Power Quality Requirements for Reliability: Towards `Perfect' Power Quality

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What is Power Quality ?

The answer depends on who you ask.

- **Utilities**:
  Reliability of the system (interruption and availability related: *the amount of time end-users are totally without power*) (archaic concept)
  - SAIFI – system average interruption frequency index (number of interruptions per customer)
  - ASAI – average system availability index per annum, e.g., 8700 hours of available service ($^{8700}/_{8760}$) = 99.32%

- **Equipment manufacturers and end-users**:
  - "Compatibility" → Work successfully within a given operating environment:
    - software and operating system
  - Are the power system characteristics compatible with my loads?
  - Characteristics of the power supply system that enable the equipment to work properly.

What is Power Quality?

- IEEE Std 1100-1999 Recommended Practice for Powering and Grounding Electronic Equipment:
  - The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment.

- Who develops IEEE Std 1100-1999?
  - Power Systems Engineering Committee of the
  - Industrial and Commercial Power Systems Department of the
  - IEEE Industry Applications Society. (1999)

IEEE Classification of PQ Disturbances

- IEEE provides a general classification of power quality phenomena based on
  - principal spectral content
  - duration
  - magnitude of the disturbance

Table 2.2 Categories and Characteristics of Power System Electromagnetic Phenomena [4].

No.	Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0	Transients			
1.1	Impulsive			
1.1.1	Nanosecond	5-ns rise	< 50 ns	
1.1.2	Microsecond	1-μs rise	50 ns - 1 ms	
1.1.3	Millisecond	0.1-ms rise	> 1 ms	
1.2	Oscillatory			
1.2.1	Low Frequency	< 5 kHz	0.3 - 50 ms	0 - 4 pu (per unit)
1.2.2	Medium Frequency	5 - 500 kHz	20 μs	0 - 8 pu
1.2.3	High Frequency	0.5 - 5 MHz	5 μs	0 - 4 pu
2.0	Short-duration variations			
2.1	Instantaneous			
2.1.1	Interruption		0.5 - 30 cyc	< 0.1 pu
2.1.2	Sag (Dip)		0.5 - 30 cyc	0.1 - 0.9 pu
2.1.3	Swell		0.5 - 30 cyc	1.1 - 1.8 pu
2.2	Momentary			
2.2.1	Interruption		30 cy - 3 s	< 0.1 pu
2.2.2	Sag (Dip)		30 cy - 3 s	0.1 - 0.9 pu
2.2.3	Swell		30 cy - 3 s	1.1 - 1.4 pu
2.3	Temporary			
2.3.1	Interruption		3 sec - 1 min	< 0.1 pu
2.3.2	Sag (Dip)		3 sec - 1 min	0.1 - 0.9 pu
2.3.3	Swell		3 sec - 1 min	1.1 - 1.2 pu

Source: IEEE Std 1159-1995

IEEE Classification of PQ Disturbances

Table 2.2 Categories and Characteristics of Power System Electromagnetic Phenomena [4].

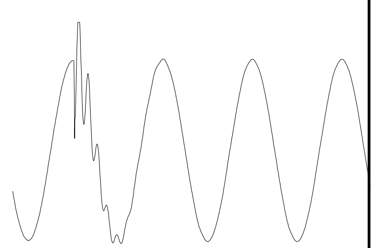
3.0	Long Duration Variations			
3.1	Interruption, Sustained		> 1 minute	0.0 pu
3.2	Undervoltages		> 1 minute	0.8 - 0.9 pu
3.3	Overvoltages		> 1 minute	1.1 - 1.2 pu
4.0	Voltage Unbalance		steady state	0.5 - 2%
5.0	Waveform Distortion			
5.1	DC Offset		steady state	0 - 0.1%
5.2	Harmonics	0 - 100th harmonic	steady state	0 - 20%
5.3	Inter-harmonics	0 - 6 kHz	steady state	0 - 2%
5.4	Notching		steady state	
5.5	Noise	Broadband	steady state	0 - 1%
6.0	Voltage Fluctuations	< 25 Hz	intermittent	0.1 - 7% 0.2 2 Pst
7.0	Power Frequency Variations		< 10 s	

Source: IEEE Std 1159-1995

Transient: Oscillatory

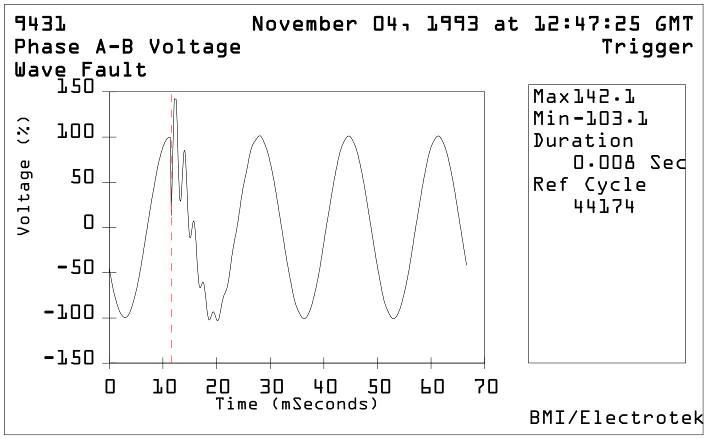
- Definition:
  - a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that includes both positive and negative polarity values.
- Capacitor switching transients
- Back-to-back cap. switching
- Cable switching
- Ferroresonance

Categories	Typical Spectral Content	Typical Duration	Typical Voltage Magnitude
1.2 Oscillatory			
1.2.1 Low Frequency	< 5 kHz	.3 - 50 ms	0 - 4 pu
1.2.2 Medium Frequency	5 - 500 kHz	20 µs	0 - 8 pu
1.2.3 High Frequency	0.5 - 5 MHz	5 µs	0 - 4 pu



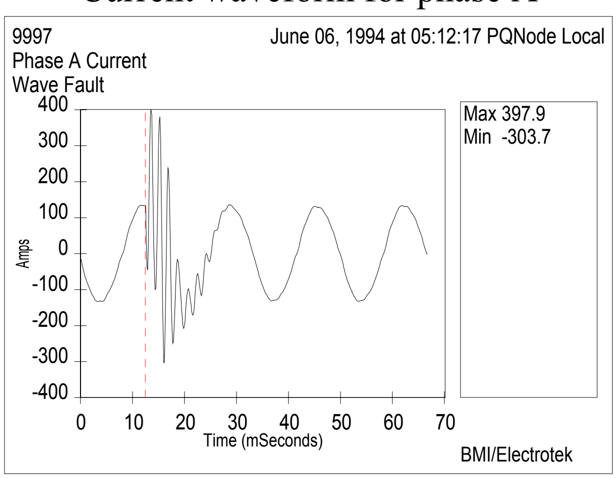
A transient event due capacitor bank energization

Voltage waveform



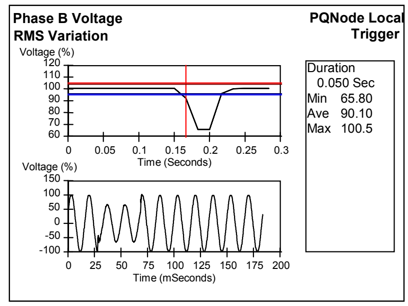
A transient event due capacitor bank energization

Current waveform for phase A



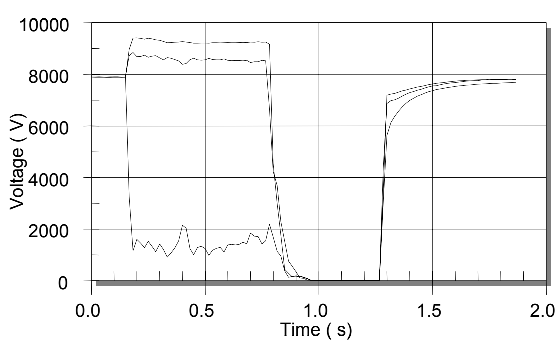
Short-duration Variations: Voltage Sags

- Voltage sags: a short-duration (0.5 – 30 cycles) ***reduction in rms voltage*** at the power frequency.
- Interruption: a ***complete loss of voltage***
  - Momentary: 0.5-3 seconds
  - Temporary: 3s – 1 min.
  - Sustained: > 1 min.
- Characteristics:
  - Voltage magnitude
  - Duration
- Primary source of voltage sags:
  - Faults on the system.
  - Starting of large loads, i.e., motors



Short-duration Variations: Momentary Interruption

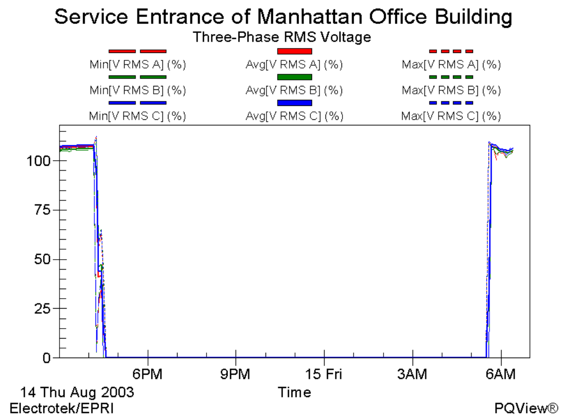
- Three-phase rms voltages due to a fault and subsequent recloser operation.
- Measurement taken downstream from the recloser.



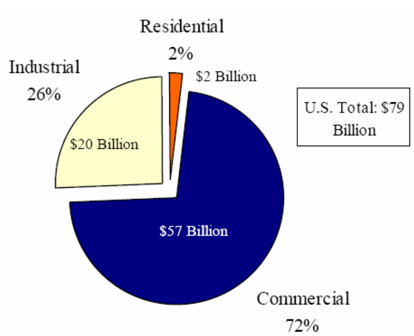
This is not a sustained interruption event.

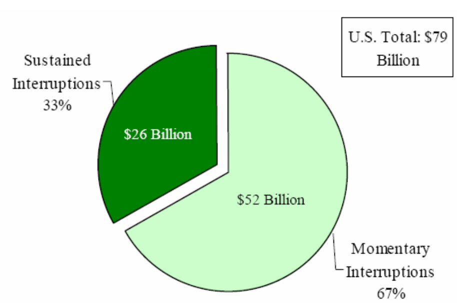
Sustained Interruption

- RMS voltage during 2003 Northeast blackout



Cost of PQ Disturbances: Lawrence Berkeley National Lab, 2004



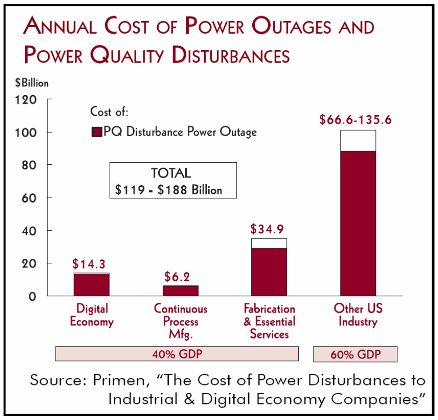


Understanding the Cost of Power Interruptions to U.S. Electricity Consumers, Ernest Orlando Lawrence Berkeley National Laboratory, 9/2004

Momentary:
30 cycles - 3 seconds

Cost of PQ Disturbances: EPRI/CEIDS 2001

ELECTRIC POWER RESEARCH INSTITUTE



- Power outages (momentary and sustained interruptions):
  - $104 billion to $164 billion a year
- Power quality phenomena: (transients, sags, harmonics)
  - $15 billion to $24 billion

Grid 2030 Vision

- Grid 2030:
  - Abundant, affordable
  - Clean, efficient, reliable
  - Anytime anywhere

VISION

"Grid 2030" energizes a competitive North American marketplace for electricity. It connects everyone to abundant, affordable, clean, efficient, and reliable electric power anytime, anywhere. It provides the best and most secure electric services available in the world.

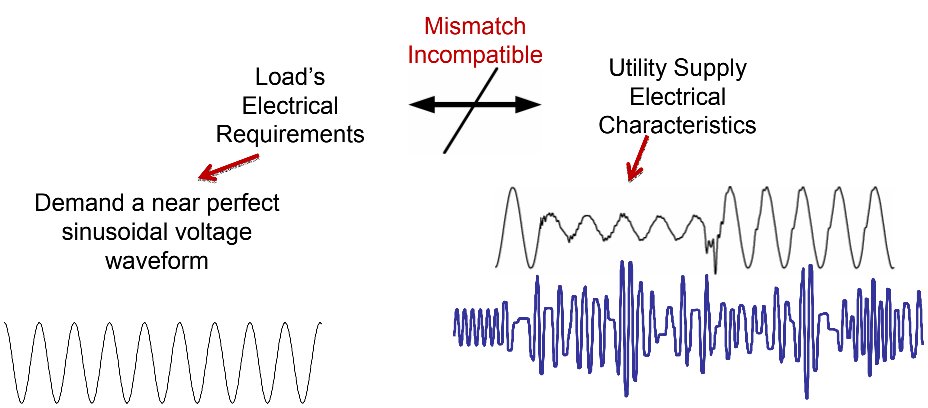
Source: "Grid 2030" – a national vision for electricity's second 100 years

Grid 2030 Vision for PQ

By 2010	By 2020	By 2030
Customer "gateway" for the next generation "smart meter", enabling two-way communications and a "transactive" customer-utility interface	Customer "total energy" systems for power, heating, cooling, and humidity control with "plug&play" abilities, leasable through mortgages	Highly reliable, secure, digital-grade power for any customer who wants it
Intelligent homes and appliances linked to the grid	"Perfect" power quality through automatic corrections for voltage, frequency, and power factor issues	Access to affordable pollution-free, low-carbon electricity generation produced anywhere in the country
Programs for customer participation in power markets through demand-side management and distributed generation	HTS generators, transformers, and cables will make a significant difference	Affordable energy storage devices available to anyone
Advanced composite conductors for greater transmission capacity	Long distance superconducting transmission cables	Completion of a national (or continental) superconducting backbone
Regional plans for grid expansion and modernization		

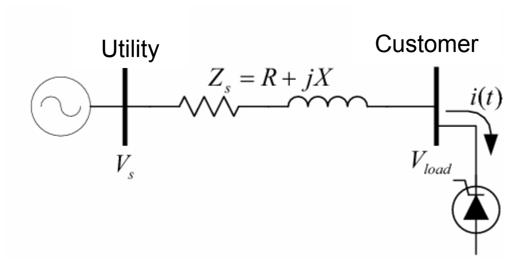
Source: "Grid 2030" – a national vision for electricity's second 100 years

Root causes of Power Quality Disturbances



Root causes: Current and Impedance

- Equipment failures or misoperations are caused by significant deviations in the voltage waveshape
- Voltage is influenced by the current flowing through the system impedance
  - When the current waveshape passing through the system impedance deviates significantly, the quality of the voltage will be impacted

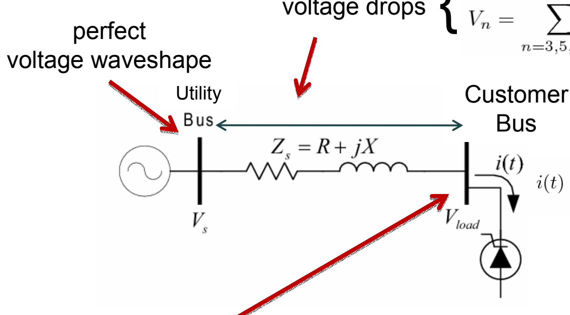


Root causes: Current and Impedance

voltage drops

$$V_1 = I_1 Z_s \sin(\omega_1 t + \theta_1)$$

$$V_n = \sum_{n=3,5,7,\cdots}^{\infty} I_n \sin(n\omega_1 t + \theta_n)(R + jnX)$$



$$i(t) = I_1 \sin(\omega_1 t) + \sum_{n=3,5,7,\cdots}^{\infty} I_n \sin(n\omega_1 t)$$

$$V_{load} = V_s - I_1 Z_s \sin(\omega_1 t + \theta_1) - \left[\sum_{n=3,5,7,\cdots}^{\infty} I_n \sin(n\omega_1 t + \theta_n)(R + jnX) \right]$$

Source: S.Santoso, Fundamentals of Electric Power Quality, Pre. Ed. 2007

Current and Impedance

- Who has control over *currents*:
  - Harmonics: End-users have control over the currents since their equipment draw currents from the system.
  - Short-circuit currents: faults in the system causes sags or interruptions
  - Lightning: currents cause high-impulse voltage → flashover ++
- Who has control over *impedances*:
  - Utilities: overhead lines, underground lines, transformers

Got ideal solutions to all PQ problems ?

Get rid of offending currents and the system impedances

First PQ Problem: *Distorted Voltage Waveshape*

- Early 1890s – power industry was just in its infancy
- Symptoms: (1893)
  - High voltage and high currents at a motor facility (Hartford, Conn)
  - Overheating of motors
  - Generator was 10 miles away.
- Root cause:
  - Voltage waveshape at the generator terminals was not sinusoidal (!!) but distorted
  - Synchronous generators had **concentrated windings**
  - Transmission line resonance
- Solutions: (1895)
  - Redesigned: with distributed windings
  - Voltage waveshape: very close to sinusoidal
  - No more PQ problems at the generator terminals !!

Absolute PQ Solutions ??

Got holistic solutions to all PQ problems ?

Technologies to get rid of offending currents
Technologies to get rid of system impedances

Most common and on-going PQ disturbances: Short-duration variations

- Short-duration variations:
  - instantaneous: 0.5 – 30 cycles
  - momentary: 30 cycles – 3 sec
  - temporary: 3 sec – 1 min

- Voltage sags: (0.1 – 0.9 pu)
  - Short circuit conditions or faults
  - Starting of large industrial motors (inrush currents)
- Interruptions: (less than 0.1 pu)
  - Operation of protective devices such as line reclosers.

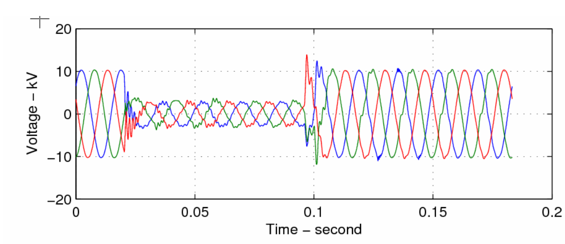
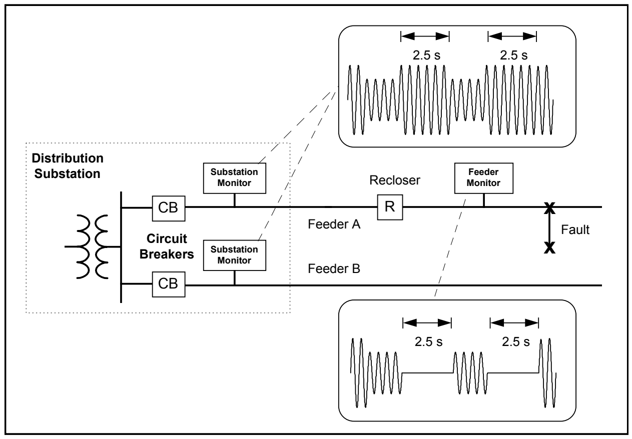
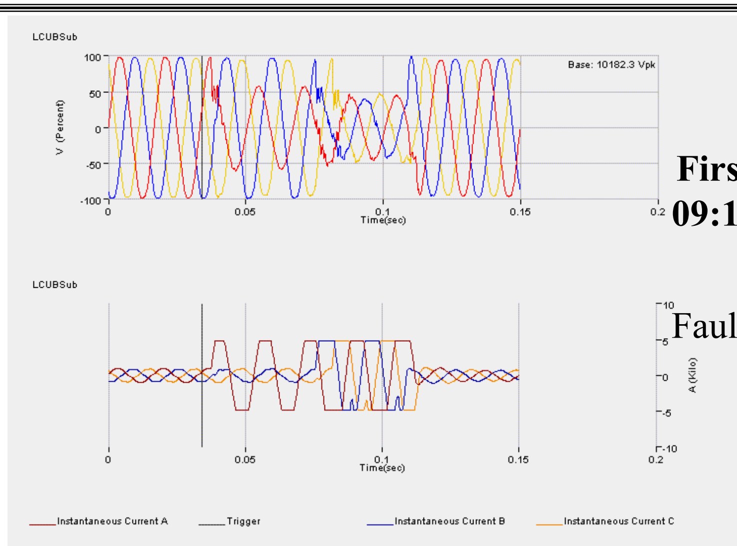


Figure 3.1 Voltage sags due to a three-phase fault on a 12.47 kV distribution feeder.

Voltage Sags and Momentary Interruptions



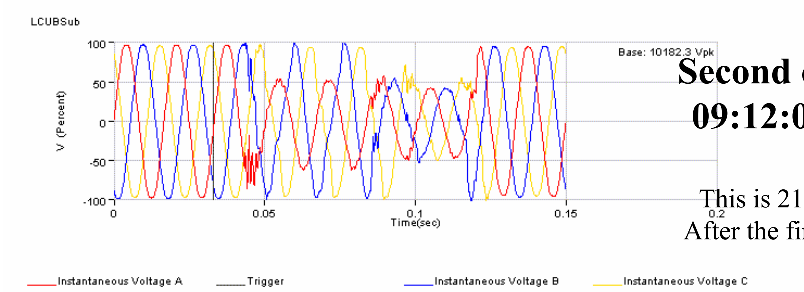
Example of a fault clearing with a recloser



First event: 09:12:02.45

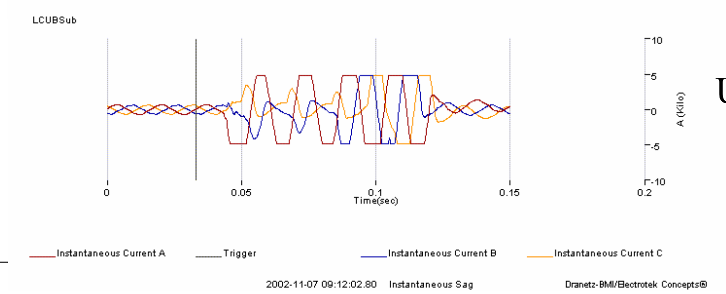
Fault occurs

Sequence of Events



Second event:
09:12:02.80

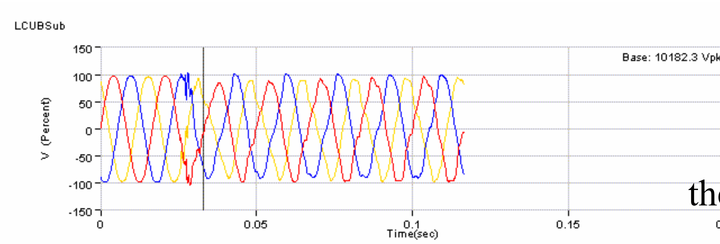
This is 21 cycles
After the first event



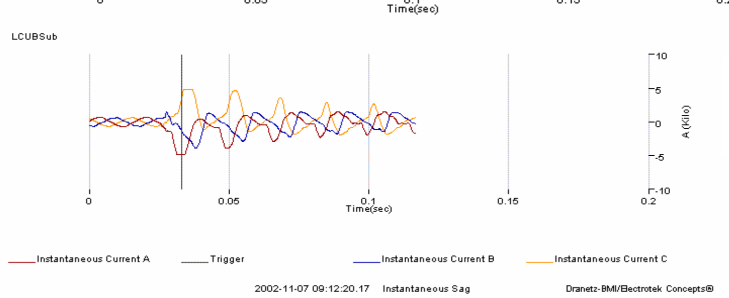
Unsuccessful
reclose

Sequence of Events

Third event:
09:12:20.17



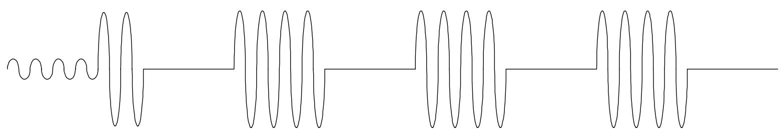
18 sec after
the second event



Successful
reclose

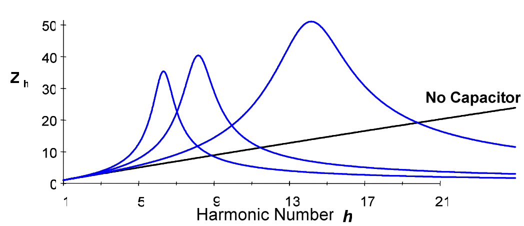
Technologies of ridding of offending currents

- Fault currents
  - Preventive: monitoring, maintenance, …
  - Better fault detection and clearing practices
  - Overcurrent miscoordination



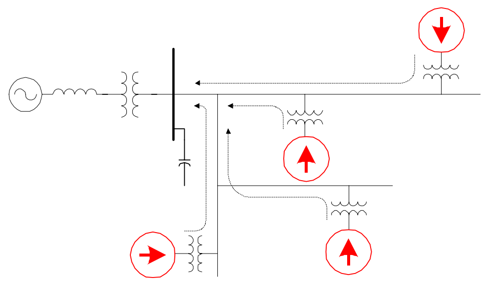
Growing concerns: *Harmonic Distortion Levels*

- Harmonic distortion levels:
  - More and more nonlinear loads: energy-efficient appliances, electric vehicles, power-electronic interfaced loads
  - Capacitor banks are widespread → create/shift power system resonant frequencies
  - Harmonic currents interact with the system impedance → harmonic resonance more likely



Parallel resonance

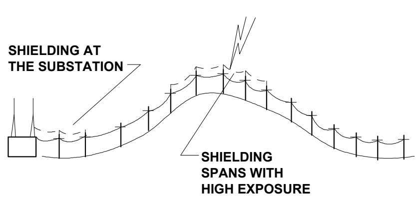
- When the system resonant frequencies corresponds to one of the harmonic frequencies being produced by the nonlinear load (characteristic frequencies), harmonic resonance can occur.

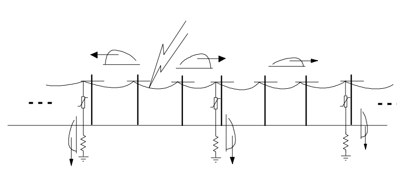


Technologies of ridding of offending currents

- Harmonic currents:
  – Harmonic filters: passive and active, hybrid
  – Capacitor banks: (silent partner) do away with capacitor banks

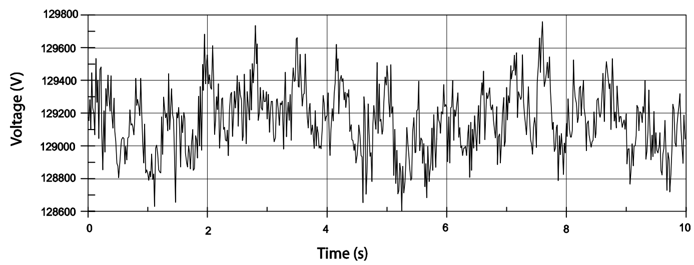
- Lightning strokes
  – Better shielding technologies: sky/ground wires
  – Better arrester materials





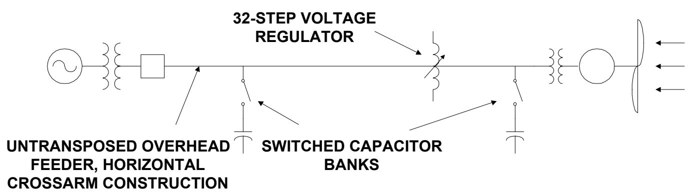
Growing concerns: *Voltage fluctuations*

- Lighting flicker arises from voltage fluctuation.
  - Arc furnace/welders
  - Intermittent/variable power sources: wind power
    - variations in the wind speed
    - intermittent wind
    - tower shadowing



Growing concerns: *Voltage Regulations*

- Feeder voltage regulations with intermittent and variable power sources are very difficult.
  - current practices not adequate.
  - excessive switching operations of regulators and capacitor banks



Technologies of ridding of impedances

- Superconducting technologies
  - Overhead and underground lines
  - Transformers
  - Electric machines

Cordless and wireless power transmission and distribution?

Cordless power distribution

Wireless Power Transfer via Strongly Coupled Magnetic Resonances
André Kurs,Aristeidis Karalis,Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljac˘ic´

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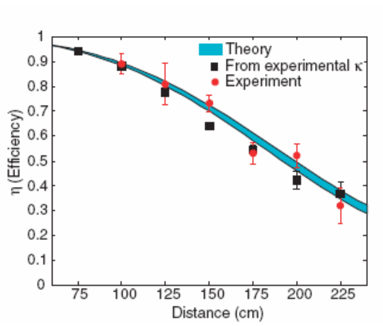
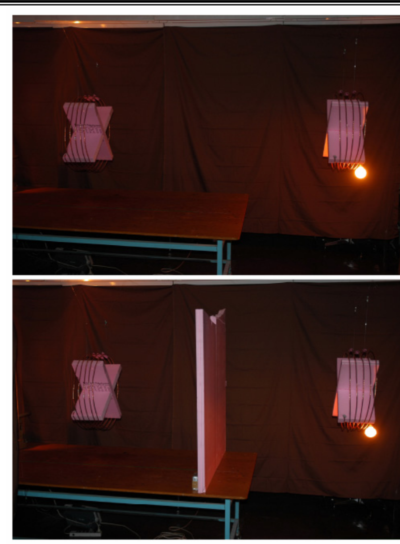
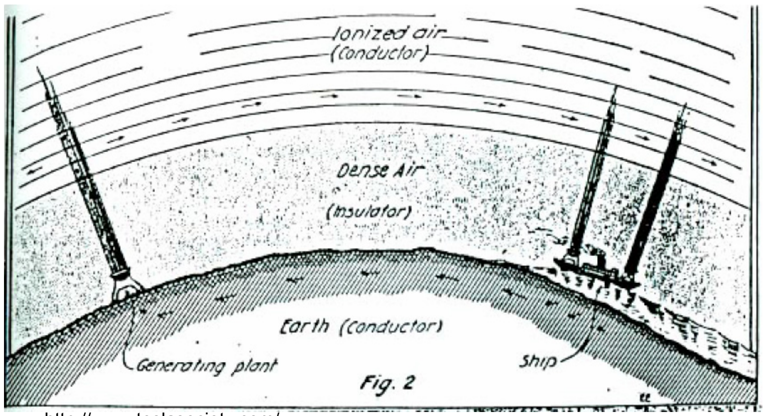




Tesla Wireless Power Transmission



http://www.teslasociety.com/

N. Tesla, "The Future of the Wireless Art,"
Wireless Telegraphy & Telephony, 1908

Ultimate Requirements to Achieve Perfect PQ

- Prevent offending currents from entering the grid
- Get rid of offending currents

- Need new technologies and operating practices

- Minimize system impedances
- Get rid of system impedances

- Need new technologies