only consolidates generation resources across multiple regions to facilitate participation in electricity markets, but also enhances grid reliability, security, and resilience against challenges posed by increasing renewables and large-scale loads.

The VPP controller leverages advanced forecasting models for renewable generation and load demand to optimize dispatch decisions across two dimensions: (i) controllable generators and flexible loads within the aggregation layer, and (ii) bidding strategies and storage charging/discharging schedules on the data center side. This capability is critical in balancing supply-demand dynamics under large load interconnections. Furthermore, the VPP interacts with wholesale electricity markets, where dynamic pricing mechanisms—such as real-time pricing and locational marginal pricing—are increasingly adopted to reflect system conditions and uncertainty. These pricing signals incentivize demand-side flexibility and resource participation, enabling VPPs to provide ancillary services, capacity support, and energy arbitrage.

From the data center perspective, on-site infrastructures—including nuclear or gas generation units and energy storage—ensure secure and reliable operation even during market volatility or grid contingencies. Based on wholesale price signals, the data center formulates bidding strategies that align with operational constraints, cost minimization, and sustainability objectives. This may involve scheduling energy-intensive tasks during periods of low prices or leveraging storage for peak shaving and arbitrage opportunities. Consequently, the integration of VPPs with electricity markets not only supports grid stability but also enables data centers to op-

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timize energy consumption and contribute to decarbonization goals.

B. Optimization Model

As discussed in section A, the VPP operates with two primary control loops: the dispatch problem at the aggregation layer and energy management within the data center. On the data center side, this can be formulated as an optimization problem aimed at minimizing total costs while maximizing the utilization of local generators and storage systems.

The objective function is as follows:

$$\min \sum_{t\in\mathcal{T}} \Big[\pi_t^E\, P_t^{\text{grid}}\,\Delta t - \sum_{r\in\mathcal{R}^{\uparrow}} \pi_{t,r}^R\, R_{t,r}^{\uparrow}\,\Delta t - \sum_{r\in\mathcal{R}^{\downarrow}} \pi_{t,r}^R\, R_{t,r}^{\downarrow}\,\Delta t + C^{\text{gen}}(P_t^g)\,\Delta t + C^{\text{bess}}(P_t^c, P_t^d)\,\Delta t\Big]. \tag{1}$$

where $\mathcal{T}$ is time periods, indexed by t; $\mathcal{R}^{\uparrow}$ and $\mathcal{R}^{\downarrow}$ are upward and downward reserve products, respectively. π_t^E is the wholesale energy price at the Point of Interconnection (POI); $\pi_{t,r}^R$ is reserve price for product r; P_t^{grid} is Net grid exchange at POI; P_t^g is local generator real power output; P_t^c, P_t^d are BESS charge and discharge power; $C^{\text{gen}}(\cdot)$, $C^{\text{bess}}(\cdot)$ are the operation cost functions of local generators and BESS, respectively.

Constraints:

a) Power balance at the POI:

$$P_t^{\text{grid}} + P_t^g + \left(P_t^d - P_t^c\right) - P_t^{\text{load}} = 0. \tag{2}$$

where P_t^{load} is net data center real power demand (GW scale).

b) Generator operating limits:

$$0 \le P_t^g \le \overline{P}^g \tag{3}$$

c) BESS operating limits:

$$0 \le P_t^c \le \overline{P}^c, \quad 0 \le P_t^d \le \overline{P}^d \tag{4}$$

$$E_t = E_{t-1} + \eta_c P_t^c \Delta t - \frac{1}{\eta_d} P_t^d \Delta t \tag{5}$$

$$\underline{E} \le E_t \le \overline{E} \tag{6}$$

where E_t is BESS state of charge (SOC); $\underline{E}$, $\overline{E}$ are BESS SOC bounds; $\eta_c, \eta_d \in (0,1]$ are BESS charge/discharge efficiencies.

d) Charging/discharging limit:

$$P_t^c \le \overline{P}^c y_t^c, \quad P_t^d \le \overline{P}^d y_t^d, \quad y_t^c + y_t^d \le 1 \tag{7}$$

where $\overline{P}^c/\overline{P}^d$ is BESS charge/discharge power limits; $y_t^c, y_t^d \in \{0,1\}$ are binary variables used to ensure that charging and discharging do not occur simultaneously.

e) Reserve limits:

Upward reserves limited by upward headroom:

$$\sum_{r\in\mathcal{R}^{\uparrow}} R_{t,r}^{\uparrow} \;\le\; (\overline{P}^g - P_t^g) + (\overline{P}^d - P_t^d) \tag{8}$$

Downward reserves limited by downward room:

$$\sum_{r\in\mathcal{R}^{\downarrow}} R_{t,r}^{\downarrow} \;\le\; P_t^g + (\overline{P}^c - P_t^c) \tag{9}$$

Reserve revenues are the sums $\sum_r \pi_{t,r}^R R_{t,r}^{\cdot} \Delta t$. Coupling constraints (8)–(9) ensure reserves do not exceed physical headroom/footroom given the chosen dispatch.

Variable domains are specified as:

$$P_t^{\text{grid}} \in \mathbb{R},\; P_t^g, P_t^c, P_t^d \ge 0,\; E_t \in \mathbb{R}_+,\; R_{t,r}^{\uparrow}, R_{t,r}^{\downarrow} \ge 0.$$

Note that variations in resource adequacy, such as the availability of DERs, can influence dynamic electricity prices in the wholesale market. Therefore, uncertainty in resource availability and market conditions would impact the VPP controller. However, the model assumes to be deterministic: π_t^E and $\pi_{t,r}^R$ are exogenous forecasts given to the VPP. Furthermore, it is necessary to assess whether the given control actions from VPP would result in violations under contingency scenarios.

C. Contingency Analysis

According to NERC TPL-001-5 [10], steady-state analysis—based on load flow calculations—is required for any new interconnection and represents a critical aspect of transmission system planning. To investigate the effectiveness of the proposed VPP solution for GW-scale data center, multiple contingencies will be simulated in PSS®E and results will be evaluated to identify potential violations. The overall simulation diagram is illustrated in Fig. 3. Based on the dispatch and control actions provided by the VPP, scenarios are generated using the base case model developed by the operator. Next, the planning engineers create multiple contingencies (P0–P7) as input files for the study. These inputs are then integrated with automation scripts to execute simulations in PSS®E automatically. Finally, the results are returned to the analysis side for post-processing to identify any thermal or voltage violations.

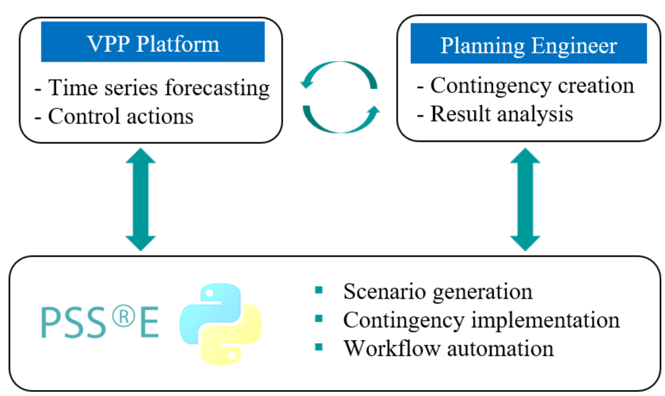

Fig. 3. Steady state analysis diagram.

Transmission planning typically incorporates seasonal scenarios such as summer/winter peak and summer/winter shoulder conditions. Under a deterministic optimization framework, the VPP controller is assumed to adopt a greedy dispatch strategy (remain maximum demand). For instance, during summer peak conditions, when the marginal cost of grid electricity significantly exceeds that of local generation ($\pi^E \gg C^{gen}$), the data center would maximize on-site generation and discharge BESS at its rated capacity. During summer shoulder periods, when electricity price declines, the data center prioritizes maximizing on-site generation while strategically reducing BESS discharge to optimize resource utilization.

III. Simulation Results

Steady-state analysis was performed using PSS®E version 35. Contingencies were solved with transformer tap adjustment enabled, area interchange adjustment disabled, phase shifter adjustment disabled, and switched shunt adjustment enabled.

A. Model Development

Steady-state contingency analysis was performed on the benchmark (pre-project) cases and study (post-project) cases. Fig. 4 illustrates the single-line diagram of the key components of the study system in PSS®E, including the data center point of interconnection, the locations of the BESS and on-site generator.The benchmark power flow cases were built from MISO MTEP25 models. P0-P7 contingencies (about 45k events) were simulated using the filtered MTEP25 fault files.

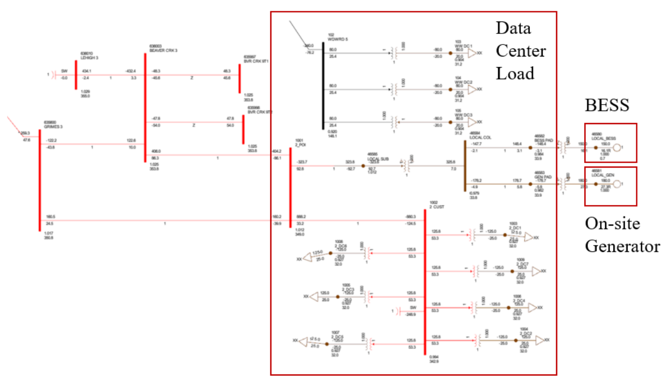

Fig. 4. Single line diagram of study system.

Two study cases were created for comparison and system performances were benchmarked using cases without data center interconnection:

1) Study–DC: power flow model was built with the new data center load interconnection
2) Study–VPP: power flow model was built with the new data center load along with on-site facilities like generators and BESS by the proposed VPP framework.

The parameters of study system are shown in Table I.

AC contingency analysis was performed on the benchmark and study cases, and the incremental impacts of the data center load were evaluated by comparing the steady-state performance of the system. Two scenarios were studied:

- Summer peak (SPK)
- Summer shoulder high wind (SHHW)

TABLE I
System Configuration

Parameter	SPK	SHHW
Data Center Load (MW)	1,115	1,115
Local Generation (MW)	180	180
BESS (MW)	150	50

B. Performance Criteria

Voltage violation criteria: bus voltage is monitored using the voltage limits in the MISO power flow cases. The continuous voltage planning criteria is shown in Table II.

Thermal violation criteria: lines and transformers are monitored using normal or emergency ratings as appropriate:

- 89.5% of normal rating (rate A) for system intact conditions.
- 89.5% of emergency rating (rate B) for post-contingent conditions.

A facility is significantly affected if the applicable thermal or voltage rating is exceeded, and the impact of the load interconnection exceeds 1% of the thermal rating or nominal voltage.

C. Results

After post-processing, we identified the total number of voltage and thermal constraints impacted by the data center interconnection. Table III presents a comparative analysis of two study cases—Study-DC and Study-VPP—under SPK and SHHW scenarios. The results clearly demonstrate the superior performance of the proposed VPP-based dispatch strategy. Specifically, Study-VPP reduces thermal violations by 84.6% for SPK (from 13 to 2) and by 90.6% for SHHW (from 32 to 3) relative to Study-DC. These remaining thermal violations correspond to NUs that have already been planned and, therefore, can be considered operationally negligible. Furthermore, voltage violations are completely eliminated under Study-VPP (0 vs. 2 for SPK and 0 vs. 4 for SHHW), indicating consistent compliance with voltage constraints. In contrast, Study-DC exhibits significantly higher violation counts, particularly in the SHHW scenario with 32 thermal and 4 voltage violations, underscoring the limitations of direct large-load interconnection.

Therefore, these findings illustrate the effectiveness of the proposed VPP-based solution for hyperscale data center integration under SPK and SHHW scenarios. By applying VPP-determined dispatch, data center interconnection can achieve zero operational violations even at GW-scale peak demand, thereby ensuring grid reliability and minimizing the need for additional network upgrades. However, the current approach is constrained by its deterministic modeling framework. Future research should focus on developing intelligent control algorithms for VPP, incorporating complex energy market models and addressing uncertainties arising from DERs and variable load patterns. Within the proposed workflow for integrating VPP with data centers, additional scenarios can

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TABLE II
STEADY-STATE VOLTAGE CRITERIA FOR MONITORED ELEMENTS.

Contingency Event	Bus Type	Nominal kV	Minimum Voltage (p.u.)		Maximum Voltage (p.u.)
			Continuous	1 Hour Emergency	
P0	Transmission & Generation POI	$\geq$ 100 kV to 300 kV	0.950	0.950	1.05
		$\geq$ 300 kV	0.960	0.960	1.05
P1, P2.1	Transmission	$\geq$ 100 kV to 300 kV	0.950	0.930	1.05
		$\geq$ 300 kV	0.960	0.940	1.05
	Generation POI	$\geq$ 100 kV to 300 kV	0.950	0.950	1.05
		$\geq$ 300 kV	0.960	0.950	1.05
P2.2–P2.4 P3–P7	Transmission	$\geq$ 100 kV to 300 kV	0.930	0.900	1.05
		$\geq$ 300 kV	0.940	0.900	1.05
	Generation POI	$\geq$ 100 kV	0.950	0.950	1.05

TABLE III
PERFORMANCE COMPARISON OF STUDY CASES.

Performance	SPK		SHHW	
	Study-DC	Study-VPP	Study-DC	Study-VPP
Thermal violation #	13	**2**	32	**3**
Voltage violation #	2	**0**	4	**0**

be generated to further validate the advantages of the method. Furthermore, this technology could be extended to real-time control applications to mitigate frequency oscillations, improve power quality and enhance system stability.

IV. CONCLUSION

This paper proposes a VPP-based framework for GW-scale data center interconnection, aiming to ensure grid reliability and support AI-driven infrastructure from the transmission planning stage. A steady-state contingency analysis workflow is implemented using PSS®E, offering a robust framework for integrating VPP platforms with power flow simulations to support comprehensive scenario-based studies. It spans from VPP controller dispatch to scenario generation, automated simulation, and contingency analysis. Simulation results demonstrate the effectiveness of the proposed VPP mechanism in dispatching on-site facilities without additional NUs, thereby accelerating the interconnection process for large-scale data centers.

Despite these promising results, the study is limited to steady-state analysis. Future research should focus on incorporating dynamic and complex energy market models and designing intelligent optimization algorithms for real-time VPP control. Another critical direction is the development of accurate data center load models. Unlike traditional loads, data center demand—driven by AI hardware such as GPUs—exhibits highly unpredictable patterns. Without valid load models, stability analysis and compliance studies for grid interconnection cannot be effectively performed. Addressing these challenges will be essential for ensuring reliable and scalable integration of GW-scale data centers into modern power systems.

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