Most protection devices are not meant to protect people, nevertheless, we'll start there.

People Protection Devices

Disconnect Switches It is common to find large, open-air switching devices in substations. It should be easy to see when they are open and they cannot be closed remotely. They are NOT used to open or close energized circuits. The purpose of these switches is to allow lineman working on the equipment, busses, and lines in the yard to visually confirm that items are de-energized.

(saVRee)

See giphy.gif on the website for a short video of opening these type of switches. The arcing is due to voltages present due to capacitive coupling between lines.

(Wikipedia)

GFCI (**G**round-**F**ault **C**ircuit **I**nterrupter) devices are placed where end-users are exposed to electrical power. A GFCI compares the current flowing out the "hot" connection with the return current in the neutral connection. They trip when a difference between these two currents indicate some current has found another path to ground, possibly through a person.

(Amazon)

GFCI Outlet

GFCI Breaker

Protection Devices

"Protection" almost always refers to the protection of power company equipment and lines and reducing fire risks, not the protection humans, animals, or the environment. Most protection devices are used to detect or interrupt undesirable currents. These could be currents which are too high (over-currents) and/or flowing where they shouldn't be (short circuits). Over-voltage problems are actually more common, but they are handled in a relatively simple way.

Requirements
1. Reliability (Fully protect all the equipment from every fault)
2. Speed (React quickly to a problem)
3. Selectivity (Don't trip when there really isn't a fault)
4. Simplicity
5. Minimize Customer Impact

Over-Voltage Protection

Surge & Lightning Arresters are highly nonlinear devices which have a high resistance at normal voltages and low resistance at voltages over their threshold. They are designed to return to high resistance after the over-voltage event. Surge arresters protect transformers and other devices from over-voltages.

Almost all over-voltage events are caused by lightning, but a few are the results of transients caused by faults or switching, esp. breakers tripping.

(Megger.com)

Most faults are short-duration short circuits cause by tree branches, birds or mylar balloons. All of these would be blown to smithereens by the large short-circuit current and not cause permanent damage, at least to the power system.

Sometimes a short-duration short circuit or a lightning strike can establish an arc from line to line or from a line to the tower (flashover). An arc through the air ionizes the air and makes it a conductor. Once the air is ionized, the arc typically continues until the power is shut off for a short time. Relays at both ends of a transmission lines should detect this short and cut the power using large circuit breakers. It is common for these relays to automatically reclose the breakers after a short time (1/3 second or so) to see if the problem has cleared. You have almost certainly experienced these very short power outages that make the lights flicker and alarms and microwaves go "beep".

Fuses The simplest over-current protection Local distribution lines are usually protected by fuses rather than expensive breakers or reclosure devices, so even transient faults in local systems can result in longer-term outages.

The fuse wire itself is housed within a tube and also holds the tube in place. When the fuse wire burns though, the tube is no longer held in place and it flops open. That way it's easy to visually detect blown fuses and replace them from the ground.

A fuse tube in position.

open fuses

Fuses can be replaced from the ground.

(Hastings)

Some reclosure devices are meant to be deployed in the field. They work independently of relays or operators and replace the, more common, fuses.

A 3-phase reclosure device (Eaton)

Pole-mounted Reclosure Devices (Eaton)

Breakers

Breakers used in your home are self-contained in that they sense a current problem and "trip" all by themselves. (A breaker "trips" by opening the connection.) Most of the breakers used in commercial installations are also self-contained, although some have more complex time and current settings.

Large breakers come in two types. Oil-filled breakers are mostly phased out now in favor of gas filled. Both oil and SF_6 gas are very good insulators, but it's much easier to move the contacts in the gas than the oil, especially when it's cold. Some SF_6 breakers can open in as little as 2 cycles (1/30th of a second). Both types use stored mechanical energy to move the contacts, typically spring-loaded or high-pressure air. They can open and close several times even when the substation power is down.

Oil-filled Older, slower style (Arn)

SF_6 gas-filled Newer (Arn)

Breakers use a variety of methods to blow out or extinguish the arc that occurs when the contacts open.

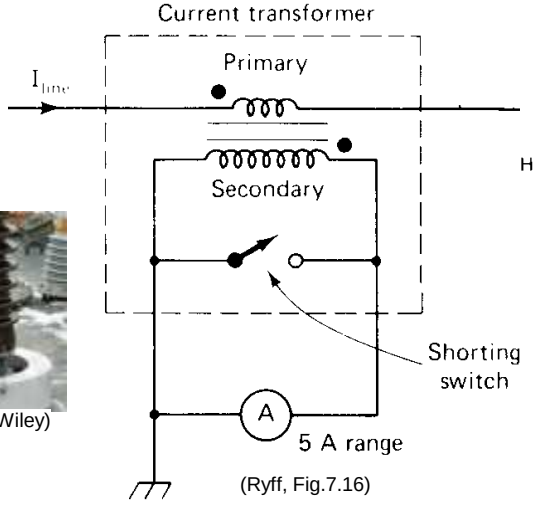
Not all breakers are used for protection, some are simply used as switches:

SF_6 gas-filled breakers & capacitor bank (Arn)

Instrument Transformers

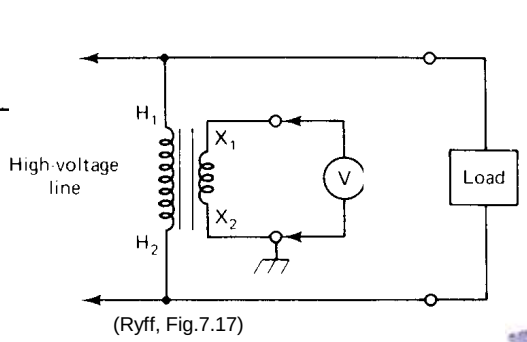
Special transformers measure voltages and currents to provide information to the relays which in-turn, control the breakers.

(IET Wiley)



(Ryff, Fig.7.16)

CT



(Ryff, Fig.7.17)

"Potential" transformer, for voltage monitoring

VT or PT

base grounded

(powerlinedelhi)

Many newer PTs are actually voltage dividers, not transformers.

Relays

Relays are the brains. They take information from the CTs and VTs and trip the breakers when they detect a fault. Conversely, they should "block" (not trip) when there isn't a fault, even during over-current conditions like transformer inrush currents.

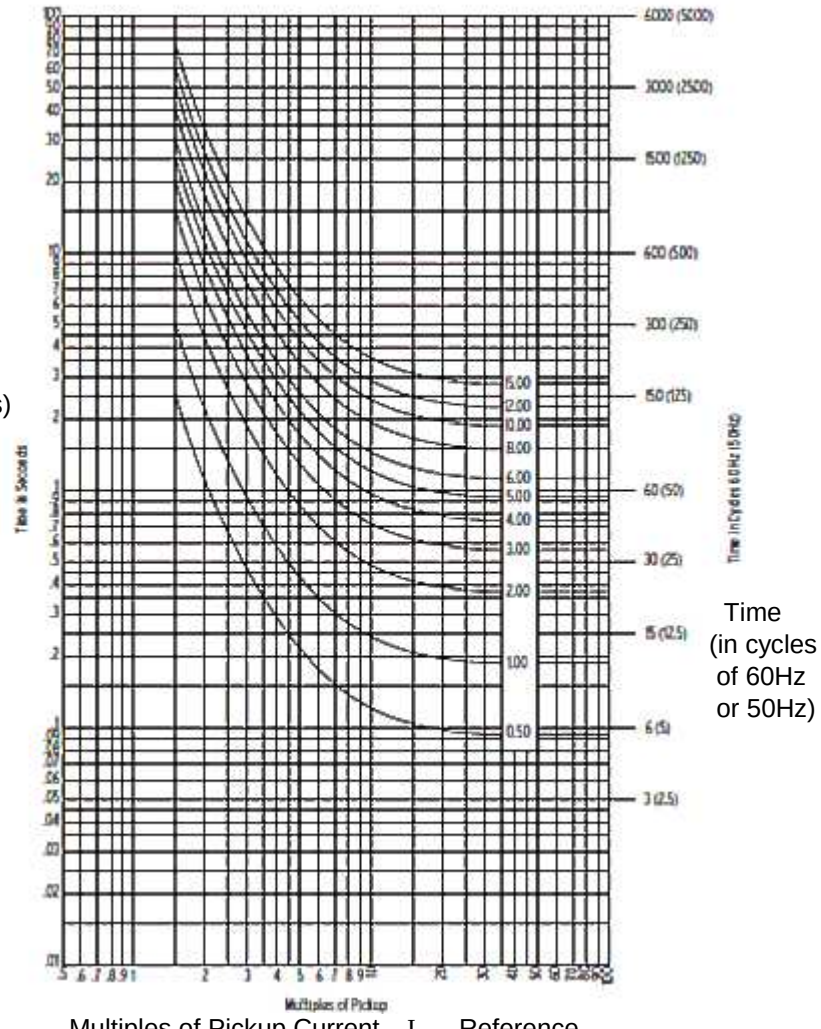
Digital Relays (wikitestguy)

Electromechanical Relay (Arn)

Digital Relays (Arn)

Over-Current Relay
Some of these relays immediately trip when any over-current is detected, but more commonly, they include some time delay to allow a breaker closer to the fault to trip first. A sample time-delay curve is shown here.

This particular relay has 11 different settings, that's why there are so many different curves.



Directional Relay
In addition to detecting over-currents, a directional relay uses phase differences between the voltage and current to determine where the fault is relative to the measuring location. They will only trip for faults on one side of the relay and not the other. They are useful for lines which could carry power in either direction.

Distance (Impedance) Relay
A distance relay is used for transmission lines. It uses voltage and current measurements to determine an impedance. Since a transmission line's impedance increases with distance, the impedance can indicate the distance to the fault. They will only trip if the impedance is within a specified region on the complex plane.

Differential Relay
A differential relay monitors the currents flowing into and out of some device or bus. A difference indicates a current "leak" and the relay will trip breakers to isolate the region with the undesired current.

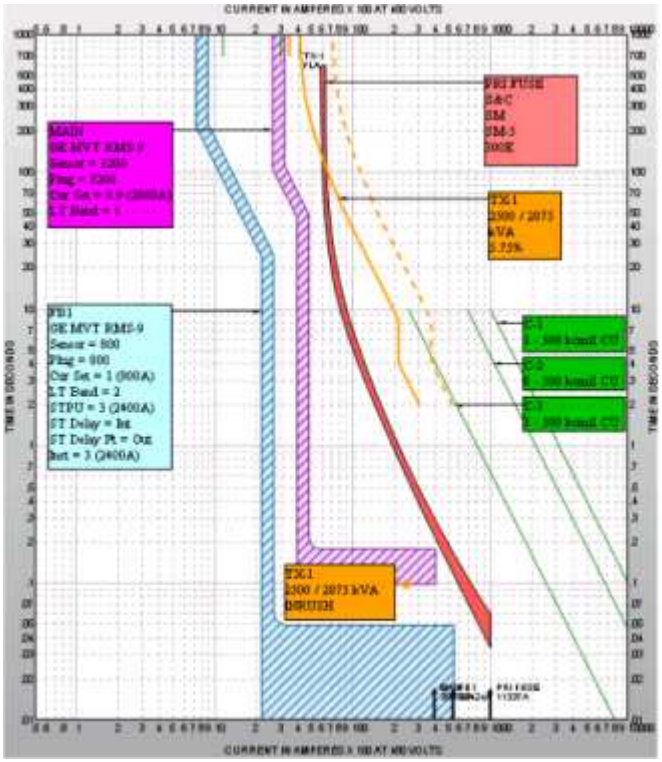
Pilot Relay
A pilot relay is a type of differential relay used for transmission lines. It uses one or more communication systems to exchange information with it's counterpart at the other end of the transmission line.

Protection Strategy

Minimize Customer Impact. Make sure that the breaker closest to the actual fault trips first, thus preventing other trips and minimizing the region of power outage. This is where the current / time curves for time-delay relays are used.

Relay Coordination is the process to make this happen, no matter where the fault may be. The curves at right are used to coordinate relays and breakers.

Zones of Protection are used for a similar purpose, to isolate the fault into the smallest possible region.



(EasyPower)

The battery room at Terminal substation (Arn)

DC Power and Battery Backup

Relays, breakers and communication equipment work on DC power so that battery backups can keep them working even if there's a power outage. Or, rather, *especially* if there's a power outage.

Communications

The power company likes to maintain at least 3 separate, redundant, communication systems across their grid. Typically: Fiber optics, wireless microwave, and wired telecommunications. They keep separate from the internet for security reasons.

More Information
https://wiki.testguy.net/t/protective-relay-testing-and-maintenance-overview/76
https://www.easypower.com/resources/article/overcurrent-coordination-and-protection-basics
https://www.mavtechglobal.com/pdf/white-papers/Time-Current-Curves-Whitepaper-2019.pdf

Restoring Connections

Rigorous safety protocols must be met before breakers are switched back on.

If the breaker connects two regions with separate power generation, then operators may have to wait for the regions to synchronize, much like placing a generator on-line.

Sources: Power Systems Analysis and Design, Glover, Sarma & Overbye
Electric Power Systems, Schaum's Outline, Syed A. Nasar
First Course on Power Systems, Ned Mohan