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Harmonics in electrical distribution networks

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Introduction

Mains power supply systems are becoming increasingly polluted by harmonic currents, causing a wide range of problems and hazards

This presentation briefly describes:

1. The origins of harmonic currents
2. The problems and hazards they create
3. Methods for controlling harmonics

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The origins of harmonic currents

- Assuming a perfect sine-wave supply voltage waveform, harmonic currents are caused by non-linear loads, e.g....
  - motors and transformers
  - arc furnaces
  - fluorescent lighting
  - semiconductor power control / conversion
  - AC - DC 'power supplies' (e.g. computers, UPSs, most other electronic products)

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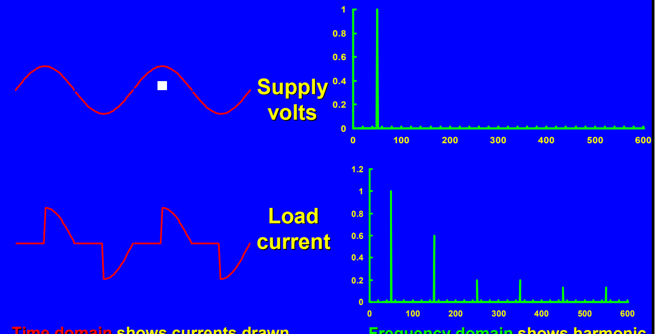
Phase angle controlled 1ϕ SCRs:



Time domain shows currents drawn depend on conduction angle (90° here)

Frequency domain shows harmonic currents clearly

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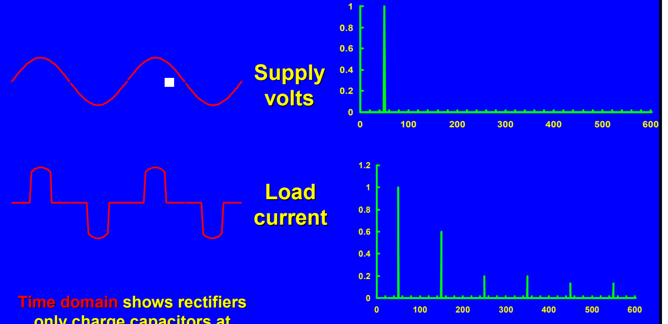
1ϕ rectifiers with capacitive loads:



Time domain shows rectifiers only charge capacitors at supply voltage peaks

Frequency domain shows harmonic currents clearly

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Half-wave power converters

- The previous examples assumed full-wave rectification or control
  - all harmonics were odd-order (3rd, 5th, 7th, 9th, etc.)
- Half-wave rectification or control gives rise to even-order harmonics...
  - 0th (= DC), 2nd, 4th, 6th, 8th, etc.
  - and should be avoided because even-order currents (especially DC and 2nd) cause transformers, motors, and other magnetic devices to saturate and overheat

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Balanced 3-phase power converters

- ‘Six-pulse’ converters (i.e. full-wave three-phase bridges) have low triplen harmonics (3rd, 9th, etc.)
  - when compared to 1-phase devices
- ‘Twelve-pulse’ converters use star and delta transformers to phase shift and get six-phase full-wave bridge operation
  - reduces levels of 5th and 7th harmonics
    - 24-pulse converters can also be designed, with even lower levels of harmonics

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The problems caused by harmonics

a. Problems caused by the harmonic currents themselves

b. Voltage distortion caused by the harmonic currents

c. Problems caused by the voltage distortion

d. Telephone interference

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Problems caused by the harmonic currents themselves

- Transformer, cable and motor losses all increase
  - causing overheating, unreliability, even toxic fume, smoke and fire hazards
- Unanticipated operation of protective devices (fuses, MCBs, etc.)
  - causing unreliability and downtime

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Problems caused by the harmonic currents themselves continued...

- Harmonic currents don't cancel in the ‘zero phase’ of 3ϕ systems…
  - harmonic currents in 3ϕ neutrals can be almost double the phase currents
    - causing overheating problems, especially where half or quarter-sized neutrals are used
  - delta wound transformers can overheat due to zero-phase flux

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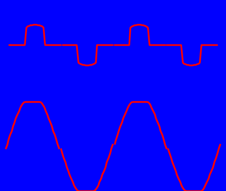
Voltage distortion caused by harmonic currents

The mains distribution network has impedance, so harmonic mains currents distort the mains waveform

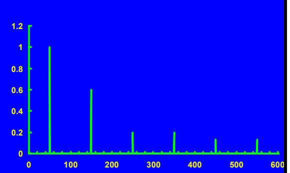
Load current

Resulting supply voltage

(a simple example)



Time domain



Frequency domain

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The problems caused by voltage distortion

- Loads (even linear) draw harmonic currents
  - 3ϕ motors suffer overheating, torque ripple
- Unreliable performance of electronic systems
  - due to distortion of peak / rms ratio of waveform
    - e.g. unregulated DC rails in power supplies too low
  - due to errors in the zero crossing points
- Incorrect power consumption metering

Excitation of resonances in power distribution networks

- Power distribution networks plus their loads all resonate at higher frequencies than 50Hz
  - when excited at resonant frequencies by harmonic currents and voltages, waveform distortion can increase dramatically
- This can cause many problems, especially overvoltages, e.g.…
  - damaging the power factor correction capacitors in fluorescent lamps and power distribution rooms

Telephone interference

- Most common is 'longitudinal magnetic interference'
  - over long distances, fields from residual harmonic currents in power lines couple to telephone lines
    - "hum" is bad enough, but "harmonic whine" is terrible
- Other ways harmonics interfere with telephones
  - loop induction, longitudinal electrostatic coupling, and conduction due to earth potentials in MEN systems

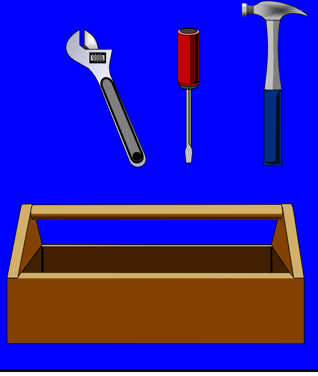
Controlling harmonics

a. Measurements

b. Prediction

c. Standards

d. Remedial methods



Measurements

- EN 61000-4-7 defines harmonic measurements
- Time domain plus frequency domain helps
  - i.e. oscilloscope plus spectrum (waveform) analyser
    - can now get both in one handheld unit
- 230/400V systems can use precision wideband voltage probes and current clamps
  - but MV / HV needs special dividers or probes, which can have bandwidth and phase problems

Examples of clip-on current transducers

Fluke i200s Current Clamp

0.1 to 24A @ 100mV/A
0/5 to 240A @ 10mV/A
40Hz - 10kHz
Max. test conductor: 20mm

Tektronix A622 Current Probe

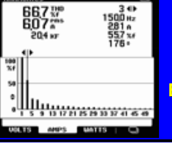
0.05 to 100A @ 10 to 100mV/A
DC - 100kHz

Examples of hand-held power quality analysers

Fluke 43B

Fluke 41B

A TekScope: THS720P



Example of a Fluke 43B's harmonics display

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Voltage / current measurements *MUST BE 'TRUE RMS'*

– and accurate up to at least 2kHz (i.e. the 40th harmonic)

- Most electricians use 'average responding' meters (because they cost less)
  – but they are only accurate for pure 50Hz sine waves
  – and read low when measuring harmonic currents or distorted voltages
    - e.g. seriously underestimating their actual heating effect

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Prediction: get data on –

- Harmonic currents drawn by loads
  – especially single-phase loads used in large numbers
  – e.g. luminaires and lamps, computers, etc.,
  – even though individually they may be low power
- Supply voltage distortion
  – actual harmonic content, not just THD
  – the voltage distortion tolerance of the loads

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Prediction continued...

- Supply network's impedance versus frequency
  – which will vary depending on the loads connected
- Power supplier's specifications or agreements
  – concerning the maximum harmonic distortion they might supply (and not simply the THD)
- Power distribution component ratings
  – e.g. transformers, motors, neutral cables, power factor capacitors, etc.

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Then estimate –

- Combined harmonic current loading on system
- Resonance possibilities
- Worst-case voltage distortions
- Whether the loads will handle the voltage distortions
  – don't forget their sensitivity to zero-crossing errors
- Reliability of power distribution components

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Standards on harmonics

- There is a general lack of knowledge about the harmonic performance of power distribution components
- Various standards and engineering guides exist
  – but none has yet been proven to be more effective than others in practical harmonic control
- UK uses "Recommendation G5/4 2001" to limit the harmonic currents at the point of common connection to the MV or HV electricity supply

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Harmonic standards for manufacturers

- EN/IEC 61000-3-2 sets harmonic current emission limits for equipment up to 16 A/phase
  – for "unfettered connection to the public LV supply"
- IEC 61000-3-4 is available (but not yet mandatory) for equipment > 16A/phase which needs permission before connection to supply
  – and IEC 61000-3-6 is available (but not yet mandatory) for MV and HV equipment

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Remedial methods: Filtering

- Tuned filters are used for individual harmonics (taking care not to cause resonances in the network)
  - series and/or shunt tuned filters are used to restrict a particular harmonic current to a branch of the distribution network
    - when using a high-impedance filter in series, a low-impedance shunt filter is usually necessary to provide a path for the harmonic current concerned
- Broad-band filters (e.g. low-pass) are useful for controlling all of the high-order harmonics

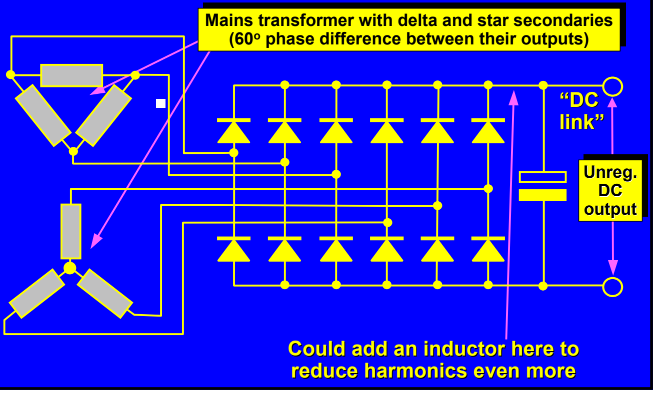
Remedial methods: Delta windings

- Delta-wound transformers resist the passage of balanced *triplen* harmonics (3rd, 9th, 15th, etc)
    - providing the harmonic currents of the loads are balanced
  - most distribution transformers are delta-star, helping to keep triplens isolated in low-voltage networks
    - but don't forget that transformers must be rated to cope with the additional harmonic loading and zero-phase flux

Remedial methods: Linearised loads

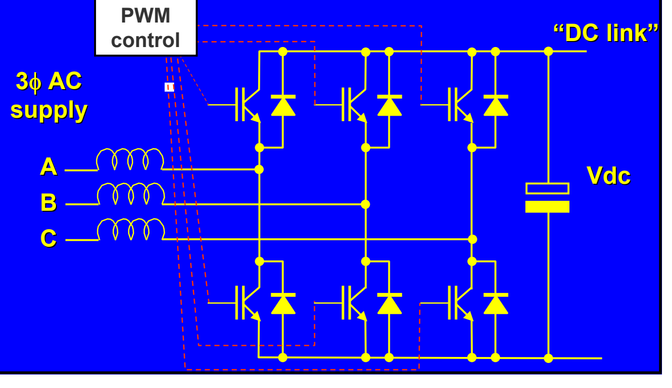
- Modify or replace loads to achieve more sine-wave-like currents, e.g.…
  - use equipment that complies with EN / IEC 61000-3-2 (even if it is over 16A/phase)
  - use 12-pulse (or 24-pulse) power converters instead of 6-pulse types
  - use 3ϕ 'boost rectifier' PWM type AC-DC converters

A 6ϕ bridge (known as a 12-pulse rectifier)



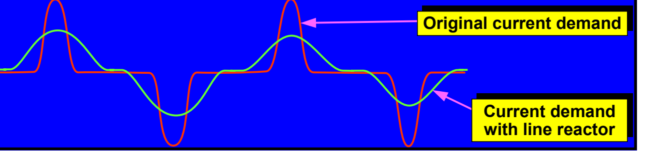
A 3 phase 'boost' rectifier

(Note: can also allow bi-directional energy transfer)



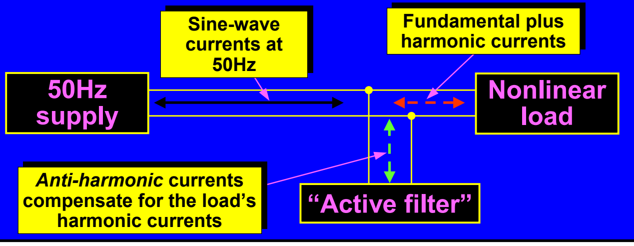
Remedial methods: Line reactors

- Adding series inductors in the mains supply to an equipment can reduce its harmonic currents
  - by forcing its rectifiers to conduct for longer periods
    - which reduces their peak current
  - these are often called line reactors



Remedial methods: "Active Filters"

- Electronic 'anti-harmonic' current injection
  - often called "active filtering" or "active compensation"



Remedial methods: Regenerating the mains supply with a motor-generator set

- To protect equipment from poor mains quality
  - or to protect the network from a non-linear load
- Beware – some generators do not have low-distortion voltage outputs
- The generator must be suitably uprated when driving non-linear loads

Remedial methods: Regenerating the mains supply with an Uninterruptible Power Supply (UPS)

- Similar technique to a motor-generator set
  - but only use a UPS that *continuously* supplies the load from its battery-powered inverter
    - note: some UPS's do not have low distortion outputs
    - and some emit high levels of harmonic currents into their mains supply
    - remember to uprate the UPS for non-linear loads

Remedial methods: Uprating the mains supply distribution

- Uprating is still required even if every load meets EN 61000-3-2:2000
- Uprate transformers, motors, PF capacitors, etc.
  - HD 428.4 S1:1994 gives rules for specifying oil-immersed 50Hz transformer ratings for use with non-sine-wave loads
  - BS EN 61378 "Convertor transformers, Part 1 (1998) Transformers for industrial applications" also includes guidance on rating for harmonics

Remedial methods: Uprating distribution
continued...

- Uprate mains cables/terminals to cope with the additional heating effect, especially the neutrals
  - USA specifies neutrals to have 1.7 x cross-sectional-area (CSA) of the phase conductors
  - some people recommend using neutrals with double the CSA of the phase conductors
- Once all the other parts have been uprated, their protective devices can then be uprated
  - e.g. to achieve the power rating originally required

Remedial methods: Immunising equipment

- Employ equipment which is tolerant of distorted supply voltages
  - IEC 61000-4-13 is a new standard for testing equipment for immunity to supply voltage distortion
    - not mandatory (yet), but available for use in contract specifications

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- the end

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Some useful references

- The "Banana Skins Compendium" is a continually growing collection of reports of EMC problems and incidents
  - including problems caused by mains harmonics, see 'Banana Skins' 1, 7, 46, 59, 101, 102, 104 and 200
  - visit the EMC & Compliance Journal's home page at: www.compliance-club.com and scroll down to find 'Banana Skins'

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Some useful references continued...

- IEC 61000-4-7:2002
  - "Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto"
    - from BSI: www.bsi-global.com or IEC: www.iec.ch
- Engineering Recommendation ER G5/4, 2001
  - "Planning levels for harmonic voltage distortion & the connection of non-linear equipment to transmission systems & distribution networks in the United Kingdom"
    - The Electricity Association, www.electricity.org.uk

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Some useful references continued...

- "Why the electricity industry needs to control the harmonic emissions and voltage changes associated with equipment rated less than 16A"
  - G.S.Finlay, EMCTLA Seminar concerning EN 61000-3-2 and EN 61000-3-3, 19th May 2000, www.emctla.org
- "Power System Harmonics", ISBN 0 471 90640 9
  - Arrilaga, Bradley and Bodger, John Wiley 1985
    - this is a key work on power harmonics: what causes them; how to measure them; and what effects they can have

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Some useful references continued...

- EN 61000-3-2 Edition 2, 2000
  - "Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current up to and including 16 A per phase)"
    - from BSI: www.bsi-global.com
- "Design Techniques for EMC – Part 6"
  - at: www.compliance-club.com/KeithArmstrongPortfolio
- "EMC Testing – Part 7"
  - at: www.compliance-club.com/KeithArmstrongPortfolio