MODULE 5 · STUDY NOTES

Data Center Physical Infrastructure - Power

Following critical power from the utility feed through transformers, switchgear, backup, and distribution to the rack — plus measuring, monitoring, and electrical safety

A data center runs 24/7 on critical power, so its electrical distribution system is engineered for redundancy and minimal downtime. This module follows electricity from the street to the server. Utility power arrives at high voltage — normally 480 V to 21 kV, sometimes higher at scale — and a transformer steps it down: first to the 480/277 V that runs the building and HVAC, then again to the 208/120 V that PDUs and racks consume. Switchgear protects and transfers that power and can switch to a generator when the utility fails. Because generators need roughly 20 to 30 seconds to start, an uninterruptible power supply (UPS) carries the load from its batteries in the meantime. From there, power distribution units (PDUs), wireways, busways, and in-rack rPDUs deliver electricity to the equipment, while metering and monitoring systems track efficiency (PUE, DCiE, CADE) and preventive maintenance keeps everything running. Throughout, the same electricity that keeps the facility alive is a serious hazard — capable of an arc flash reaching 35,000 °F — so the module closes with the OSHA, NFPA, and IEEE regulations and the six safety measures that protect the technicians who work on it.

LEARNING OBJECTIVES

- Identify the components of a data center electrical distribution system and the relationships among the power infrastructure components
- Recognize the roles and characteristics of a transformer, describe how it works, and distinguish step-up from step-down transformers
- Describe the importance of backup power systems and recognize the use of generators in a data center
- Identify the types and applications of uninterruptible power supply (UPS) systems
- Identify the common types of power distribution units (PDUs) and the basic considerations for PDU-to-rPDU distribution
- Identify how power is measured and monitored, and recognize the role of routine preventive maintenance
- Identify common electrical hazards and recognize the safety regulations and measures that help prevent them

5.1 Electrical distribution system components

High availability is vital to a data center because it houses critical IT applications and processes enormous volumes of data every day. Supporting those operations around the clock consumes a great deal of power and demands a solid infrastructure built for **redundancy** and **minimal downtime**. The electrical distribution system is built from five key components **— transformers, switchgears, power backup, power distribution, and rack power —** and power flows through them in that order, from the utility feed all the way to the equipment inside a rack.

THE FIVE DISTRIBUTION COMPONENTS

- **Transformers** — step utility high voltage down to the lower voltages data center equipment can use.
- **Switchgears** — protect and safely transfer power from the utility, and transfer to a generator when utility power fails.
- **Power backup** — generators (primary backup) plus a UPS (bridges the gap until the generator starts).
- **Power distribution** — wireways, PDUs, distribution panel boards, and busways that carry power out to the racks.
- **Rack power** — the in-rack rPDUs that feed and monitor the individual rack components.

Transformers step the voltage down. Utility power normally ranges from **480 V to 21 kV** (and can run higher for a larger-scale data center). Most data centers use a single transformer per lineup that converts the voltage to **480 V** phase-to-phase (or **277 V** phase-to-neutral) to power the building and the HVAC equipment. The voltage is then stepped down a second time to **208 V** phase-to-phase (or **120 V** phase-to-neutral), which is consumed by the PDUs and racks. These exact values are an example — they vary with country, scale, and design.

Switchgears protect and transfer power. A switchgear is composed of electrical disconnect switches, fuses, and circuit breakers that control, protect, and isolate electrical equipment across the facility. A circuit breaker inside it works two ways: as a *switch* connecting a circuit (load) to its main power source, and as a *protective device* that isolates and clears faults downstream. Switchgears also monitor and control the power dispersed in the data center, function as **automatic transfer switches (ATSs)** to move to a generator when utility power fails, and use trip points and fault-interruption systems. Their main job is to disconnect the supply from the main source when power rises beyond the safe limit — a sudden shift can damage the entire distribution system or create unsafe working conditions.

Power backup is managed by generators and a UPS. Generators are the *primary* source of backup in a power failure, but they cannot start instantly, so a **UPS** provides power until the generators come online. **Power distribution** then carries that power to the racks. Wireways are modular tracks of wires that distribute power from the main supply to the racks, and there are three methods for getting power to a rack, summarized below.

TABLE 5.1 Three methods of distributing power to the racks

METHOD	DESCRIPTION
PDUs	Include distribution panels and transformers; installed on raised or slab floors. Wireways connect racks directly to the PDUs — or through a remote power panel (RPP), a freestanding distribution system without a transformer that extends a PDU's circuit capacity without adding PDUs
Distribution panel boards	Typically wall-mounted; used for small-capacity requirements and when low cost is a top priority. Wireways connect the panels to the racks
Busways	Modular tracks placed above or below the racks; wireways that can distribute three-phase power (AC over three lines so current is always available from any two)

Rack power is the final component. PDUs inside the racks provide power to the rack components and monitor the power those components consume. These devices — essentially power strips with additional functionality — are called **rack power distribution units (rPDUs)** and are used for critical IT equipment. Operations must monitor and improve the efficiency of the distribution system: an efficient system raises the input voltage for the same current, thereby reducing power consumption, and the design should stay flexible enough to add distribution capacity as the data center expands.

COMMON PITFALL

Keep the component roles straight. The **transformer** lowers the voltage; the **switchgear** transfers power from the utility to the transformer; the **wireway** distributes power from the PDUs to the racks; and the **rPDU (power strip)** in the rack provides power to the components inside it.

5.2 Power infrastructure components and how they relate

Zooming in, the power infrastructure of a data center is a chain of related components, each with an individual function: the **service entrance, main electrical service panel, transformers, feeders, subpanels, branch circuits, and receptacles**. Power enters at the service entrance and flows through the panels and circuits until it reaches a receptacle at the equipment.

KEY TERMS

Service entrance
Where the power supply begins to enter the facility from the main utility provider. It powers all the electrical equipment and charges the UPS batteries, so the UPS can supply power if an outage occurs.

Main electrical service panel
Technically a load center, commonly known as the breaker box: a steel box with a hinged door holding all the circuit breakers. It obtains inward utility power and distributes it to the circuits feeding lighting, outlets, and equipment. Every unit can be switched here except the incoming utility feed; a reliable data center may use more than one panel.

Transformer
Converts the received supply into mid-to-low voltages, connects the supply to the UPS, and is used with switchgear. It steps incoming utility voltages down to lower rated voltages that feed the switchgears and distribution panels. Ratings are given in VA (volt-amperes).

Feeder (feeder cable)
Supplies power from one part of the data center to another, used when power is required for a short period — for example, between the main service panel and the distribution transformers, or between transformers and switchgears.

Subpanel
A smaller panel that feeds power to a specific area. It draws from the main service panel (not directly from the utility) and distributes, controls, and monitors the power flowing from the UPS to the IT racks.

Branch circuit
The last part of the circuit, connecting the breaker box to the devices. Individual per-equipment circuits can be altered — instead of the main circuit — when voltage needs increase, a simple, economical way to handle equipment changes, relocation, and updates. They demand exposure to live power, so take proper precautions.

Receptacle
An electrical fitting that provides power, available in different voltage ratings with a three-plug-in slot. A UPS receptacle is one example — critical systems stay connected to the UPS so they keep power during an outage.

The circuit breakers in the main service panel are the **fail-safe units** in every electrical circuit: they block the flow of excess power and protect equipment from damage. Because the service panel can switch every unit except the incoming utility feed, it is the single control point for shutting down and energizing the facility's power.

COMMON PITFALL

A **subpanel draws from the main service panel, not directly from the utility** — and it is what distributes, controls, and monitors UPS power to the racks. Do not confuse it with the service entrance (where power first enters) or the main service panel (which obtains the inward utility power).

5.3 Transformers – roles, characteristics, and how they work

Transformers are static devices that transfer energy from one circuit to another using electromagnetic induction — the generation of electricity with a magnetic field. A transformer is commonly used to decrease or increase the voltage levels between circuits, and it is a critical component of every data center because it performs several roles in the power infrastructure: **conversion circuits, harmonic currents, and main voltages**.

TABLE 5.2 The roles a transformer performs

ROLE	WHAT THE TRANSFORMER DOES
Conversion circuit	An important part of the power conversion circuit — steps voltage down from a medium-voltage mains supply to a utilization voltage, while creating a local ground-bonded neutral
Harmonic currents	Reduces the harmonic currents in the UPS and distribution units
Main voltages	Accommodates abnormally high and low main voltages; eliminates ground loops across several generators or main sources; steps down the distribution voltage (480 V, 600 V, or 208 V); and provides extra utilization voltages

CHARACTERISTICS THAT SET A TRANSFORMER APART

- The **input and output power (watts) are almost the same**.
- **No windage or friction losses** occur — there are no moving parts in the energy transfer.
- Only a **small amount of energy loss** occurs.
- The **voltage and current can be increased or decreased**, depending on the configuration.
- The input and output voltages have a **constant (same) frequency**.

How it works. A transformer uses the principle of electromagnetism to convert voltage to another level. It has a pair of insulated wires, or coils, wound on all sides of a magnetic **core**. The coil connected to the voltage being converted is the **primary winding**; the coil that sends the output is the **secondary winding**. Magnetism is directly related to the current passing through — the larger the current, the stronger the magnetism — and the core increases the magnetic field of that current, creating a stronger current and improving efficiency. The **ratio of input to output voltage equals the ratio of the primary and secondary windings**, where the number of turns is how many times each coil is wound around the core.

WORKED EXAMPLE – TURNS, VOLTAGE, AND CURRENT

Because power is the product of voltage and current and stays the same across both windings, changing the turns ratio trades voltage for current. In a **step-up** transformer with a secondary of 100 turns and a primary of 50 turns, the secondary voltage is *double* the primary and the secondary current is *half* — voltage up, current down. Flip the ratio for a **step-down** transformer: a primary of 100 turns and a secondary of 50 turns yields half the voltage on the secondary, and the current rises from low to high.

TABLE 5.3 Step-up vs step-down transformers

FEATURE	STEP-UP	STEP-DOWN
Primary vs secondary turns	Fewer turns on the primary	More turns on the primary
Voltage	Secondary higher than primary	Secondary lower than primary
Current	Falls (high → low)	Rises (low → high)
Data center use	Increases voltage or current	Steps utility voltage down for equipment — the common case

COMMON PITFALL

The **core increases the magnetic field** of the current passing through the winding (making a stronger current and higher efficiency) — it does not by itself convert HV to LV. And on step-up vs step-down: the **step-up** transformer has *fewer* turns on the primary than the secondary; reverse it for step-down.

5.4 Backup power – generators and UPS

The role of a backup system is to provide uninterruptible power during an outage, because data centers are expected to deliver **100 percent uptime —** the amount of time the facility stays up and running. A data center draws power from the utility to run equipment such as computers, servers, and routers, but outages happen from utility disturbances, equipment failure, or weather. A robust backup system ensures continuous power, avoids downtime risk, and supports the facility until the primary supply is restored.

BUILDING A BACKUP INFRASTRUCTURE – THREE TASKS

- **Install primary backup power systems** — backup (redundant) power for outages and equipment failures, achieved with generators and UPSs.
- **Provide a secondary backup strategy** — some data centers add a secondary backup generator in case the primary fails, and keep backup fuel available to run the generators during an outage.
- **Coordinate the generator and the UPS** — synchronize the two so the transfer of power is seamless.

Coordination is a timing problem. The average time to start a generator and bring it up to operational parameters during an outage is **20 to 30 seconds**; barring a failure, it comes online and takes the electrical load within about 30 seconds. The **UPS batteries bridge the gap** between the power failure and the generator starting **—** when power fails, the UPS supplies power until the generator is running. For the handoff to be smooth, the generator and the UPS must be synchronized.

Choosing a generator starts with size and fuel. Generators provide different power supply outputs and are procured based on the data center's power needs **—** sizing comes from **power requirement calculations**, not from outage frequency or operating cost. The fuel type is a major factor because it drives long-term operating cost; the two types are diesel and natural gas.

TABLE 5.4 Generator fuel types

FUEL	CHARACTERISTICS	STORAGE / REGULATION
Diesel	The most common type; has an on-site fuel storage tank; a data center often stores additional backup fuel	Environmental safety regulations apply — emissions are monitored, and particulate matter, nitrogen oxide, and carbon monoxide must stay well below the specified limits
Natural gas	A useful alternative; fuel is distributed through a pipeline	Requires no backup fuel storage; delivery is uninterrupted unless the utility provider itself fails

THE ATS CONTROLS THE GENERATOR DURING AN OUTAGE

- Each generator has an **automatic transfer switch (ATS)**, which is either available and engaged, or unavailable.
- **ATS available** — the generator starts and runs automatically during an outage, and switches off automatically when the main utility supply is restored.
- **ATS unavailable** — a technician must manually start the generator (transferring the load from the utility) and manually switch it off when power returns.

UPS systems play the vital bridging role. A UPS provides temporary power to critical components, bridges the gap between the power failure and generator startup, makes stored battery power available during the outage, and stays on standby while utility power is available so it can supply power immediately. Three common UPS types are available, differing mainly in surge protection and how they operate.

TABLE 5.5 The three UPS system types

TYPE	SURGE PROTECTION	HOW IT OPERATES
Standby	None — no surge protection	Offline / on standby until the main supply is disconnected; widely used for desktops
Line-interactive	Protects against sudden surges	Active even when the main power supply is connected
Double-conversion	Highest level of protection	Converts AC to DC, sends some DC to charge the battery, and reconverts the rest to AC — preventing electricity from flowing directly to the server

COMMON PITFALL

The UPS does **not** start the generator — it *bridges the gap* until the generator starts. And a **standby** UPS offers no surge protection (it just waits offline); **line-interactive** and **double-conversion** UPSs work while utility power is connected.

5.5 From PDU to rack – power distribution units

A **PDU** is a floor-mounted panel consisting of a transformer and breakers that distributes power to racks; an **rPDU** installs in the rack (horizontally or vertically) and distributes power to the IT equipment inside it. Some PDUs also provide monitoring and measurement, and that data feeds the **power usage effectiveness (PUE)** calculation. A PDU lets many devices plug directly into a power supply by converting one or several inputs into multiple outputs.

WHAT A PDU CAN AND CANNOT DO

- **Cannot** generate power.
- **Can** only deliver AC power — sourced from a power supply, UPS, utility power, or generator.
- **Can** monitor and track power consumption using meters (metered PDUs).
- **Can** provide various features, power ratings, and cord combinations.
- **Can** offer web interfaces for remote management if the PDU is advanced.

A **floor-mounted PDU** (sometimes called a main distribution unit, or MDU) is the management bridge between a building's primary power and the equipment racks in a data center or network operations center (NOC). Each one handles far more energy than an ordinary power strip **— 300 kVA and higher** depending on the model **—** and typically feeds multiple racks, so an input on one PDU can serve as an output to another PDU to extend the available plug points. The common PDU types range from basic distribution to fully controllable intelligent units.

TABLE 5.6 Common PDU types

PDU TYPE	CAPABILITY
rPDU	Mounted horizontally or vertically, inside or outside the rack enclosure; distributes power to the IT equipment inside the rack; some can be accessed remotely
Floor-mounted	Larger, higher-cost unit that transforms one or more raw power feeds into any number of lower-capacity distributed feeds; typically stands alone and sends power to many racks
Basic	Provides reliable power distribution to multiple devices
Metered	Network-grade; can locally monitor load level and avoid potential overloads
Monitored	Network-grade; remotely monitors single- or three-phase voltage, frequency, and load levels in real time over a built-in network connection
Switched	Network-grade; adds remote monitoring plus outlet control — switching power on or off, shutting down power remotely, and assigning power efficiently

BASIC CONSIDERATIONS FOR SELECTING AN RPDU

- Plan around **virtualization needs, efficiency improvements, and future expansion**.
- Weigh the equipment mounted on the racks, the site's power distribution, and any preference for **remote management**.
- Estimate the rack's **highest possible power capacity** and plan for future increases in rPDU outlets to avoid redesigns.
- Specify input/output voltage requirements, connectors, cord length, whip length, and mounting options for every rack.

Power quantity and plugs. Choose the outlet type and quantity to match the IT equipment's needs; most data centers use **C13** and **C19** connectors, and waterproof connectors are preferable because raised floors can flood during a fire. Select the input power cord from the site's power distribution scheme. To avoid overloads, use rPDUs **≤ 40 A for single-phase** and **≤ 32 A for three-phase** applications, and prefer **≤ 20 A** rPDUs where possible because they do not need circuit breakers (a breaker eliminates a component from the power path and adds reliability). Provide adequate whip length so the cord has slack to reach the outlet. Rack PDUs commonly use a locking `NEMA L6-30` connector — **L** = locking, **6** = 250 V rating, **30** = amperage rating — or `IEC 309` plugs.

Mounting orientation comes in two forms. **Horizontal** mounting puts the PDU on a 482.6 mm (19-inch) rack and is used with open-frame racks and audio and video equipment. **Vertical** mounting puts the distributing outlets closer to the equipment they power; it is preferred because it uses space more efficiently and allows shorter cords, which makes future cord management easier.

> **PDU-TO-RPDU REDUNDANCY**
>
> - Maintaining high availability requires redundant equipment for both the data-centric and the primary support equipment.
> - Every piece of IT equipment carries **extra (redundant) power supplies** to keep systems running when the main supplies falter.
> - Redundant power supplies connect to **different redundant rPDUs**, so the entire load does not drop when a single power path has an issue.

> **COMMON PITFALL**
>
> A PDU **cannot generate power** — it only delivers AC from an upstream source — and only a **metered** (or higher) PDU tracks consumption. On amperage, remember the pair: **≤ 40 A single-phase, ≤ 32 A three-phase**, with ≤ 20 A adding reliability.

5.6 Measuring, monitoring, and maintaining power

Maintaining a power supply's quality and consistency is essential for proper upkeep and service-level maintenance, and the information gathered from proper measurements and evaluations is used to improve power management over time. The first step is measuring, and power can be measured from several locations in the facility.

> **POWER MEASUREMENT LOCATIONS**
>
> - **Power entry locations** — where power is fed from the utility source; measured by a submeter on the facility floor (power-sharing facilities also read the percentage consumed by cooling equipment).
> - **UPSs** — which provide power to some equipment.
> - **rPDUs** — which send power to the IT equipment on the racks.
> - **rPDU outlets** — providing rack power-consumption information at the outlet level for individual devices.
> - **CPUs** — providing the exact power required to perform computational work.

Measurement begins with overall efficiency, and there are **three essential power efficiency metrics —** PUE, DCiE, and CADE. Note that DCiE is simply the inverse of PUE.

TABLE 5.7 Power efficiency metrics

METRIC	WHAT IT TELLS YOU	EQUATION
PUE (power usage effectiveness)	How effectively power is being consumed — the fundamental metric	total facility power ÷ IT equipment power
DCiE (data center infrastructure efficiency)	The overall infrastructure efficiency (the inverse of PUE)	IT equipment power ÷ total facility power
CADE (corporate average data center efficiency)	Facility energy efficacy, its rate of utilization, and the server utilization level	facility efficiency ÷ IT asset efficiency

HOW POWER MEASUREMENT DATA IS USED

- Create initiatives for improving **energy efficiency**, and install individual outlet-level metering.
- Test the original power allocation and discover the presence of **stranded power**.
- Reduce a rack's vulnerability during a power shutdown in a **peak-load** situation.
- Periodically monitor devices and set up racks by device intake to **ergonomically** support more IT equipment.
- Reduce risks such as **breaker trips** and keep the required loading levels.

Monitoring extends measurement across time. Loss of power has a significant impact on a mission-critical facility, so it is vital to monitor and control the entire electrical system — from the incoming utility supply and all electrical equipment through to the racks — for decision-making and optimization. Readings taken from multiple locations (all IT and non-IT components) help calculate the data center's PUE. Electrical equipment such as switchgears, transformers, generators, and UPSs carry smart communicating devices — protective devices, energy meters, power quality meters, and analyzers — and a **power monitoring system** ties them together into a single interface for real-time monitoring and control, letting staff visualize power distribution, watch load flow through equipment, see the status of critical equipment and boards, analyze trends, and optimize energy.

BENEFITS OF POWER MONITORING SYSTEMS

- **Measure cooling requirements** so servers run at an accurate temperature — extending lifespan and lowering heat and power use.
- **Analyze power usage** of data center equipment; UPS monitoring software also manages the battery systems, internal resistance, and battery cycles.
- **Reduce energy costs** and operational overhead — helping qualify for energy-star and green certifications and shrinking the carbon footprint.

Preventive maintenance (PM) keeps the monitoring — and the equipment — running. PM is the systematic, methodical inspection of equipment to identify issues before they arise, and it includes daily checks and site rounds that also ensure cleanliness for safety. Trained professionals visually observe the infrastructure, take meter readings, and listen to the sounds equipment makes. Repairs made as part of PM include **condition-based maintenance, replacing weak parts, thermal scans of breaker panels, component or system adjustments, cleaning air and water filters, and regular software updates**.

COMMON PITFALL

DCiE is the inverse of PUE, so watch which is on top: `PUE = total facility power ÷ IT equipment power`, `DCiE = IT equipment power ÷ total facility power`. And monitoring does not eliminate preventive maintenance — it *supports* it; both are needed to avoid unpredicted downtime.

5.7 Electrical safety in the data center

Electricity sustains the data center, but operating, maintaining, and repairing electrical equipment places personnel within hazardous work boundaries. Technicians protect themselves by following proper handling procedures and strictly adhering to personal protective equipment (PPE) requirements — but first they must recognize what makes these systems inherently dangerous.

COMMON ELECTRICAL HAZARDS

- Use of **large loads of AC and DC power** and cooling units for high efficiency.
- **Design complexity** and high-power equipment that can switch between supplies within a few milliseconds and without warning.
- **Servicing equipment while it is energized**, which creates shock hazards.
- Larger power capacities carrying a **high level of available fault current**, which raises the risk to personnel.

Arc flash is the signature catastrophe. An arc flash occurs when the insulation between two energized conductors is insufficient for the applied voltage and the current arcs through the air; it can produce temperatures up to **35,000 °F**, and the resulting explosion — an **arc blast** — is powerful enough to throw an employee across a room. Beyond electrical shocks, burns, injuries, and fatalities, an arc flash can cause infrastructure and equipment damage, business disruption, huge regulatory penalties, legal liability, raised insurance premiums, and financial losses.

To protect against arc flash hazards, data centers follow specific standards governed by two organizations: the **Occupational Safety and Health Administration (OSHA)**, a regulatory body that sets legal, federally enforceable requirements for a safe workplace, and the **National Fire Prevention Association (NFPA)**, a global organization with more than 300 published consensus codes and standards that advocates fire prevention and protection. Together they enforce four essential regulations.

TABLE 5.8 The four essential electrical safety regulations

REGULATION	BODY	SCOPE
OSHA 29 CFR, Part 1910	OSHA	Occupational safety and health standards, specifically for work practices (enforceable under federal law)
NFPA Standard 70	NFPA	Benchmark for safe electrical design, installation, and inspection to protect people and property from electrical hazards
NFPA 70E	NFPA	Safety-related work practices, maintenance requirements, and controls — including installing conductors, safe operation, and selecting appropriate PPE
IEEE 1584	IEEE	Guide for performing arc flash hazard calculations — determining safe working distance and the incident energy workers could be exposed to

SIX ELECTRICAL SAFETY MEASURES

- **Regular audit** of the electrical safety policies — annually or biannually, evaluating every technician and worker for compliance with the applicable standards.
- **Arc flash hazard analysis** — per IEEE 1584, determining the incident-energy potential of all equipment; field-marked (arc flash) labels are reviewed for accuracy at intervals **not exceeding 5 years**, and the equipment owner is responsible for the label.
- **Electrical equipment labeling** — NFPA 70E requires labels showing the nominal system voltage, the arc flash boundary, and at least one of: the arc flash PPE category or available incident energy with working distance, the minimum arc rating of clothing, or the site-specific PPE level.
- **Adequate PPE supply** — arc-rated gloves, foot and eye protection, hard hats, earplugs or muffs, and full body suits; wearing PPE is mandatory, and employers who fail to supply it are fined heavily by OSHA.
- **Safety training** — workers must know the systems and be retrained at least once every **three years** (per NFPA 70E) and whenever new technology or equipment is introduced.
- **Electrical distribution maintenance** — electrically active components (UPSs, batteries, cooling equipment) can cause an arc flash if not maintained; NFPA 70E specifies the practices, and noncompliance risks workers and invites financial consequences.

COMMON PITFALL

The danger comes from a **high** level of available fault current, not a low one — a distractor answer flips this. And keep the standards distinct: **NFPA 70** governs safe *design and installation*; **NFPA 70E** governs safe *work practices and PPE*; **IEEE 1584** is the arc flash *calculation* guide; **OSHA 29 CFR 1910** is federal work-practice law.

Module summary

- The electrical distribution system has five components in sequence — transformers, switchgears, power backup, power distribution, and rack power — carrying power from the utility feed to the rack.
- Transformers step utility voltage (480 V–21 kV) down to 480/277 V for the building and HVAC, then to 208/120 V for PDUs and racks; switchgears protect, isolate, and transfer power and act as ATSs.
- The power infrastructure chain runs service entrance → main service panel (breaker box / load center) → transformer → feeder → subpanel → branch circuit → receptacle; a subpanel draws from the main panel, not the utility.
- Transformers are static devices using electromagnetic induction; they have almost equal input/output watts, no windage or friction loss, small energy loss, and a constant frequency, and their roles cover conversion circuits, harmonic currents, and main voltages.
- Turns ratio sets the outcome: a step-up transformer has fewer primary turns (voltage up, current down); a step-down transformer has more primary turns (voltage down, current up) — the common data center case.
- Backup targets 100 percent uptime: generators are the primary backup but take ~20 to 30 seconds to start, so the UPS bridges the gap on battery power; the two must be synchronized. Generator size is based on power requirement.
- Generators run on diesel (most common, on-site fuel tank, monitored emissions) or natural gas (pipeline-fed, no storage); an ATS starts and stops the generator automatically when available, or a technician does it manually.

- The three UPS types are standby (offline, no surge protection), line-interactive (surge protection, active on utility), and double-conversion (AC→DC→AC, highest protection).
- PDUs cannot generate power — they deliver AC and, when metered or higher, monitor it; common types are basic, metered, monitored, switched, floor-mounted (MDU), and rPDU; keep rPDUs ≤ 40 A single-phase and ≤ 32 A three-phase, with redundant supplies on different rPDUs.
- Measure power at entry points, UPSs, rPDUs, outlets, and CPUs; track efficiency with PUE (total facility ÷ IT power), DCiE (its inverse), and CADE; monitor the whole system and run preventive maintenance.
- Electrical systems are dangerous due to large AC/DC loads, complex fast-switching equipment, energized servicing, and high available fault current; an arc flash can reach 35,000 °F.
- OSHA and the NFPA govern safety through four regulations — OSHA 29 CFR 1910, NFPA 70, NFPA 70E, and IEEE 1584 — enforced by six measures: policy audits, arc flash analysis, equipment labeling, PPE, training, and distribution maintenance.

Review questions

1. **Trace the power path from the utility feed to a server, naming the main components in order.**

   Answer: Utility feed → transformer (steps the voltage down) → switchgear (protects, isolates, transfers, ATS to generator) → UPS/generator backup → PDU (floor-mounted) → wireway or busway → rPDU (in the rack) → the IT equipment.

2. **If generators are the primary backup, why is a UPS still essential, and what must be true for the handoff to work?**

   Answer: Generators take about 20 to 30 seconds to start and pick up the load, so the UPS supplies stored battery power to bridge that gap the moment utility power fails. For a seamless transfer, the generator and the UPS must be synchronized.

3. **How do the windings, voltage, and current differ between a step-up and a step-down transformer?**

   Answer: A step-up transformer has fewer turns on the primary than the secondary, so secondary voltage is higher and current falls (high to low). A step-down transformer has more turns on the primary, so secondary voltage is lower and current rises (low to high) — the common data center case, since power (V × I) stays constant.

4. **Name the three UPS system types and one distinguishing trait of each.**

   Answer: Standby — offline until the main supply is disconnected, with no surge protection. Line-interactive — protects from surges and is active even while utility power is connected. Double-conversion — converts AC to DC and back to AC for the highest protection, preventing electricity from flowing straight to the server.

5. **Can a PDU generate power? Which PDUs can track consumption, and what are the recommended amperage limits for an rPDU?**

   Answer: No — a PDU cannot generate power; it only delivers AC power from an upstream source. Only metered (and higher) PDUs track consumption, using meters. Keep rPDUs ≤ 40 A for single-phase and ≤ 32 A for three-phase, with ≤ 20 A adding reliability (no breaker needed).

6. **Write the equations for PUE and DCiE and explain their relationship.**

   Answer: PUE = total facility power ÷ IT equipment power (how effectively power is consumed). DCiE = IT equipment power ÷ total facility power (overall infrastructure efficiency). DCiE is the inverse of PUE.

7. **Which four regulations govern data center electrical safety, and which body owns each?**

   Answer: OSHA 29 CFR Part 1910 (OSHA — work-practice standards, federal law); NFPA 70 (NFPA — safe electrical design, installation, and inspection); NFPA 70E (NFPA — safe work practices, maintenance, and PPE); IEEE 1584 (IEEE — guide for arc flash hazard calculations).

8. **What is an arc flash, how hot can it get, and what six measures help prevent electrical hazards?**

   Answer: An arc flash is the energy release when insulation between energized conductors fails and current arcs through the air, reaching up to 35,000 °F (its explosion is an arc blast). The six safety measures are: regular safety-policy audits (annual/biannual), arc flash hazard analysis, electrical equipment labeling, adequate PPE, safety training (retraining at least every three years), and electrical distribution maintenance.