Universidade de Coimbra

Power Quality Problems and New Solutions

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Power system constraints

- Random external factors
  - Weather
  - Human activities
  - Animals
  - Vegetation

- Increasing share of non-linear loads

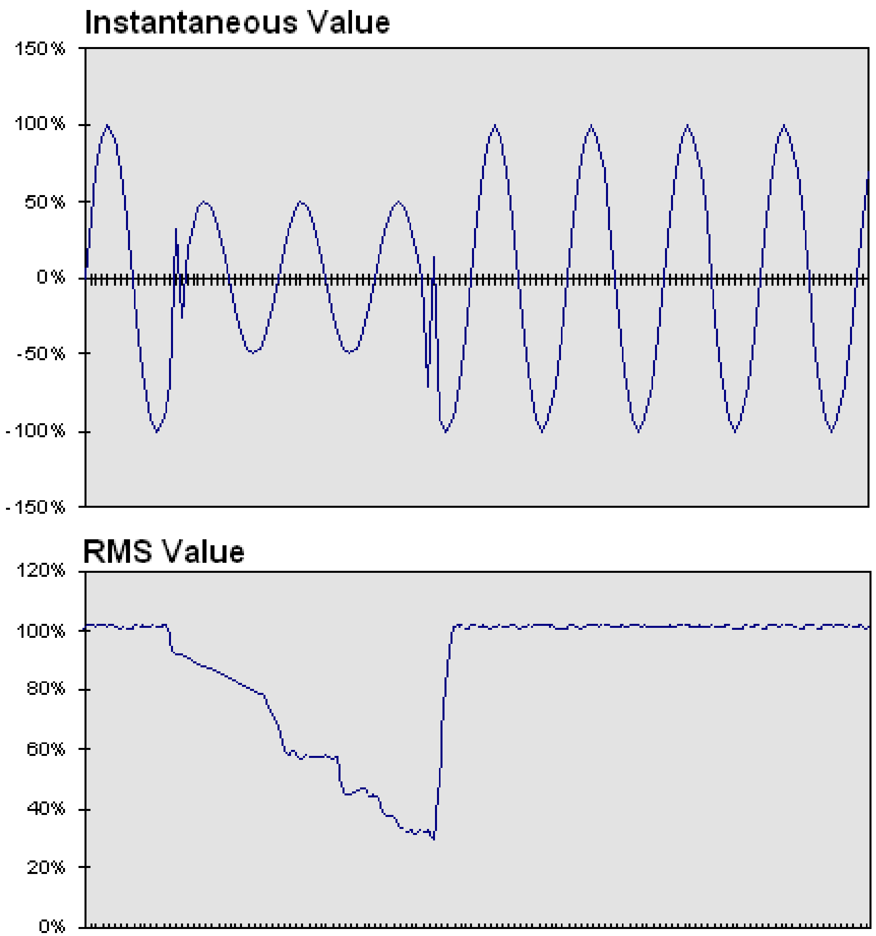
- Increasing demand for high PQ

Main PQ problems

- Voltage sags
- Micro-interruptions
- Long interruptions
- Voltage spikes
- Voltage swells
- Voltage fluctuations
- Voltage unbalance
- Noise
- Harmonic distortion

Voltage Sags

A decrease of the normal voltage level between 10 and 90% of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute.



Causes:

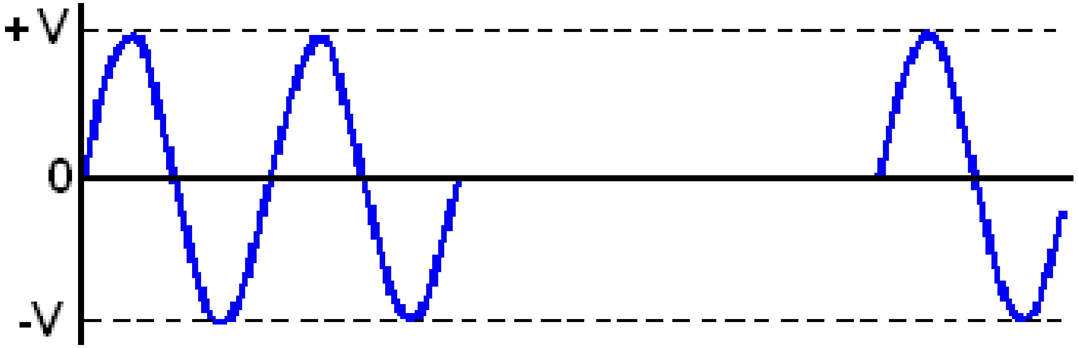
- Faults on the transmission or distribution network.
- Faults in consumer's installation.
- Connection of heavy loads and start-up of large motors.

Consequences:

- Malfunction of microprocessor-based control systems (PCs, PLCs, ASDs, etc) that may lead to a process stoppage.
- Tripping of contactors and electromechanical relays.
- Disconnection and loss of efficiency in electric rotating machines.

Micro-Interruptions

Total interruption of electrical supply for duration from few milliseconds to one or two seconds.



Causes:

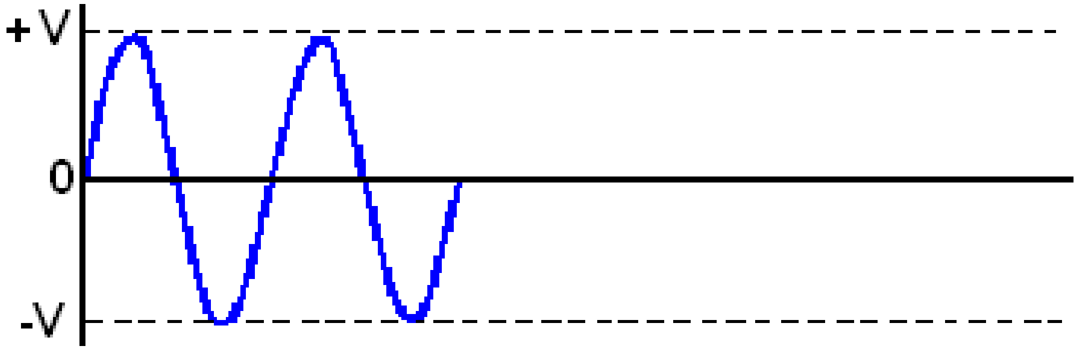
- Opening and automatic reclosure of protection devices.
- Insulation failure, lightning and insulator flashover.

Consequences:

- Tripping of protection devices.
- Loss of information and malfunction of data processing equipment.
- Stoppage of sensitive equipment (such as ASDs, PCs, PLCs).

Long Interruptions

Total interruption of electrical supply for duration greater than 1 to 2 seconds.



Causes:

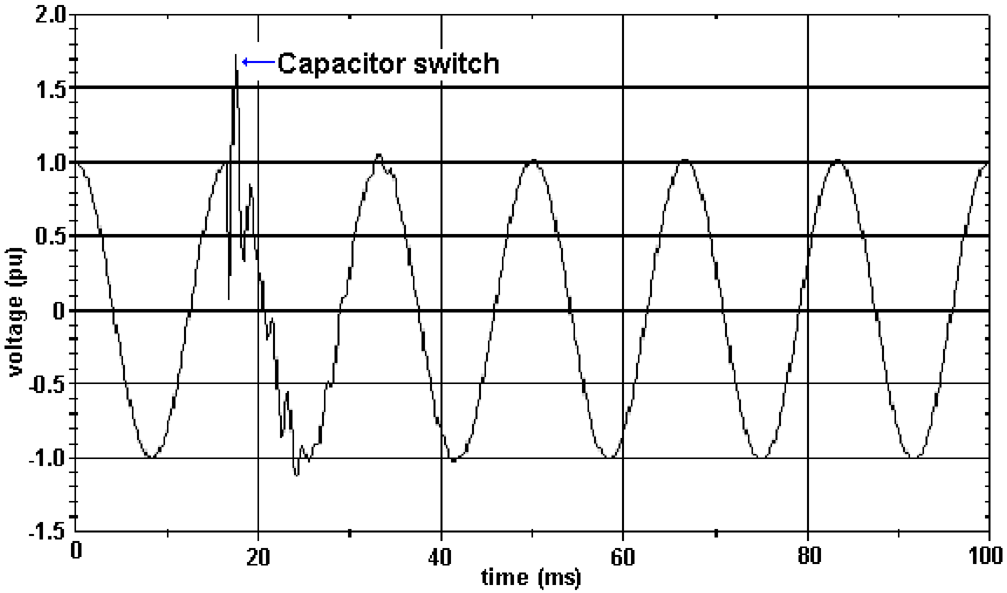
- Equipment failure in the power system network.
- Storms and objects (trees, cars, etc) striking lines or poles, fire.
- Human error, bad coordination or failure of protection devices.

Consequences:

- Stoppage of all equipment.

Voltage Spikes

Very fast variation of the voltage value for durations from a several microseconds to few milliseconds.



Causes:

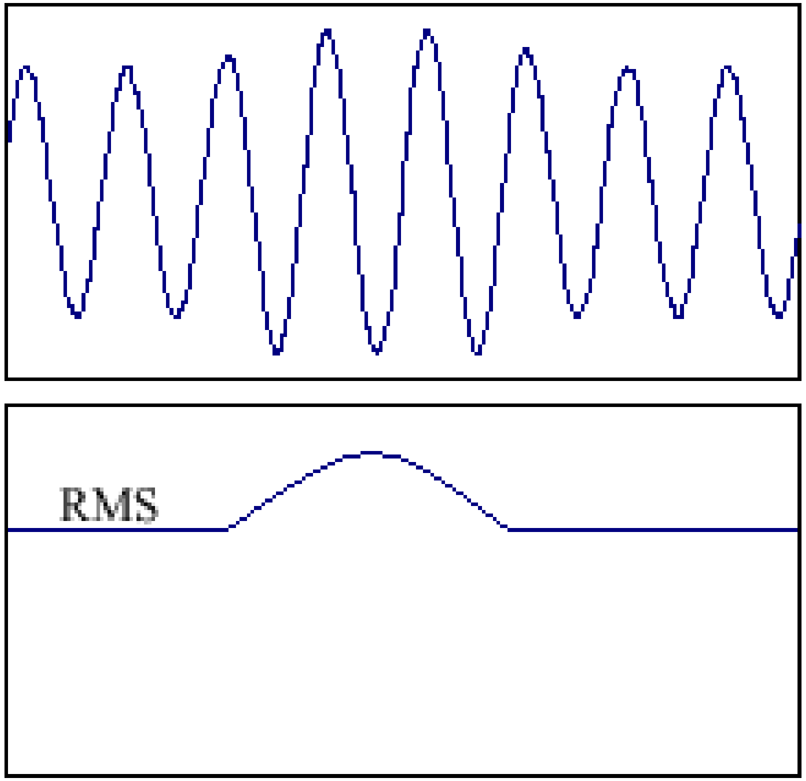
- Lightning.
- Switching of lines or power factor correction capacitors.
- Disconnection of heavy loads.

Consequences:

- Destruction of components and of insulation materials.
- Data processing errors or data loss.
- Electromagnetic interference.

Voltage Swells

Momentary increase of the voltage, at the power frequency, outside the normal tolerances, with duration of more than one cycle and typically less than a few seconds.



Causes:

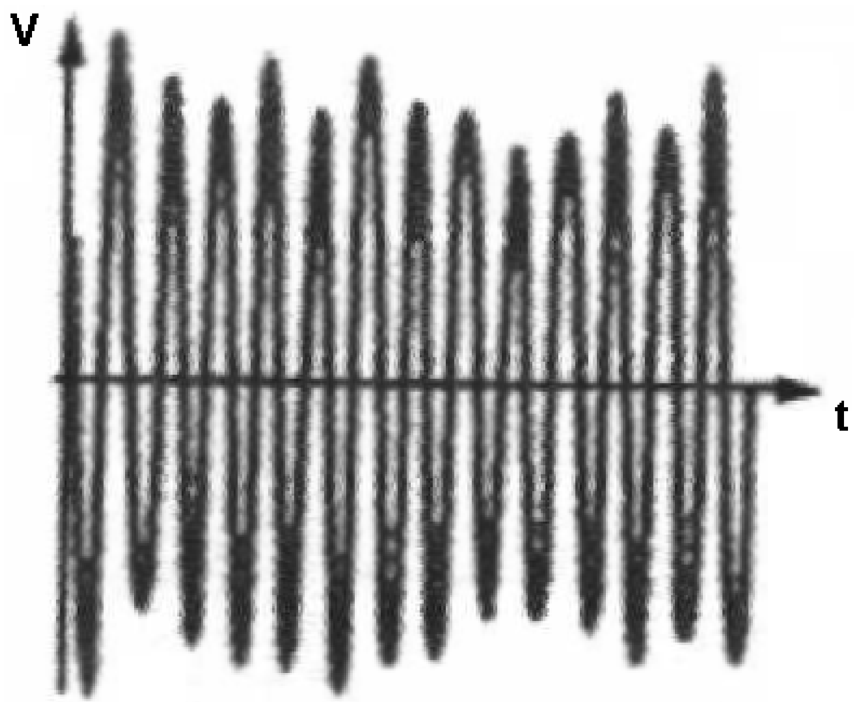
- Start/stop of heavy loads.
- Poorly dimensioned power sources.
- Poorly regulated transformers.

Consequences:

- Flickering of lighting and screens.
- Damage or stoppage or damage of sensitive equipment.

Voltage fluctuation

Oscillation of voltage value, amplitude modulated by a signal with low frequency.



Causes:

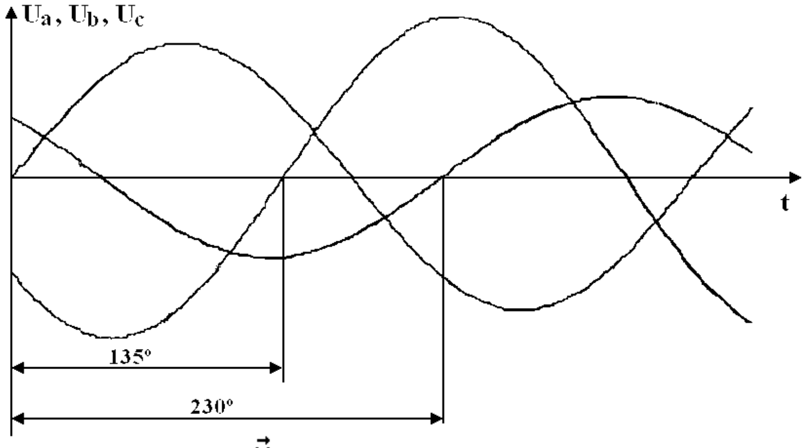
- Arc furnaces.
- Frequent start/stop of electric motors (for instance elevators).
- Oscillating loads.

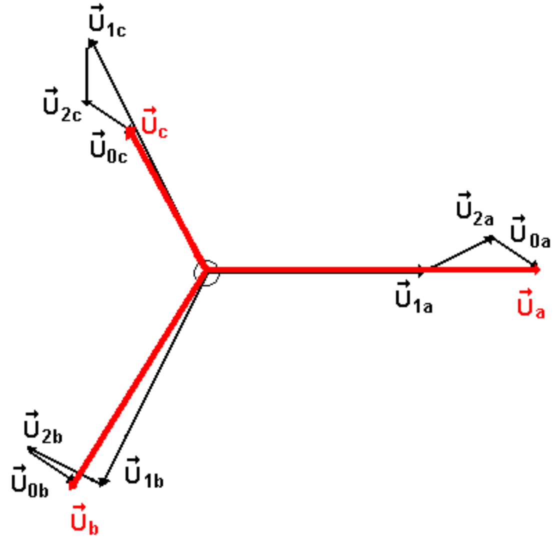
Consequences:

- Most consequences are common to undervoltages.
- Flickering of lighting and screens.

Voltage Unbalance

A voltage variation in a three-phase system in which the three voltage magnitudes or the phase-angle differences between them are not equal.





Causes:

- Large single-phase loads (induction furnaces, traction loads).
- Incorrect distribution of loads by the three phases of the system.

Consequences:

- The most affected loads are three-phase induction machines.
- Increase in the losses.

Noise

Superimposing of high frequency signals on the waveform of the power-system frequency.

Causes:

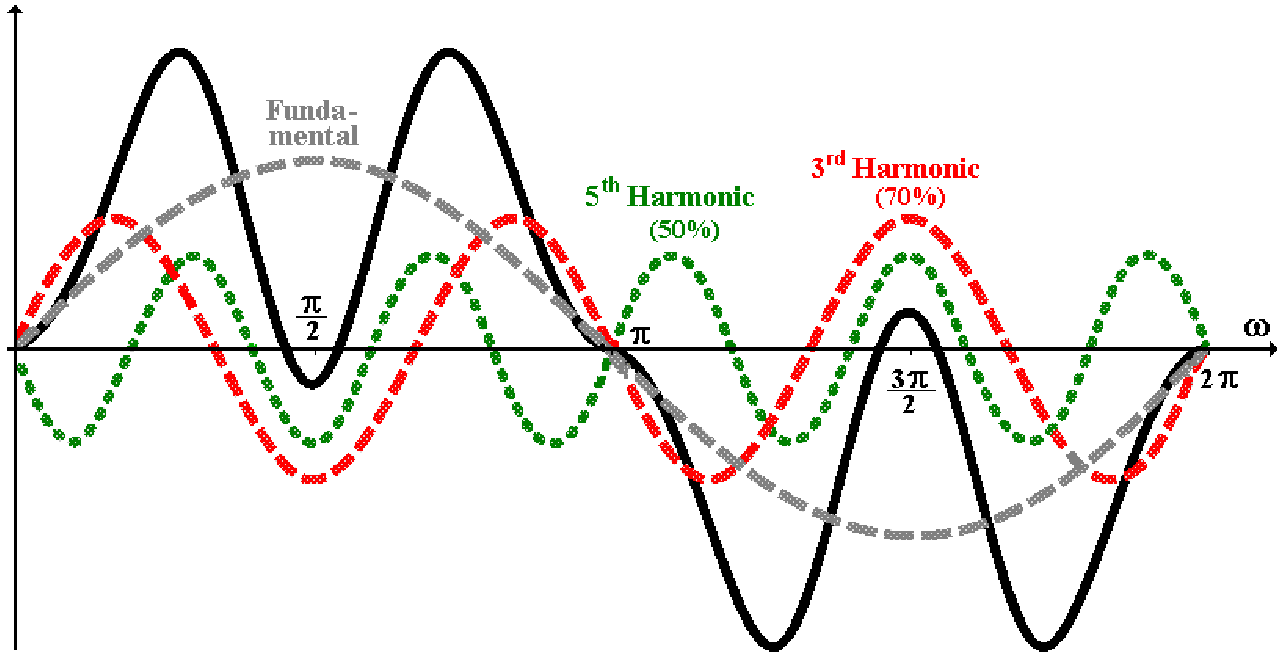
- Electromagnetic interferences.
- Improper grounding may also be a cause.

Consequences:

- Disturbances on sensitive electronic equipment.
- May cause data loss and data processing errors.

Harmonic Distortion

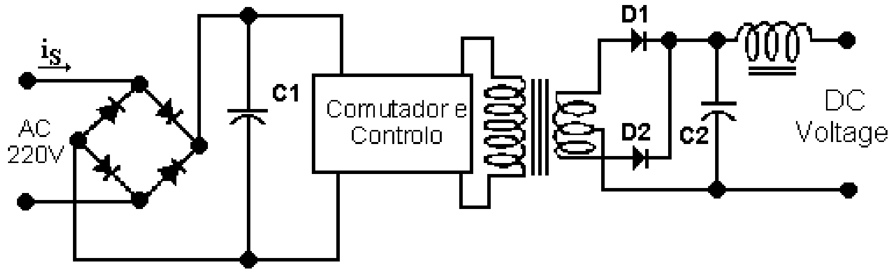
Voltage or current waveforms assume non-sinusoidal shape.

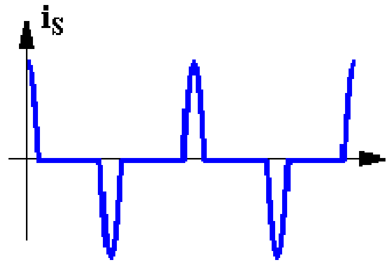


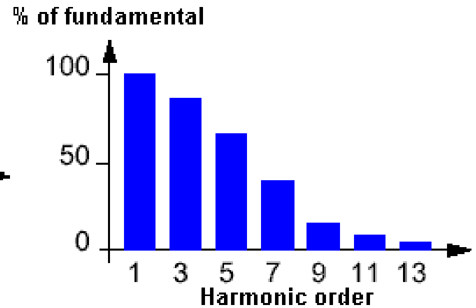
The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency.

Harmonic Distortion

Sources of harmonic distortion (1)

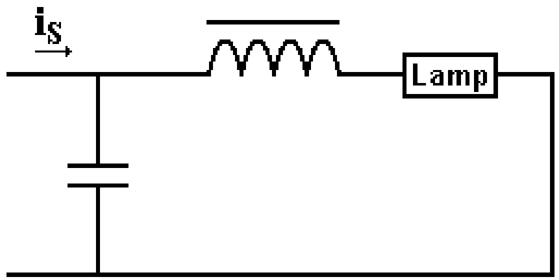


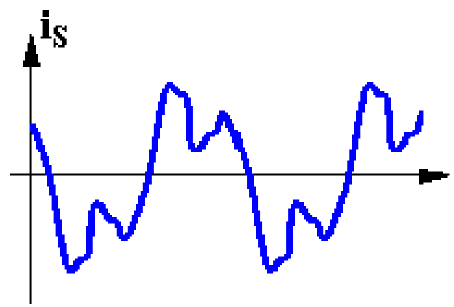


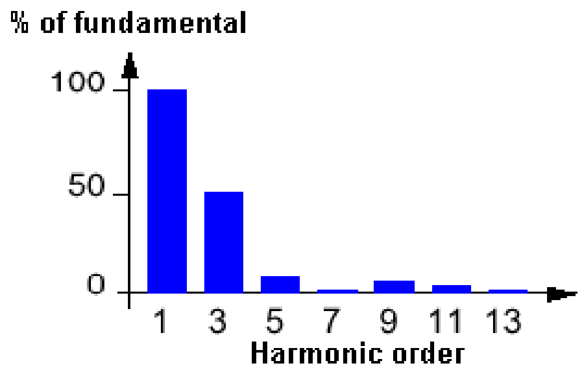


Switched mode power supply

Fluorescent lighting

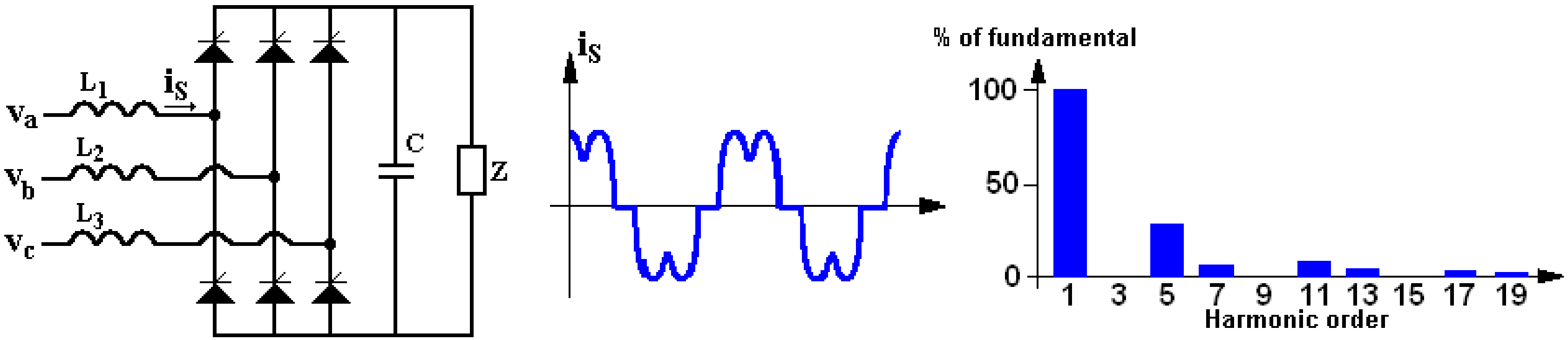






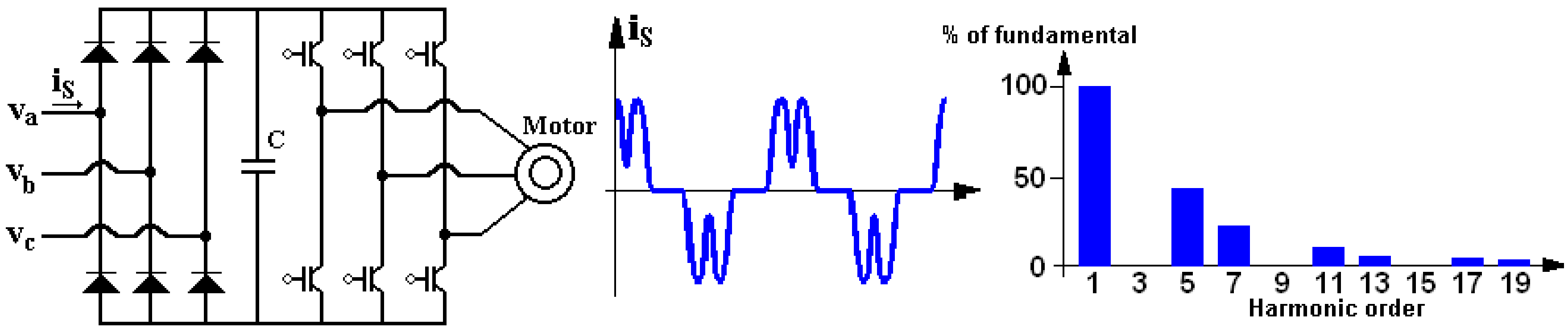
Harmonic Distortion

Sources of harmonic distortion (2)



3-phase rectifier

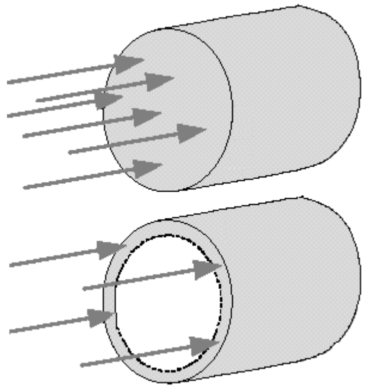
Adjustable speed drive

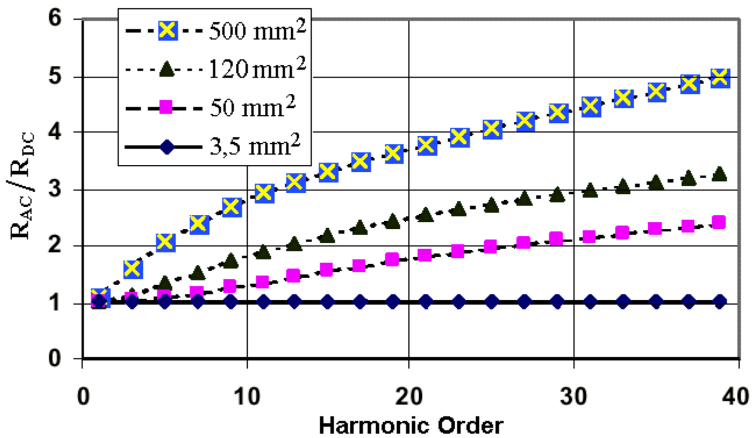


Harmonic Distortion

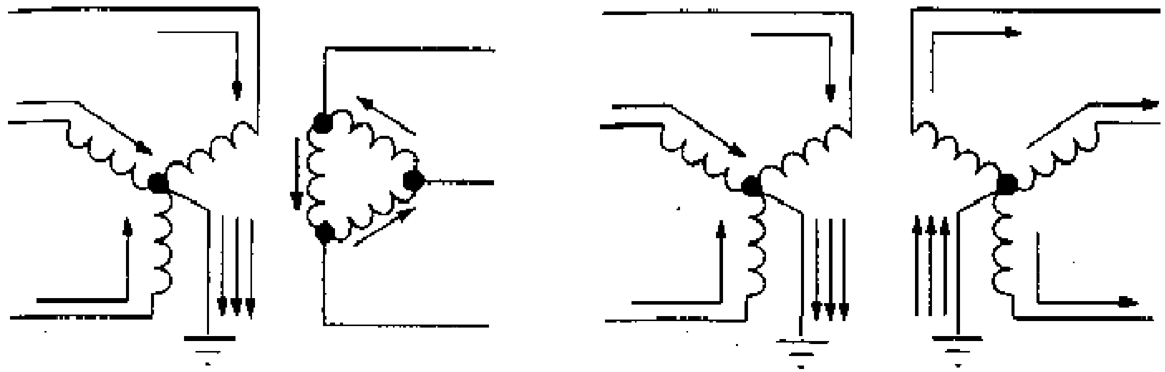
Consequences of harmonic distortion (1)

- Conductor overheating (skin effect end proximity effect)





- Neutral overloading (triplen harmonics)



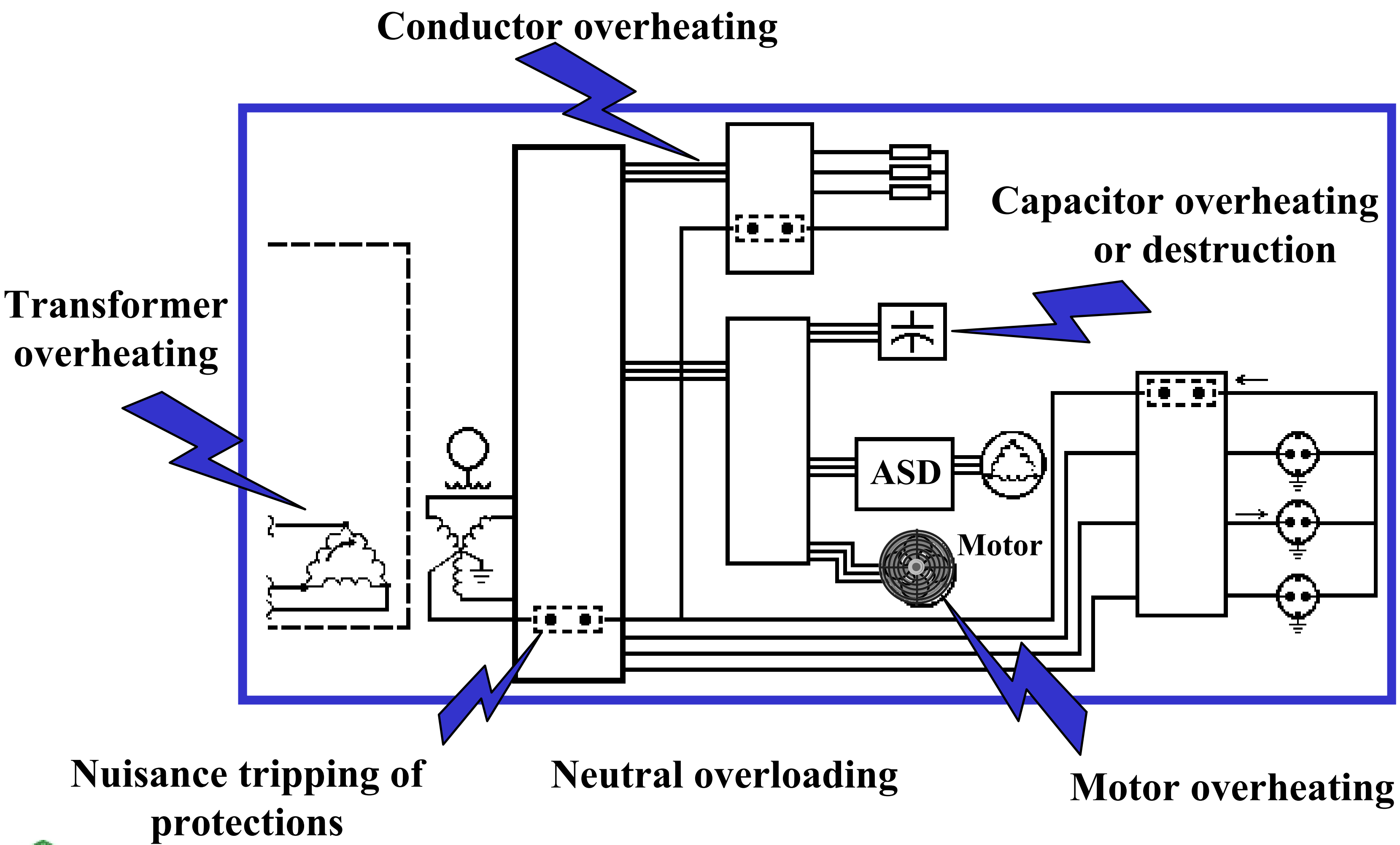
Harmonic Distortion

Consequences of harmonic distortion (2)

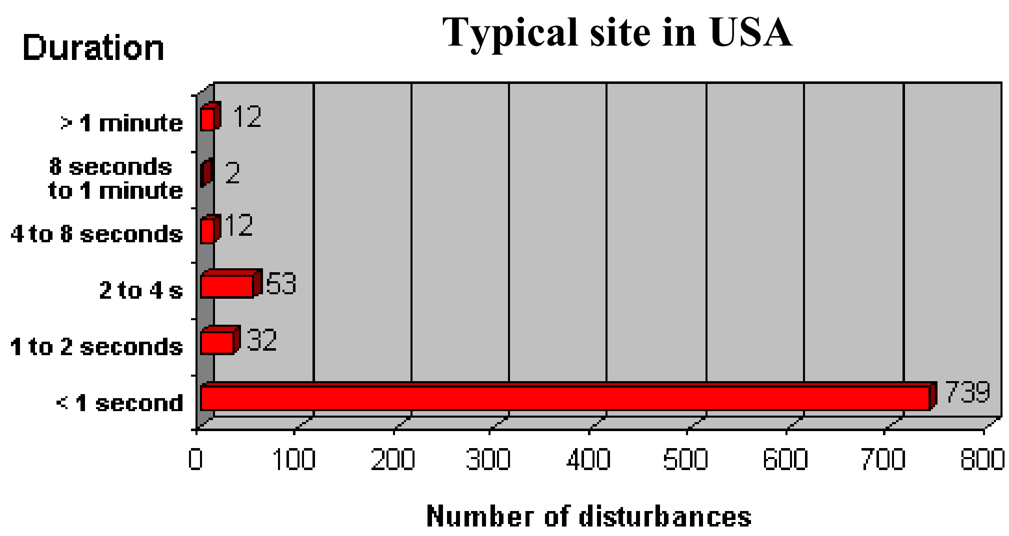
- Increased probability of occurrence of resonance.
- Nuisance tripping of thermal protections.
- Electromagnetic interference.
- Increase in the losses.
- Loss of efficiency in electric machines (e.g. 5th harmonic).

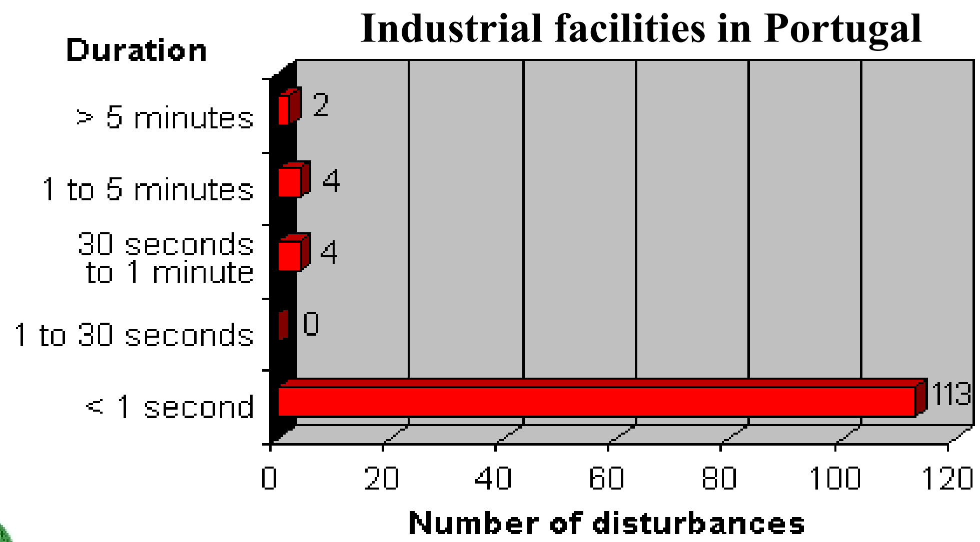
Harmonic distortion

Consequences of harmonic distortion (summary)



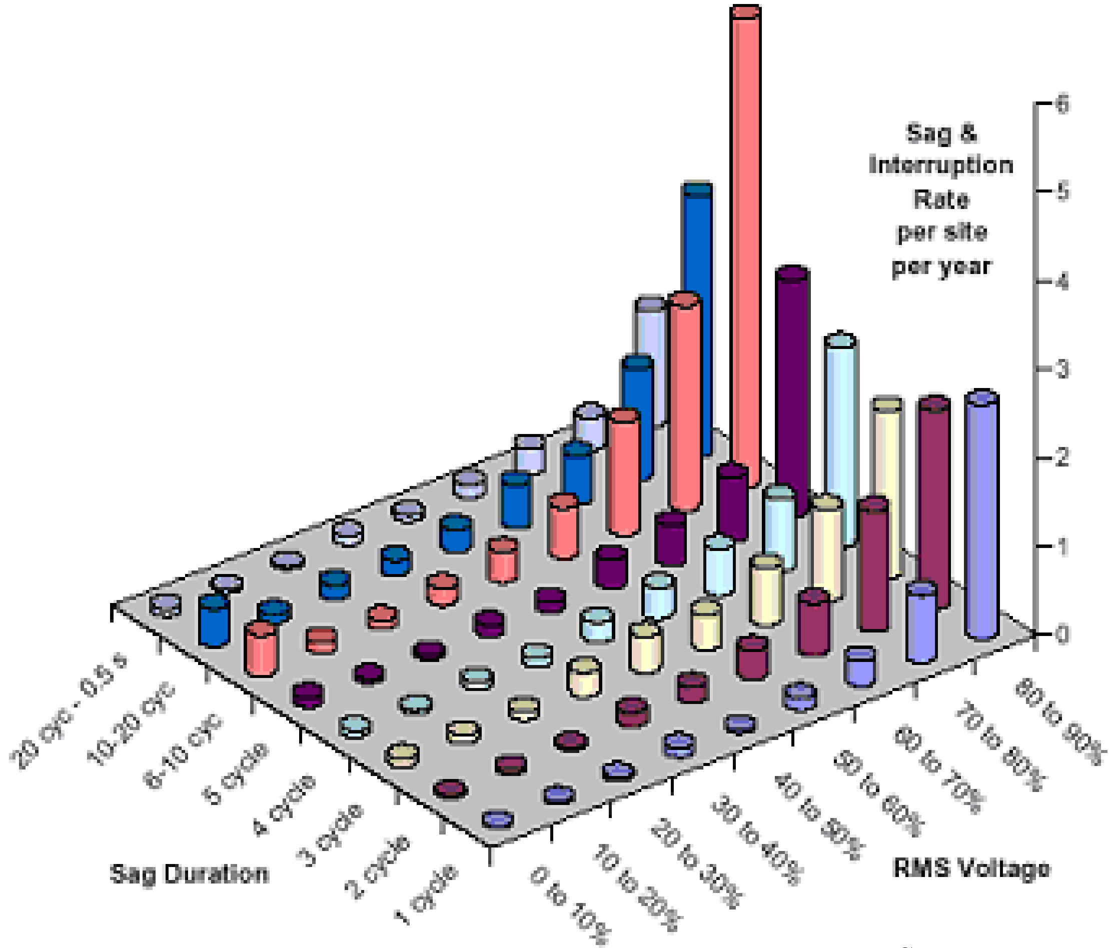
Power Quality characterization





In both cases, about 90 % of PQ events have duration below 1 second.

Power Quality characterization



Source: EPRI

92% of PQ disturbances were voltage sags with amplitude drops up to 50% and duration below 2 seconds.

Power Quality costs

Direct costs

- Damage in the equipment
- Loss of production and raw material
- Salary costs during non-productive period
- Restarting costs

Indirect costs

- Inability to accomplish deadlines
- Loss of future orders

Non-material inconvenience

- Inconveniences that cannot be expressed in money, such as not listening to the radio or watch TV

Power Quality costs

• **Business Week (1991)** - 26,000 million USD per year in the United States

• **EPRI (1994)** - 400,000 million USD per year in the United States.

• **US Department of Energy (1995)** - 150,000 million USD per year for United States.

• **Fortune Magazine (1998)** - Around 10,000 million USD per year in United States.

• **E Source (2001**) - 60,000 to 80,000 USD per installation, per year for continuous process industries, financial services and food processing in the United States.

• **European Copper Institute (2001)** - 10,000 million EUR per year, in EU in industry and commerce.

Power Quality Costs

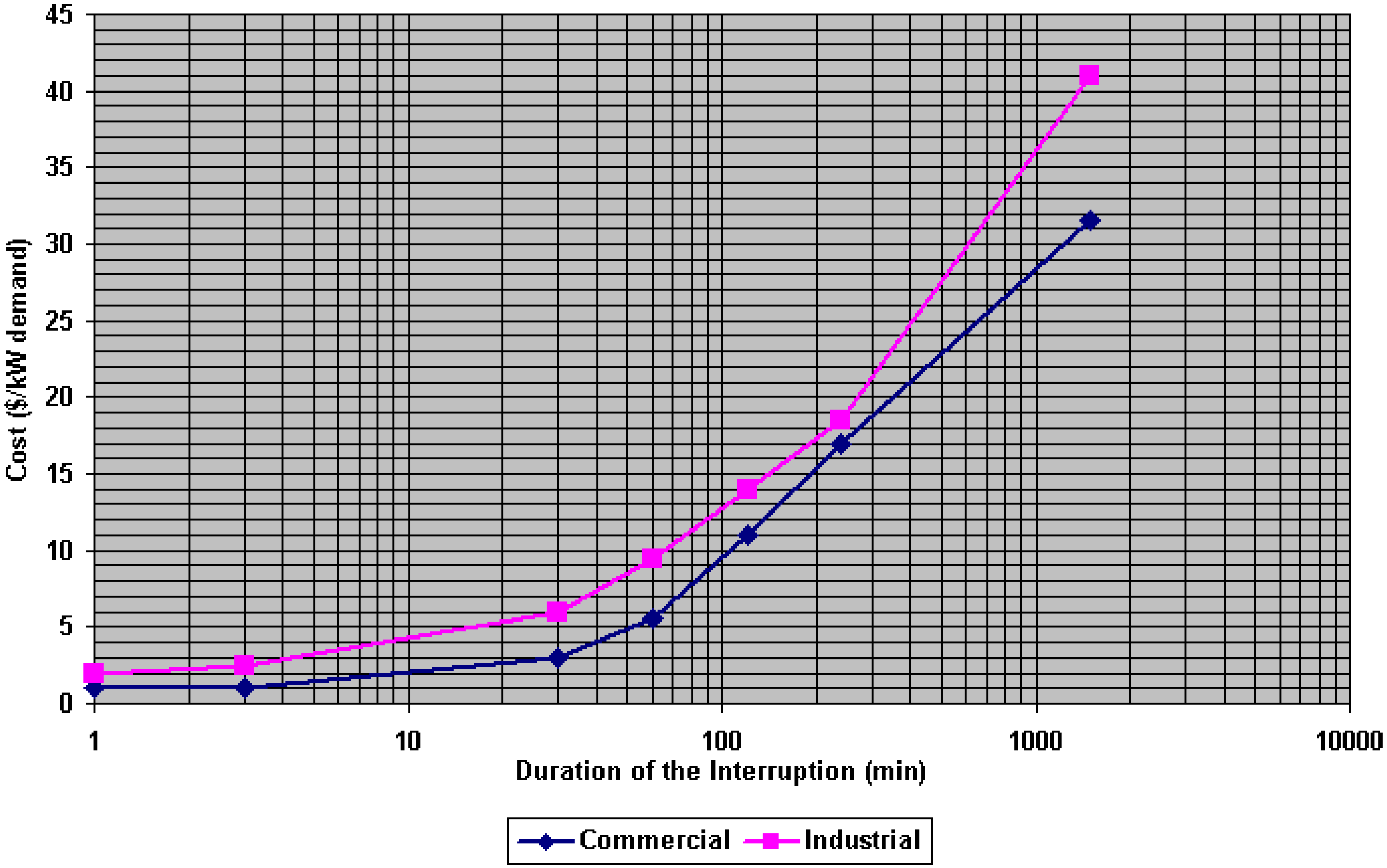
Cost of momentary interruption (1 minute), in $/kW demand

	Maximum	Minimum
Industrial		
Automobile manufacturing	5.0	7.5
Rubber and plastics	3.0	4.5
Textile	2.0	4.0
Paper	1.5	2.5
Printing (newspapers)	1.0	2.0
Petrochemical	3.0	5.0
Metal fabrication	2.0	4.0
Glass	4.0	6.0
Mining	2.0	4.0
Food processing	3.0	5.0
Pharmaceutical	5.0	50.0
Electronics	8.0	12.0
Semiconductor manufacturing	20.0	60.0
Services		
Communication, information processing	1.0	10.0
Hospitals, banks, civil services	2.0	3.0
Restaurants, bars, hotels	0.5	1.0
Commercial shops	0.1	0.5

Source: Electrotek Concepts

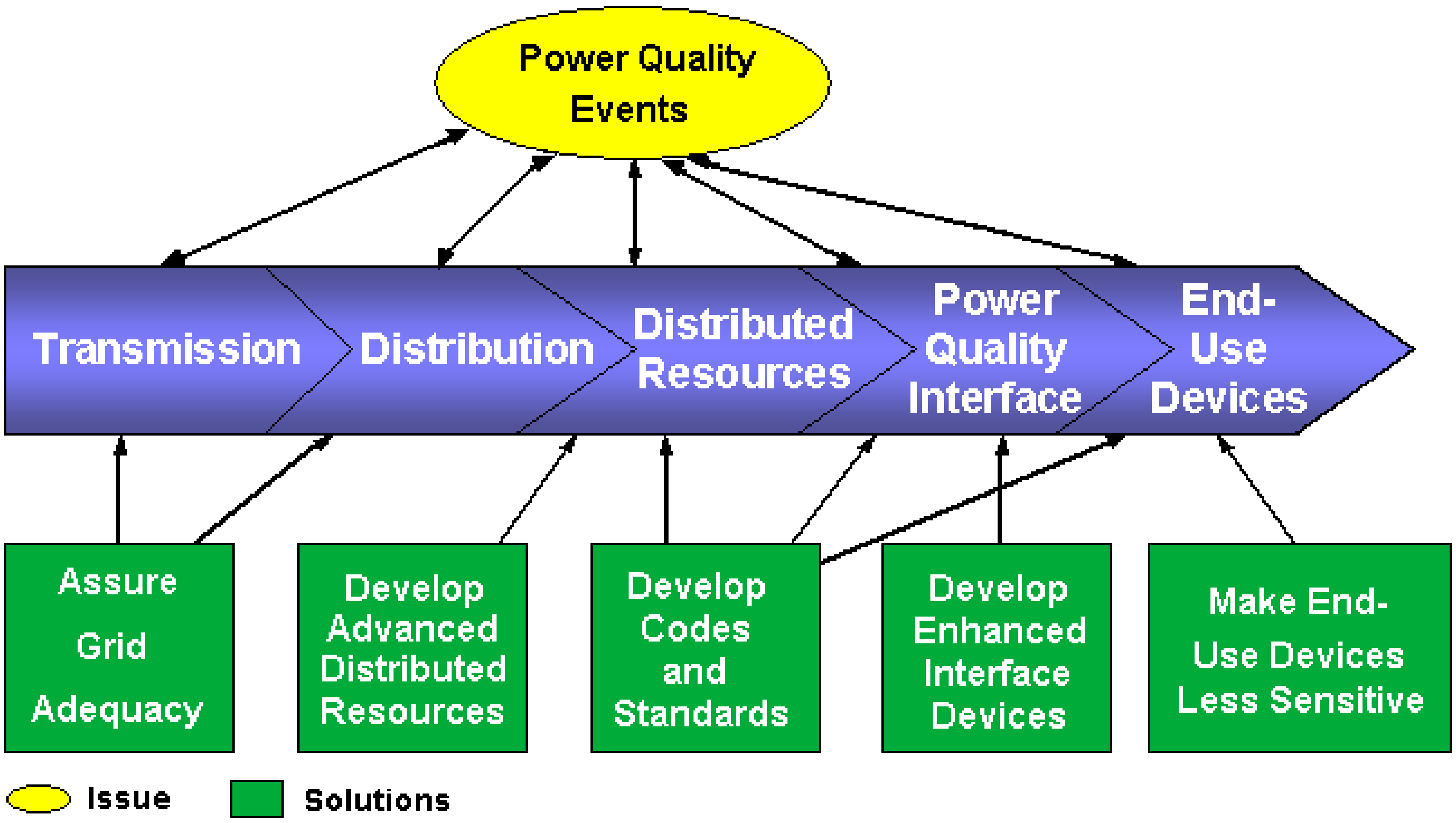
Power Quality costs

Costs of interruptions vs. duration



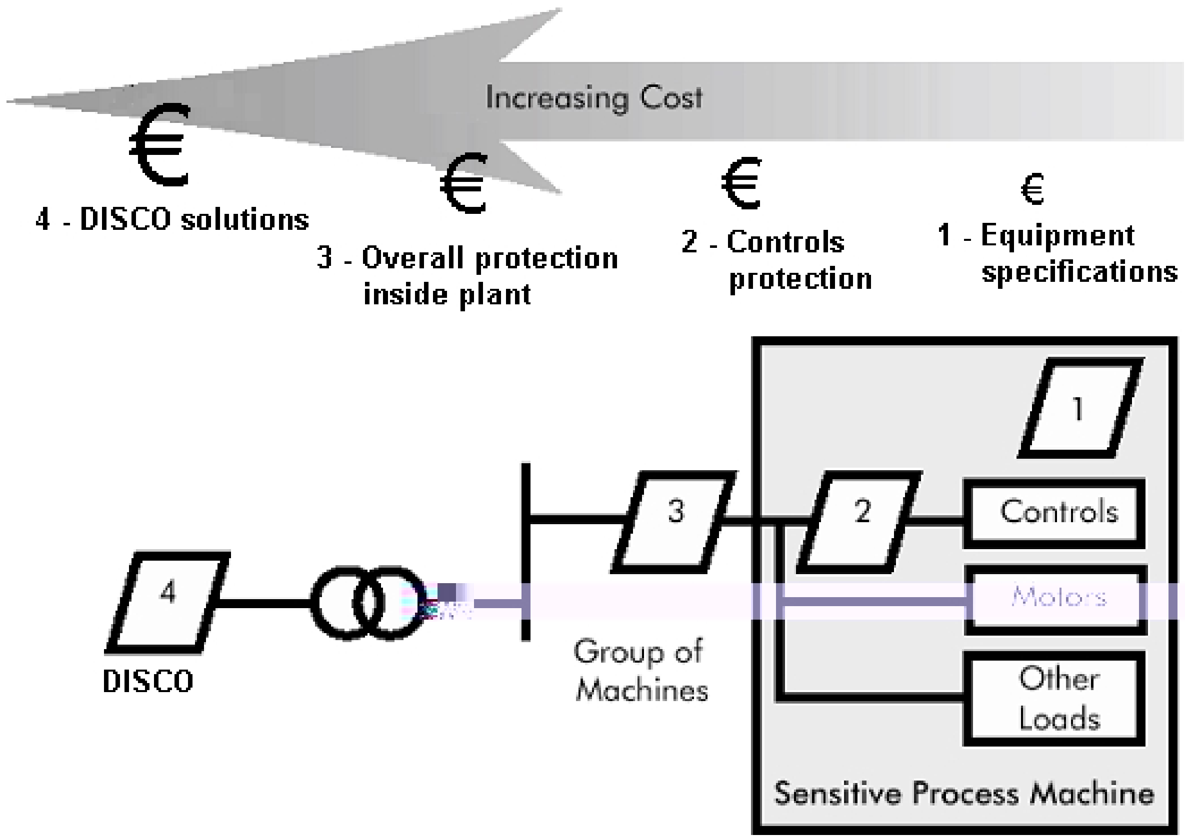
Source: Electrotek Concepts

Power Quality solutions



Costs of improving PQ

The lowest cost is to implement item 1 at the design stage.



Grid Adequacy

Many PQ problems have origin in T&D network.

A proper planned and maintained grid will avoid many PQ problems.

- High level of redundancy;
- Cleaning of insulators;
- Trimming of trees nearby power lines…

Codes and Standards

Need to regulate:

- the minimum PQ level that utilities have to provide to consumers, and
- the immunity level that equipment should have.

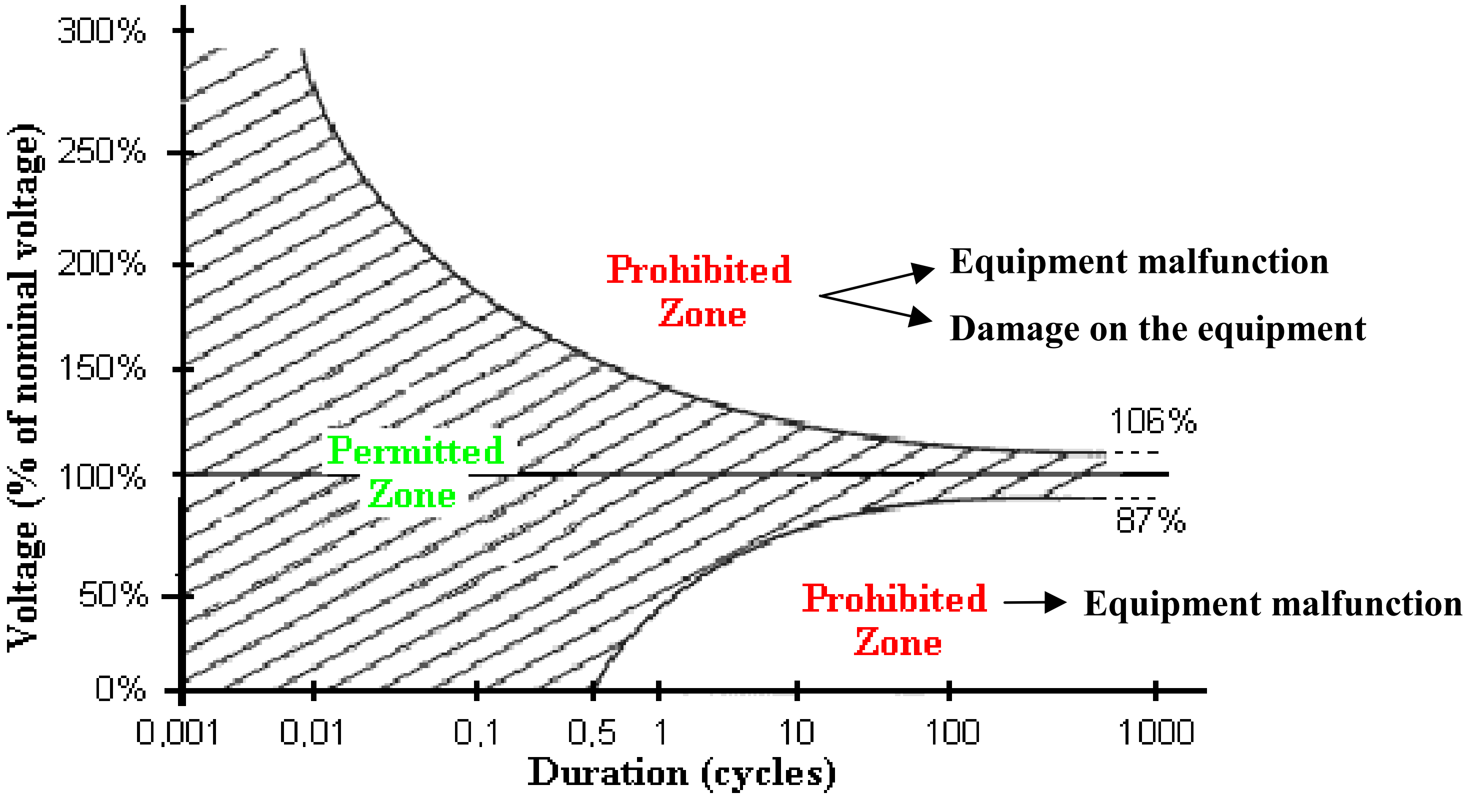
Most relevant standards:

- CBEMA curve
- ITIC curve
- IEC 61000
- EN 50160:2001
- IEEE standards
  - 519-1992 → Harmonics
  - 1100-1992 → Powering and grounding sensitive equipment
  - 1159-1992 →Monitoring power quality
  - 1250-1995 → Service of sensitive equipment

CBEMA curve

CBEMA – Computer and Business Equipment Manufacturers Association (1978).

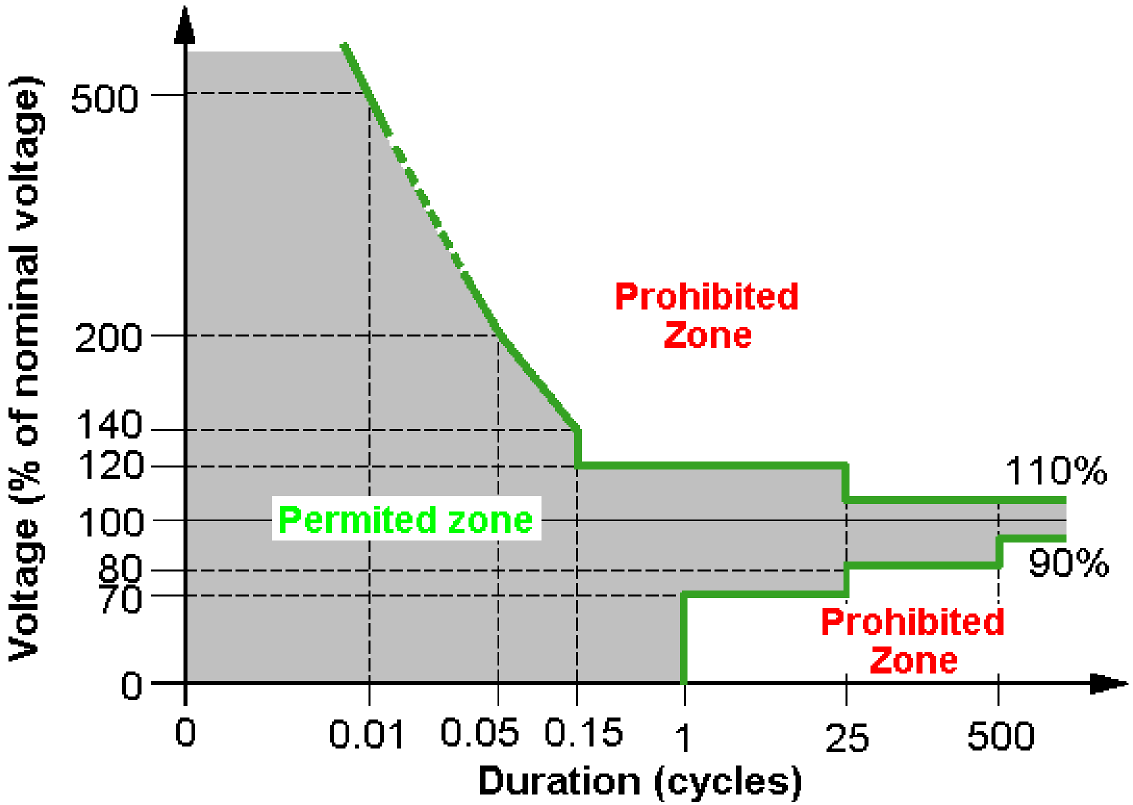
Specifies the maximum and minimum limits that sensitive electronic equipment should be able to withstand.



ITIC curve

ITIC – Information Technology Industry Council (1996, revised 2000).

Specifies the maximum and minimum limits that sensitive electronic equipment should be able to withstand.



EN 50160

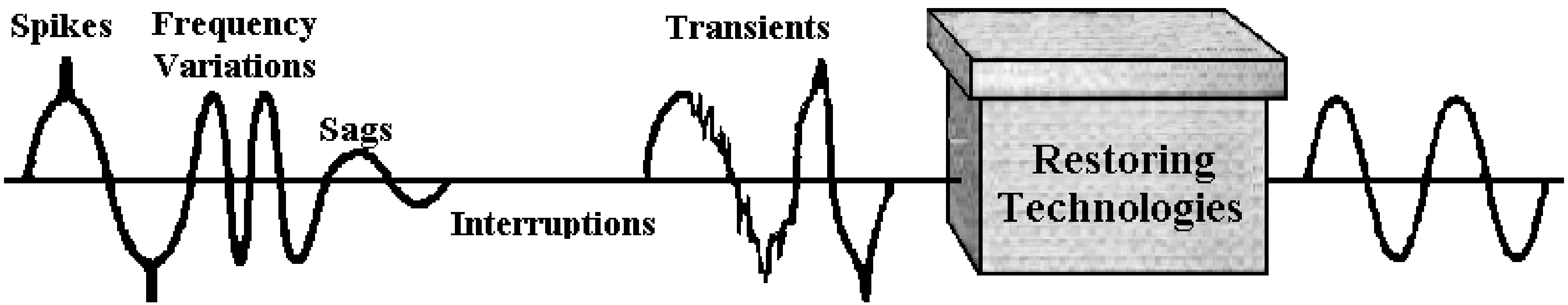
European Norm created by CENELEC (European Committee for Electrotechnical Standardization).

Defines the voltage characteristics of electricity supplied by public distribution systems.

	Limits
Frequency	Must remain between 49.5 (-1%) and 50.5 Hz (+1%).
Voltage	The voltage must be between 90% and 110% of nominal voltage.
Voltage Unbalance	The negative sequence cannot assume magnitude higher than 2% of the direct sequence.
Harmonic voltage	THD < 8 % $V_3 < 5.0\%$ $V_5 < 6.0\%$ V7 < 5.0%

Restoring technologies

Restoring technologies are used to provide the electric loads with ride-through capability in poor PQ environment.



Distributed Resources

Distributed Generation (DG)

- Reciprocating engines
- Microturbines
- Fuel Cells

Energy Storage (restoring technologies)

- Electrochemical batteries
- Flywheels
- Supercapacitors
- SMES
- Compressed air

Distributed Generation

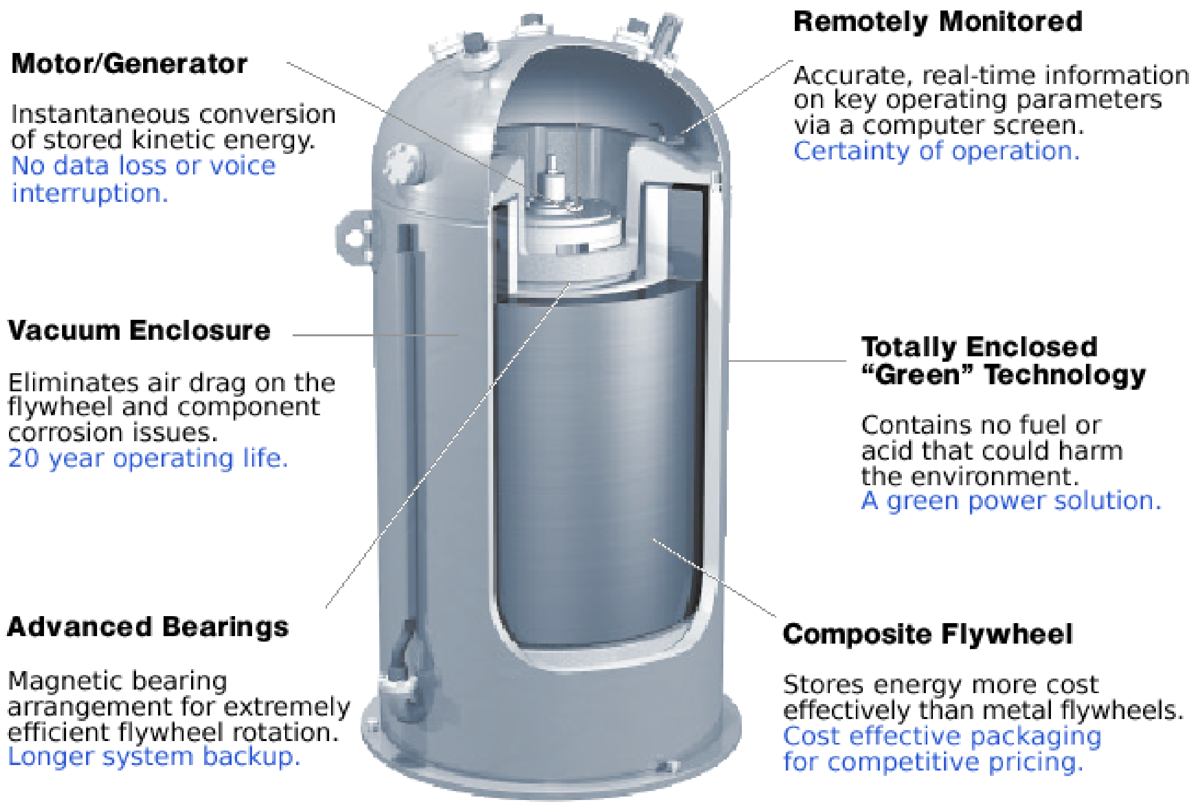
•Used to provide "clean power" to critical loads, isolating them from disturbances with origin in the grid.

• Backup generators to assure energy supply to critical loads during sustained outages.

	Reciprocating Engines	Microturbines	Fuel Cells
Timing	• Ongoing	• Emerging now	• Mid-2000's
Market	• Standby/backup utilization	• Peak-shaving and PQ	• Prime power and PQ
Economics	• 300 a 600 $/kW	• 750 $/kW	• 1000* a 4000 $/kW
	• 33-45% efficient	• 20-30% efficient	• 45-60% efficient
	• <5% utilization	• ~20% utilization	• >80% utilization
	• 15-30 cents/kWh	• 10-15 cents/kWh	• 5*-15 cents/kWh * predicted

Flywheels

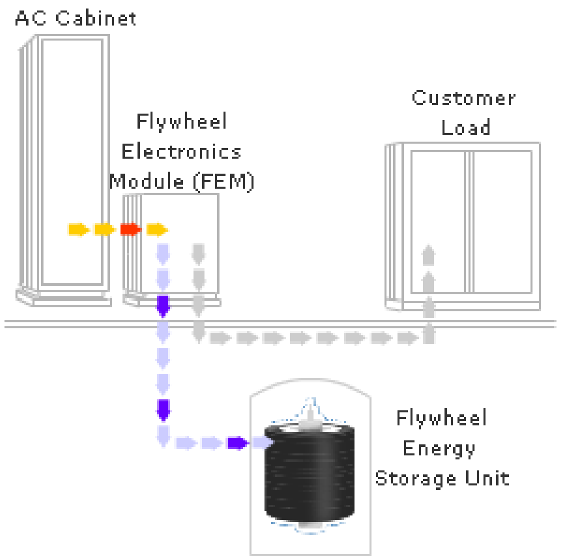
Electromechanical device that couples a rotating electric machine (motor/generator) with a rotating mass to store energy for short durations.



Source: http://www.beaconpower.com

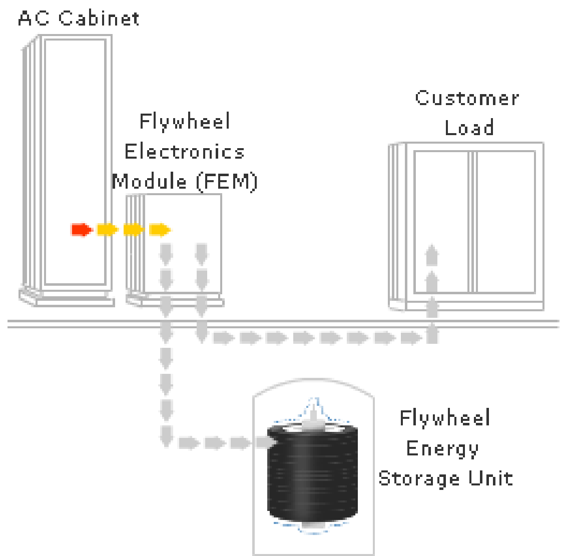
Flywheels

Working Principle



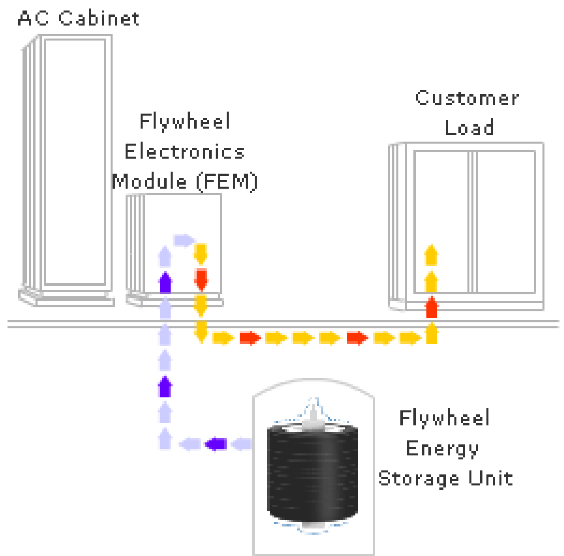
1. The Flywheel Charge Mode:

- AC power is supplied to the Flywheel Electronics Module (FEM)
- The FEM powers up the Flywheel to full speed within a few hours



2. The Flywheel Float Mode:

- Flywheel maintains full energy and speed with minimal AC power
- Flywheel stays in this mode until called upon for power



3. The Flywheel Discharge Mode:

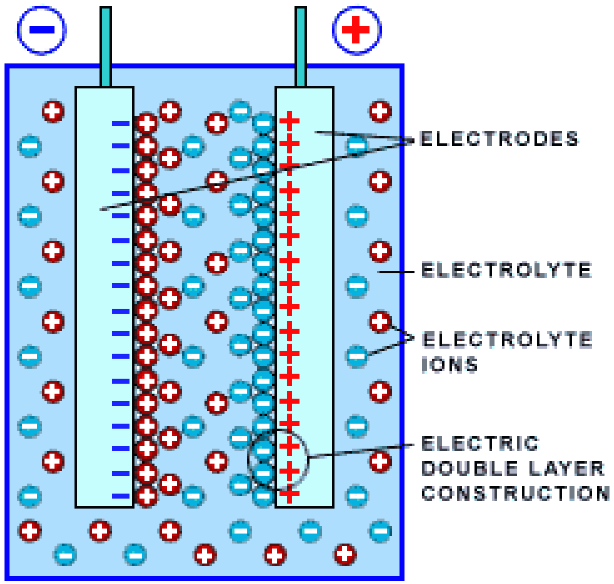
- AC power is disrupted
- Flywheel supplies power to the FEM
- The FEM provides uninterrupted power to the Customer Load
- Flywheel speed decreases

Source: http://www.beaconpower.com

Supercapacitors

New technology applied to capacitors

- High power density
- Long life and non-toxic

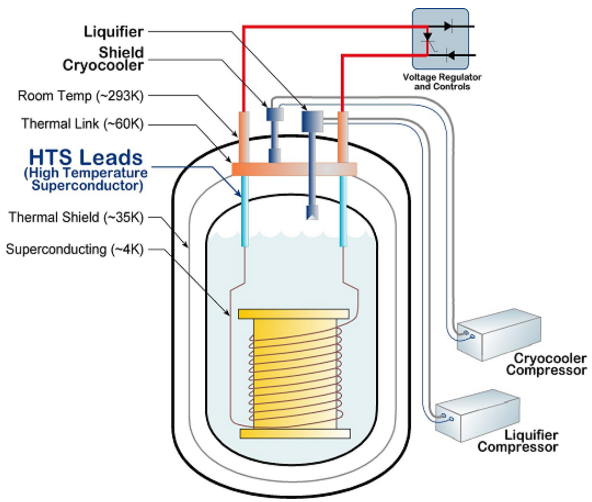


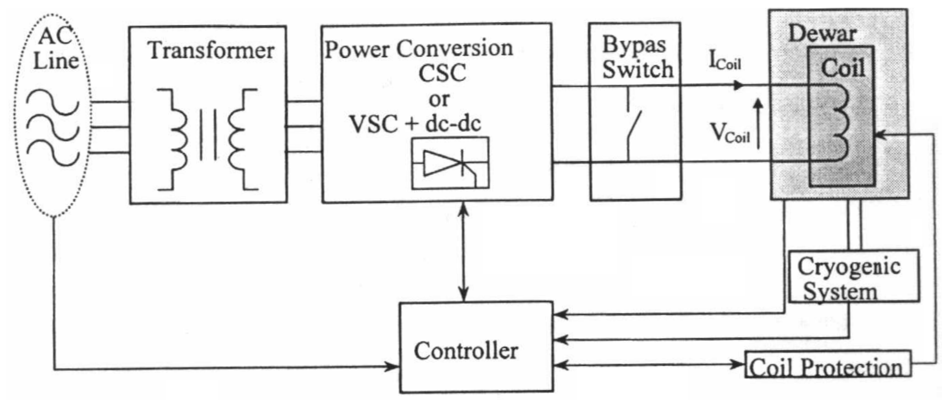
UPS with supercapacitors ESMA
(1 MJoule, 1000 kg)

Superconducting Magnetic Energy Storage (SMES)

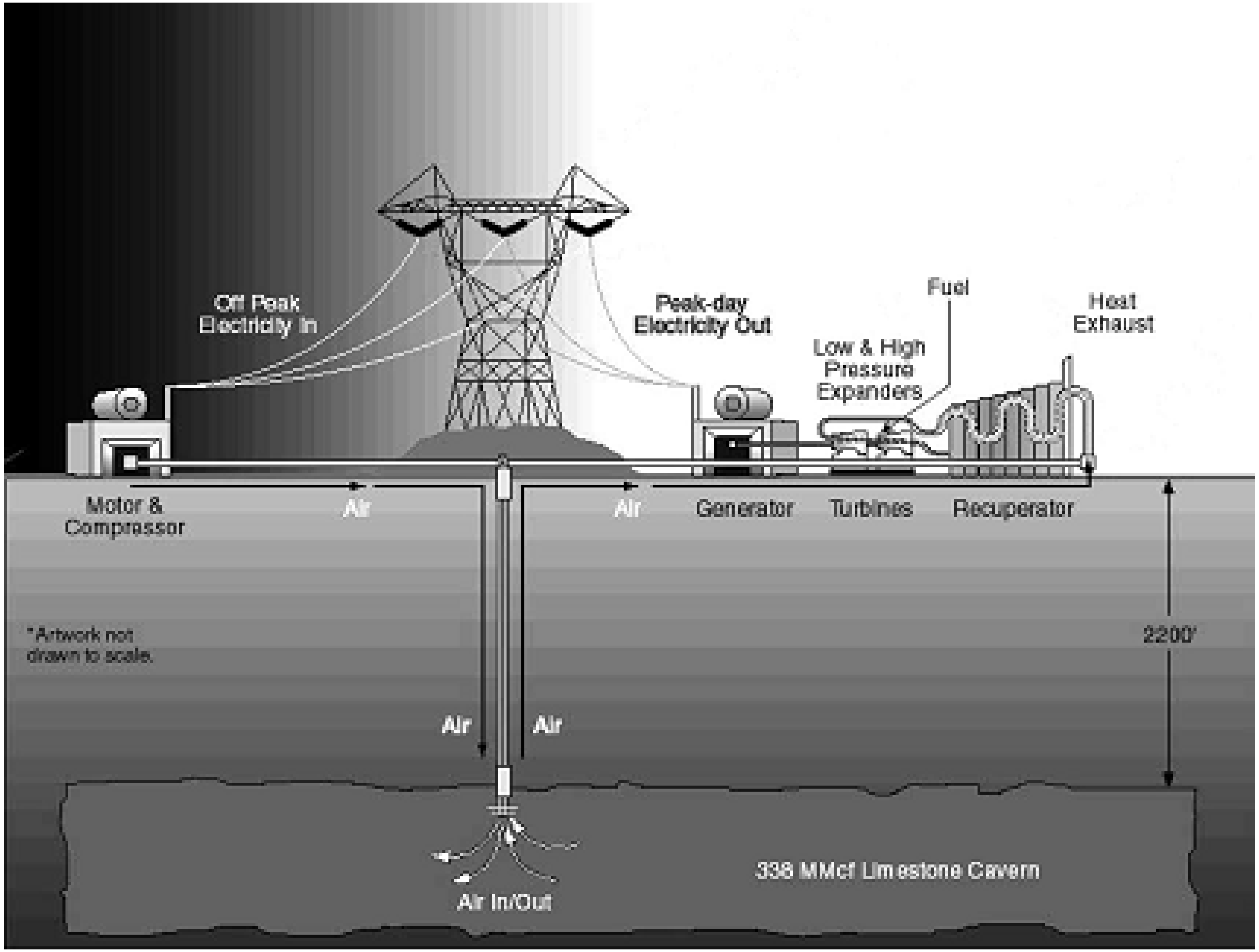
Energy is stored in the magnetic field of a coil made of superconductor material.

- High power density
- Very fast response
- Very expensive (on development)

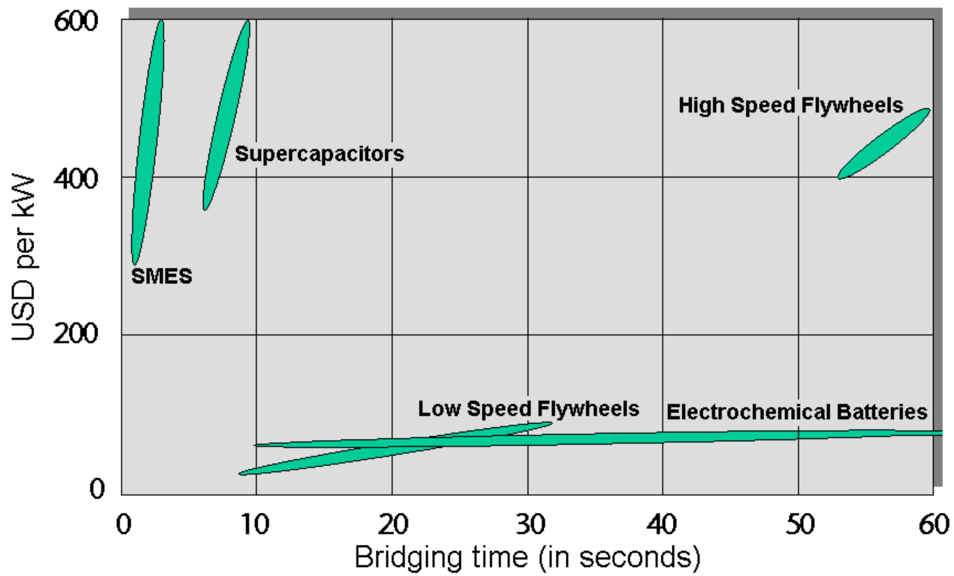


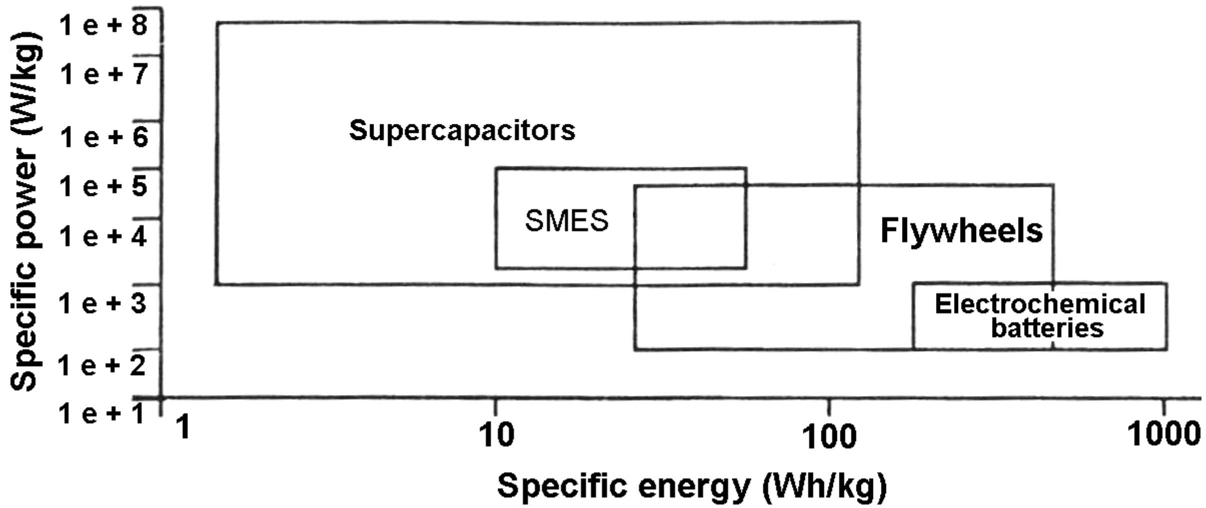


Compressed Air



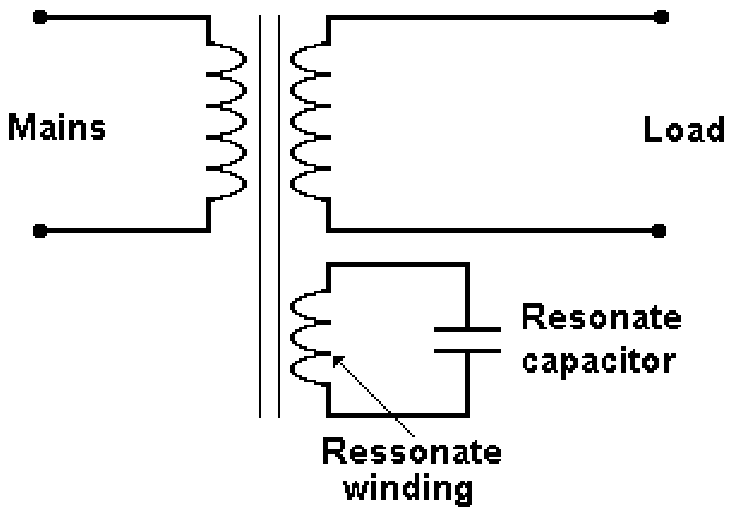
Energy storage technologies comparison





Constant voltage transformers (CVT)

Use the principles of resonance and core saturation to provide an output voltage approximately constant, when the input voltage decreases.

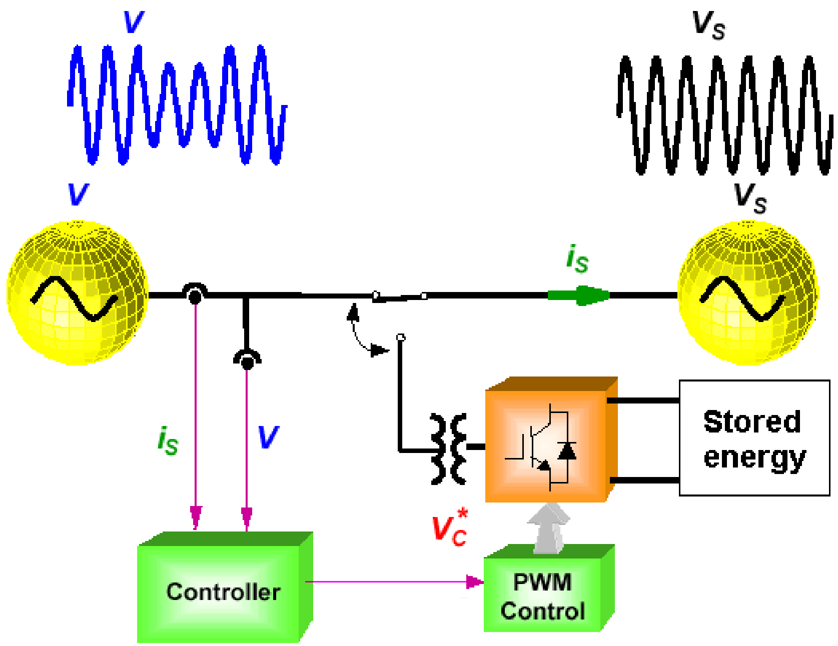


- ✓ Simple technology
- ✓ Low price

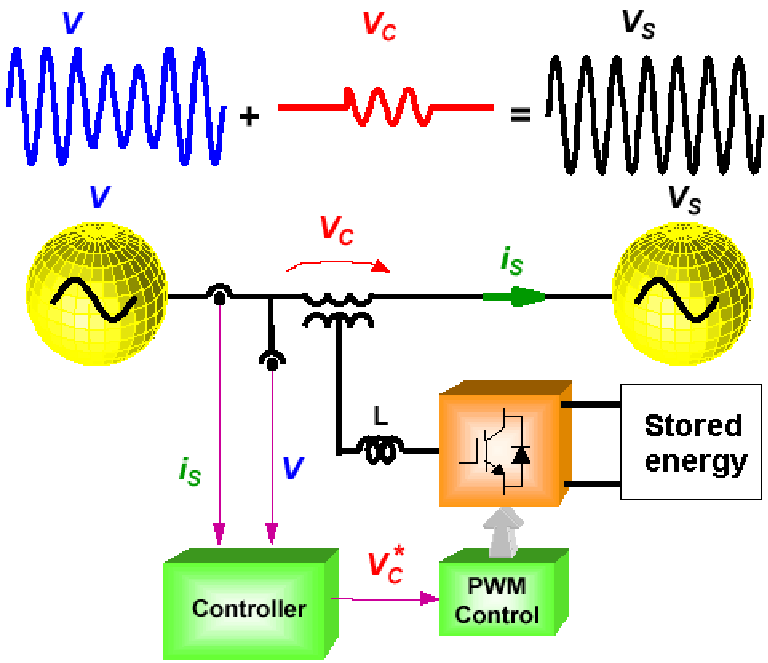
- ✘ Low efficiency (80% at full load)
- ✘ Can produce harmonics and transients
- ✘ Vibration and noise, when resonance occurs

Voltage compensator

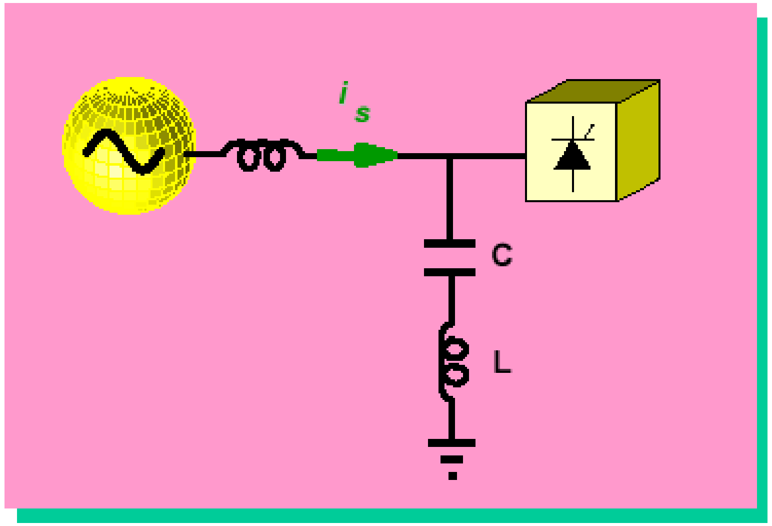
Shunt voltage compensator

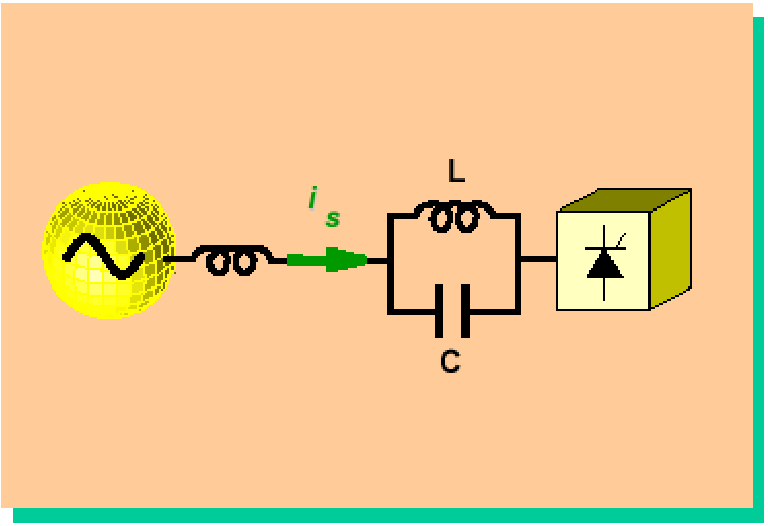


Series voltage compensator



Passive harmonic filters





✓ Low price

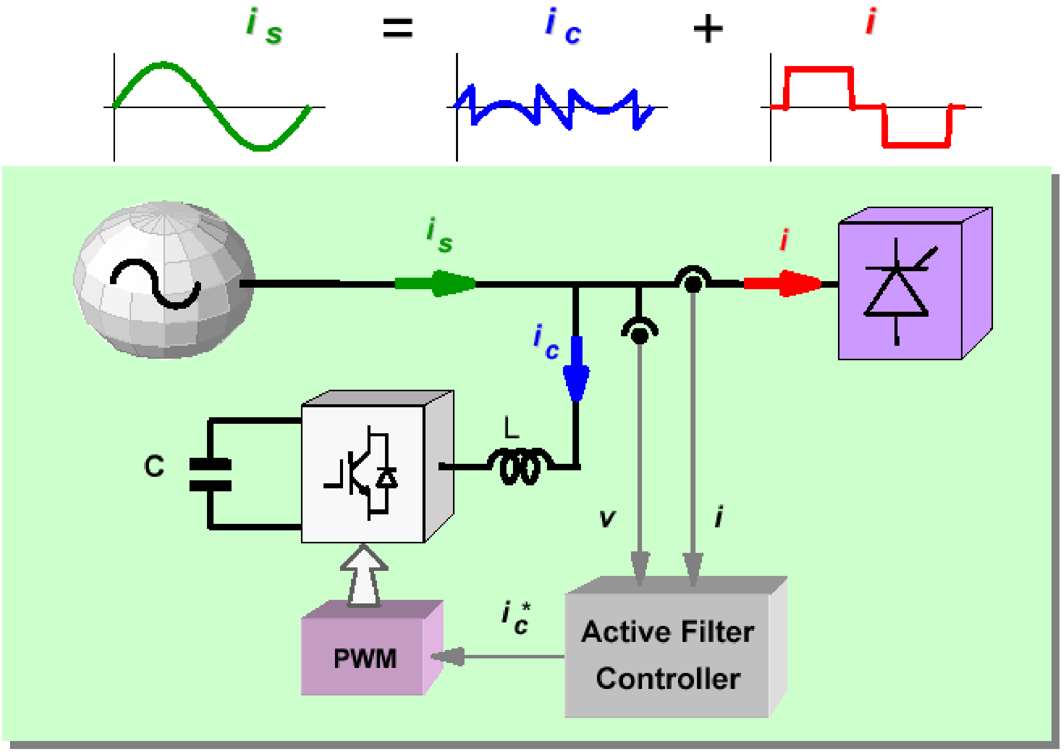
✓ Available for high equipment power

✘ It's necessary one circuit to filter each harmonic

✘ Ineffective if load conditions are variable

✘ Increases the probability of resonance occurrence

Active harmonic filters



✓Filters several harmonics at the same time

✓ Filtering independent of grid topology and load conditions

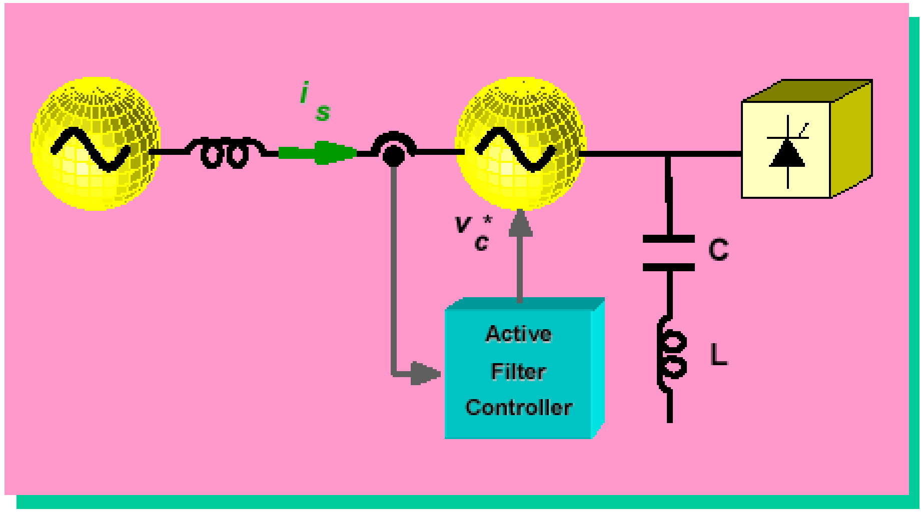
✓Doesn't increase the risk of resonance

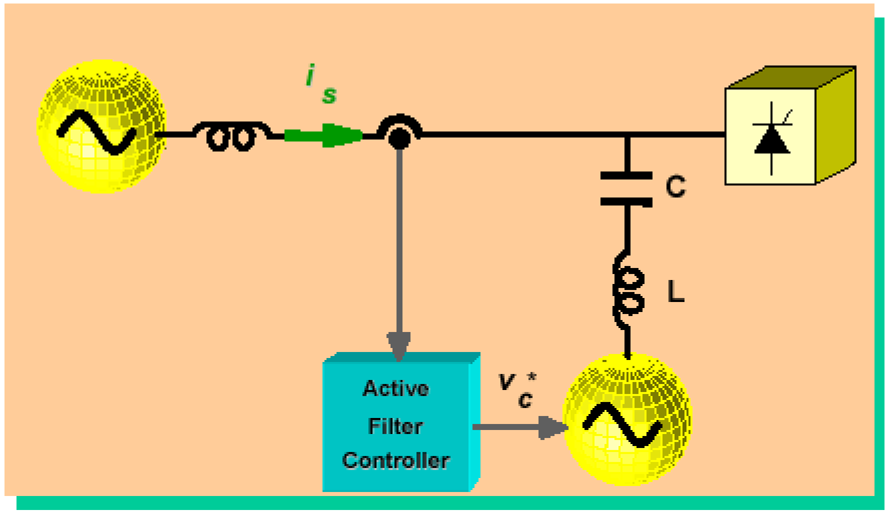
✓ Can be used to compensate other PQ disturbances (flicker, unbalance)

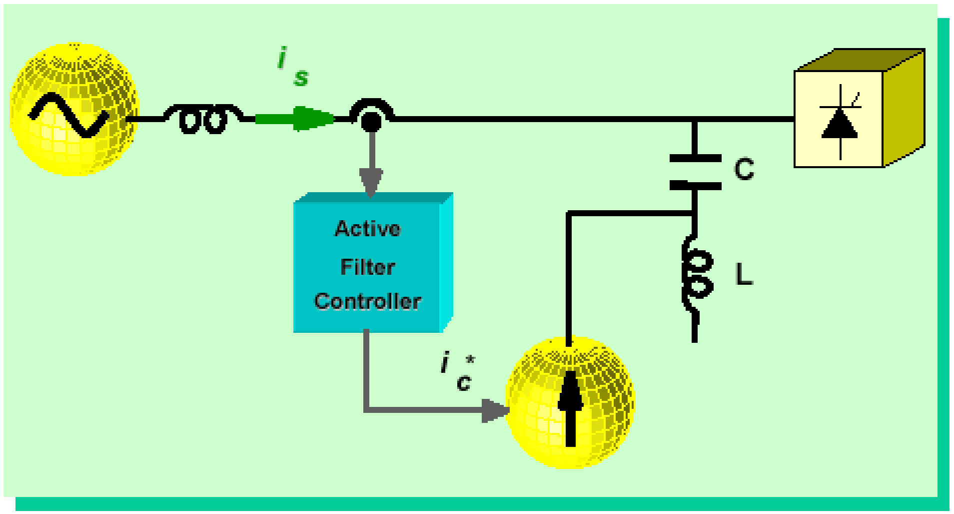
✘ Price

✘ Limited equipment power

Hybrid harmonic filters







End-use Devices Less Sensitive

- In most cases, making the end-use devices less sensitive to PQ disturbances is more cost effective than buying equipment to mitigate these problems.

- Some measures to increase equipment immunity:
  - Add a capacitor with larger capacity to power supplies;
  - Use cables with larger neutral conductors;
  - Derate transformers;
  - Use of oversized active front-ends.