Electric Propulsion

Battery Energy Storage Systems – BESS

Contents

Conventional Electrical Power Grid

"The North American interconnected power system is the largest and most complex machine ever devised by man".
By P.C.Steinmetz, Electrical Engineer and Scientist – (1865-1923)

The Electrical Grid is an interconnected network for delivering electricity from producers to consumers.
It is a very wide and complex Power System.

In a conventional Electrical Grid electricity is produced in Generating Stations (GS), by alternators (synchronous machines) operating in a voltage range 11kV – 35kV and transmitted to users through a transmission network at higher voltage, including :

- Transmission Power Lines (HHV) with "mesh" configuration
- Subtransmission system (HV)
- Distribution Network (MV) with "radial" configuration
    - Primary distribution < 35kV
    - Secondary distribution (LV)

Power flow is one direction, from top to bottom, from GSs to passive users

Electrical Power System Control

Electrical Power System Control has several objectives :

- The system must meet the continuously changing load demand for active (P) and reactive power (Q). A reasonable "**power reserve**" must be maintained both for P and Q.
- Supply of energy at minimum cost and with reduced ecological impact
- Power supply must meet some quality standards :
  - **Constant voltage**
  - **Constant frequency**
  - **High reliability**

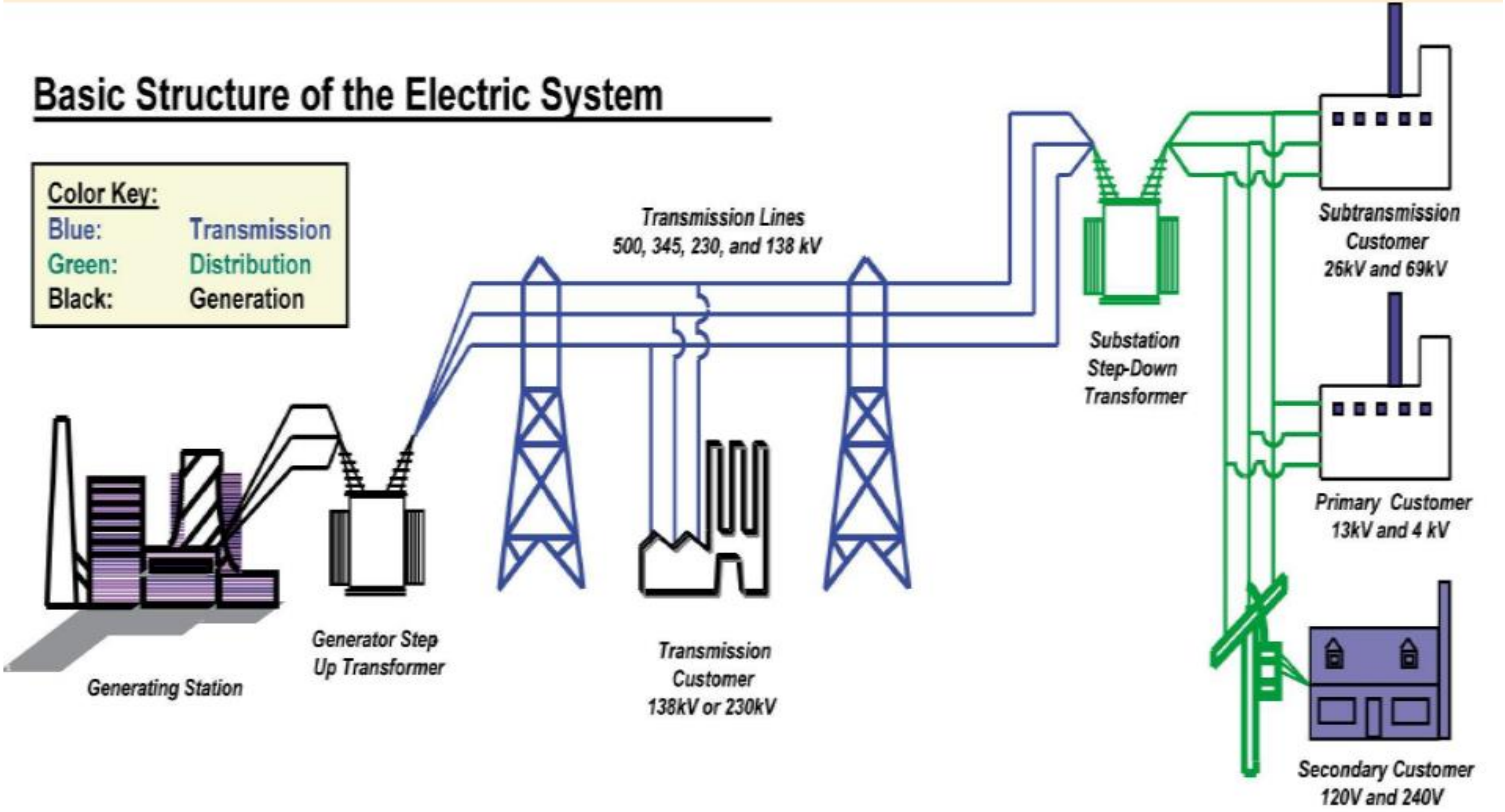
Power system stability consists in :

- Remaining in a state of operating equilibrium under normal operating conditions
- Regaining an acceptable state of equilibrium after being subject to a disturbance

Active power (P) control is related to frequency control → **P(f)**
Reactive power (Q) control is related to voltage control → **Q(V)**

Since the quality of power supply is determined by the ability to maintain frequency and voltage constant all over the system, the control of P and Q is a vital aspect of the performance of the entire power system.

Electrical Power System Structure



Evolution of Electrical Power Systems

Evolution of Electrical Power Systems

- Growth of DG mostly based on RES
- Deregulation of electricity markets
- Progress of technology towards Smart Grids

Factors affecting the change

- ***Standards*** → technical rules (national and international)
- ***Regulation*** → government directives, activity of regulatory authorities
- ***Economic forces*** → incentives, fuel prices, CapEx & OpEx of power plants built with different technology, constraints on electricity prices (€/kWh)

Smart Grid

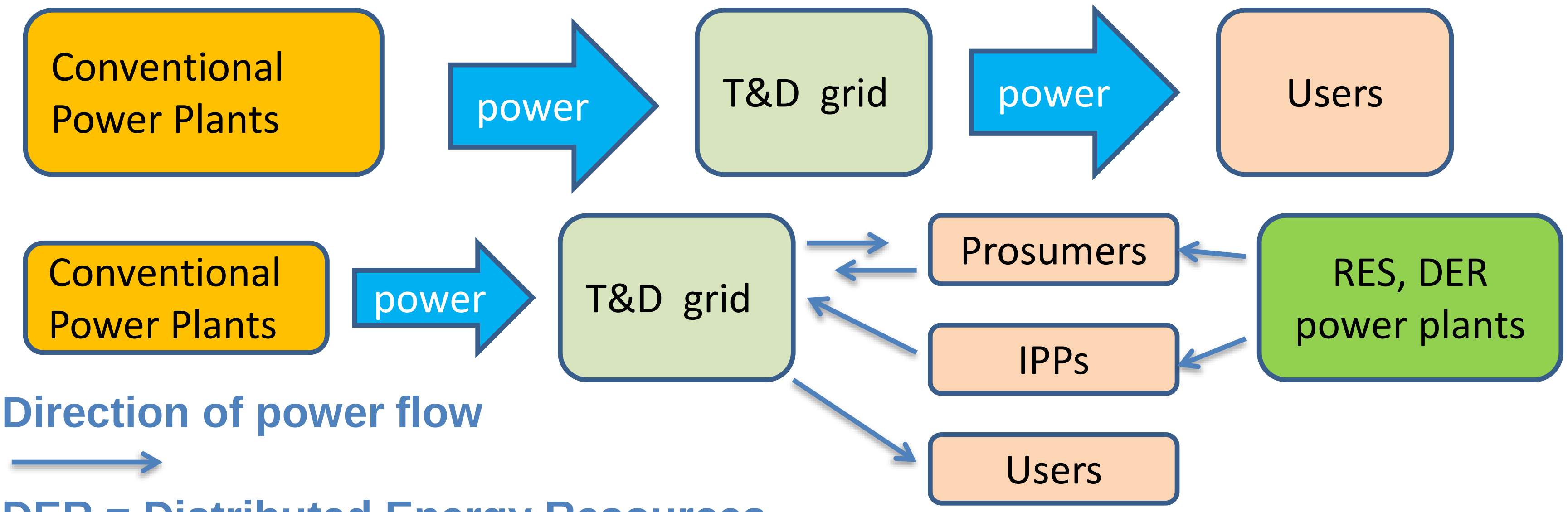
An intelligent electrical network which shall efficiently deliver sustainable, economic and secure electricity supplies.

Building Blocks :

Microgrids and DERs
Virtual Power Plants
Energy Storage

Growth of Renewables and Distributed Generation

Large and centralized conventional power plants, which feeds the load through a wide T&D grid, are replaced with distributed smaller generators, mainly based on Renewable Energy Sources (RES), which are located near the user load



DER = Distributed Energy Resources

Some users are transformed in independent power producers (IPP).
Some **active users** can generate power from RES and may invert the direction of power flows in the distribution network (**Prosumers**).
Architecture of modern power systems is more complex than in the past.

The Power Balancing Problem

TSOs are responsible of the technical/economic operation of the power grid

Load Forecasting → where and when power will be required
Power usage is cyclical, demand varies by season, day of week, time of the day. Load depends also on local power requirements. Base load and peak demand are estimated by TSO to determine the required generation.

Electrical market → power schedule, clearing price, economic dispatch
TSO acts on the Electrical Market where the continuous match between demand and supply of electricity is achieved by daily power auctions, on a ***"day ahead "***and on an ***"intra day"*** real time basis. On the day ahead market Generators are selected according to bids, clearing price is set by marginal power plant, a Power Schedule is created, typically with 15min time steps. Real time adjustments to match demand and supply against prediction errors and fluctuations are made on the intra day auction.

Operation of the Power Infrastructure → Grid stability, power quality
TSO must assure a stable and secure grid operation. Power generation and load must be balanced at any time, since electricity is difficult to be stored, while frequency and voltage must be kept stable within narrow bands, in all nodes of the grid, both in steady state and during transients. Furthermore congestions on power lines must be avoided.

Grid Stability with High Share of RES

Power Reserve Requirements

Reserves are required to maintain the generation/load balance and to compensate for the variability and uncertainty of load, forced outages of conventional generation (contingency reserves), and variable generation.

Transmission system operators (TSOs) keep adequate control power reserve, available to maintain stable and reliable supply.

Growth of RES → reduction of rotating inertia

Conventional power plants (fed by oil, coal, nuclear, gas) are programmable and controllable, while RES are intermittent and non programmable by nature.

A high share of RES introduces grid stability problems which can be solved only by an advanced management of resources (weather forecast to predict RES production, energy storage, Demand Side Management)

Sunday 16th June 2013, historical date for RES

The 16th of June 2013, on Sunday afternoon, between 2pm and 3pm the electricity generated by RES in Italy has covered the entire national power demand for the first time ever.

Similar situations happen in the same period of the year in Germany

Rotating mass inertia of synchronous machines

During the first seconds of a transient with a significant unbalance between generated and consumed power, the **frequency change** is limited only by the **rotating inertia** of the synchronous generators in operation at that time.

$$E_{kin} = \frac{1}{2} J\,\omega^2 = (Joule)$$

Kinetic energy stored in rotating mass of a synchro generator running at w angular speed

$$H = \frac{E_{kin}}{P_{nom}} = (sec)$$

Time constant of large generators, typically ranging from 2s to 10s

$$\frac{df}{dt} = \frac{1}{2} f_0 \frac{P_{prod} - P_{cons}}{H\,P_{nom}} = \left(\frac{Hz}{sec}\right)$$

Rate of change of frequency

The growth of RES share reduces the power of grid connected conventional generators and hence the inertia of the entire system, since the inverters interfacing RES to grid normally show zero inertia.

To avoid unacceptable frequency deviations a ***Synthetic Inertia*** should be provided by the converters connecting wind generators, battery energy storage.

Inertia of Electric Power System

ROCOF = Rate of Change of Frequency

ROCOF maximum admissible value is set at 0.5Hz / s, according to ENTSO-E guidelines

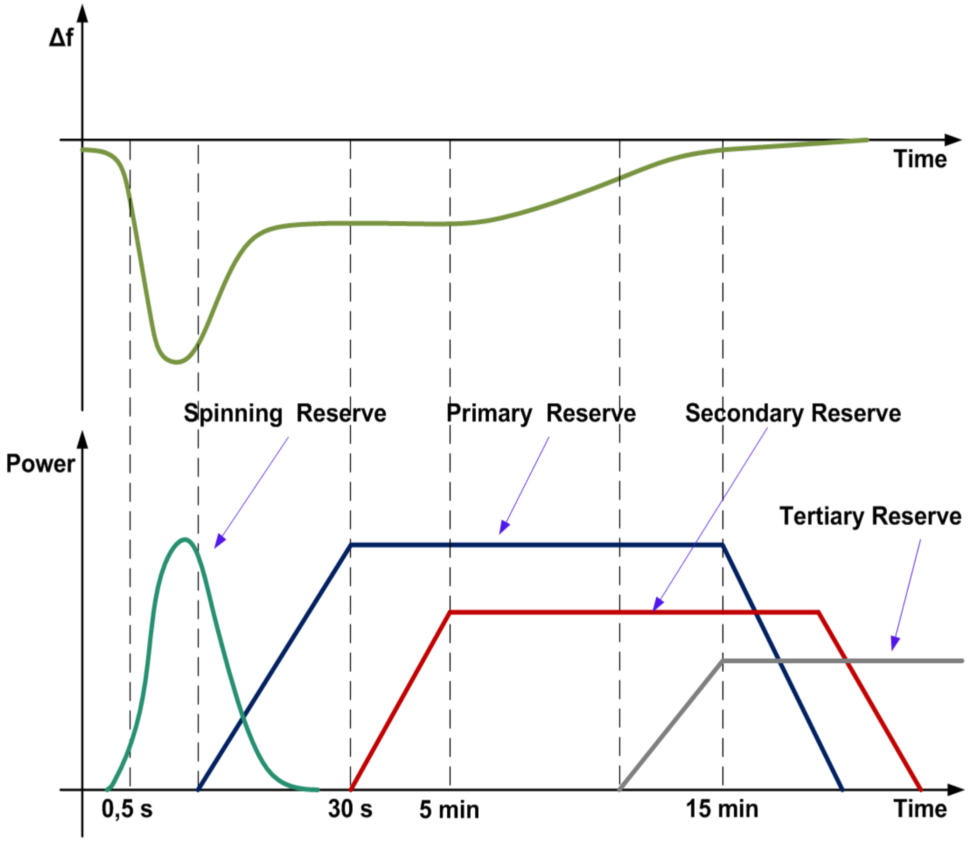
In the Italian national electricity system, separated from the interconnected European system, it is estimated that the minimum kinetic energy necessary to maintain ROCOF within the admissible limits of 0.5Hz / s is equal to 40 GWs for the loss of an 800 MW group.

The calculation only considers the inertia of the national generation park and the trip of a generation group as a reference accident equal to 800 MW (corresponding value of the largest production unit)

$df/dt = ½\ f_0\ \Delta P/(H \times Pnom) = 0.5 \times 50Hz \times 800MW\ /\ (1s \times 40GW) = 0.5Hz/s$

Source : Piano di Sviluppo 2019 - TERNA

Frequency Regulation and Power Reserve



Power Reserve in Germany. Activation times

Frequency Regulation
It consists of 4 steps and uses some power reserves that are allocated by TSO on the electrical market.

Spinning reserve (power system inertia)
Lost power is compensated by the energy stored in rotating masses of all generators.
Frequency decreases during the first seconds.

**Primary Control Reserve / **Activation time : 30s
It adapts power plants production proportionally to the frequency deviation and thus limits the frequency change.

Secondary Control Reserve (SCR)
Activation time : 5min
Lost power is compensated by secondary controlled units. It brings back frequency to nominal value and restores area load flows

Tertiary Control Reserve (TCR)
Activation time : 15min
It replaces SCR after a renewed economic load dispatch is in place

Definition of DER

Distributed Energy Resources (DER) are defined as "generation, storage, and controllable load interconnected at the low or medium voltage distribution level"

Examples of DERs:

- Renewable energy sources (solar, wind, hydro, geothermal)
- Energy storage systems (batteries, capacitors, flywheels, electrical vehicles)
- Fossil fuel (diesel generators, gas microturbines)
- Controllable load (air conditioners, pumps, cooling sytems, etc.)

Most DERs are connected to grid by "**smart inverters**" which convert power between DC and AC.

Inverters are controlled by firmware and can change voltage, frequency, active and reactive power.

Smart Inverters can be used to support the grid – either as mandatory or through market-based functions

DG/DER - Benefits and Challenges

- DERs Improve reliability and resilience of electrical power network (back up, microgrids)
- Renewable DERs minimize use of fossil fuels
- Deferral of new power generation and transmission construction since unmet load grows more slowly and DER can provide both energy and ancillary services
- DERs decrease power transmission losses
- DERs reduce energy costs
- DERs allow to shift energy usage as prices vary over time

- Renewable DER are intermittent and not dispatchable.
- PV provides power only during the day and in presence of sunlight, power fluctuations happen when clouds pass over or as the wind changes speed
- Owners of DER systems are interested in meeting their own energy requirements first and when selling energy back to the grid, they do not want power generation curtailment by utilities
- DER systems may cause voltage problems on feeders
- Disconnection of DER systems under brief voltage or frequency fluctuations may cause outages
- Management of several DER systems requires significant investments in communication equipment

Grid Codes

*A **grid code** is a technical specification which defines the parameters a facility connected to a public electric network has to meet to ensure safe, secure and economic proper functioning of the electric system. The facility can be an electricity generating plant, a consumer, or another network. The grid code is specified by an authority responsible for the system integrity and network operation. Typically a **grid code** will specify the required behavior of a connected generator during system disturbances.   (source : Wikipedia)*

Italy
CEI 0-21 and CEI 0-16 define the connection rules to LV and MV distribution networks respectively

European Union - EU
CENELEC → EN 50549-1 and EN 50549-2: Requirements for generating plants to be connected in parallel with distribution networks / Part 1 → LV, Part 2 → MV distribution network
Generating plants up to and including Type B

USA
IEEE 1547:2018
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
UL 1741 – Inverter certification standard
California Rule21 → how to connect and operate generation facilities to be connected to a utility’s distribution system

Ancillary Grid Services

Ancillary services *are necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities to maintain reliable operations of the interconnected transmission system.*
These services generally include, ***frequency control, spinning reserves and operating reserves****.*
Traditionally ancillary services have been provided by generators, however, ***the integration of intermittent generation*** *and the development of* ***smart grid technologies*** *have prompted a shift in the equipment that can be used to provide ancillary services*. (Source : Wikipedia)

Most DERs are interfaced to grid by **smart inverters**, software controlled, with very fast response time. These DERs can execute functions associated to ancillary services autonomously, based on voltage, frequency, and other status and measurement inputs.
DERs can operate in response to these inputs in millisecond timeframes
In California-USA, a **SIWG (Smart Inverter Working Group)** has been established to develop standards on smart inverters, which is still active.

The most common functions associated to **ancillary services** are :

1. Disconnect / Connect Function
2. High/Low Voltage Fault Ride-Through
3. High/Low Frequency Ride-Through
4. P(f) → Active Power as a function of frequency / Power Balancing
5. Q(V) → Reactive Power as a function of Voltage / Voltage support

European Network Codes (by ENTSO-E)

Requirements for Generators

The Network Code on Requirements for Generators is harmonising standards that generators must respect to connect to the grid.

The published network codes have become regulation :

COMMISSION REGULATION (EU) 2016/631 of 14 April 2016

European Network Codes, developed by ENTSO-E, define as significant the following categories of power generators:

Type A: connection point below 110 kV and maximum capacity of 0,8 kW or more;

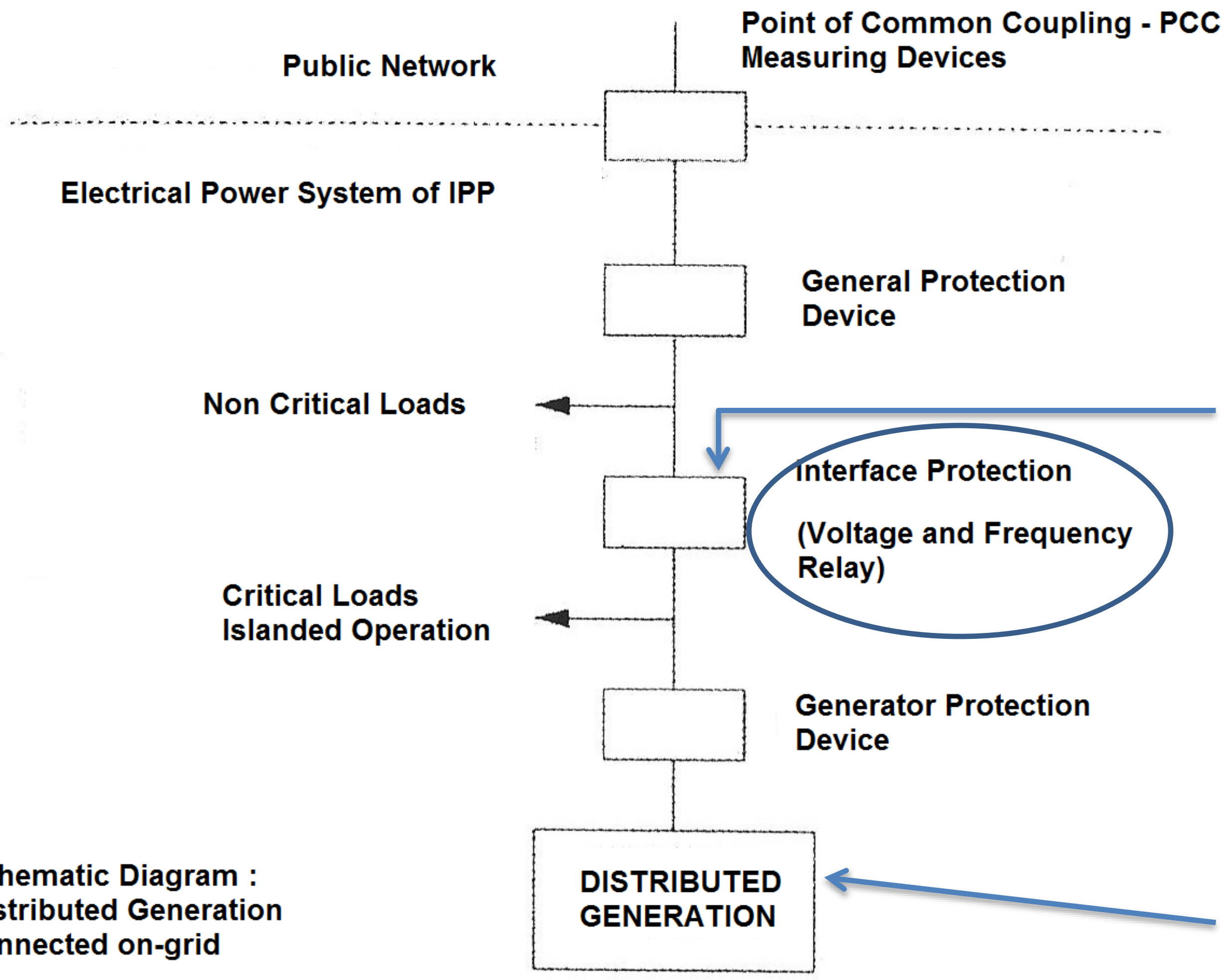
Type B: connection point below 110 kV and maximum capacity at or above a threshold and below the limit established by the relevant regulatory authority (Ranging between Baltic countries at 0.5 MW, Continental Europe at 1 MW, and Nordic countries at 1.5 MW);

Type C: connection point below 110 kV and maximum capacity at or above a threshold and below the limit established by the relevant regulatory authority
(Continental Europe = 50 MW)

Type D: connection point at 110 kV or above for all power generating modules

Each European country will specify requirements and parameter values, within these Codes

Grid Connection of DG



Schematic Diagram : Distributed Generation connected on-grid

Distributed Generation (DG) allows local electrical energy production by IPPs (Independent Power Producers)

Grid connection requires an Interface Protection to separate DG from grid in case of failure.

Main purpose is to avoid unwanted energization of grid by DG, after a mains failure.

DG output is often an inverter

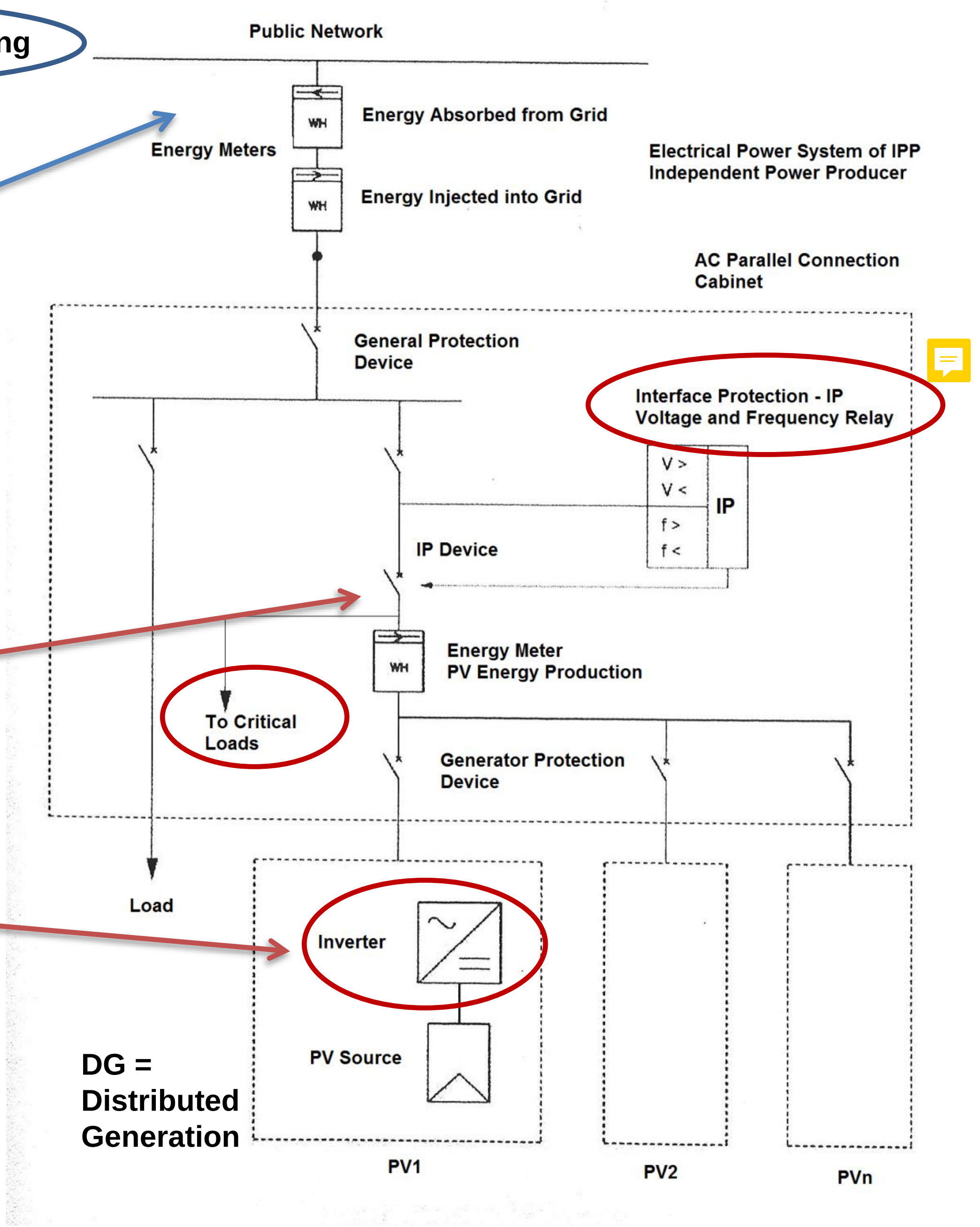
Point of Common Coupling

At the PCC (Point of Common Coupling) between public network and IPP's power system, energy meters measures energy injected or absorbed into/from grid.

In presence of grid connection the inverter control operates "on-grid"

IP Device separates DG and critical loads in case of mains failure.
The islanded section of IPP's power plant can operate off-grid, in stand-alone mode.

The inverter control has to be capable of both operation modes : On-grid and off-grid



DG = Distributed Generation

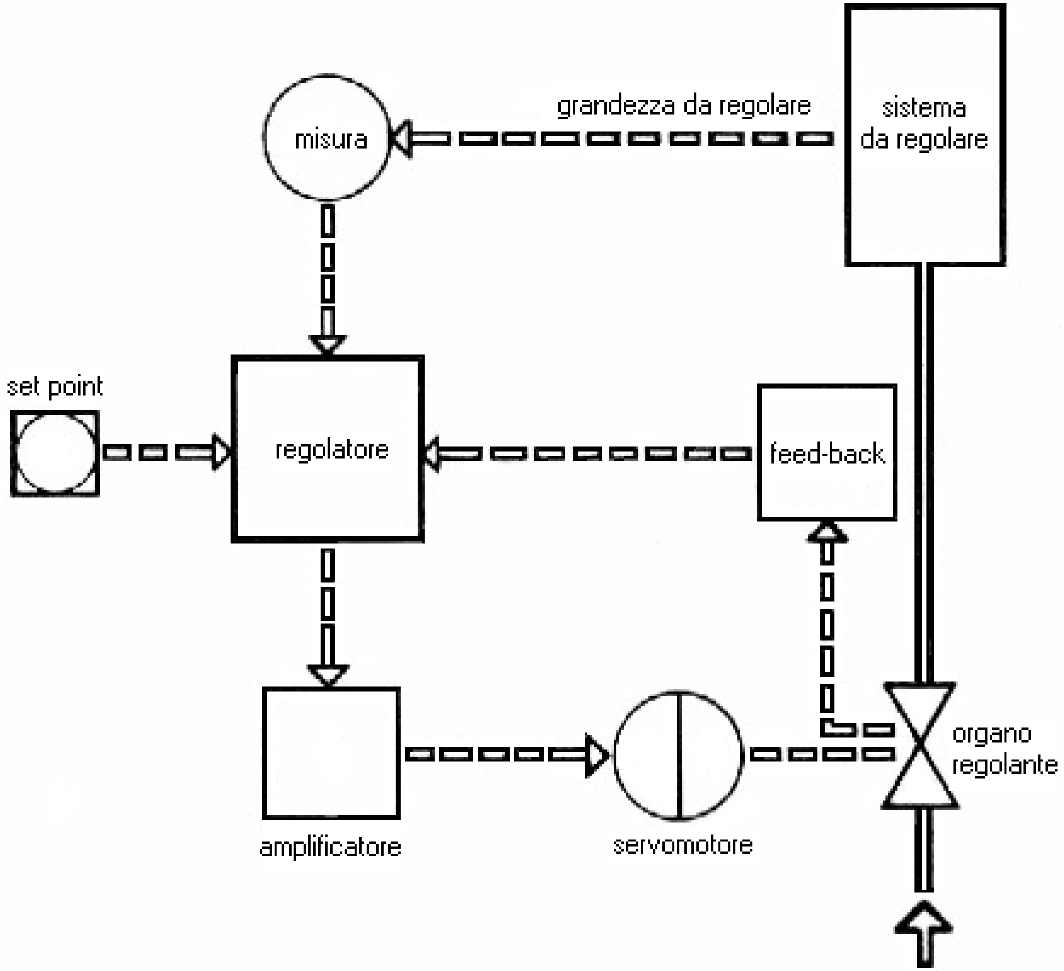
Generator Speed Regulation

When there is a torque imbalance on the generator shaft, in accordance with the formula

$$C_m - C_e = J \frac{d\Omega}{dt}$$

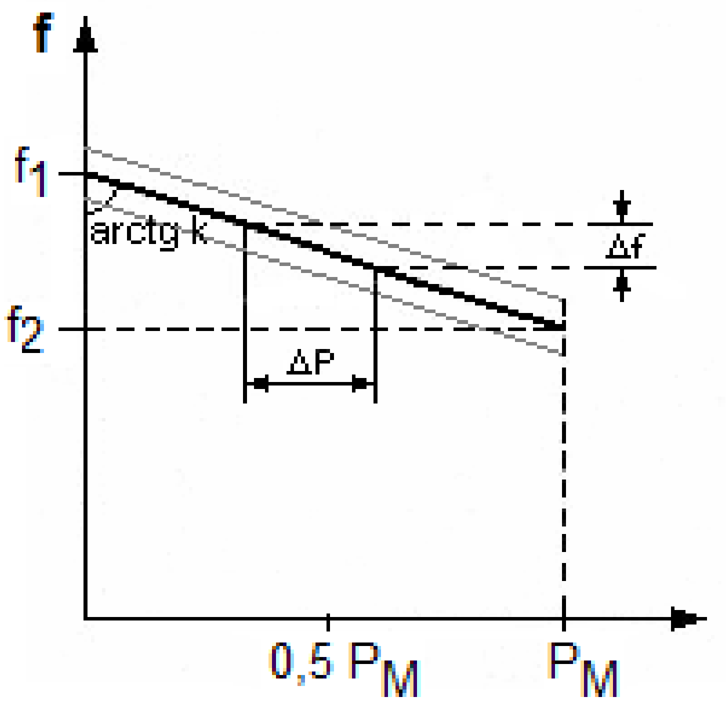
the speed would change if the generator were isolated.

The speed regulator keeps ω constant, and therefore the frequency of generated power



Droop of Frequency-Power curve

Each opening of the turbine (and therefore each value of the generated power) corresponds to a certain speed of the group: at no-load it corresponds to the frequency f1, at full load PM it corresponds to the frequency f2 less than f1.



$$s = \frac{\dfrac{\Delta f}{fnom}}{\dfrac{\Delta P}{Pnom}}$$

The regulator droop s is defined as the ratio between the frequency variation in relative value (Δf / fn) and the corresponding active power variation, also in relative value (ΔP / Pn).

Primary Frequency Regulation

The frequency or power regulation obtained through devices sensitive to the speed variations of the machine and according to the droop characteristic is called primary regulation.

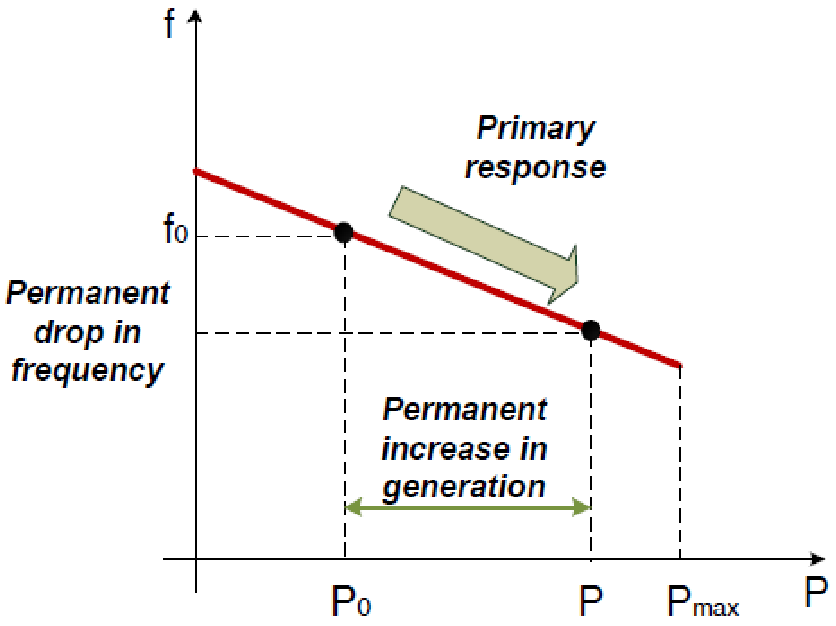
Primary regulation is performed automatically and autonomously by the speed regulators of the individual generating groups.
If, for example, the mains frequency decreases because of a generator failure, each regulator reacts by gradually increasing the power generated by the respective prime mover. This action requires an increase of the opening of the turbine valve or distributor.
The overall power fed into the grid by the generating groups that remained in service is therefore increased, gradually compensating for the lost power.
The autonomous action of the regulators ceases when the power balance in the network is re-established and the decrease in frequency has consequently stopped.
The network is now in a new steady state situation, in which the frequency has a lower value than the programmed one and the overall primary regulation reserve has been partially consumed

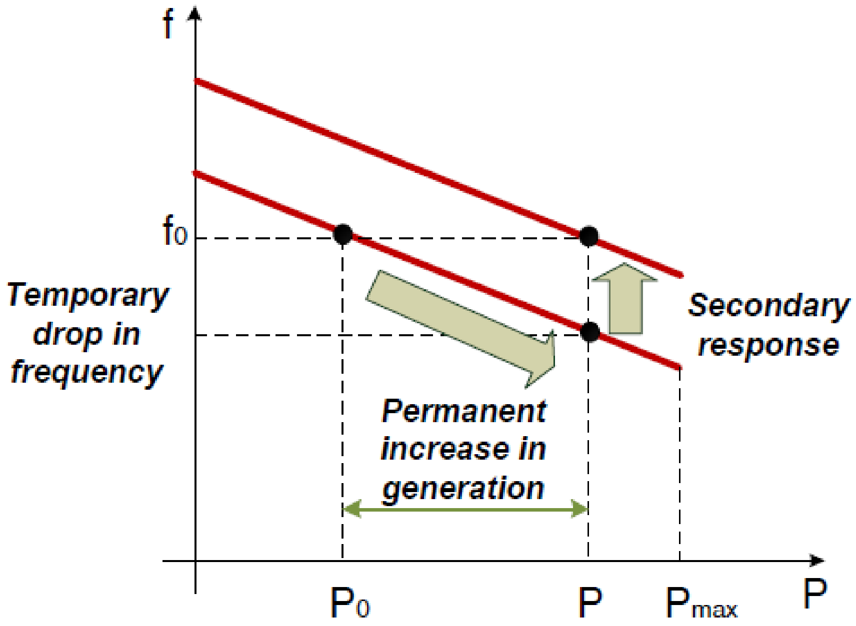
Secondary Frequency Regulation

The **secondary regulation** has the purpose of bringing the mains frequency back to the nominal value. Secondary regulation, like the primary one, is also carried out by the speed regulators of the groups, but under the control of an automatic system (secondary regulator).

This regulator, sensitive to the frequency error Δf and to the error ΔP_s on the generated power, modifies the set-points of the individual speed regulators and, if the frequency is less than 50 Hz, further increases the power supplied by the groups until the deviations Δf and ΔP_s are canceled (frequency-power regulation).

Primary and Secondary Regulation



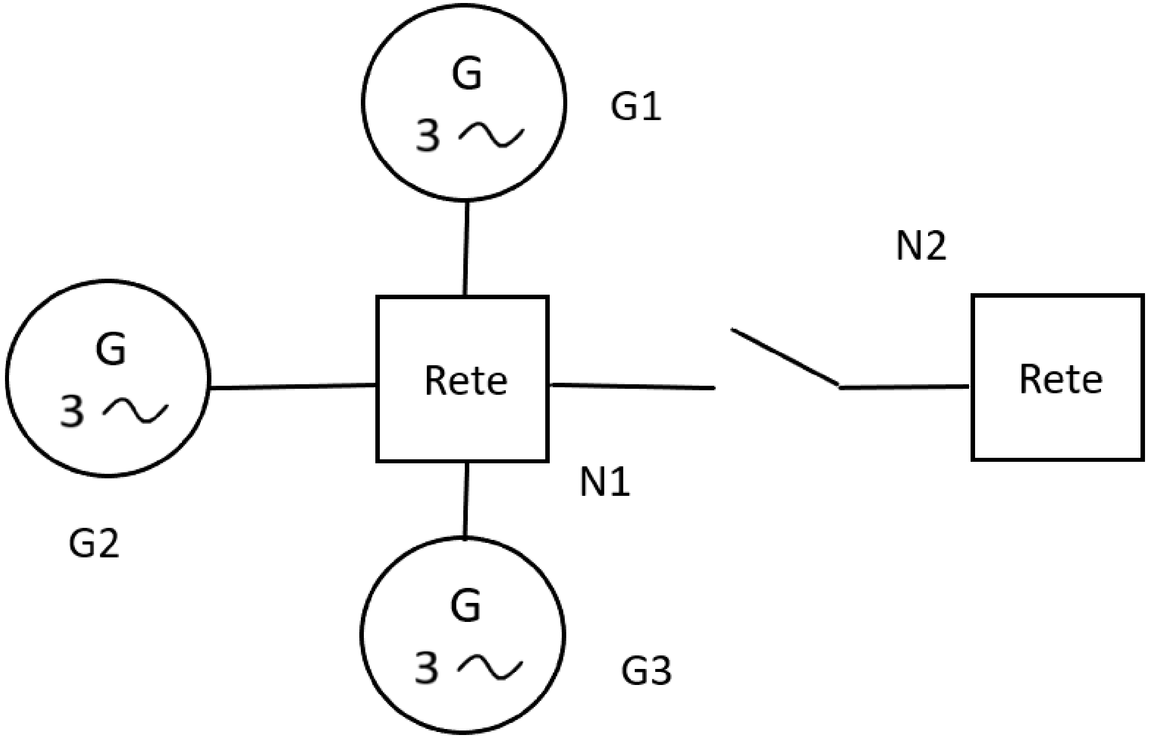


The **primary regulation** responds to the variation of frequency (and speed of the generator group) by modifying the delivered power and acts within a few seconds.

The **secondary adjustment** restores the frequency by modifying the set points of the speed regulators of the groups, then moving the regulating droop curves of the same.

It acts in longer times, of the order of minutes, so that the two adjustment rings are decoupled

Numerical Example – Frequency Regulation



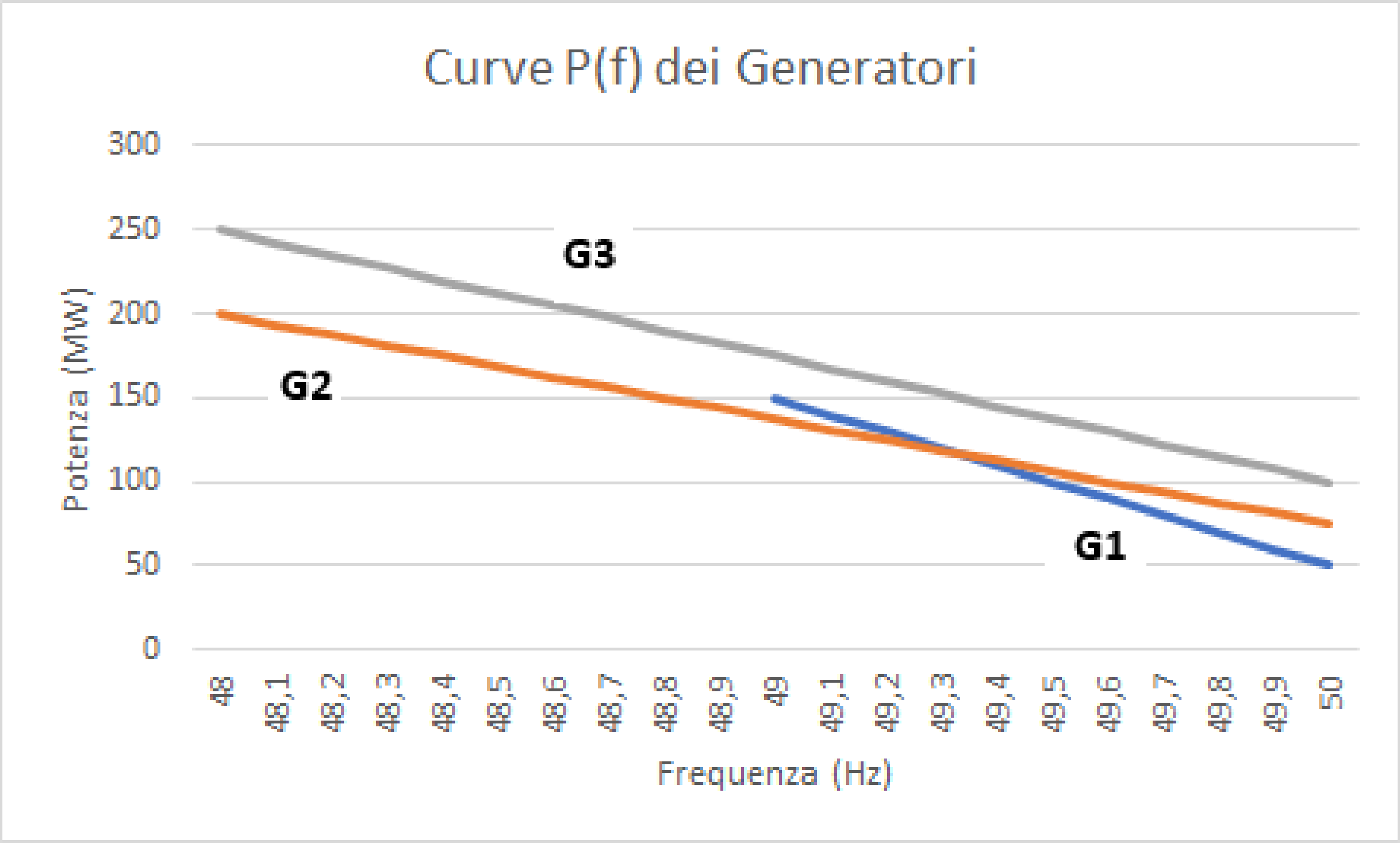
The diagram represents an off-grid electrical grid, consisting of two subnets N1 and N2.
The switch is open.
N1 is powered by three generators with nominal power:
$P1n = 150MW$, $P2n = 200MW$, $P3n = 250MW$

Minimum generating power:
$P1m = 50MW$, $P2m = 75MW$, $P3m = 100MW$

The **primary frequency regulation** is set in such a way that in the passage (ΔP) from the minimum to the nominal power, the generators undergo a frequency decrease of

$\Delta f1 = 1Hz$, $\Delta f2 = 2Hz$, $\Delta f3 = 2Hz$

Numerical Example – Frequency Regulation



The diagram shows the Power-Frequency curves of the three generators, built with the data provided.

They allow you to determine the **primary regulation droop** and the regulating energy of each generator.

The **regulating energy** of the generator represents the variation of the power supplied by the group for a frequency variation of 1 Hz

Numerical Example – Frequency Regulation

Calculate the regulating energy of the three generators

$K1 = (150-50) / 1 = 100$ MW / Hz

$K2 = (200-75) / 2 = 62.5$ MW / Hz

$K3 = (250-100) / 2 = 75$ MW / Hz

Calculate the regulating energy of the N1 network

It is equal to the sum of the regulating energies of the connected generators.

$KN1 = 100 + 62.5 + 75 = 237.5$ MW / Hz

The N1 network absorbs 300MW at time t0, the three generators each deliver 25MW above the minimum power and the frequency is regulated at 50Hz. For a short circuit at time t1, the absorbed power drops by 50MW to 250MW.

Calculate the new operating frequency in the N1 network, after the intervention of the primary regulation only.

The frequency increases and it does according to the regulating energy of the network.

$\Delta f = 50/237.5 = +0.211$Hz $\quad\quad$ $f(t1+dt) = 50 + 0.21 = 50.21$Hz

Numerical Example – Frequency Regulation

Calculate the power delivered by the three generators with the new frequency.

After the intervention of the primary regulation, the generators operate at 50.21Hz.

Each generator will have reduced its power according to its P (f) characteristic and the power reduction can be calculated using the regulating energy of each machine

ΔP1 = K1 x 0.211 = 100 x 0.211 = 21.1MW; P1 (t0) = 75MW; P1 (t1 + dt) = 75-21.1 = 53.9 MW

ΔP2 = K2 x 0.211 = 62.5 x 0.211 = 13.1MW; P2 (t0) = 100MW; P2 (t1 + dt) = 100-13.1 = 86.9MW

ΔP3 = K3 x 0.211 = 75 x 0.211 = 15.8MW; P3 (t0) = 125MW; P3 (t1 + dt) = 125-15.8 = 109.2MW

The secondary adjustment will return each of the generators to the nominal frequency of 50Hz.

Plot the power-frequency diagram of generator G1 at time t0 and the primary regulation transient at time (t1 + dt).

Trace the new power-frequency curve, after the intervention of the secondary regulation

Numerical Example – Frequency Regulation

The intervention of the secondary regulation shifts the P (f) curve of the generator and restores the nominal frequency of 50Hz, bringing the power supplied from 75MW to 53.9MW.