Power distribution

Dr Peadar Grant

September 21, 2022

1 Distribution path

Figure 1 shows the basic power distribution hierarchy in a data centre.

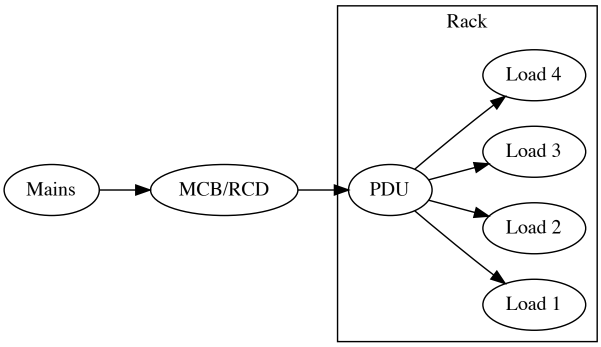

Figure 1: Power distribution schematic

We will consider the distribution path looking *backwards* from the IT equipment towards the incoming mains.

1.1 Power distribution unit (PDU)

Each rack normally has a power distribution unit, which is no more complicated than a multiplug adapter:

- PDU can be mounted vertically in the back of rack or in a rack space (facing in or out).
- PDUs are available with various combinations of input and output connectors.
- PDUs may or may not have surge protection and switches.
- Maximum current will usually be dependent on the connector type on the input to the PDU.
- "Smart" PDUs are available that can measure power demand and turn on/off sockets remotely. (See later on!)

1.2 Common connectors

Table 1 shows the most common mains power connectors (plugs and sockets) that will be encountered in a data centre environment.

Type	I_{max}	Male	Female
BS 1363	13 A		
IEC C13/14	10 A	C14	C13
IEC C19/20	16 A	C20	C19
IEC 60309	16 A		

Table 1: Common connector types

Of particular interest are the C13/15/19 connectors, Figure 2

Connector Type	Configuration	Max. Current/Voltage	Max. pin temp. (°C)	Common Application
C13		10A/250V	70	C13 connectors commonly work with inlets on computers and devices that can be attached to computers.
C15		10A/250V	120	C15 receptacles are for use in high temperature settings, such as electric kettles, computer networking closets, and PoE switches with high wattage power supplies.
C19		16A/250V	70	C19 connectors are common for devices that require higher current than which can be por-vided by C13 and C15 connec-tors. Typical applications are on enterprise-class servers, data center rack-mounted power distribution units (PDUs) and chassis switches

Figure 2: C13/15/19 connectors

2 Disturbances

Our IT equipment expects clean power with its key parameters (voltage, frequency) maintained within allowable tolerences (230 V RMS, 50 Hz). Waveform must be a *clean* sine wave, not *distorted*.

2.1 Disturbance types

Blackout: total loss of power.

Surge/sag: **short-term** (0.5 of a cycle up to 1 minute) voltage variations:

- **Surge or spike** is a short-term high-voltage condition more than 110 % of the nominal value.
- **Sag** is a short-term low-voltage condition.

Over and under-voltage conditions that **persist for time periods** ranging from minutes to days:

- **Over-voltage** is increased mains voltage.
- **Under-voltage** is reduced mains voltage. (Formerly: brownout)

Frequency fluctuations away from 50 Hz for long and short periods.

Waveform distortion when the mains voltage waveform no longer is a sinusoid. This can manifest in a number of ways: offsets, harmonics, notching and noise.

Disturbance category	Wave form	Effects	Possible causes	Possible solutions
1. Transient				
Impulsive		Loss of data, possible damage, system halts	Lightning, ESD, switching impulses, utility fault clearing	TVSS, maintain humidity between 35 – 50%
Oscillatory		Loss of data, possible damage	Switching of inductive/capacitive loads	TVSS, UPS, reactors/ chokes, zero crossing switch
2. Interruptions				
Interruption		Loss of data possible, damage shutdown	Switching, utility faults, circuit breaker tripping, component failures	UPS
3. Sag / undervoltage				
Sag		System halts, loss of data, shutdown	Startup loads, faults	Power conditioner, UPS
Undervoltage		System halts, loss of data, shutdown	Utility faults, load changes	Power conditioner, UPS
4. Swell / overvoltage				
Swell		Nuisance tripping, equipment damage/reduced life	Load changes, utility faults	Power conditioner, UPS, ferroresonant "control" transformers
Overvoltage		Equipment damage/reduced life	Load changes, utility faults	Power conditioner, UPS, ferroresonant "control" transformers
5. Waveform distortion				
DC offset		Transformers heated, ground fault current, nuisance tripping	Faulty rectifiers, power supplies	Troubleshoot and replace defective equipment
Harmonics		Transformers heated, system halts	Electronic loads (non-linear loads)	Reconfigure distribution, install k-factor transformers, use PFC power supplies
Interharmonics		Light flicker, heating, communication interference	Control signals, faulty equipment, cycloconverters, frequency converters, induction motors, arcing devices	Power conditioner, filters, UPS
Notching		System halts, data loss	Variable speed drives, arc welders, light dimmers	Reconfigure distribution, relocate sensitive loads, install filters, UPS
Noise		System halts, data loss	Transmitters (radio), faulty equipment, ineffective grounding, proximity to EMI/RFI source	Remove transmitters, reconfigure grounding, moving away from EMI/RFI source, increase shielding filters, isolation transformer
Voltage fluctuations		System halts, data loss	Transmitters (radio), faulty equipment, ineffective grounding, proximity to EMI/RFI source	Reconfigure distribution, relocate sensitive loads, power conditioner, UPS
Power frequency variations		System halts, light flicker	Intermittent operation of load equipment	Reconfigure distribution, relocate sensitive loads, power conditioner, UPS

Figure 3: Disturbances

2.2 CBEMA curve

Undesirable conditions are generally less disruptive the shorter that they persist for. This includes disturbances in the power supply. The Computer Business Equipment Manufacturers Association (CBEMA) in the 1970s generated a curve that partitioned voltage events and times into acceptable and unacceptable region. The Information Technology Industry Council (ITIC) adapted the curve in the 1990s, which was most recently updated in 2000, Figure 4

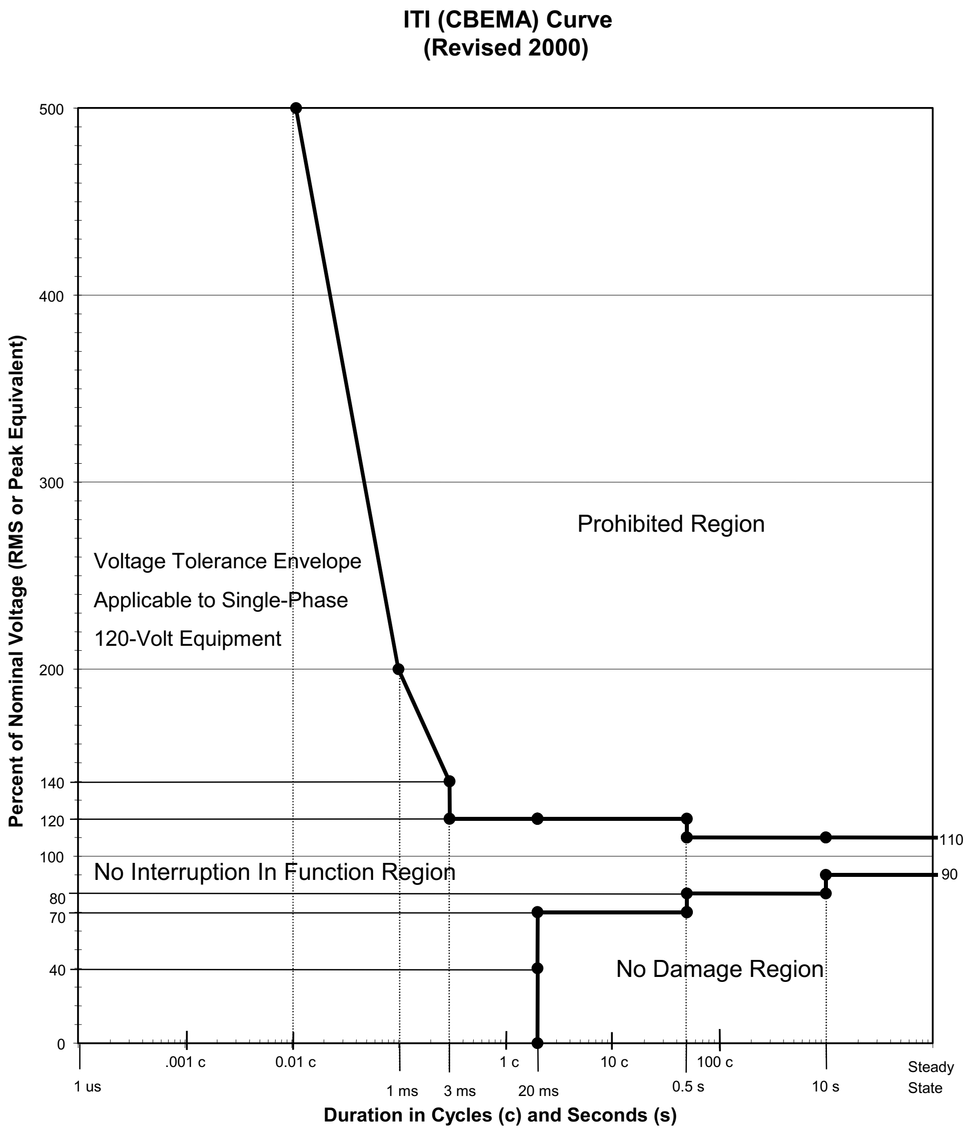

Figure 4: ITI CBEMA Curve 2000

3 Uninterruptible Power Supplies (UPS)

3.1 Key Components

UPS units are complex devices but contain a number of key building blocks you should know:

Battery as an energy storage medium. Common types include: Lead-Acid, Nickel-Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium-Ion.

Rectifier to convert mains AC to DC for battery charging.

Inverter to take DC and convert it to AC at a given voltage and frequency.

Transfer switch to swap between two sources of power. Can be a mechanical relay or contactor[1] but is more usually solid-state, called a *static transfer switch* or STS.

Surge suppressor: a solid-state device that reduces voltage by letting current flow to earth when a voltage exceeds the so-called *let through* voltage.

3.2 Form factors

UPS units are available in various form factors:

Freestanding / tower similar to PC powering a single device or multiple devices via a PDU. Usually located adjacent to the IT equipment.

Rackmount powering a single device or multiple devices via a PDU. Usually co-located inside the same rack as the IT equipment.

Floor-standing UPS devices located within the IT environment itself or in another part of the facility. These normally supply multiple IT loads and are often managed by facilities rather than IT personnel.

[1] A contactor is the conventional name used for a large relay able to switch many amperes of current.

3.3 UPS types

There are three main categories of UPS: standby, line-interactive and double conversion. All UPS devices will protect against blackout (for as long as their batteries last).

3.3.1 Standby

A standby UPS normally just passes the utility through to the output, while performing basic surge suppression, Figure 5.

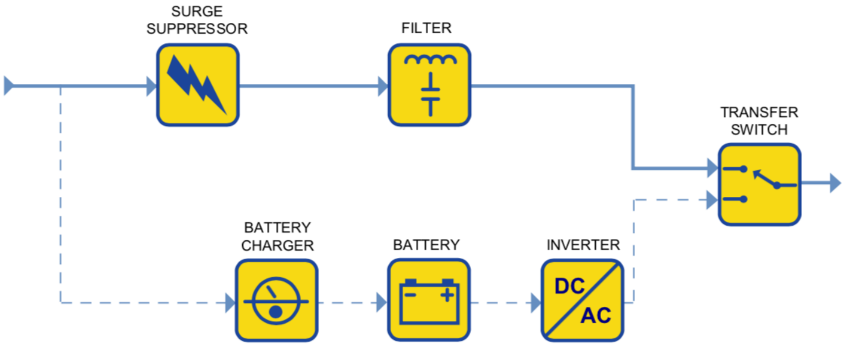

Figure 5: Standby UPS schematic (APC)

The battery is charged from the mains. Under failure of the mains supply, the UPS will use its inverter to generate AC. The transfer switch changes the output from utility to inverter.

The standby UPS protects against blackouts and small surges/sags whilst remaining online. It will transfer to inverter supply in the case of under/over voltage conditions.

3.3.2 Line interactive

A line interactive UPS is capable of correcting reasonably small under/over voltage conditions **whilst remaining online**, Figure 6.

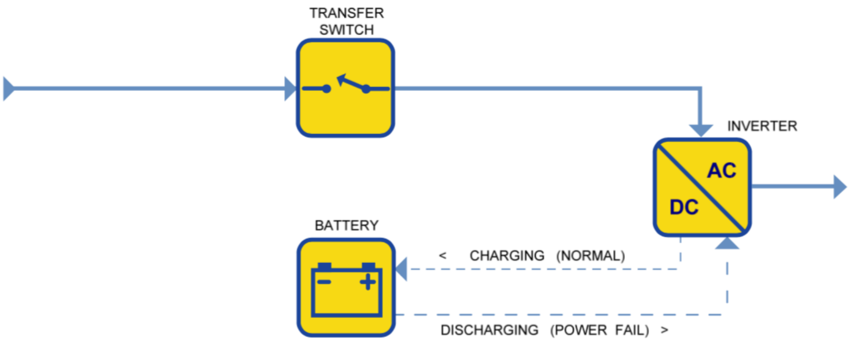

Figure 6: Line interactive UPS schematic (APC)

The line interactive UPS will correct surges/sags and under/over voltage whilst remaining online. It will use transfer to battery power to correct issues with AC frequency and waveform quality.

3.3.3 Double conversion

The double-conversion UPS differs from the standby and line-interactive UPS in that it doesn't differentiate between online/offline modes of operation. Double conversion UPS units correct both voltage and frequency disturbances. Figure 7.

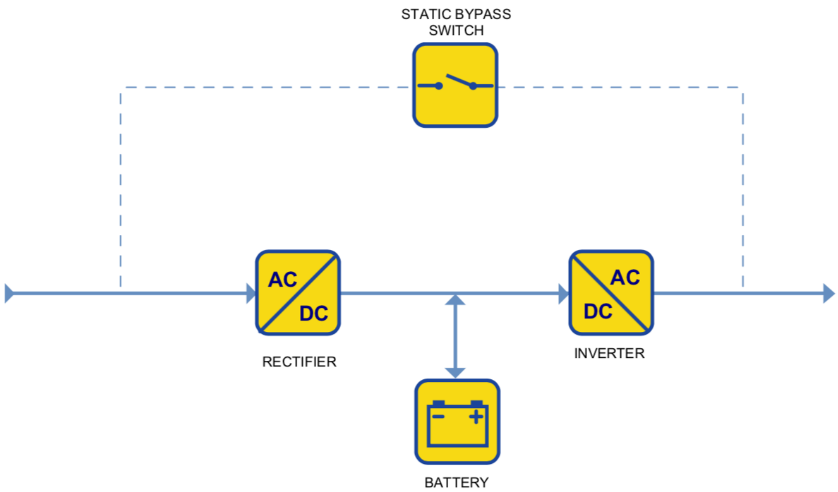

Figure 7: Double conversion UPS schematic (APC)

They consist of a battery bank charged by the mains, from which an inverter generates a clean AC waveform at the right voltage and frequency,

4 UPS sizing

UPS sizing needs to consider how much power the UPS is expected to supply (determines inverter size), and for how long (determines battery size). The reactive / apparent power requirements need to be considered.

Specifying a UPS is a somewhat inexact process. A undersized unit will not work, but an oversized unit will. Therefore, we normally pad calculated requirements by a 20 % buffer.

4.1 Real power requirements

The UPS power required, with padding, can be calculated:

$$P_{\text{total}} = \left(\sum_{\text{devices}} P_{\text{device}} \right) \times 1.2 \tag{1}$$

4.2 Apparent power

When sizing power distribution components, we need to consider the so-called Volt-Amp rather than the Watt. So far we know that the watt is the unit of power. From the power relation we first met in **??**, $P = V \cdot I$, we might reasonably expect that 1 W = 1 V A. However, in real life this isn't the case.

4.2.1 Reactive power

In simple loads like incandescent lights and heaters, regardless of size, the current and voltage will be perfectly in phase. However, with many real-world loads the current wave will lead or more usually lag the voltage wave, becuase of the dynamical nature of the circuits.

Inductive loads will cause the current wave to *lag* the voltage wave.

Capacitive loads will cause the current wave to *lead* the voltage wave.

These loads are the electrical equivalents of a hose or balloon filled with pressurised water, or a large heavy flywheel.

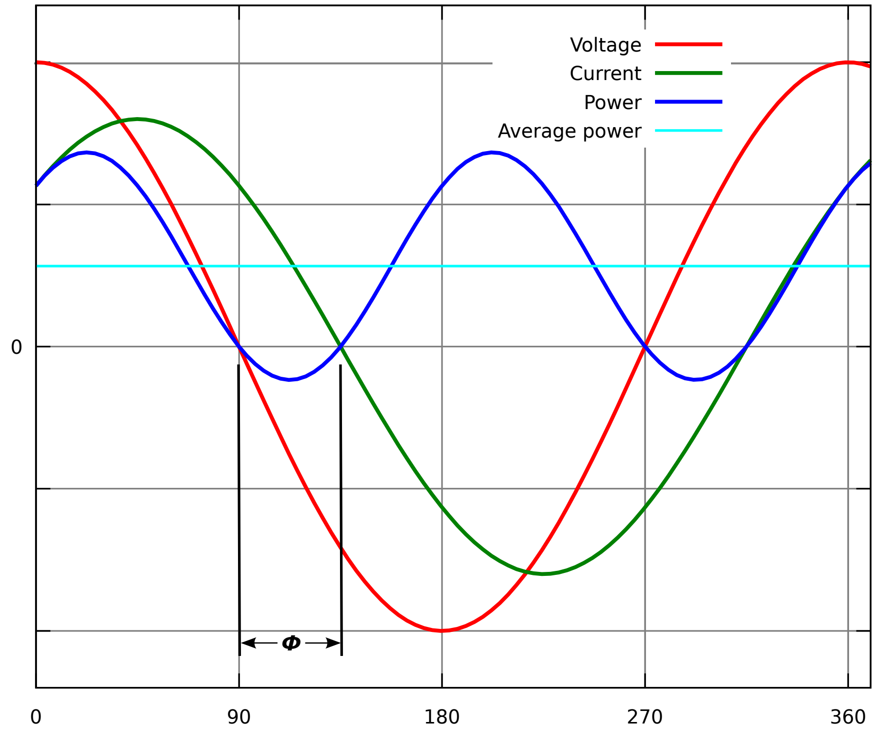

Figure 8: Reactive load showing current lagging voltage (Wikipedia)

Let P be the real power, and Q be the reactive power. The imaginary unit j is such that $j^2 = -1 \Rightarrow j = \sqrt{-1}$. (Some textbooks, including leaving cert maths use i as the imaginary unit, but it is prone to confusion with i meaning current.) We define the apparent power S by:

$$S = P + jQ \tag{2}$$

This is a complex number, which we can think of as the so-called power triangle.

The apparent power for sizing purposes of a UPS is then simply the magnitude, $|S|$.

$$|S|^2 = P^2 + Q^2 \tag{3}$$

$$|S| = \sqrt{P^2 + Q^2} \tag{4}$$

We can also re-arrange this to give the real, P, and reactive, Q, power components:

$$|P|^2 = \sqrt{|S^2| - Q^2} \tag{5}$$

$$|Q|^2 = \sqrt{|S^2| - P^2} \tag{6}$$

$$\tag{7}$$

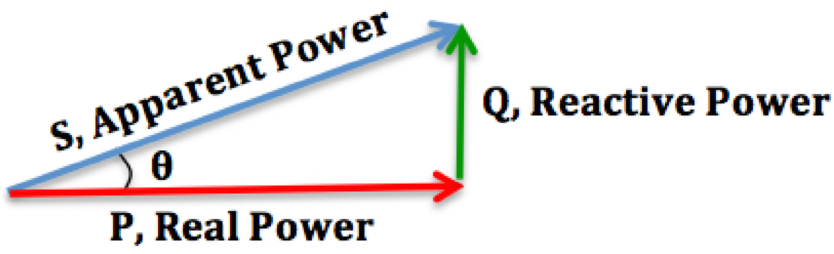

Figure 9: Power triangle (Wikipedia)

4.2.2 Power factor

Looking back at the power triangle, Figure 9, the angle θ encodes the relative breakdown between real and reactive power. Assuming we know P and Q, the angle θ is simply:

$$\theta = \tan^{-1} \frac{Q}{P} \tag{8}$$

We normally consider not the angle θ, but the cosine of it, $\cos\theta$. This gives us the ratio of real power to apparent power, and it is called the **power factor**, PF:

$$PF = \frac{P}{|S|} \tag{9}$$

In terms of its interpretation:

- Power factor is a dimensionless number between -1 and 1.
- Negative power factors imply a device generating real power, not consuming it. We will assume the power factor here is between 0 and 1.
- Power factor does not tell if current is leading/lagging the voltage. Assumed lagging unless specified.

4.2.3 Apparent power for a single device

If you have the voltage and amps **directly** specified for a particular piece of equipment, you can just multiply to get S:

$$\left|S_{\text{device}}\right| = V \times I \tag{10}$$

Example 1 (VA calculation from voltage and current)**.** A server's power supply has a rating plate claiming that it consumes up to 3.5 A when connected to a 230 V supply. Determine the VA. Here, we simply use the V and I ratings as given.

$$\begin{align} |S| &= V \times I \tag{11}\\ &= 230 \times 3.5 \tag{12}\\ &= 805\,\mathrm{V\,A} \tag{13} \end{align}$$

If you have the power drawn by the device in watts, and you know the power factor, determine $|S|$ by calculating:

$$|S_{\text{device}}| = \frac{P}{PF} \tag{14}$$

If you're not given a power factor, $PF = 0.8$ will usually work, but state that assumption.

Example 2 (VA calculation from power)**.** The specification sheet for a server shows that it consumes up to 250 W. Determine the VA requirement. Given the information we have, we will assume a power factor of 0.8.

$$|S| = \frac{P}{PF} \tag{15}$$

$$= \frac{250}{0.8} \tag{16}$$

$$= 312.5\,\text{V A} \tag{17}$$

4.2.4 Apparent power for multiple devices

Sum up the VA requirements, remembering to apply the power factor (if not uniform) to each device before summation. The padding is normally added post summation.

$$|S|_{\text{total}} = \left(\sum_{\text{devices}} |S_{\text{device}}|\right) \times 1.2 \tag{18}$$

4.3 Runtime

Runtime for a UPS is normally determined using the sizing chart on the specification sheet.

Runtime can often be extended by adding additional battery packs.

4.3.1 Battery capacity

The capacity is specified in units of A h. This means that the battery can supply the given number of amperes of current for one hour.

$$\text{hours available} = \frac{\text{capacity}}{\text{current}} \tag{19}$$

Alternatively it can trade off the amount of current delivered against the time period.

Example 3 (Battery capacity calculation)**.** A 12 V battery has a capacity of 80 A h. It is to supply a load that requires a constant 5 A. Calculate how many hours would this battery last assuming it was 100% charged when connected to the load.

$$\text{hours available} = \frac{80}{5} \tag{20}$$

$$= 16\,\text{h} \tag{21}$$