

Article

Probabilistic Assume–Guarantee Contracts for Islanded Mission-Critical Power System Operations

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Abstract

Design of large-scale power systems is getting increasingly complex nowadays from an operational and reliability standpoint due to the uncertainties associated with the injection of renewables and consumption of load. These uncertainties pose a great challenge in gauging and subsequently obtaining reliable system-level assurances from subsystem-level guarantees, particularly in mission-critical systems such as those seen in data centers. We propose a formal and modular framework of probabilistic assume–guarantee contracts (PAGCs) for compositional reasoning and control of uncertain power systems, motivated by the need for resilient and verifiable operation in data center power networks. In contrast to classical contracts, which require absolute satisfaction of assumptions and guarantees, PAGCs allow for high-probability satisfaction under system uncertainty and variability. We formalize the syntax and semantics of PAGCs, develop soundness and compositionality theorems, and demonstrate their applicability to power grid components such as generators, transformers, circuit breakers, and loads. Given the current approval bottlenecks in interconnection requests, a growing number of data center operators are opting for islanded generation configuration. A case study on such a modular islanded data center power system is presented to validate the proposed theory. The proposed PAGC application in power networks is promising in several aspects to solve several existing open problems in distributed systems, particularly in future large-scale smart power networks.

Keywords: assume–guarantee contracts; probabilistic assume–guarantee contracts; PAGC; data center power network; parallel and series contract; probabilistic contract theory



Academic Editor: Francisco Javier Ruiz-Rodríguez

Received: 18 January 2026

Revised: 10 February 2026

Accepted: 16 February 2026

Published: 18 February 2026

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1. Introduction

While the past two decades have seen intense efforts to improve the energy efficiency of computing, the continued expansion of computing scale has caused the power demand of the largest systems to increase more than a thousandfold, from 115 kW for the Cray-1 in 1975 to an estimated 280 MW for Colossus in 2025 [1]. Recent analyses such as that of [2] suggest that the computational performance of leading AI supercomputers is currently doubling every nine months, largely driven by the rapid deployment of increasingly powerful AI chips. The electric grid in the US and globally is experiencing unprecedented growth, primarily driven by the escalating energy requirements of AI research and computation, with strong drivers in the area of large language models (LLMs) such as GPT [3], LLaMA [4], and Gemini [5] needing to be trained. As these LLMs become more sophisticated, training them requires an exponentially larger amount of energy; for instance, training GPT-3 required approximately 1.29 GWh of energy, whereas GPT required over

50 GWh of power for training [6,7]. At a global scale, the International Energy Agency (IEA) projects that under assumptions of a resilient supply chain and flexible data center development, power consumption from data centers could exceed 1250 TWh by 2030; see the IEA lift-off case [8]. The growth and the commensurate stress on the power grid are expected to be more pronounced in the United States, as it is at the forefront of AI research [9]. Furthermore, given that data centers are spatially concentrated, for instance fifteen of the fifty US states account for 80% of data center power, their impact on the local power grid may be pronounced [10].

This unprecedented AI load growth has also caused a proportionate growth in large load interconnection (LLIs) requests and has caused a huge backlog of LLI requests that are under jurisdictional review. For instance, the US state of Texas, which falls under the Energy Reliability Council of Texas (ERCOT) territory, did not have a significant backlog of LLIs in its queue until 2023. A backlog was witnessed starting from 2024, with 12.27 GW of ERCOT LLI requests under review in 2025 and an estimated 29.78 GW of LLI requests projected to be under review in 2028. Figure 1 and Table 1 show a more visual illustration of the projected load growth in the ERCOT LLI queue up to 2028 [11], with a breakdown of the volume of load at various stages of the interconnection process. Note how the volume of load falling under the “approved to energize” category remains predominantly constant, while the amount of load within the “under ERCOT review” category is expected to witness an exponential growth, effectively adding to the growing backlog. For context, within the ERCOT footprint, an LLI study (LLIS) is required for any new large load (defined as 75 MW or higher) scheduled to connect to the ERCOT system within the next 24 months. The outcome of the LLIS process could be a complete denial or approval of a partial or full volume of the large load, depending on the results of the power flow and stability studies. If the TSP detects any indications of instability or transient stability issues, the proposed load must be included in the upcoming quarterly stability assessment (QSA). In such cases, the TSP is also expected to outline potential mitigation measures, which may involve transmission upgrades. Once these analyses are completed, ERCOT reviews the results and decides whether any operating limits or conditions must be placed on the load before granting approval. The obligations of performing an LLIS, including its review and approval, can be a prolonged process, with large data center loads often competing with crypto and hydrogen/industrial loads [12]. Under such constraints, a growing number of critical infrastructures such as data center operators may have an incentive to generate a portion, or all, of the generation behind the metre [13]. In addition to the sheer volume of these large data center loads, AI data center loads exhibit distinct characteristics and consumption patterns that make direct interconnection with the energy grid challenging. These factors are:

- *Large load ramps:* AI data centers exhibit highly non-uniform load profiles driven by the distinct computational phases of model development [6]. Training workloads generate the steepest and most rapid load ramps, often pushing GPU clusters toward their thermal and electrical limits. Fine-tuning introduces moderately variable but still intensive demand patterns, while inference operations produce comparatively smoother, distributed loads with shorter-duration spikes. According to findings reported in [14], uncoordinated AI-driven load fluctuations in grids with high levels of inverter-based resources can trigger voltage dips across multiple nodes, produce Rate of Change of Frequency (RoCoF) excursions nearing 0.4 Hz/s, and push the system beyond key operational limits, even without any loss of generation.
- *Voltage-sensitive nature and effect from simultaneous load loss:* Given their voltage-sensitive nature, the potential for large amounts of voltage-sensitive load loss during normally cleared faults on the bulk electric system (BES) is high. For instance, in an incident

well documented by the North American Electric Reliability Corporation (NERC) [15], a fault on a 230 kV transmission line on 10 July 2024, in the US eastern interconnect, caused an approximate 1.5 GW of voltage-sensitive load to be disconnected from the electric grid, causing a sustained rise in both voltage and frequency, before aggressive restorative actions were taken.

As such, in response to the extensive requirements associated with large load interconnection studies (LLISs) and the grid integration challenges posed by such large data center loads, many data center developers are increasingly pursuing islanded, behind-the-metre generation as a strategy to bypass traditional transmission-level interconnection obligations. While this approach can offer economic and operational advantages, it also shifts full responsibility to the facility. Consequently, the design of the islanded system must rigorously support contractual service-level commitments, including guaranteed uptime of on-site generation assets and reliable performance of downstream power delivery infrastructure. Ensuring that the generating turbines, distribution architecture, and protection schemes meet these guarantees is essential for maintaining the operational continuity expected in modern hyper-scale and AI-driven data center environments.

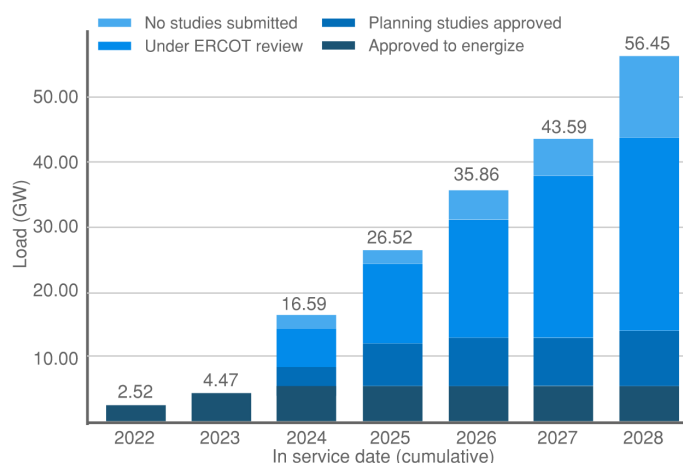


Figure 1. Growth of ERCOT LLI queue between 2022 and 2028, projected as of September 2024.

Table 1. The ERCOT LLI queue (in GW) current as of September 2024.

Project Status	2022	2023	2024	2025	2026	2027	2028
No studies submitted	-	-	2.04	2.04	4.64	5.54	12.58
Under ERCOT review	-	-	6.07	12.27	18.08	24.91	29.78
Planned studies approved	-	-	2.98	6.71	7.63	7.63	8.59
Approved to energize	2.53	4.47	5.49	5.49	5.49	5.49	5.49
Total (GW)	2.53	4.47	16.59	26.52	35.86	43.59	56.45

It is in this context that assume–guarantee contracts (AGCs) offer a powerful reliability modeling framework for compositional reasoning. In terms of fundamentals, the authors in [16] define a contract as a phenomenon that allows one to distinguish hypotheses made about a system, referred to as the “guarantees”, from those made about the system’s environment, referred to as the “assumptions”. In our research, each component is associated with a contract that states what it assumes from its environment and what it guarantees in return, as described in [17]. However, classical AGCs are deterministic and ill-suited for systems where uncertainty is intrinsic, such as fluctuating loads, stochastic generation, or switching events with probabilistic timing. To address this, we propose the use of probabilistic assume–guarantee contracts (PAGCs), closely related to the ones proposed

in [18]. These PAGCs relax the requirement of absolute satisfaction and instead demand satisfaction of assumptions and guarantees with high probability. Specifically, we will use the symbols δ and ϵ to denote the violation probabilities of assumptions and guarantees respectively in the context of PAGCs. This allows explicit incorporation of statistical knowledge, risk margins, and robustness into the design and verification pipeline in terms of (δ, ϵ) . Interested readers are referred to [19] and the references therein for further reading on the literature related to PAGCs and their associated complexities.

Note that [20] presented a well-studied formalism that is naturally suited to modeling multi-component probabilistic systems. On the other hand, the authors in [21] used AGCs in software composition and modular verification (in the case of distributed systems). On a parallel note, things get really interesting in large-scale learning-based distributed systems, as the learning procedure (similar to the distributed minimax adaptive control technique described in [22]) naturally induces stochasticity and this in turns calls for PAGC-based guarantees. In [23], the authors implemented probabilistic contracts for the case of an autonomous vehicle emergency braking situation. Similarly, in [24], the authors used stochastic contracts for cyber-physical system design under probabilistic requirements, where they demonstrated their approach on an aircraft power distribution example. However, a direct PAGC formalism for the real-world power system application (which naturally has a modular architecture with multiple components) is sparse and positions our work as among the first to tailor PAGCs to detailed electrical power network reliability analysis at scale. With the human-in-the-loop and controller-level complexities associated with power systems, the idea of applying PAGCs to address the complex problems in that domain is still in its nascent stage, as it is an unexplored research territory with promising outcome prospects. While traditional reliability methods such as fault tree analysis, Markov models, or reliability block diagrams provide valuable estimates of component- and system-level failure probabilities, they are often limited by assumptions of independence, flat failure modeling, and lack of compositionality. In contrast, PAGCs provide a logic-based, modular and compositional framework in which each component is certified through their respective PAGCs. This allows one to reason about the conditional performance of components, propagate reliability across the network using formal theorems, and build abstractions suitable for large-scale, heterogeneous components. As such, a PAGC complements and generalizes classical reliability analysis, particularly in settings involving software, controllers, or mission-level specifications. To this end, our two main contributions are as follows:

- We define PAGCs and their satisfaction semantics over uncertain system models and prove key theoretical results, including soundness and compositionality (both parallel and series compositions) under probabilistic satisfaction.
- We apply PAGCs to a modular power system network model representing a data center and demonstrate their use in subsystem-level probabilistic reasoning.

The rest of this paper is organised as follows: Following a short summary of notations and preliminaries, the PAGC problem formulation for an uncertain power network is introduced in Section 2. The core theoretical results concerned with the development of PAGCs in the power system context are presented in Section 3. The proposed idea is demonstrated using numerical simulation and the results are discussed in Section 4. Finally, this paper is closed in Section 5 along with discussions regarding promising directions for future research.

Notation and Preliminaries

The sets of real numbers, integers and natural numbers are denoted by $\mathbb{R}, \mathbb{Z}, \mathbb{N}$ respectively and the subset of real numbers greater than a given constant, say $a \in \mathbb{R}$, is denoted by $\mathbb{R}_{>a}$. The subset of natural numbers between two constants $a, b \in \mathbb{N}$ with $a < b$ is denoted by $[a : b]$. The symbols $\models$ and $\not\models$ denote the satisfaction and dissatisfaction events

respectively. The probability space is defined using a triplet $(\Omega, \mathcal{F}, \mathbb{P})$, where Ω , $\mathcal{F}$, and $\mathbb{P}$ denote the sample space, event space, and the probability function, respectively, with $\mathbb{P} : \Omega \rightarrow [0, 1]$. A zero-mean random variable x following a Gaussian distribution with covariance Σ_x is denoted by $x \sim \mathcal{N}(0, \Sigma_x)$.

2. Problem Formulation

We will begin the problem formulation with a formal definition of the PAGCs. Following the definitions, we will describe the problem of analyzing uncertain power systems using PAGCs.

2.1. Formal Definition of PAGC

Definition 1. A probabilistic assume–guarantee contract is defined using a tuple $\mathcal{C}^{\delta, \epsilon} := (\mathcal{A}^{1-\delta}, \mathcal{G}^{1-\epsilon})$, where $\mathcal{A}^{1-\delta}$ denotes the assumption $\mathcal{A}$ being satisfied with a probability of at least $1 - \delta$, and similarly $\mathcal{G}^{1-\epsilon}$ denotes the guarantee being satisfied with a probability of at least $1 - \epsilon$. That is, $\mathbb{P}(\mathcal{A}) \geq 1 - \delta$ and $\mathbb{P}(\mathcal{G}) \geq 1 - \epsilon$.

Note that we can define the PAGC for the case of a vector of assumptions (which can be independent or have a joint pdf) and distribute the satisfaction/violation probability to each component of the assumption vector. A similar reasoning will also hold for the case of a vector of guarantees. Briefly speaking, a PAGC is a formal verification tool that enables us to encode different assumptions and guarantees in the form of statements and use them to formally verify and certify the operation of networked systems like power grids. To better connect the motivating challenges with the proposed methodology, we explicitly interpret operational phenomena such as large load ramps, voltage sensitivity, and frequency excursions as violations of component-level assumptions, while safe delivery of power, voltage regulation, and protection actuation are modeled as guarantees within the PAGC framework. For instance, a generator’s assumption may encode bounded ramp rates and frequency stability, while its guarantee specifies reliable power output under those conditions. Similarly, transformers and breakers assume acceptable voltage/current limits and guarantee safe energy transfer or isolation. By formalizing these physical constraints as probabilistic assumptions and guarantees, PAGCs directly translate grid reliability requirements into verifiable contracts. This establishes a PAGC not as a generic abstraction, but as a targeted, structured mechanism for encoding and reasoning about the very operational risks highlighted above.

Definition 2. Given an assumption violation probability $\delta \in [0, 1]$ and a guarantee violation probability $\epsilon \in [0, 1]$, a dynamical system Σ satisfying the PAGC given by $\mathcal{C} := (\mathcal{A}^{1-\delta}, \mathcal{G}^{1-\epsilon})$ is denoted by $\Sigma \models \mathcal{C}$ and

$$\Sigma \models \mathcal{C} \iff (\mathbb{P}(\mathcal{A}) \geq 1 - \delta \implies \mathbb{P}(\mathcal{G}) \geq 1 - \epsilon). \quad (1)$$

2.2. Probabilistic Guarantees on Power Network

We consider a power system network (denoted by Σ) consisting of $N_{\text{comp}} \in \mathbb{N}$ components in total indexed by $i \in \{C_1, \dots, C_{N_{\text{comp}}}\}$, where each component C_i is modeled as a stochastic system Σ_i whose dynamics are given by

$$x_i(t+1) = f_i(x_i(t), u_i(t), w_i(t)) \quad (2a)$$

$$y_i(t) = h_i(x_i(t)), \quad (2b)$$

with state $x_i \in \mathbb{R}^{n_i}$, input $u_i \in \mathbb{R}^{m_i}$, and disturbance $w_i \sim \mathcal{N}(0, \Sigma_{w_i})$ with covariance $\Sigma_{w_i} \succeq 0$. Its outputs are denoted y_i . The nonlinear mappings f_i and h_i satisfy the regu-

lar assumptions, such as being Lipschitz with Lipschitz constants $L_{f_i} > 0$ and $L_{h_i} > 0$ respectively for each component $i \in \{C_1, \dots, C_{N_{\text{comp}}}\}$. For ease of exposition and so as not to digress from the presented problem formulation, we shall not be using the stochastic dynamics (keeping in mind that each component in the grid shall have its own stochastic dynamics) henceforth in this paper. A component C_i in a power network might refer to things like generators, circuit breakers, load, an electricity bus, transformers and so on. Each component C_i is associated with a PAGC denoted by

$$C_i = (\mathcal{A}_i^{1-\delta_i}, \mathcal{G}_i^{1-\epsilon_i}), \quad (3)$$

where $\mathcal{A}_i^{1-\delta_i}$ denotes an assumption on the environment satisfied with probability at least $1 - \delta_i$ and $\mathcal{G}_i^{1-\epsilon_i}$ denotes a guarantee satisfied with probability at least $1 - \epsilon_i$ under the assumption as per (1). In a power network setting, the satisfaction probabilities of PAGCs for every component are usually specified in terms of the mission time meant for the operation of the underlying power network. We shall implicitly assume that each component in the power network shall have the same mission time.

Usually a power network Σ consists of connecting multiple components through a network of cables, which can be modeled using graph theory. Further, there can be multiple units of the same components (such as $N_{\text{gen}} \in \mathbb{N}$ units of generators) present in the same power network Σ . An example illustration is shown in Figure 2, where typical power network components such as generators, circuit breakers, transformers and loads are connected to form an interconnected system and their corresponding assumptions and guarantees are also shown to connected to form the network-level assumption and guarantee. To find the total count of units present in the power network Σ , we denote the number of units of a component C_i as $N_i := |C_i|$. Hence, there would be a total of N_{total} units in the network, where $N_{\text{total}} := \sum_{i=1}^{N_{\text{comp}}} N_i$. The graph modeling the power network formed by connecting the N_{total} units will have N_{total} number of nodes and E_{total} number of edges, and the topology of the graph is denoted by $\mathcal{T}$. We denote the set of all nodes and edges of that power network graph as $\mathcal{V}$ and $\mathcal{E}$ respectively, and hence $|\mathcal{V}| = N_{\text{total}}$ and $|\mathcal{E}| = E_{\text{total}}$. Given the above uncertain power network setup, we will now present the problems of interest that are considered in this paper.

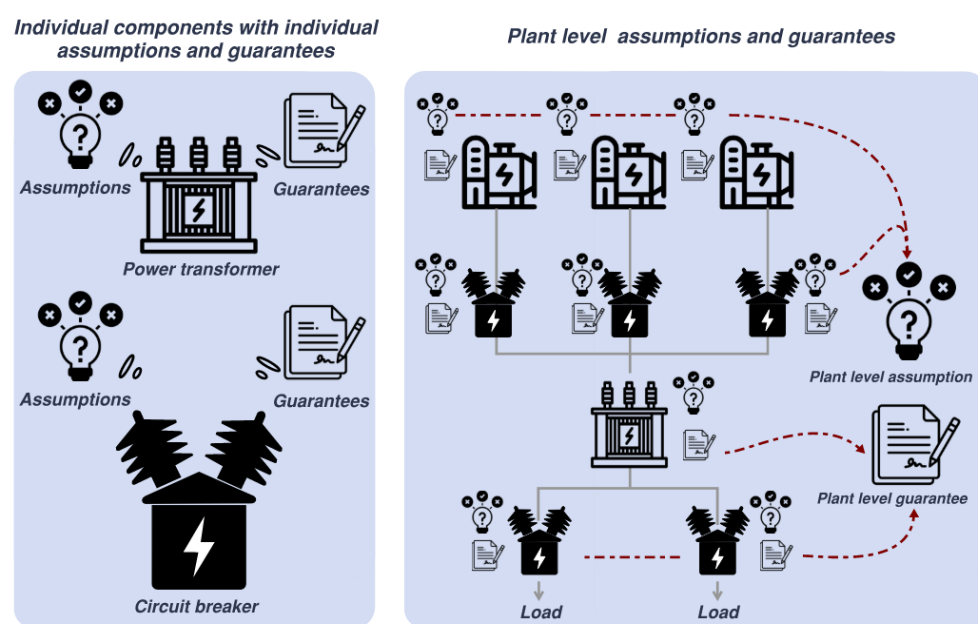


Figure 2. A visual abstract of PAGCs for uncertain power networks is shown in this figure.

Problem 1. Given an uncertain power network Σ with network topology $\mathcal{T}(\mathcal{V}, \mathcal{E})$ consisting of N_{total} units comprising N_{comp} components, with each component C_i (whose dynamics are given by (2)) satisfying the PAGC given by (3), infer the associated global PAGC for the entire network Σ .

3. Main Results

In this section, we will establish results on the composition of a PAGC when we connect component units together. Typically, PAGC theory assigns a local contract to each subsystem, capturing its behavior via probabilistic assumptions and guarantees. These contracts are self-contained in the sense that they enable independent specification and verification of each component. As a result, system-level behavior can be derived through compositional rules using union/multiplicative bounds of probability theory corresponding to series and parallel interconnection of components. This allows scalable analysis of large networks by reasoning locally but verifying globally. Briefly speaking, a PAGC provides a modular and hierarchical framework for formally verified and certified operation of power networks affected by component-level uncertainties.

Following a preliminary result on the connection involving just two units, we will expand through the rule of induction and deduce results for any number of connections. The following theorem formally establishes the soundness of the PAGC by providing a bound on the probability that the system fails to meet the guarantee even when the environment rarely violates the assumption or when the system rarely fails to meet the guarantee despite the assumption holding with a satisfaction probability. At any time $t \in \mathbb{N}$, we will denote the output of a component (following the dynamics given by (2)) under the effect of a disturbance $w(t)$ as $y_w(t)$. Since the satisfaction probabilities of the PAGC concerned with the assumptions and guarantees of any component shall hold $\forall t \in \mathbb{N}$, we shall be dropping the notation (t) from now on in associated variables, which by the way also enables convenience of writing.

Theorem 1. Let the stochastic system in (2) satisfy a PAGC denoted by $\Sigma \models \mathcal{C} := (\mathcal{A}^{1-\delta}, \mathcal{G}^{1-\epsilon})$ so that

$$\mathbb{P}(w \models \mathcal{A} \Rightarrow y_w \models \mathcal{G}) \geq 1 - \epsilon. \quad (4)$$

Then, its output y_w under the disturbance w satisfies

$$\mathbb{P}(y_w \models \mathcal{G}) \geq 1 - (\delta + \epsilon). \quad (5)$$

Proof. We know that $\mathbb{P}(w \models \mathcal{A}) \geq 1 - \delta$ or equivalently $\mathbb{P}(w \not\models \mathcal{A}) \leq \delta$. Further, from (4), we see that

$$\mathbb{P}(w \models \mathcal{A} \Rightarrow y_w \models \mathcal{G}) \geq 1 - \epsilon \iff \mathbb{P}(w \models \mathcal{A} \Rightarrow y_w \not\models \mathcal{G}) \leq \epsilon.$$

Then, the probability of the system not satisfying its guarantee can be decomposed into when the system guarantee fails whenever its assumption holds and when the system guarantee fails whenever its assumption fails. That is,

$$\mathbb{P}(y_w \not\models \mathcal{G}) = \mathbb{P}(w \models \mathcal{A} \wedge y_w \not\models \mathcal{G}) + \mathbb{P}(w \not\models \mathcal{A} \wedge y_w \not\models \mathcal{G}) \leq \epsilon + \delta.$$

Thus, $\mathbb{P}(y_w \models \mathcal{G}) \geq 1 - (\delta + \epsilon)$. $\square$

3.1. Composition of PAGCs: Series Interconnection

Often in power networks, several units of multiple components are usually connected in series and in parallel. We will now first consider the case when two units are connected in series, meaning that the first one feeds into the second one. Given local PAGC satisfaction

for each of the two units, the following theorem establishes the PAGC satisfaction for the composition of two units. Suppose two subsystems Σ_1, Σ_2 satisfy PAGCs, namely $\mathcal{C}_1 = (\mathcal{A}_1^{1-\delta_1}, \mathcal{G}_1^{1-\epsilon_1})$ and $\mathcal{C}_2 = (\mathcal{A}_2^{1-\delta_2}, \mathcal{G}_2^{1-\epsilon_2})$ respectively. Before stating the theorem, we need the following assumption about the two units connected in series with each other.

Assumption 1. *The first unit feeds into the second unit, meaning that the guarantee of the first is sufficient to satisfy the assumption of the second. That is, $\mathcal{G}_1 \Rightarrow \mathcal{A}_2$.*

Theorem 2. *Under Assumption 1, the system $\Sigma_{12} := \Sigma_2 \circ \Sigma_1$ satisfies the PAGC given by*

$$\mathcal{C}_{1:2} = (\mathcal{A}_1^{1-\delta_1}, \mathcal{G}_2^{1-(\delta_1+\epsilon_1+\epsilon_2)}). \quad (6)$$

Proof. Given that Assumption 1 holds true and the satisfaction of local PAGCs, namely $\mathcal{C}_1 = (\mathcal{A}_1^{1-\delta_1}, \mathcal{G}_1^{1-\epsilon_1})$ and $\mathcal{C}_2 = (\mathcal{A}_2^{1-\delta_2}, \mathcal{G}_2^{1-\epsilon_2})$, by subsystems Σ_1 and Σ_2 respectively, we infer from Theorem 1 that

$$\begin{aligned} \mathbb{P}(y_{1w} \models \mathcal{G}_1) &\geq 1 - (\delta_1 + \epsilon_1), \quad \text{and} \\ \mathbb{P}(y_{2w} \models \mathcal{G}_2 \mid w \models \mathcal{G}_1) &\geq 1 - \epsilon_2 \\ \iff \mathbb{P}(y_{2w} \not\models \mathcal{G}_2 \mid w \models \mathcal{G}_1) &\leq \epsilon_2. \end{aligned}$$

Note that the guarantees of the composed system Σ_{12} can fail if the first subsystem Σ_1 fails or if the first subsystem Σ_1 succeeds but the second subsystem Σ_2 fails. In that case, the guarantee concerned with the output of subsystem Σ_2 (which also happens to be the guarantee concerned with the output of the composed system Σ_{12} because the subsystems are in series) satisfies

$$\mathbb{P}(y_{2w} \not\models \mathcal{G}_2) \leq \mathbb{P}(y_{1w} \not\models \mathcal{G}_1) + \mathbb{P}(y_{2w} \not\models \mathcal{G}_2 \mid w \models \mathcal{G}_1) \leq (\delta_1 + \epsilon_1) + \epsilon_2.$$

which is equivalent to

$$\mathbb{P}(y_{2w} \models \mathcal{G}_2) \geq 1 - (\delta_1 + \epsilon_1 + \epsilon_2).$$

From the above result and using the fact that subsystem Σ_1 feeds into subsystem Σ_2 , the PAGC, namely $\mathcal{C}_{1:2}$, for the composed system Σ_{12} follows (6). $\square$

We now extend the result for N subsystems in series in the following corollary. We denote the composition of N units in series by

$$\Sigma_{1:N} := \Sigma_N \circ \Sigma_{N-1} \circ \cdots \circ \Sigma_1. \quad (7)$$

Corollary 1. *Suppose that Assumption 1 holds true for any two of the subsequent subsystems Σ_i and Σ_{i+1} in series interconnection. Then, $\Sigma_{1:N}$ defined using (7) satisfies the PAGC given by*

$$\mathcal{C}_{1:N} = (\mathcal{A}_1^{1-\delta_1}, \mathcal{G}_N^{1-(\delta_1+\sum_{i=1}^N \epsilon_i)}). \quad (8)$$

Proof. The proof for obtaining (8) is simple and straightforward as it follows by induction and hence is omitted. $\square$

Remark 1. *Note that no assumptions were made about the subsystems Σ_i being independent of each other. If they are independent, then the above union-bound-based PAGC results can be tightened using multiplicative probability bounds. The independence assumption makes sense when components are physically and electrically decoupled, such as geographically separated generators or*

independent feeders, where disturbances arise from local hardware failures. On the other hand, in many practical settings geographically co-located equipment, shared buses, common environmental factors such as weather, and faults exhibit correlation and independence may not hold. In such cases, the union-bound-based results provide conservative but safe guarantees. Based on the actual power network setting and the inferred engineering evidences, which might possibly support approximate independence, the power system engineer is encouraged to select and apply the appropriate PAGC methodology (with or without the independence assumption).

Let us denote the events $A_i := (w_i \models \mathcal{A}_i)$ and $E_i := (w \models \mathcal{A}_i \Rightarrow y_{iw} \models \mathcal{G}_i)$ for $\forall i \in 1, \dots, N$.

Assumption 2. Events A_i and $E_i \forall i \in 1, \dots, N$ are independent.

Theorem 3. Under Assumptions 1 and 2, $\Sigma_{1:N}$ satisfies the PAGC given by

$$\mathcal{C}_{1:N} := (\mathcal{A}_1^{1-\delta_1}, (\mathcal{G}_N)^{(1-\delta_1) \prod_{i=1}^N (1-\epsilon_i)}). \quad (9)$$

Proof. We know for Σ_1 that its assumption satisfies $\mathbb{P}(w \models \mathcal{A}_1) \geq 1 - \delta_1$ and $\mathbb{P}(y_{1w} \models \mathcal{G}_1 \mid w \models \mathcal{A}_1) \geq 1 - \epsilon_1$. Using Assumption 2, we observe that

$$\mathbb{P}((w \models \mathcal{A}_1) \wedge (y_{1w} \models \mathcal{G}_1)) = \mathbb{P}(w \models \mathcal{A}_1) \mathbb{P}(y_{1w} \models \mathcal{G}_1 \mid w \models \mathcal{A}_1) \geq (1 - \delta_1)(1 - \epsilon_1).$$

Using Assumption 1, we repeat the process through the chain. Then,

$$\mathbb{P}\left(\left(\bigwedge_{i=1}^N y_{iw} \models \mathcal{G}_i\right) \mid w \models \mathcal{A}_1\right) \geq \prod_{i=1}^N (1 - \epsilon_i).$$

Then, the probability of satisfying the guarantee of the last subsystem in series is given by

$$\mathbb{P}(y_{Nw} \models \mathcal{G}_N) \geq \mathbb{P}(w \models \mathcal{A}_1) \mathbb{P}\left(\left(\bigwedge_{i=1}^N y_{iw} \models \mathcal{G}_i\right) \mid w \models \mathcal{A}_1\right) \geq (1 - \delta_1) \prod_{i=1}^N (1 - \epsilon_i).$$

Hence the result (9) follows. $\square$

3.2. Composition of PAGCs: Parallel Interconnection

The above developments using series connection of subsystems inform us of how PAGCs would scale as we connect more and more units in series. A similar development for parallel interconnection shall be studied below. Two subsystems Σ_1 and Σ_2 in parallel interconnection with each other shall be subject to the same disturbance w and evaluated independently. The following theorem and its associated corollary formally establish the result for PAGCs associated with the parallel interconnection of subsystems.

Theorem 4. Let Σ_1 and Σ_2 be two subsystems, each with their own PAGCs given by $\mathcal{C}_1 = (\mathcal{A}_1^{1-\delta_1}, \mathcal{G}_1^{1-\epsilon_1})$ and $\mathcal{C}_2 = (\mathcal{A}_2^{1-\delta_2}, \mathcal{G}_2^{1-\epsilon_2})$ respectively. Suppose that Σ_1 and Σ_2 are connected in parallel to each other. Then the parallel composition $\Sigma_{\text{par}} := \Sigma_1 \parallel \Sigma_2$ satisfies the PAGC given by

$$\mathcal{C}_{\text{par}} = \left(\left(\bigwedge_{i=1}^2 \mathcal{A}_i \right)^{1 - \sum_{i=1}^2 \delta_i}, \left(\bigwedge_{i=1}^2 \mathcal{G}_i \right)^{1 - \sum_{i=1}^2 (\delta_i + \epsilon_i)} \right). \quad (10)$$

Proof. We know that $\mathbb{P}(w \models \mathcal{A}_1) \geq 1 - \delta_1$ and $\mathbb{P}(w \models \mathcal{A}_2) \geq 1 - \delta_2$. Then by the union bound, we see that

$$\begin{aligned} \mathbb{P}(w \not\models \mathcal{A}_1 \vee w \not\models \mathcal{A}_2) &\leq \mathbb{P}(w \not\models \mathcal{A}_1) + \mathbb{P}(w \not\models \mathcal{A}_2) \\ &\leq \delta_1 + \delta_2. \end{aligned}$$

$$\text{Then, } \mathbb{P}(w \models \mathcal{A}_1 \wedge \mathcal{A}_2) \geq 1 - (\delta_1 + \delta_2).$$

Now, under the assumption that both $\mathcal{A}_1$ and $\mathcal{A}_2$ hold, we consider the satisfaction of the guarantees:

$$\begin{aligned} \mathbb{P}(w \models \mathcal{A}_1 \Rightarrow y_{1w} \models \mathcal{G}_1) &\geq 1 - \epsilon_1, \\ \mathbb{P}(w \models \mathcal{A}_2 \Rightarrow y_{2w} \models \mathcal{G}_2) &\geq 1 - \epsilon_2. \end{aligned}$$

Using the union bound again, the probability that either guarantee fails under the assumptions is bounded by

$$\begin{aligned} \mathbb{P}(y_{1w} \not\models \mathcal{G}_1 \vee y_{2w} \not\models \mathcal{G}_2) &\leq \mathbb{P}(y_{1w} \not\models \mathcal{G}_1) + \mathbb{P}(y_{2w} \not\models \mathcal{G}_2) \\ &\leq \epsilon_1 + \epsilon_2. \end{aligned}$$

Hence, the guarantees of the combined system Σ_{par} satisfy

$$\mathbb{P}(y_{1w} \models \mathcal{G}_1 \wedge y_{2w} \models \mathcal{G}_2) \geq 1 - \left(\sum_{i=1}^2 \delta_i + \sum_{i=1}^2 \epsilon_i \right).$$

Hence the result (10) follows. $\square$

Similarly to the series interconnection of $N \in \mathbb{N}$ subsystems, we provide the analogous result for the parallel interconnection of $N \in \mathbb{N}$ subsystems in the following corollary of the above theorem. Let us denote the system formed using parallel interconnection of N subsystems as

$$\Sigma_{\text{par}} := \Sigma_1 \parallel \cdots \parallel \Sigma_N. \quad (11)$$

Corollary 2. The PAGC satisfied by Σ_{par} defined using (11) is given by

$$C_{\text{par}} = \left(\left(\bigwedge_{i=1}^N \mathcal{A}_i \right)^{1 - \sum_{i=1}^N \delta_i}, \left(\bigwedge_{i=1}^N \mathcal{G}_i \right)^{1 - \sum_{i=1}^N (\delta_i + \epsilon_i)} \right). \quad (12)$$

Proof. By applying the same reasoning as Theorem 4 recursively, we get the result (12). $\square$

Remark 2. If the subsystems in parallel are assumed to be independent of each other, then we can substitute the union bound using multiplicative probabilities to get a tighter PAGC satisfaction result.

Assumption 3. The events $A_i := (w \models \mathcal{A}_i)$ and $E_i := (w \models \mathcal{A}_i \Rightarrow y_{iw} \models \mathcal{G}_i) \forall i \in 1, \dots, N$ are independent.

Theorem 5. Under Assumption 3, Σ_{par} satisfies the PAGC given by

$$C_{\text{par}} = \left(\left(\bigwedge_{i=1}^N \mathcal{A}_i \right)^{\prod_{i=1}^N (1 - \delta_i)}, \left(\bigwedge_{i=1}^N \mathcal{G}_i \right)^{\prod_{i=1}^N (1 - \delta_i)(1 - \epsilon_i)} \right).$$

Proof. Since the events $A_i, \forall i \in 1, \dots, N$ are independent, we see that

$$\mathbb{P}\left(\bigwedge_{i=1}^N A_i\right) = \mathbb{P}\left(\bigwedge_{i=1}^N w \models \mathcal{A}_i\right) = \prod_{i=1}^N \mathbb{P}(w \models \mathcal{A}_i) \geq \prod_{i=1}^N (1 - \delta_i).$$

Similarly, due to the independence of events $E_i, \forall i \in 1, \dots, N$, we observe that

$$\mathbb{P}\left(\bigwedge_{i=1}^N (w \models \mathcal{A}_i) \Rightarrow (y_{iw} \models \mathcal{G}_i)\right) = \prod_{i=1}^N \mathbb{P}(E_i) \geq \prod_{i=1}^N (1 - \epsilon_i).$$

Then, by the law of conditional probability, we see that

$$\mathbb{P}\left(\left(\bigwedge_{i=1}^N A_i\right) \wedge \left(\bigwedge_{i=1}^N E_i\right)\right) \geq \prod_{i=1}^N (1 - \delta_i) \cdot \prod_{i=1}^N (1 - \epsilon_i) = \prod_{i=1}^N (1 - \delta_i)(1 - \epsilon_i).$$

Hence the result follows. $\square$

Note that in the power system setting, it is common to encounter tightly coupled subsystems such as generator–circuit breaker. For instance, with probability at least $1 - \delta_{\text{joint}}$, both the generator could work and the breaker could pass current; if they do, then the output voltage remains within the specifications with a probability of at least $1 - \epsilon_{\text{joint}}$. This motivates us to study joint PAGCs for tightly coupled subsystems. By tightly coupled subsystems, we mean to emphasize that a pair or tuple of subsystems (say the generator and its circuit breaker) should be treated as a single logical subsystem and hence joint PAGCs should be associated with them. Note that joint PAGCs are different from the composition of PAGCs via series or parallel interconnections, as the latter is based on modularity, scalability and deriving system-level guarantees from subsystem-level information.

Theorem 6. Consider the tightly coupled system denoted by Σ_{joint} comprising subsystems Σ_1 and Σ_2 with assumptions $\mathcal{A}_1, \mathcal{A}_2$ and guarantees $\mathcal{G}_1, \mathcal{G}_2$ respectively. Define the joint events $\mathcal{A}_{12} := \mathcal{A}_1 \wedge \mathcal{A}_2$, and $\mathcal{G}_{12} := \mathcal{G}_1 \wedge \mathcal{G}_2$. Suppose that $\exists \delta_{12}, \epsilon_{12} \in [0, 1]$ such that $\mathbb{P}(\mathcal{A}_{12}) \geq 1 - \delta_{12}$ and $\mathbb{P}(\mathcal{G}_{12} \mid \mathcal{A}_{12}) \geq 1 - \epsilon_{12}$. Then, Σ_{joint} , satisfies the joint PAGC given by $\mathcal{C}_{12} := (\mathcal{A}_{12}^{1-\delta_{12}}, \mathcal{G}_{12}^{1-\epsilon_{12}})$.

Proof. By construction, $\mathcal{A}_{12} = \mathcal{A}_1 \wedge \mathcal{A}_2$ denotes the event that both subsystems Σ_1, Σ_2 respect their corresponding assumptions. Hence the probability that the environment satisfies the requirements of the coupled subsystem is given by $\mathbb{P}(\mathcal{A}_{12}) = \mathbb{P}(\mathcal{A}_1 \cap \mathcal{A}_2)$. By hypothesis, we have $\mathbb{P}(\mathcal{A}_{12}) \geq 1 - \delta_{12}$, which means that the probability that the joint assumption is satisfied is at least $1 - \delta_{12}$. Given that both assumptions hold, safe operation requires that both guarantees hold. Hence the desired event is $\mathcal{G}_{12} = \mathcal{G}_1 \wedge \mathcal{G}_2$. Then, $\mathbb{P}(\mathcal{G}_{12} \mid \mathcal{A}_{12}) = \mathbb{P}(\mathcal{G}_1 \cap \mathcal{G}_2 \mid \mathcal{A}_1 \cap \mathcal{A}_2)$. Again by hypothesis, we have $\mathbb{P}(\mathcal{G}_{12} \mid \mathcal{A}_{12}) \geq 1 - \epsilon_{12}$. Thus, whenever the joint assumption holds, the failure probability of the joint guarantee is upper bounded by ϵ_{12} . Using the definition of a PAGC in (1), we see that the tightly coupled system $\Sigma_{\text{joint}} \models \mathcal{C}_{12} := (\mathcal{A}_{12}^{1-\delta_{12}}, \mathcal{G}_{12}^{1-\epsilon_{12}})$. $\square$

Remark 3. Note that joint PAGCs can be extended to any N tightly coupled subsystems $\{\Sigma_i\}_{i=1}^N$.

4. Simulation-Based Case Study of Base Versus Augmented Scenario

4.1. Setup Details

For the purpose of numerical simulation, we considered an islanded data center (representative of an energy park configuration) with 12 aero-derivative generators in parallel (each with their own generator circuit breaker). The circuit breakers are connected

to buses and three transformers draw from the buses, and they are protected by a circuit breaker before the power is distributed between 12 loads in parallel with each other. This is a scaled-down version of a generic islanded power network typically seen for data center plants, with the component-level detailing and the underlying network topology shown in Figure 3. In the considered power network, the violation probability of assumptions δ refer to the failure rate (failure per year) of that corresponding component. In the case of a generator, δ corresponds to the probability that operating conditions fall outside the nominal envelope, such as frequency instability or overheating. On the other hand, the violation probability of guarantees ϵ means different things for each component. For circuit breakers, ϵ refers to the % that demonstrated some form of malfunction of protective relay or mechanical breakdown due to deformation of structural parts. For transformers, ϵ refers to the % that demonstrated some form of malfunction due to transient over-voltages from lightning, switching surges or other insulator breakdowns. Finally for the generators, ϵ refers to the % that demonstrated some form of malfunction in the gear box or fuel system resulting in failure to produce rated power. To put things in perspective, this means that for the case of generators (similar statements hold for other components), they will have a failure rate of 0.638% per year and 0.10% of the generators are susceptible to malfunction due to some fault in their subsystems. The (δ, ϵ) details for each of the above-mentioned components are tabulated in Table 2, with the failure specifications derived from a combination of IEEE 493, IEEE 3006, and equipment vendor reliability data. Monte-Carlo trials amounting to 10^5 independent trials were conducted to estimate the probability of simultaneously providing power to as many loads as possible given the (δ, ϵ) specifications. Total mission time was set to be 1 year, with the (δ, ϵ) specifications (simulated in Matlab Version 2025b using Poisson distribution) given for all components of the power network in Table 2. With the same specification, the power grid was simulated with 12 generators (being referred to here as the base case) and with 14 generators (being referred to here as an augmented case) and the results are tabulated in Table 3. It may be observed that for the given (δ, ϵ) specifications for each of the components, the redundancy in the path available for the power to reach the load from the generators increases the guarantee of the power being delivered when two more generators are added into the bay. In particular, having more generators plugged into the power network in turn results in a higher assurance in terms of the probability of the number of loads simultaneously being powered by any one of the generators (which, by the way, is one of the most crucial assurances that every islanded power system network seeks to attain). The system was benchmarked against Uptime Institute's four-tier classification, with tier 1 classification having at least 99.671% reliability, tier II classification having at least 99.741% reliability, and tier III and IV classifications having at least 99.982% and 99.995% reliability. With the addition of two more generators for our use case, the data center plant's tier classification upgrades to III.

Table 2. Component inventory and failure specifications of the major equipment within the islanded power grid are tabulated here.

Component	Count	Type	δ : Failure Rate (in %)	ϵ : (% of Malfunction)
Generators (Aero-Derivative)	14	40 MW each	0.638/year	0.10
13.2 kV Circuit Breakers	12	Bay A, B	0.00578/year	0.01
34.5 kV Circuit Breakers	6	Post-Transformer	0.04675/year	0.01
13.2/34.5 kV Transformers	3	240 MW each	0.0037/year	0.10
Data Center Loads (IT+non-IT)	6	40 MW max each	—	—

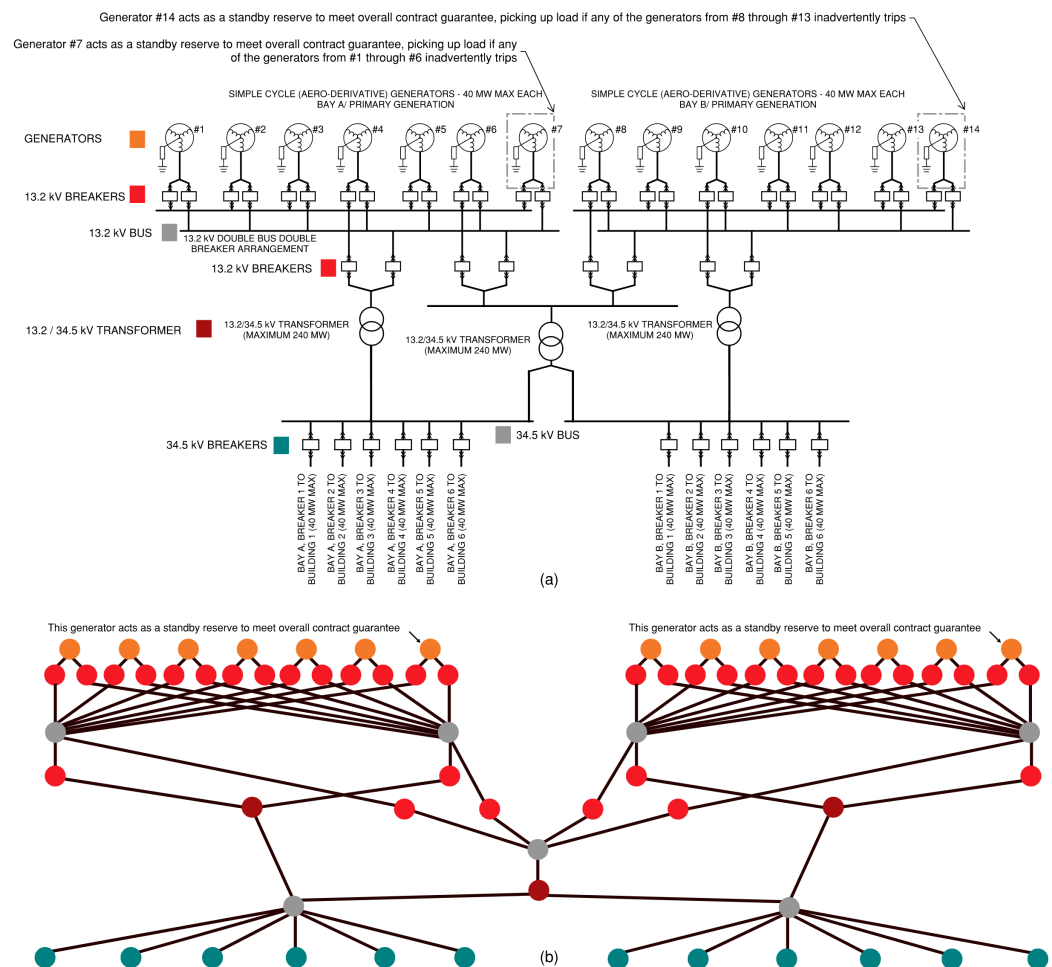


Figure 3. (a) Shows the power network under consideration with component-level detail and sub-figure (b) shows the underlying network topology of the power network depicted in sub-figure (a).

Table 3. PAGC results indicating the probability of at least powering n loads expressed in % is plotted for the case of 14 generators and 12 generators. Observe that with more generators, the path redundancy for the power reaching the load from any generators is higher, which leads to a higher probability guarantee.

# of Generators	Probability of Powering at Least n Loads (in %)											
	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	$n = 8$	$n = 9$	$n = 10$	$n = 11$	$n = 12$
12	100	100	100	99.9998	99.9918	99.9825	99.9755	99.9683	99.9611	99.6597	99.6455	99.5587
14	100	100	100	100	100	99.9998	99.9994	99.9968	99.9952	99.9945	99.9925	99.9910

4.2. Sensitivity Analysis

To analyze the sensitivity of the obtained results from the previous subsection, we varied the δ and ϵ parameters of the transformer within $\pm 10\%$, $\pm 20\%$ for δ and within $\pm 20\%$, $\pm 50\%$ for ϵ and recorded the probability of powering all 12 loads with 14 generators. For our given network, the power transformers were the largest and most limiting electrical equipment and showed the greatest variance in our sensitivity analysis. The results are tabulated in Table 4, and clearly, it shows that as the failure rates δ and malfunction ϵ increased, the violation of PAGCs increased dramatically, leading to a decreased probability of powering all the 12 loads simultaneously.

Table 4. The results of the sensitivity analysis are tabulated here. The (δ, ϵ) parameters for the transformer component (14-generator case) were varied between $\pm 10\%$ and $\pm 20\%$ for δ and between $\pm 20\%$ and $\pm 50\%$ for ϵ from their base values reported in Table 2, and the resulting probability of powering all the 12 loads is tabulated here. It is evident that as (δ, ϵ) increase, the violations of PAGCs increase and as a result of that the probability of powering all the 12 loads decreases.

δ : Failure Rate (in %)	ϵ : Malfunctions (in %)				
	0.05	0.08	0.10	0.12	0.15
0.00296	100	100	99.9985	99.9400	99.8557
0.00333	100	100	99.9981	99.9396	99.8553
0.00370	100	100	99.9910	99.9077	99.8534
0.00407	100	100	99.8957	99.8072	99.7929
0.00444	100	99.9881	99.8001	99.7366	99.5532

5. Conclusions

A systematic framework for establishing probabilistic assume–guarantee contracts for power system planning and design was proposed in this paper. Typically, components in a power network come with assumptions and associated guarantees, both of which are vulnerable to violation with small probability due to uncertainties. Using grounded probability theory-based results and network theory-based modeling, probabilistic assume–guarantee contracts are derived for individual components and hence for the entire power network. The proposed idea was demonstrated on a small-scale power network model, where each subsystem (component) had its corresponding probabilistic assumptions and associated probabilistic guarantees.

The theory of PAGCs has promising potential to address several challenging problems in the distributed systems literature. In particular, with learning-based control algorithms for network systems (such as large-scale renewables injected into uncertain power networks) getting popular, they come with inevitable stochasticity due to the learning component in them and this opens the door to use PAGCs to give high-confidence assurances. We believe that it is an unexplored territory with several open and promising research problems.

Another future research area may consist of extending this analysis by considering the operational trade-offs associated with such configurations. In particular, incorporating additional spinning reserve capacity improves reliability but also introduces important considerations related to acoustic emissions and environmental impact. To mitigate these effects, future work could investigate hybrid network configurations that employ non-spinning turbine-based generation units in conjunction with battery energy storage systems (BESSs). In these configurations, the BESS would operate as a short-term bridging resource following a generator trip, maintaining supply continuity until non-spinning units can be brought online. Subsequent studies could focus on extending the probabilistic assume–guarantee (PAG) contract framework to include such hybrid operational dynamics, thereby integrating reliability, environmental performance, and transitional response characteristics into a unified contract-based formulation.

Author Contributions: Conceptualization, V.R. and S.G.; methodology, V.R.; software, V.R. and S.G.; validation, V.R. and S.G.; formal analysis, V.R. and S.G.; resources, V.R.; writing—original draft preparation, V.R. and S.G.; writing—review and editing, V.R. and S.G.; visualization, S.G.; supervision, V.R. All authors have read and agreed to the published version of the manuscript. The views and conclusions expressed are solely those of the authors and do not represent the views of any affiliated organization or employers.

Funding: The authors declare that no financial support was received for the research and/or publication of this article. This study was conducted independently without institutional or agency sponsorship.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. During the preparation of this work, the authors used Claude (Anthropic) 4.5 and ChatGPT 5.2 to assist with sentence formatting and grammar checking. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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