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Methodology for Designing Substations for High-Power Data Centers and Charging Hubs

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Abstract

The methodology addresses the fact that amid rapid digitalization and transportation electrification, modern power systems face an unprecedented challenge driven by the emergence of new classes of high-power, highly sensitive loads such as hyperscale data centers and electric vehicle (EV) charging hubs. Classical substation design approaches, developed for traditional industrial and utility customers, are unable to meet these facilities' extreme requirements for reliability, power quality, and load dynamics. The present work constitutes a comprehensive academic methodology aimed at closing this gap. At its core is an original four-stage design algorithm that systematically integrates business-requirement analysis (Uptime Institute Tier standards), quantitative reliability assessment (IEEE Std 493), optimal power-supply architecture selection, and the development of adaptive protective-relay logic. The proposed method provides a reproducible and scalable way to design substations with very high reliability, fault tolerance, and low cost, meeting the new requirements of next-generation loads. The main innovation of the work is the integration of the most modern international design standard in this field with know-how from large energy projects to help design engineers, critical energy projects, and energy companies achieve a more stable, lean power system. The methodology is intended for design engineers, data-center and high-power EV-hub developers and operators, power companies, investors, and critical-infrastructure clients who require reproducible, economically justified solutions for creating highly reliable, fault-tolerant substations for next-generation loads.

Keywords: *Reliability, Redundancy, Adaptive Protective Relaying, BESS, Breaker-And-A-Half Bus Scheme.*

INTRODUCTION

The evolution of the global digital economy and the transition to sustainable transport are shaping a new landscape in electric power systems, characterized by the emergence of two consumer types with unique, previously unseen attributes: hyperscale data centers (DCs) and high-power EV charging hubs. These loads call into question the adequacy and validity of classical substation-design methods, which historically targeted relatively stable, predictable, and less sensitive industrial and residential loads.

The fundamental mismatch manifests along several axes, first, the scale of power demand. Modern data centers, especially those supporting artificial-intelligence workloads, require from 100 MW to 500 MW and beyond, comparable to the consumption of a small or medium-sized city (Chen et al., 2025). Second, reliability requirements. For data centers certified to Uptime Institute Tier III or Tier IV, even brief supply interruptions are unacceptable, as they result in significant financial and reputational losses. These standards require availabilities of 99.982% and 99.995%, respectively, translating into stringent redundancy and fault-tolerance requirements across the entire supply chain beginning at the high-voltage substation (HPE, n.d.).

EV charging hubs pose a different challenge. Their load is stochastic, peaky, and nonlinear, creating significant difficulties for distribution networks. The simultaneous fast charging of dozens of EVs can cause abrupt power surges, overloading transformers, depressing feeder voltages, and injecting harmonic distortion, thereby degrading power quality for all customers (Li & Jenn, 2024).

Classical approaches based on deterministic peak-load calculations and standard redundancy schemes account for neither the probabilistic nature of EV-hub loads nor DCs' absolute intolerance to even minimal power-quality deviations. The second gap is due to faster data center construction. In contrast, upgrades or construction of substations and related grid infrastructures are slower, creating severe bottlenecks for the digital economy. This gap between current engineering models and future load requirements indicates the need for a new design model (Cañigueral et al., 2023).

The objective of the present work is to develop and present a systematic, reproducible, and scalable substation design algorithm that enables the creation of highly reliable, efficient, and fault-tolerant power-supply systems tailored to the specific requirements of high-power data centers and EV charging hubs. The methodology is intended to serve as a practical, theoretically grounded guide for engineers, providing a precise sequence from business-requirements analysis through equipment selection and control-logic development.

The scientific novelty of this work lies in an original, unified design algorithm that delivers a comprehensive and coherent approach, overcoming the fragmentation of traditional methods. In contrast to existing practices, which often treat power sizing, topology selection, UPS integration, and relay-protection settings in isolation, the proposed algorithm integrates these critical aspects into a single, interconnected system.

Novelty emerges through the synergistic integration of four key engineering domains:

Goal-setting based on business metrics. Formalization of translating business continuity requirements, expressed in Uptime Institute Tier standards, into specific engineering specifications for redundancy levels (N+1, 2N).

Quantitative reliability analysis. Adoption of probabilistic methods grounded in IEEE Std 493 to quantitatively confirm that the chosen substation topology truly delivers the required availability.

Hybrid power-supply architecture. A systematic approach to integrating multiple sources, utility grids, diesel generator units (DGUs), and battery energy storage systems (BESS), into a unified, controllable complex.

Adaptive protection logic. Application of intelligent protective-relaying principles capable of adapting settings and operating logic to the system's mode (e.g., grid-connected versus islanded), minimizing misoperations and maximizing fault-isolation speed.

Accordingly, the proposed methodology constitutes an original scientific contribution that synthesizes international standards, the theoretical foundations of reliability analysis, and the practical experience of implementing complex energy facilities into a single, structured, and reproducible engineering algorithm.

CHAPTER 1. THE SPECIFICITY OF MODERN HIGH-POWER LOADS AS A CHALLENGE FOR POWER SYSTEMS

Digitalization and electrification of mobility have created a new class of electricity users, such as hyperscale data centers and hyper-scale EV charging hubs, whose consumption patterns are fundamentally different from those of conventional consumers. These new consumption patterns pose challenges to power systems planners and operators and require a reconsideration of the customary approach to supply assurance.

Data-Center Load Characteristics

From a power-engineering perspective, a data center is a unique facility characterized by three defining parameters: enormous power, exceptionally high continuity requirements, and extreme sensitivity to power quality.

The scale and density of demand have grown exponentially. Whereas traditional server racks consumed on the order of 7–10 kW, modern racks equipped with GPUs for AI workloads require 80–150 kW and beyond (Chen et al., 2025). Consequently, hyperscale DC campuses today exceed 100 MW, and next-generation projects are planned with power approaching the gigawatt level (Chen et al., 2025). Such concentration imposes formidable stress on the upstream grid and demands commensurate substation infrastructure.

Continuity requirements are formalized in Uptime Institute standards that serve as the industry benchmark for DC reliability. The most common levels are Tier III and Tier IV. Tier III (Concurrently Maintainable) entails the ability to conduct planned maintenance and replace any infrastructure component without interrupting IT operation. This is achieved by N+1 redundancy, where N components are required at full load, with +1 component on standby. Tier III has 99.982% availability, which equates to a maximum of 1.6 hours of downtime per year (Uptime Institute, n.d.). Tier IV (Fault Tolerant): The infrastructure is fault-tolerant, meaning that no single event or failure of equipment or of a distribution path will disrupt the operation of the IT load (2N/2N+1). All elements of the infrastructure are fully redundant. Tier IV's 99.995% availability limits downtime. The foundational principle of Tier IV is the absence of any single point of failure.

Sensitivity to power quality is the third defining factor. IT equipment containing millions of semiconductor devices is susceptible to variations in supply voltage. Voltage sags and swells, impulsive transients, and harmonic distortion can all cause equipment malfunctions, damage, or data loss. These electromagnetic phenomena are classified and monitored by IEEE Std 1159 (Shao et al., 2024). For DCs, it is essential not merely to avoid total outages but to keep voltage continuously within the tight bounds defined by equipment-ride-through curves such as CBEMA/ITIC.

EV-Charging-Hub Load Characteristics

The load of EV charging hubs presents an entirely different challenge due to its stochastic nature, high peaks, and potential to degrade network power quality.

An EV hub's profile is not a stable baseload like that of a DC; rather, it is the superposition of numerous independent random events, EV charging sessions. Arrival time, initial state of charge, required charging power, and session duration are random variables. Proper determination of design power and network impact assessment requires probabilistic modeling, such as Monte Carlo methods, using driver-behavior statistics to generate realistic daily load curves (Zhang et al., 2020). These models reveal pronounced peaks, typically in morning and evening windows that coincide with traffic flows.

Uncontrolled charging can severely stress the network. The concurrent connection of many high-power DC fast chargers produces a sharp demand surge that may thermally overload power transformers and cables, shortening asset lifetimes and increasing the risk of outages. It also induces substantial feeder-voltage drops, affecting other customers. Large AC-to-DC converters, such as chargers, are sources of current harmonics that distort voltage waveforms, creating problems for sensitive equipment and increasing losses.

A key element for mitigating these effects is the integration of battery energy storage systems (BESS). BESS performs several critical functions. These include peak shaving, in which the BESS is charged when demand is low and discharged when demand is high, reducing the maximum demand, demand charges, and transformer operating at or near full capacity, and eliminating the need for network upgrades. It may also provide voltage support and reactive power compensation. Third, BESS turns a hub from a passive load into an active component of the power system, providing ancillary services (such as frequency regulation) or grid-supporting services (controlling active power, reactive power, power factor, etc.). BESS are therefore needed for the efficient and safe operation of high-power EV hubs.

Key Problems of Traditional Approaches

Analysis of DC and EV-hub load characteristics clarifies why established substation design approaches are ineffective and insufficient. The fundamental issue is a philosophical divergence between the design paradigm and the actual requirements of these facilities.

Customarily, the substation is treated as a passive 'pipe' which takes power from a generator and delivers it to the consumer (Nutkani et al., 2024): the design process is then to determine the maximum likely load plus a standard margin of safety and to select equipment accordingly. Protection relays can act on apparent faults (e.g., short circuits) and have little to no tolerance for any other slight deviation from normal operating conditions.

This approach fails against next-generation loads. For a Tier IV DC, the substation cannot be a mere pipeline. It must function as an active energy firewall, robustly isolating sensitive IT infrastructure from disturbances originating in the external grid. Even a short-lived voltage sag, imperceptible to a traditional industrial load, constitutes a critical event for a DC. Standard practice does not envisage multilayer, wholly duplicated systems and intelligent automation capable of seamless sub-second transfer to backup sources.

For a charging hub, the substation must act as an energy shock absorber, smoothing and absorbing abrupt, unpredictable load impacts, shielding the external network from destabilization. Deterministic peak-load sizing cannot adequately capture the stochastic nature of sessions, leading to either over-sizing (and inflated CAPEX) or systematic overload risk. Nor does it provide for native integration of active elements, such as BESS, for dynamic power-flow control.

Hence, the crux of traditional approaches is passivity and non-adaptivity. These limitations prevent achieving the desired high level of isolation and fault tolerance for the DCs, as well as the damping and controllability requirements for the DC that are essential for the functioning of the EV hubs. This suggests that a new design model should treat the substation as an integral part of critical infrastructure, with active, innovative, and dynamic interaction with the load and the grid.

CHAPTER 2. THE DESIGN ALGORITHM: FROM POWER SIZING TO REDUNDANCY TOPOLOGY

To address the challenges posed by contemporary high-power loads, an authorial design algorithm is proposed, as shown in Figure 1. It constitutes a structured sequence of four interdependent stages that enables a systematic progression from customer business requirements to detailed technical solutions, ensuring the requisite levels of reliability, fault tolerance, and efficiency.

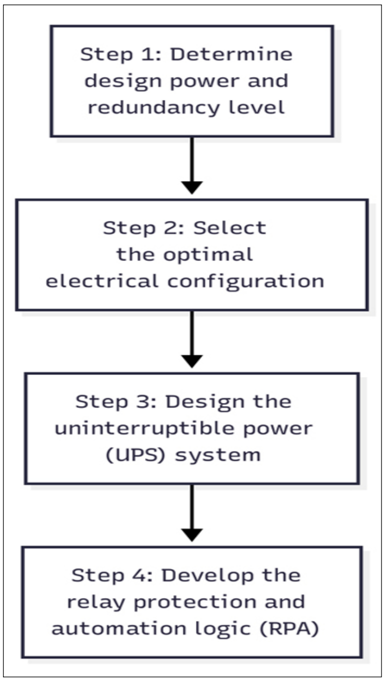

Figure 1. Block diagram of the author's design algorithm

Step 1: Determination of Design Power and Redundancy Level

The first step of the algorithm is foundational, as it translates high-level project business objectives into concrete engineering parameters. This stage comprises two interlinked tasks: precise computation of the total design power and formal specification of the required redundancy level.

The computation of the design power must be comprehensive. It begins by determining the power of the principal process load, IT equipment in a data center or the aggregate rating of charging stations in an EV hub. A critical error is neglecting auxiliary systems. In data centers, the power of the cooling system (HVAC) is commensurate with the IT load and can account for up to 40% of total energy consumption. The power for lighting, security, and other auxiliary equipment must likewise be accounted for. An essential element is the provision of headroom for future expansion. The design power must be calculated concerning plans for increased rack density or the number of charging ports over a 5–10-year horizon.

Determining the redundancy level is a direct consequence of business-continuity requirements. For data centers, this process is strictly governed by Uptime Institute standards. If the business objective mandates Tier III compliance, all critical power-supply systems at the substation and downstream must be designed with N+1 redundancy. In normal operation, N components (N transformers) are switched into the load. In case of failure of one component, an N+1 scheme is used, where N+1 components are provided and any one can be taken out of service for maintenance without affecting the supply. For Tier IV conformance, a fault-tolerant scheme of 2N or N+2 is required.

However, qualitative selection of a redundancy scheme is insufficient. The proposed methodology requires quantitative corroboration using probabilistic reliability-analysis methods, as recommended in IEEE Std 493 (Gold Book). This approach entails constructing a reliability block diagram of the system, wherein each element (transformer, circuit breaker, cable) is assigned statistical failure rates and mean time to repair. Based on these data, system-level reliability indices, such as Availability and expected annual Downtime, are computed. The objective of this analysis is to demonstrate that the selected configuration (for example, 2N), given the reliabilities of specific components, indeed provides the target availability (for example, 99.995% for Tier IV). This transforms design from an art into a data-driven science.

Step 2: Selection of the Optimal Electrical Scheme

At the second step of the algorithm, the topology of the substation's high-voltage section, namely, the busbar scheme, is determined. This choice is strategic, as it sets the ceiling for reliability, operational flexibility, and future expansion prospects. The selection must rest not on habitual solutions but on a formalized comparative analysis of alternatives against key criteria. Several principal busbar schemes exist, each bearing distinct advantages and limitations.

Double Busbar. Ensures high flexibility and reliability. It permits connecting any line or transformer to either of the two bus systems, simplifying maintenance and operational switching without interruption of power supply.

Ring Main. Likewise, it is characterized by high reliability. All feeders are included in a closed ring, and failure of any single element or circuit breaker does not result in loss of supply to other feeders. Maintenance of any breaker can be performed without disconnecting the corresponding line.

Breaker-and-a-Half. Among the most reliable and flexible schemes. Three circuit breakers serve every two feeders. This scheme enables maintenance of any breaker without de-energizing feeders and even maintenance of any bus system without loss of supply. Owing to its exceptional reliability, it is frequently deployed at nodal grid substations and is the preferred choice for Tier IV facilities.

To systematize the selection process, a decision matrix is proposed. This instrument enables the evaluation of each scheme by a set of weighted criteria and the selection of an optimal option for the specified requirement level.

Table 1. Matrix for selecting the optimal substation busbar scheme

Criterion	Single sectionalized bus system	Double bus system	Ring bus	One-and-a-half bus scheme
Reliability	Low	High	High	Very high
Operational flexibility	Low	High	Medium	Very high
Maintainability (concurrent maintainability)	Low	High	High	Very high
Capital expenditure (CAPEX)	Low	Medium	Medium	High
Overall score for Tier III	4	8	7	6
Overall score for Tier IV	2	7	8	10

Note: The ratings are illustrative and should be calibrated for each specific project, taking into account the criteria weighting factors.

The use of such a matrix enables formalization and objectification of the choice, ensuring its conformity with the reliability requirements defined in Step 1. For a Tier III facility, where concurrent maintainability is paramount, a double-bus system may be optimal. For a Tier IV facility, where maximum fault tolerance is required, preference is likely to be given to the breaker-and-a-half scheme despite higher capital expenditures.

Step 3: Design of the Uninterruptible Power System

The third step of the algorithm is devoted to developing a multilayer uninterruptible power system (UPS) architecture, which serves as the core of continuity assurance for the critical load. This system must be engineered as an integrated complex that provides defense-in-depth against disturbances in the power supply, from microsecond-scale voltage sags to multi-hour outages of the external grid. The UPS architecture is hierarchical and comprises three principal protection tiers:

Uninterruptible Power Supplies (UPS). The first line of defense. Double-conversion online UPS units continuously feed the IT load through their inverters, delivering high-fidelity voltage and instantly transitioning to their battery strings upon the slightest deviation of external-grid parameters. UPS autonomy generally ranges from 5 to 15 minutes, sufficient to initiate the next protection tier.

Diesel Generator Units (DGUs). The second tier is intended for extended autonomous operation. Upon loss of external supply and as UPS batteries discharge, the automation system starts the DGUs. After reaching nominal operating conditions, the DGUs assume the entire facility load while simultaneously recharging UPS batteries. The fuel reserve must ensure autonomous operation for 24–96 hours, depending on reliability requirements.

Battery Energy Storage Systems (BESS). BESS is increasingly integrated into UPS architecture as a multifunctional asset. They can serve as both short-term reserve (analogous to UPS but with greater power and duration) and long-term reserve (provided sufficient capacity). A decisive advantage of BESS is its instantaneous response and the ability not only to supply but also to absorb energy, enabling functions of grid stabilization, peak shaving, and power-quality enhancement.

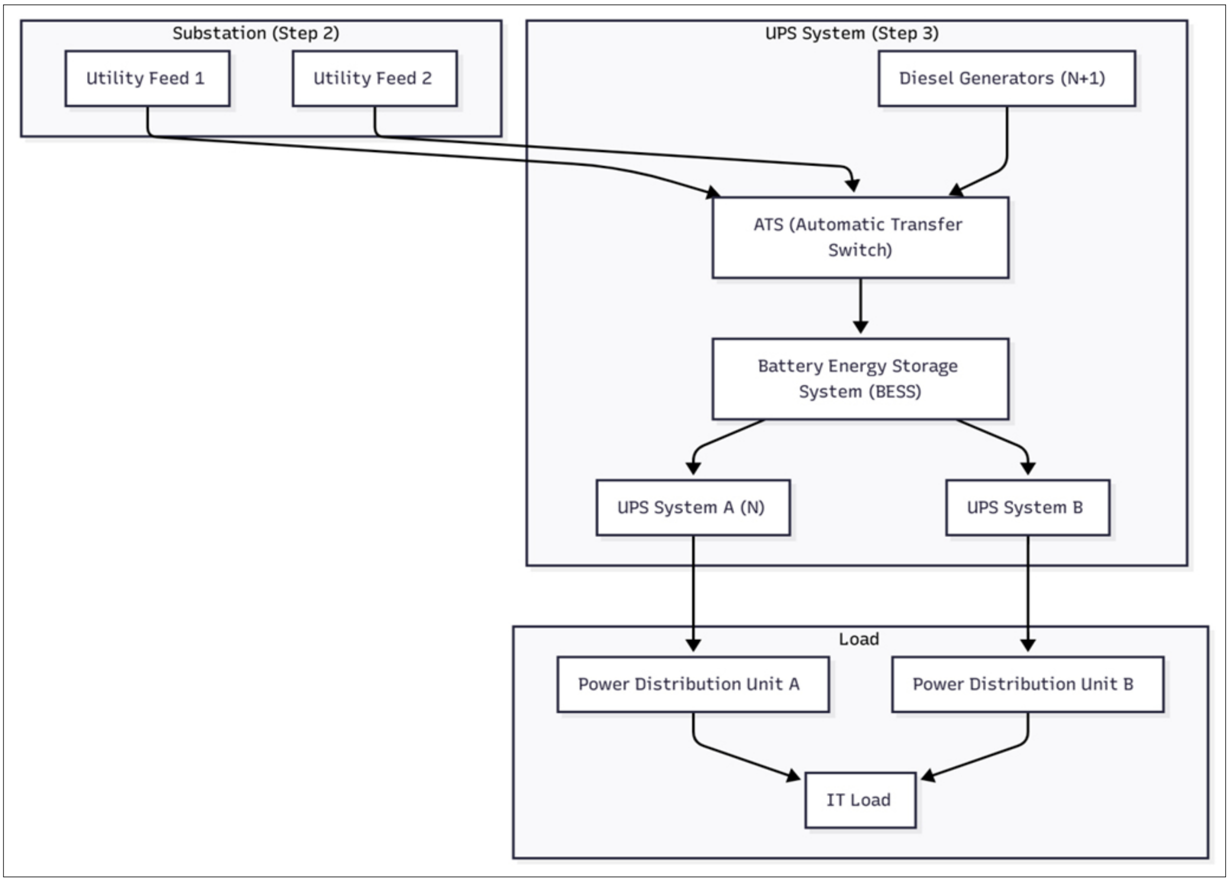

Figure 2. Simplified block diagram of an integrated power supply system for a Tier IV data center

The control logic of this complex system must be founded on hierarchical control principles analogous to those of microgrids. A central controller (SCADA system) must monitor the state of all sources and, depending on the situation (voltage sag, complete outage, command to transition to islanded operation), coordinate the operation of automatic transfer switches (ATS), UPS, DGUs, and BESS to ensure absolutely seamless transitions among operating modes.

Step 4: Development of Protective-Relaying and Automation Logic

The fourth and final step of the algorithm is the development of the substation's nervous system, the complex of protective relaying and automation (RPA). For facilities with highly sensitive loads, the RPA must resolve a paradox: it must be, on the one hand, swift and sensitive to instantaneously isolate short circuits and prevent damage to expensive equipment, and, on the other, absolutely blind to nonhazardous transients (for example, motor inrush currents, remote short circuits in the grid) to avoid nuisance trips that, for a data center, are tantamount to an actual incident.

A fundamental shift in RPA design lies in moving from traditional device-to-device coordination to device-to-load coordination. The classical approach involves selective grading of protections so that, under a short circuit, the breaker closest to the fault operates. In this context, such an approach is insufficient. The entire sequence, from fault inception, its detection by protection, issuing the trip command, and transferring to a redundant source, must be completed before the bus voltage feeding the IT equipment exits the bounds defined by its ride-through curve (for example, the ITIC curve). Consequently, the primary input parameter for RPA design becomes not the characteristic of the upstream protection but the vulnerability profile of the protected load.

To accomplish this, the methodology prescribes the use of modern digital (microprocessor-based) relays, which possess several key advantages. First, adaptive settings. A digital relay can store multiple setting groups and automatically switch among them depending on the system's operating mode. For example, under grid-connected operation, one set may be used, whereas upon transitioning to DGU-supplied islanded operation, where short-circuit currents are significantly lower, the relay switches to a more sensitive group. This approach was successfully validated in the Skole Wind Power Plant project (LLC "Orivska WPP") to ensure stable autonomous operation and is directly applicable to data-center microgrids.

Second, high-speed logic and communications. Minimizing transfer time to a redundant source requires ultra-fast information exchange among RPA devices. Use of IEC 61850 with GOOSE messaging enables the transmission of trip and blocking signals among relays within milliseconds, bypassing traditional, slow, hardwired circuits. This enables the implementation of sophisticated logical schemes, such as high-speed automatic transfer switching (ATS), delivering restoration times below 0.3 seconds, which is critical for preventing server reboots. A comparable solution was implemented in the power-supply project for the Lviv Ukraerorukh Air Traffic Services Center.

Thus, at this stage, what is developed is not merely a set of protections but an intelligent control system that acts as an active guarantor of power quality and continuity, operating in strict conformity with the requirements of the protected load.

CHAPTER 3. APPLICATION OF THE ALGORITHM IN PRACTICE: EQUIPMENT SELECTION AND CASE STUDIES

The theoretical provisions of the authorial algorithm gain practical value only when translated into concrete engineering solutions and corroborated by real-world experience. This chapter demonstrates how the stepwise execution of the algorithm directly determines the selection of primary power equipment, and how the principles embedded in the methodology have already been successfully implemented in complex power projects.

Selection of Primary Equipment in Accordance with the Algorithm

The process of specifying and selecting equipment ceases to be subjective and becomes a logical corollary of the decisions made at each stage of the algorithm.

Power Transformers (100–250 MVA)

Rated power (MVA) is determined in Step 1 as the outcome of a comprehensive design-power calculation that accounts for the IT load, auxiliary systems (HVAC), and expansion plans. The redundancy level (N+1 or 2N) determines the number of transformers to be installed.

Short-circuit voltage is selected based on short-circuit current calculations performed within Step 2 (Selection of the Electrical Scheme) and Step 4 (Development of Protection Logic). A higher value constrains fault currents, potentially reducing the interrupting-capacity requirements of circuit breakers, yet it increases load-condition voltage drop.

Cooling-system selection, e.g., ONAN/OFAF, depends on the load profile and overload-capacity requirements. For data centers with virtually constant high load, transformers with forced-cooling (oil-to-air with forced circulation) are often chosen to optimize size and cost.

High-Voltage Circuit Breakers

Rated current and interrupting capacity (kA) are the result of the system analysis carried out in Step 2. The chosen bus scheme (e.g., breaker-and-a-half) and the computed fault currents set the maximum current that the breaker must withstand and interrupt.

Reliability requirements established in Step 1 (Tier III/IV) influence the selection of breaker technology (SF_6 or vacuum) and the drive mechanism. For critical facilities, preference is given to mechanisms with the highest reliability indices and minimal operating time, as part of implementing the Step-4 protection logic.

SCADA and Automation Systems

The architecture of the supervisory control and data acquisition (SCADA) system is fully dictated by the tasks defined in Steps 3 and 4. Implementing sophisticated control logic for a hybrid power-supply system (grid–DGU–BESS) and adaptive protection algorithms requires a high-performance SCADA with redundant servers and communication channels (often using IEC 61850), capable of processing thousands of real-time signals.

Case Studies: Adapting Substation-Design Experience for PV/Wind Plants

Successful project implementations confirm the practical soundness of the proposed algorithm in adjacent domains where analogous engineering challenges were addressed. The principles underlying the methodology were validated in the design of a power supply for facilities with variable generation and stringent reliability requirements.

Skole Wind Power Plant (LLC "Orivska WPP"): Prototype Microgrid for a Tier IV Data Center

Project "Connection to the electrical networks of the State Territorial-Branch Association 'Lviv Railway' for the power-supply facility 'Skole Wind Power Plant' of LLC 'Orivska WPP', in the village of Oriv, Skole District, Lviv Region." The engineering task was to ensure stable operation both in parallel with the grid and in fully autonomous (islanded) mode. This is a direct analogue to the operation of a Tier IV data center that, upon loss of external supply, must transition to a microgrid regime powered by on-site DGUs and BESS. The key solution was the development of adaptive protective-relaying algorithms that altered settings depending on the operating mode. This enabled stable islanded generation with a frequency deviation of no more than ±0.2 Hz, a level of stability required for sensitive IT loads. This experience aligns directly with Step 4 of the algorithm, demonstrating the efficacy of adaptive protection for managing complex, multi-mode power-supply systems.

Lviv Ukraerorukh Air Traffic Services Center: An Example of Tier III Implementation

Project "Laying of a 6 kV, 1 MW electric cable line to the Lviv Air Traffic Services Center of Ukraerorukh." The task was to ensure compliance with the N+1 reliability criterion, with automatic backup in the event of failure of the main feeder. A scheme with two independent incomers was developed, and microprocessor-based automation was implemented, providing transfer times to backup of less than 0.3 seconds. This realization is a classical instance of an architecture conforming to Tier III (Concurrent Maintainability). It demonstrates the practical application of Steps 2 (selection of a redundant scheme), 3 (design of a system with automatic transfer switching), and 4 (development of high-speed automation logic) to achieve high availability.

O.F. Herbachevskyi Regional Clinical Hospital (Zhytomyr Regional Council): A Tier IV Fault-Tolerance Model

Project "Technical re-equipment of power-supply networks. Installation of a 500 kVA diesel generator station and bringing the Municipal Non-Commercial Enterprise 'O.F. Herbachevskyi Regional Clinical Hospital' of the Zhytomyr Regional Council to Category I (special)," located at: Zhytomyr, 3 Chervonoho Khresta St. An N+2 architecture was developed, including two independent incomers, a sectional ATS, and a dedicated circuit for automatic startup of a backup diesel generator. The pivotal element was a multi-tier switching logic that prioritizes supply to critical loads (e.g., intensive-care equipment). This project constitutes a practical implementation of Fault Tolerance and the elimination of single points of failure. It illustrates how the integrated application of all four steps of the algorithm yields a system capable of withstanding multiple failures without interrupting vital consumers, entirely consonant with Tier IV philosophy.

Comparative Analysis and Economic Efficiency

Justifying the deployment of the proposed, more intricate and capital-intensive design methodology requires rigorous economic analysis. The most appropriate instrument is Life-Cycle Cost Analysis (LCCA). This method enables comparison of alternatives not only by initial capital expenditure (CAPEX), but also by all future operating expenses (OPEX) and, crucially, potential downtime losses. The comparison is conducted between two scenarios:

Traditional design, executed by classical methodology with minimally sufficient redundancy (e.g., N) and standard protection. Characterized by lower CAPEX.

Designed by the authorial methodology, developed using the proposed algorithm with redundancy at N+1 or 2N, an integrated UPS architecture, and adaptive protection. Characterized by higher CAPEX.

The key parameter in this comparison is the expected annual cost of downtime losses. This indicator is computed as the product of the system failure probability (determined in Step 1 via probabilistic reliability analysis) and the cost per hour of downtime. For a hyperscale data center, the hourly cost may reach millions of dollars, including direct losses, SLA penalties, and reputational damage. For a significant charging hub, it represents a direct revenue loss. Table 2 presents a comparative life-cycle-cost assessment of different design approaches.

Table 2. Comparative LCCA analysis of design approaches (illustrative example in monetary units)

Metric	Traditional design	Proprietary-method design (Tier IV)
Capital expenditure (CAPEX)	100 MU	150 MU
Annual operating expenses (OPEX)	10 MU	12 MU
Calculated system availability	99.9% (8.76 hours/year downtime)	99.995% (0.44 hours/year downtime)
Cost per hour of downtime	1,000,000 MU	1,000,000 MU
Expected annual losses from downtime	≈ 8.76 million MU	≈ 0.44 million MU
Total lifecycle cost (10 years, r = 5%)	≈ 277 MU	≈ 245 MU

As the illustrative analysis indicates, despite a substantially higher initial investment (by 50%), a project executed under the proposed methodology proves economically superior in the long term due to a drastic reduction in risk and expected downtime losses. This analysis provides a compelling financial rationale for adopting more reliable and fault-tolerant engineering solutions.

CONCLUSION

A comprehensive methodology for designing electrical substations serving high-power data centers and charging hubs has been developed and presented. The central result is an authorial four-stage algorithm that constitutes a unified, systematic approach to resolving this complex engineering task. The algorithm guides the designer sequentially from business-requirements analysis and quantitative reliability assessment (Step 1), through the selection of an optimal electrical topology (Step 2) and the design of a multilayer uninterruptible power system (Step 3), to the development of intelligent, adaptive protective-relaying logic (Step 4).

The key conclusion is that traditional passive design approaches are inadequate for next-generation loads. The proposed methodology articulates a new paradigm in which the substation is conceived as an active, intelligent complex functioning as both an energy firewall and a shock absorber. It demonstrates that only the holistic integration of reliability analysis, redundancy architecture, energy-storage systems, and adaptive automation can deliver the requisite levels of fault tolerance and power quality.

The practical value of the methodology is exceptionally high for a broad spectrum of specialists in the power and IT sectors. For design engineers, it provides a clear, structured, and reproducible workflow that reduces error risk and enables well-founded decisions at every design stage. Underpinned by references to international standards (IEEE, Uptime Institute) and real-world case studies, the methodology provides a reliable foundation.

For data-center developers and charging-infrastructure operators, the methodology provides a tool for translating business reliability requirements into concrete technical specifications and for substantiating the necessary investments through LCCA analysis. International energy companies can employ this approach to formulate standard solutions for connecting high-power consumers of a new class while ensuring the stability and reliability of their networks.

The proposed substation design approach has significant potential for further development and will positively influence power systems as a whole. As the number of data centers and EV hubs grows, their impact on grid stability will only intensify. Thus, these substations can be equipped with BESS and intelligent control to convert a usually passive load into a controllable element of the power system.

In the longer term, such installations will also be able to provide system services with which they will provide frequency and voltage control services, reserves, such as primary, secondary, tertiary reserves or spinning and cold reserves, as well as ease the integration of variable generation technologies by offsetting their variable production with the flexibility of the storage resources. This development path will improve the security of critical digital and transport infrastructure as well as the reliability, flexibility, and sustainability of future power systems.

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