EE6508 - Power Quality

Power System Harmonics

presented by

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References

- Books:
  - J Arrillaga, NR Watson, Power System Harmonics, 2nd Edition, John Wiley & Sons 2003.
- Standards:
  - IEEE Std 1459-2000 Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions.
  - IEC 61000-2-1:1990 Electromagnetic Environment for Low-Frequency Conducted Disturbances and Signaling in Public Power Supply Systems
  - IEC 61000-2-2:1990 Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Low-Voltage Power Supply Systems
  - IEEE Std 519-1992 Recommended Practices and Requirements for Harmonic Control.
  - IEEE Std 1531-2003 Guide for Application and Specification of Harmonic Filters.
  - Chapter 10 of IEEE Std 399-1997 Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems Analysis.
  - Chapter 9 of IEEE Std 141-1993 Recommended Practice for Electric Power Distribution for Industrial Plants.
  - IEEE Std C57.110-1998 Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load Currents.
  - IEEE Std 18-2002: Standard for Shunt Power Capacitors.
  - IEC 61000-4-7:2002 General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto.
  - IEC 1000-3-6:1996 Assessment of Emission Limits for Distorting Loads in MV and HV Power Systems.

Lecture outline

- Introduction
  - Fourier series; waveform symmetry
- Harmonic sources
  - Single-phase rectification
  - Three-phase current-source and voltage-source conversions
- Effects of harmonic distortion
  - System response to harmonics; resonances; triplens
  - Effect on power system equipment, rotating machines, transformers and capacitors
  - Harmonic loss factor, K-factor, establishing transformer loading capability
  - Harmonic interferences
- Harmonic elimination or coping with harmonic distortions
  - Solutions for triplens
  - Passive and active filters
- Controlling harmonic voltage and current
  - Meeting IEEE 519 voltage and current distortion limits
  - Establishing and applying harmonic limits
  - Harmonic limit allocation

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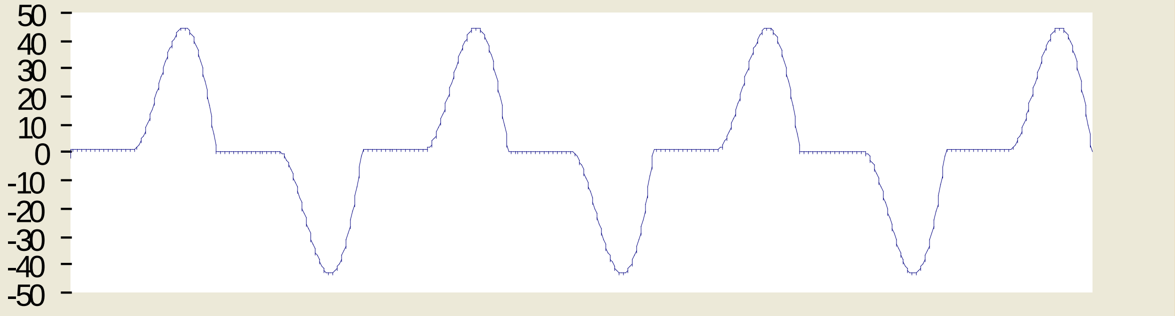
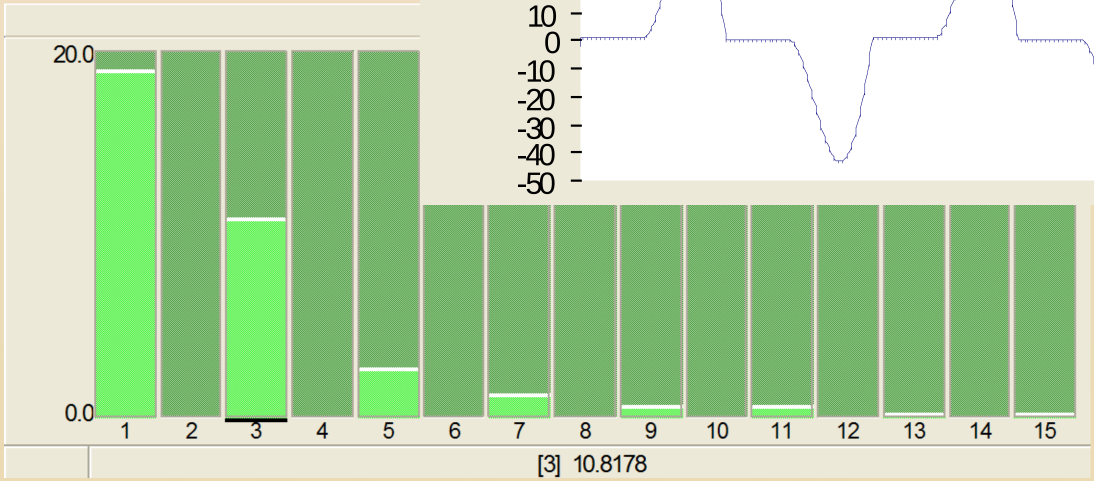
Introduction

- Voltage and current waveforms in power systems are often distorted
  - They are non-sinusoidal in shape
  - A distorted or non-sinusoidal waveform is said to comprise of a multitude of harmonics in addition to the fundamental component
  - A harmonic is a periodic sinusoid having frequency that is a whole multiple of the fundamental frequency

Time-domain waveform of a typical converter current





Frequency-domain characterization of the current

Harmonic order	Magnitude
Fundamental	19 A
3rd harmonic	11A
5th harmonic	4A
7th harmonic	2A
9th harmonic	1A

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Significance of harmonic distortions

- Existed in the past but has minimal impacts
  - Majority of past loads were linear
  - Current waveform follows the sinusoidal shape of supply voltage
- Nowadays, prolific increase in the use of nonlinear (especially switching) devices result in much higher levels of harmonics
  - Use of new semiconductor (power electronic) technology to achieve higher efficiency in energy use and more controllability
  - Unfortunately, these devices draw non-sinusoidal currents (even if the supplied voltage is sinusoidal) which has major impacts on the power systems and the other connected apparatus
- Growing significance or importance
  - Proliferated use of nonlinear devices increases the level of distortions
  - Continuing increase in the power ratings of these devices
  - Increasing use of capacitor has lowered the resonant frequency, making system more vulnerable to harmonic distortions (particularly those “transient harmonics” from energization of transformers)
  - Loads with new technologies are more vulnerable and sensitive to harmonic distortions as their designs may assume that a sinusoidal supply voltage

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Fourier series and coefficients

- Any continuous repetitive function (with period *T*) can be represented by the summation of a dc component, a fundamental sinusoidal component and a series of higher-order sinusoidal components (harmonics)

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right)\right) \quad \begin{cases} a_0 = \dfrac{1}{T}\displaystyle\int_{-T/2}^{T/2} x(t)\,dt \\ a_n = \dfrac{2}{T}\displaystyle\int_{-T/2}^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt \\ b_n = \dfrac{2}{T}\displaystyle\int_{-T/2}^{T/2} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt \end{cases}$$

  - a_0 – average value of function $x(t)$
  - a_n and b_n – coefficients of the series; rectangular components of n^{th} harmonic
- Each harmonic vector has magnitude A_n and angle ϕ_n

$$A_n\angle\phi_n = a_n + jb_n \quad \begin{cases} A_n = \sqrt{a_n^2 + b_n^2} \\ \phi_n = \tan^{-1}\left(\dfrac{b_n}{a_n}\right) \end{cases}$$

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Waveform symmetry

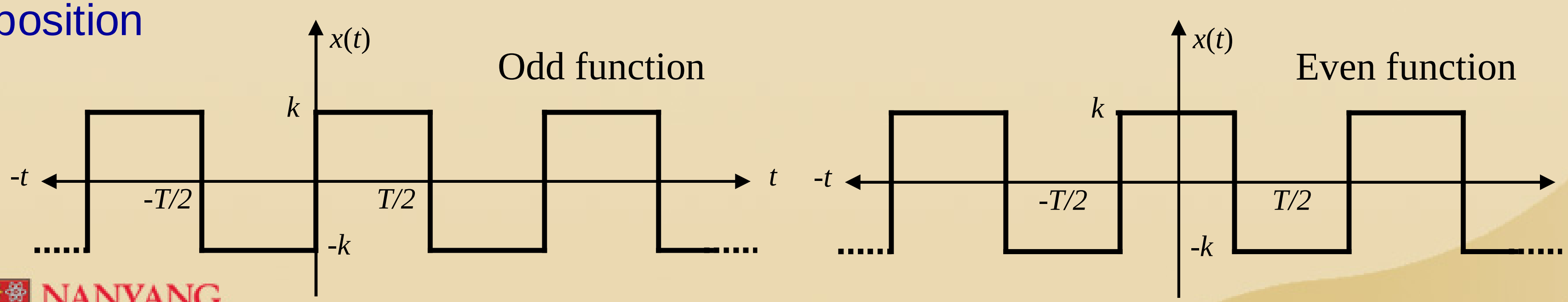
- Odd symmetry: $x(t) = -x(-t)$
  - a_n becomes zero for all n
  - The Fourier series contains only sine terms with amplitude b_n

$$b_n = \frac{4}{T}\int_0^{T/2} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt$$

- Even symmetry: $x(t) = x(-t)$
  - b_n becomes zero for all n
  - The Fourier series contains only cosine terms with amplitude a_n

$$a_n = \frac{4}{T}\int_0^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt$$

- Certain waveform can be odd or even depending on the chosen time reference position



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Halfwave symmetry

- A function has halfwave symmetry if $x(t) = -x(t + T/2)$
  - Shape of the waveform over a period of $t+T/2$ to $t+T$ is the negative of the shape of the waveform over the period t to $t+T/2$
  - To have a common integration limits, replace (t) by ($t+T/2$) in the interval ($-T/2$,0)

$$a_n = \frac{2}{T}\int_0^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt + \frac{2}{T}\int_{-T/2}^{0} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt$$

$$= \frac{2}{T}\int_0^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt + \frac{2}{T}\int_{-T/2+T/2}^{0+T/2} x(t+T/2)\cos\left(\frac{2\pi n(t+T/2)}{T}\right)dt$$

$$= \frac{2}{T}\int_0^{T/2} x(t)\left[\cos\left(\frac{2\pi nt}{T}\right) - \cos\left(\frac{2\pi nt}{T} + n\pi\right)\right]dt$$

$$= \frac{2}{T}\int_0^{T/2} x(t)\left[\cos\left(\frac{2\pi nt}{T}\right) - \cos\left(\frac{2\pi nt}{T}\right)\cos(n\pi)\right]dt$$

- a_n and b_n are zero when n is an even integer
- only when n is an odd integer, a_n and b_n are non-zero

$$a_n = \frac{4}{T}\int_0^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt$$

$$b_n = \frac{4}{T}\int_0^{T/2} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt$$

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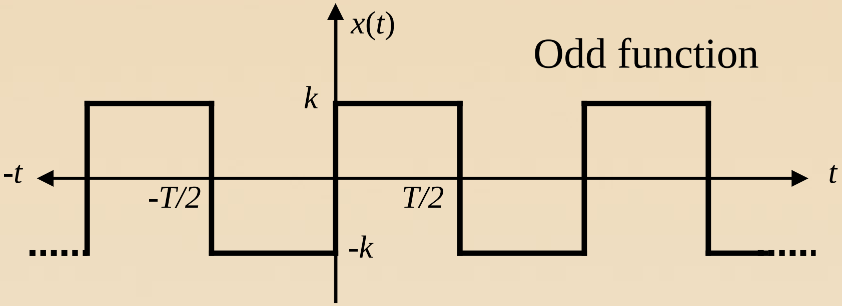
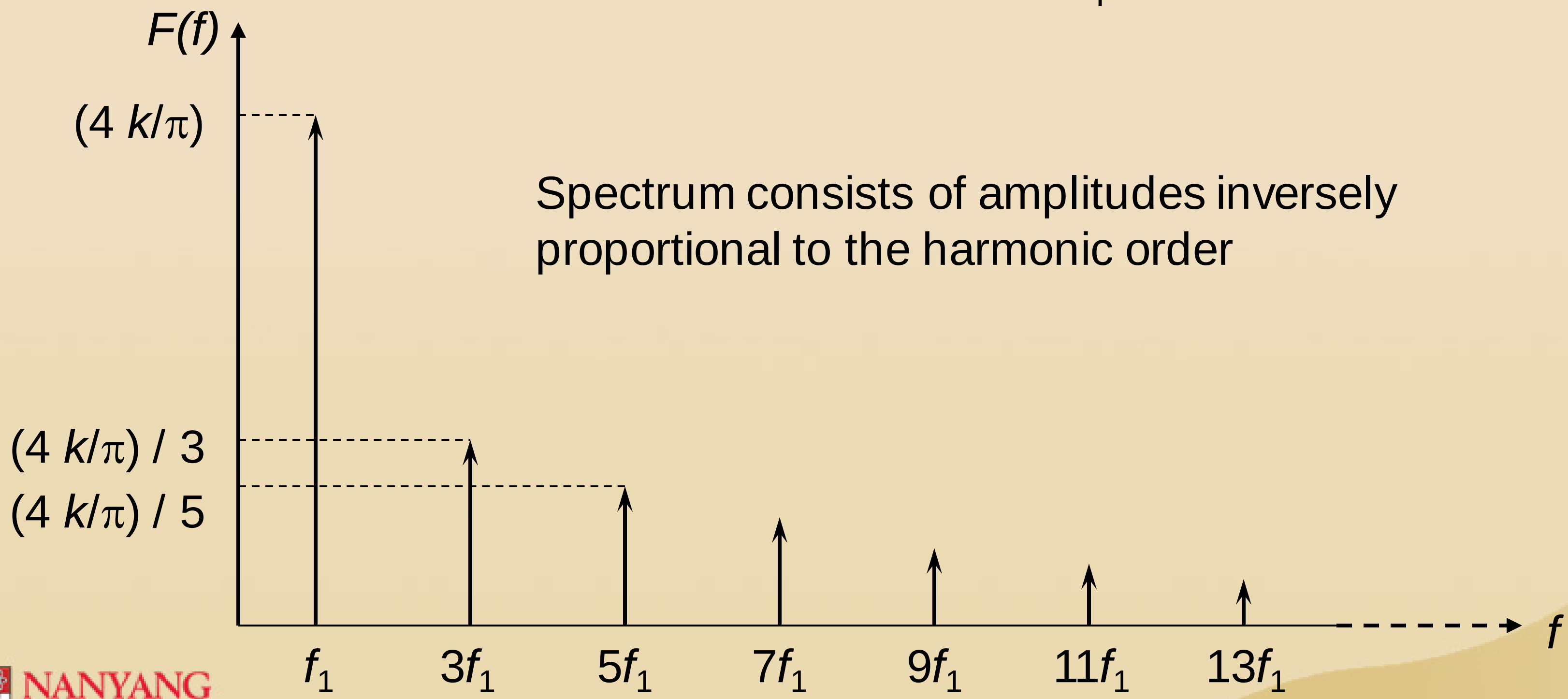
Halfwave symmetry

- The square wave is an odd function with halfwave symmetry
  - Only b_n coefficients and odd harmonics will exist

$$b_n = \frac{8}{T}\int_0^{T/4} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt$$





Spectrum consists of amplitudes inversely proportional to the harmonic order

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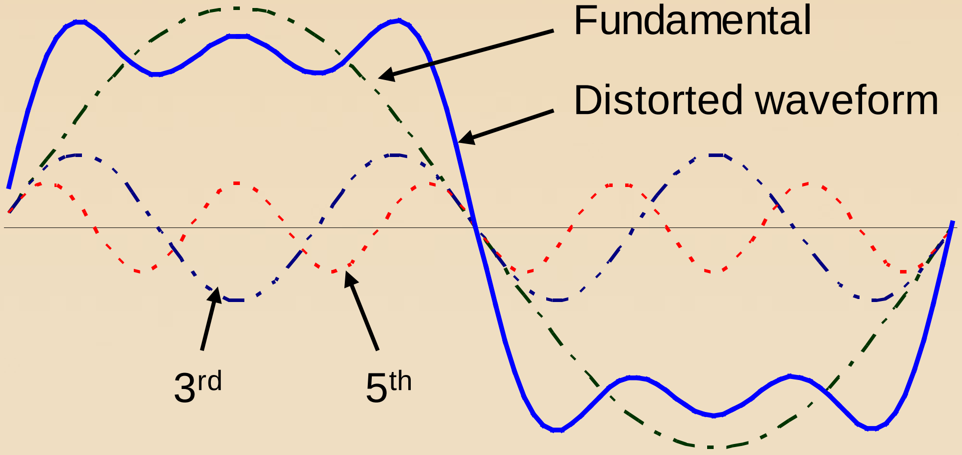
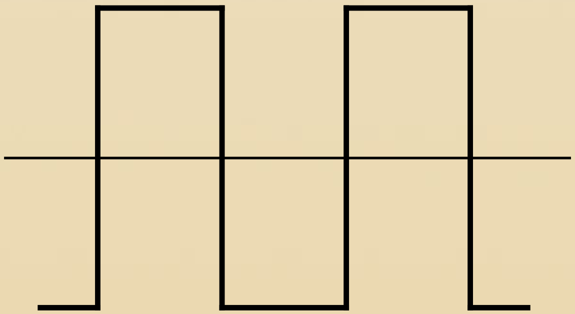
Harmonics of a rectangular wave

- Harmonics are sinusoids having frequencies that are whole multiples of the fundamental frequency
  - The distorted solid-line waveform is made up of fundamental component and two other harmonic components



- A rectangular waveform is made up of all odd harmonics
  - Magnitude of harmonics is related to the fundamental by 1/*h* (harmonic order)



Harmonic Order	Frequency (Hz)	Amplitude in p.u.
Fundamental	50	1.0
3rd	150	1/3
5th	250	1/5
7th	350	1/7
9th	450	1/9
.	.	.
nth	50n	1/n

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Harmonic indices

- Total harmonic distortion (THD)
  - RMS value of the harmonic content expressed as a percentage of the fundamental

$$\text{THD}(\%) = \frac{\sqrt{\text{Sum of the squares of all harmonic amplitudes}}}{\text{Amplitude of the fundamental}} \times 100\,\%$$

- Total demand distortion (TDD)
  - Current THD is misleading during light load conditions when I_1 is small
  - Similar to THD except that the distortion is expressed as a percentage of some rated load current magnitude rather than as percentage of the fundamental current
  - For a device with 50A ratings, but operating at 20% loading

n	Amplitude (20% load)
Fund	$50.0 \times 20\% = 10.0$ A
5^{th}	$15.0 \times 20\% = 3.0$A
7^{th}	$10.5 \times 20\% = 2.1$ A
11^{th}	$8.8 \times 20\% = 1.76$ A
13^{th}	$6.7 \times 20\% = 1.34$ A

$$\begin{aligned}
\text{THD}_{20\%} &= \frac{\sqrt{(3.0)^2 + (2.1)^2 + (1.76)^2 + (1.34)^2}}{10.0} \times 100\,\% \\
&= 42.8\% \\
\text{TDD}_{20\%} &= \frac{\sqrt{(3.0)^2 + (2.1)^2 + (1.76)^2 + (1.34)^2}}{50.0} \times 100\,\% \\
&= 8.6\,\%
\end{aligned}$$

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Harmonic sources

- Traditional sources prior to the appearance of power semiconductors
  - Electric arc furnaces
  - Fluorescent lamps
  - Electrical machines
    - Flux is never distributed perfectly sinusoidally around the air gap ➔ the e.m.f. generated is not perfectly sinusoidal
  - Transformer
    - Non-linear magnetization characteristics
    - Inrush current at energization
    - d.c. magnetization
- Power electronic converter
  - Switches allowing power to be transferred at different frequencies including d.c.
  - Most prevalent is single-phase rectifier used to power most modern electronic appliances
    - Individual ratings are small but combined effect is significant
    - Contributes to most of the distribution level low voltage harmonics
  - Three-phase static power converters (rectifier and inverter) of considerable power ratings
    - Contributes mainly to higher voltage distribution / sub-transmission level harmonics
- Many harmonic sources are treated as current sources
  - Non-linear loads draw distorted current even when the supply voltage is sinusoidal

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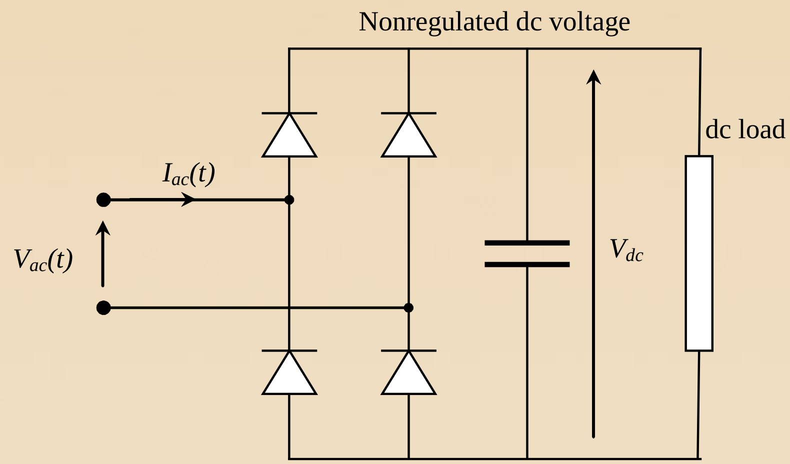
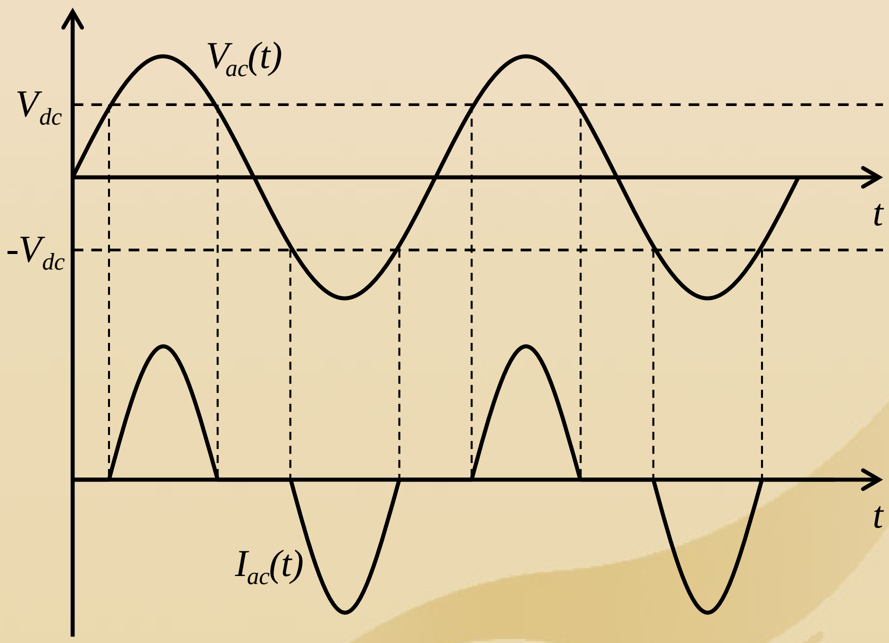
Harmonics from single-phase converter

- Diode rectifier with a capacitor on dc bus to reduce ripples on dc voltage
- Diodes are forward-biased and conduct only when
  - $V_{ac}(t) > V_{dc}$ during positive half cycle
  - $V_{ac}(t) < -V_{dc}$ during negative half cycle
- AC current $I_{ac}(t)$ is discontinuous with high harmonic content



Typical harmonic current magnitude in I_{ac} (p.u.)			
Harmonic	Magnitude	Harmonic	Magnitude
1	1.00	9	0.157
3	0.81	11	0.024
5	0.606	13	0.063
7	0.370	15	0.079



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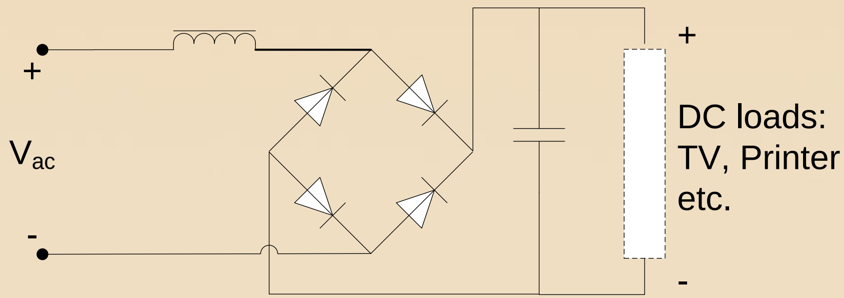
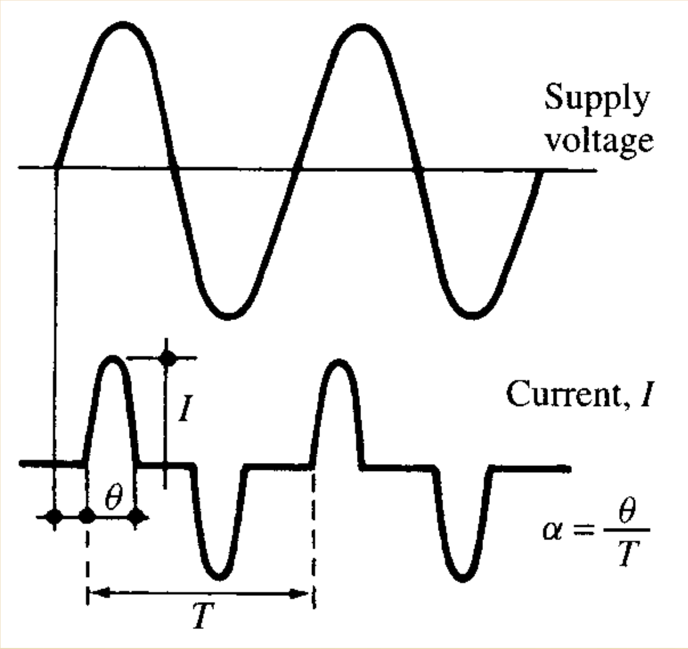
Distribution level harmonic: single-phase converter

- D.C. power supplies
  - Provides direct current for the operation of commercial and domestic appliances
  - Single-phase uncontrolled diode bridge rectifier input with d.c. bus capacitor
  - Low cost and relatively low sensitivity to supply voltage variations





  - Discontinuous current with very narrow current pulse at every half cycle of the supply frequency
  - d.c. capacitor is recharged only when the supply voltage exceeds the d.c. level (which only occur close to the peak of the voltage waveform)
  - Halfwave symmetry ➔ Odd harmonics only

$$I_n(t) = \frac{8\alpha I}{\pi}\cdot\frac{\cos(n\alpha\pi)}{(1-n^2\alpha^2\pi^2)}\cos(n\omega t)$$

- n = 1, 3, 5, …
- I is current impulse peak value
- $\alpha = \theta/T$ is duration as proportion of the fundamental waveform

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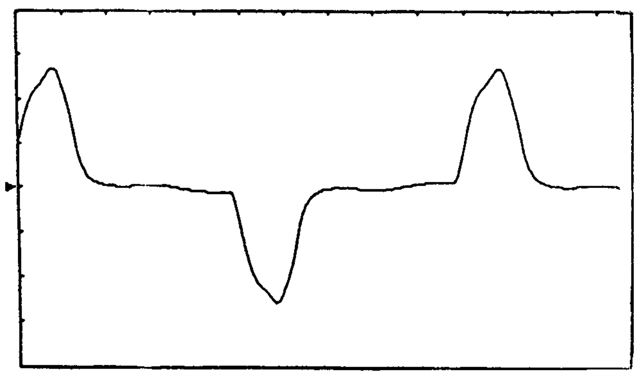
Typical harmonics from electrical appliances



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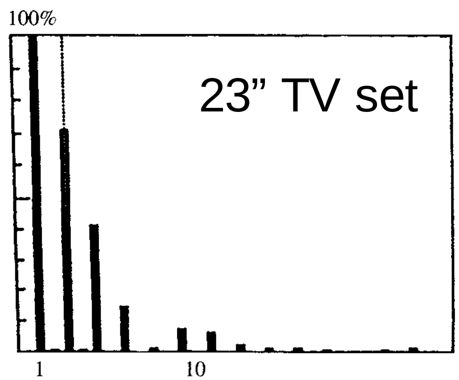

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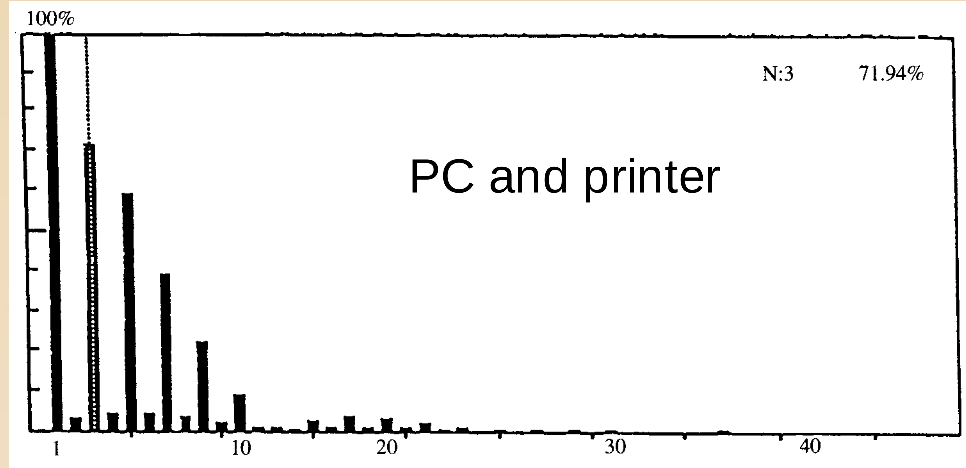

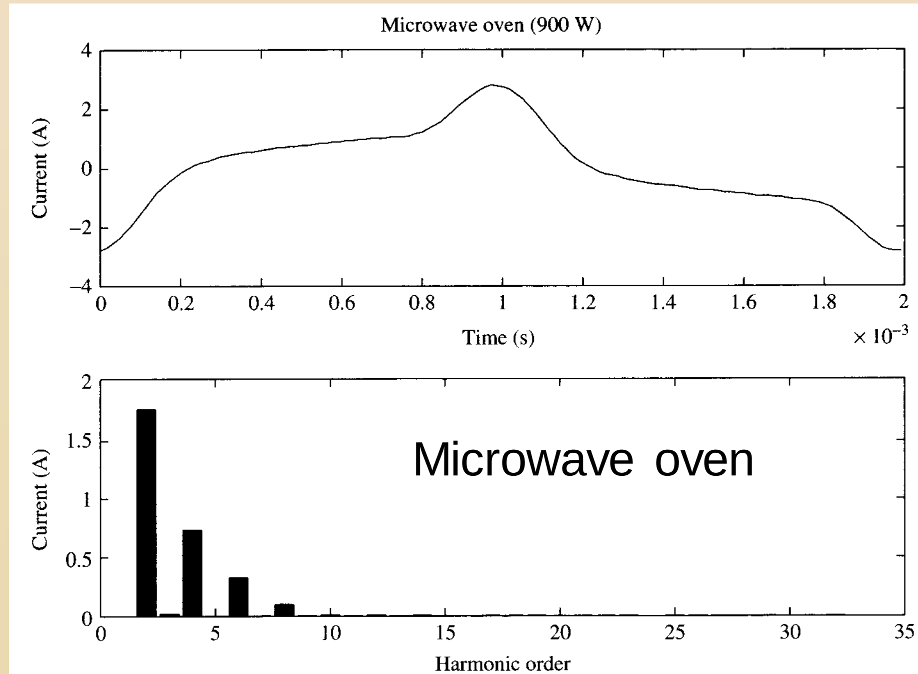

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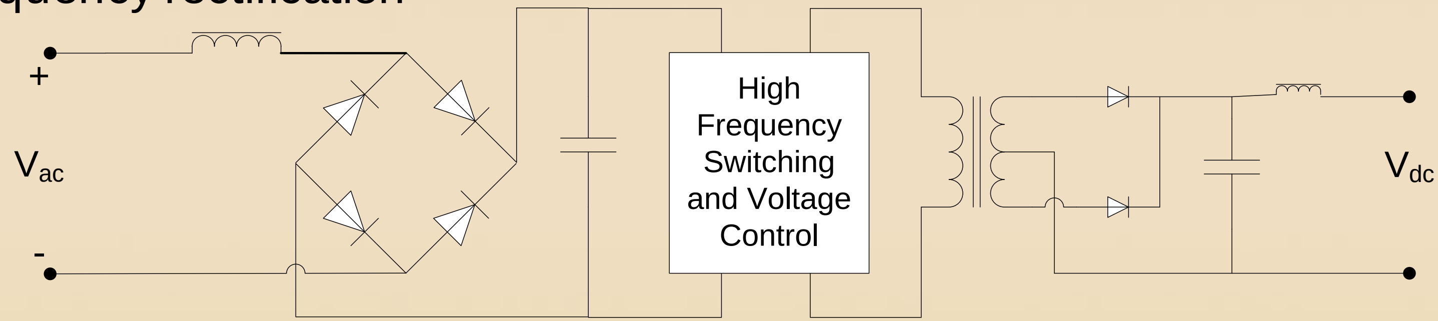
Single-phase rectification

- Effect from a.c. side voltage control transformer
  - Transformer leakage reactance has a smoothing effect that results in lower harmonic current levels (Linear power supplies are equipped with 50/60 Hz step down transformer)
- Switched mode power supplies
  - Line-frequency rectification; high-frequency inversion; isolation and high-frequency rectification



  - Provides a very compact design and efficient operation
    - Widely used in many office and domestic electrical appliances such as PC and electronic ballast for modern fluorescent lighting systems
  - Lack of a.c. side inductance smoothing causes the narrow pulses to pass directly into a.c. system, with considerable increase in current harmonic content
  - Of particular troublesome is the third harmonic that add arithmetically in the neutral of the three-phase network

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Transmission level harmonic: three-phase converter

- VSI - Voltage source conversion
  - Characterized by predominantly capacitive dc side and inductive ac system
  - Due to the presence of a large capacitor at the output of rectifier
  - dc voltage is well defined, while the ac side currents are controlled by the converter modulation process
- CSI – Current source conversion
  - Characterized by a very inductive dc side, relative to the ac system
  - Series smoothing reactor is installed on the dc side
  - ac side is connected with some capacitors or harmonic filters to make it less inductive
  - dc current is reasonably constant
  - Converter acts as the source of harmonic current on the ac side

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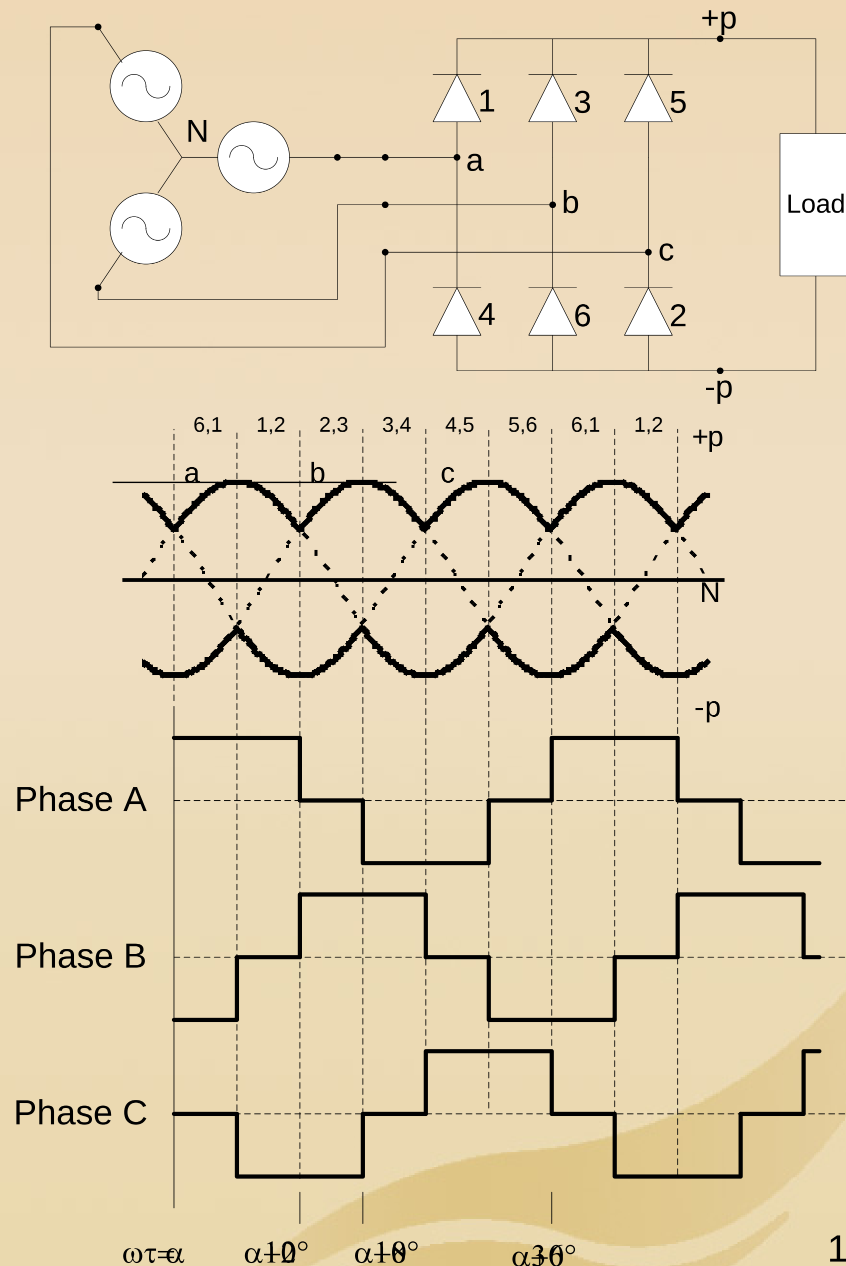
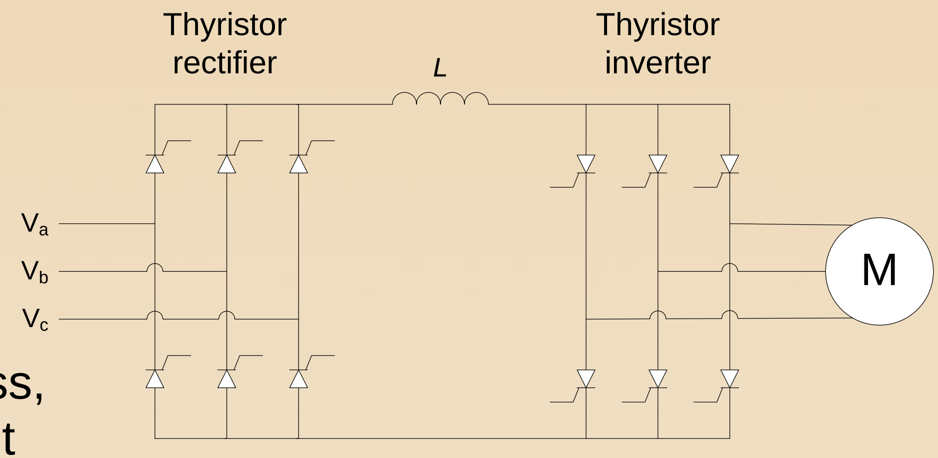
Three-phase conversion

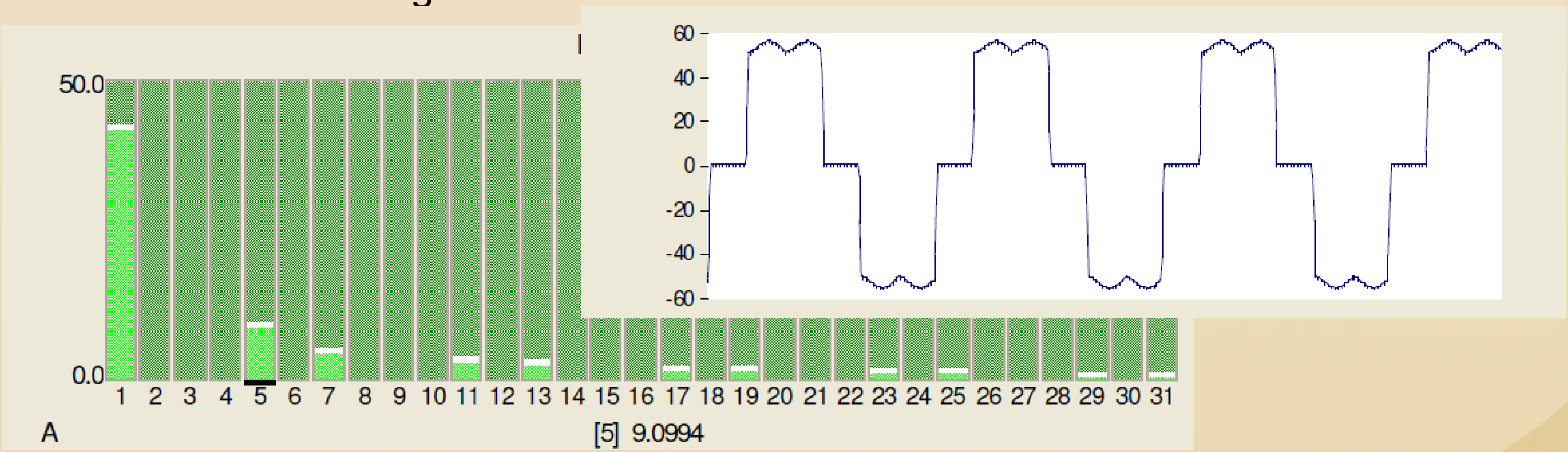
- One of three top-half diodes conducts at any one time
  - Phase with most positive voltage
- One of three bottom-half diodes conducts at any one time
  - Phase with most negative voltage
- Each diode conducts for 1/3 of cycle
- Each phase is connected to a top-half diode and a bottom-half diode
  - Each phase conducts for 2/3 of a cycle
    - 1/3 with positive current
    - 1/3 with negative current
  - Current is rectangular in shape under ideal conditions
    - DC current is perfectly smooth – large smoothing reactor on DC side
    - Current commutation between diodes is instantaneous



Current source conversion

- Large d.c. smoothing reactor *L*
  - Current waveform is close to rectangular in shape
  - Much lower harmonic contents compared to voltage source conversion
  - Affected by the commutation process, that is highly dependent on the input transformer leakage reactance





  - Smaller dc smoothing reactor *L*, less rectangular and higher harmonics

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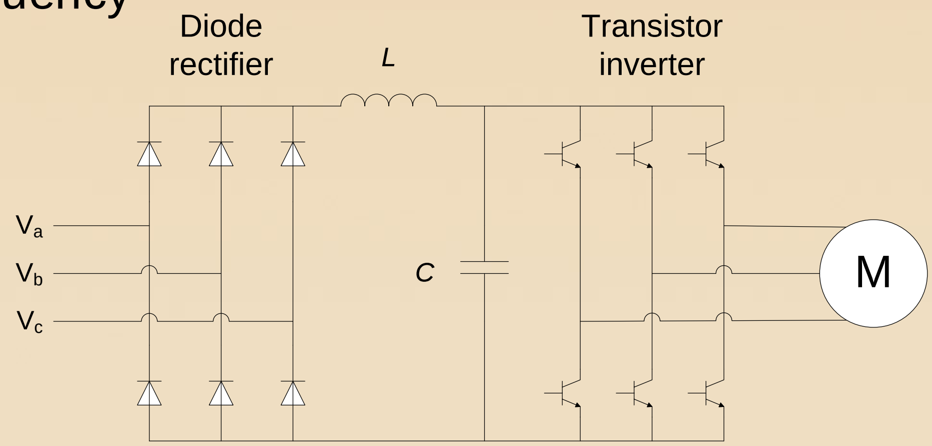
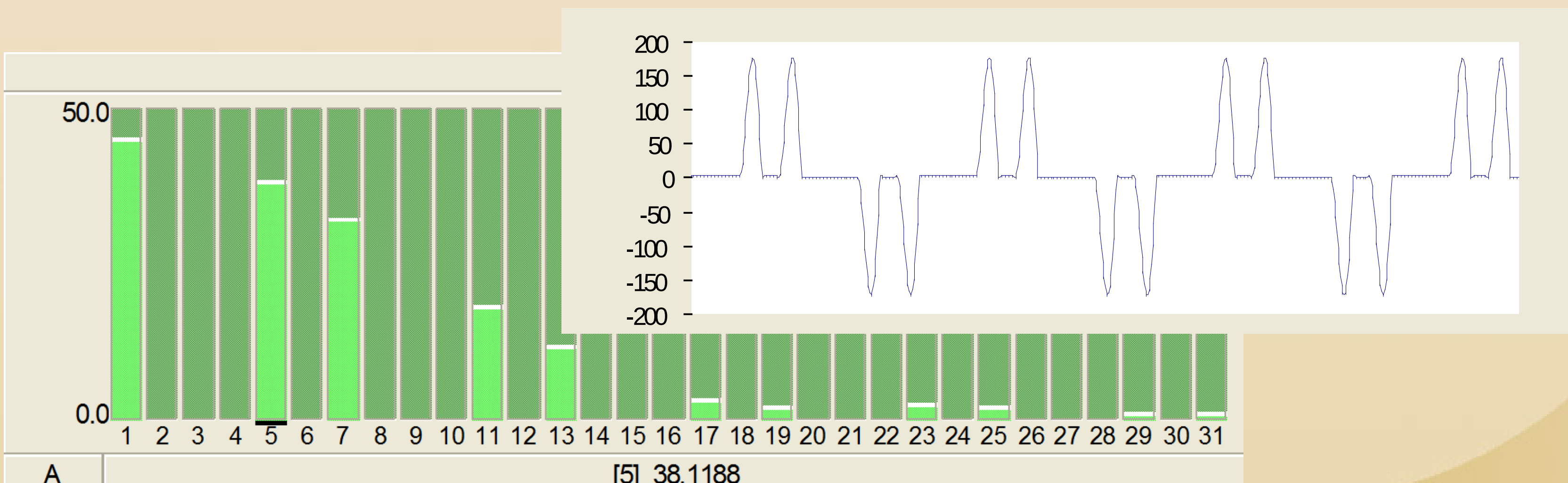
Uncontrolled voltage source conversion

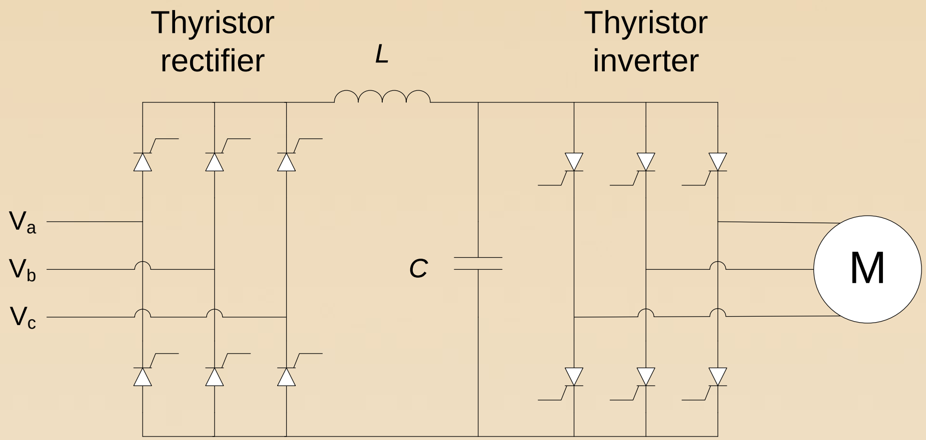
- Uncontrolled input made of three-phase diode bridge rectifier
  - Input rectifier operates at line frequency
  - With a well defined d.c. voltage, output inverter operates at very high frequency
  - PWM (pulse width modulation)
  - ASD (adjustable speed drive)
  - Slightly broader current pulses since there is no firing delay

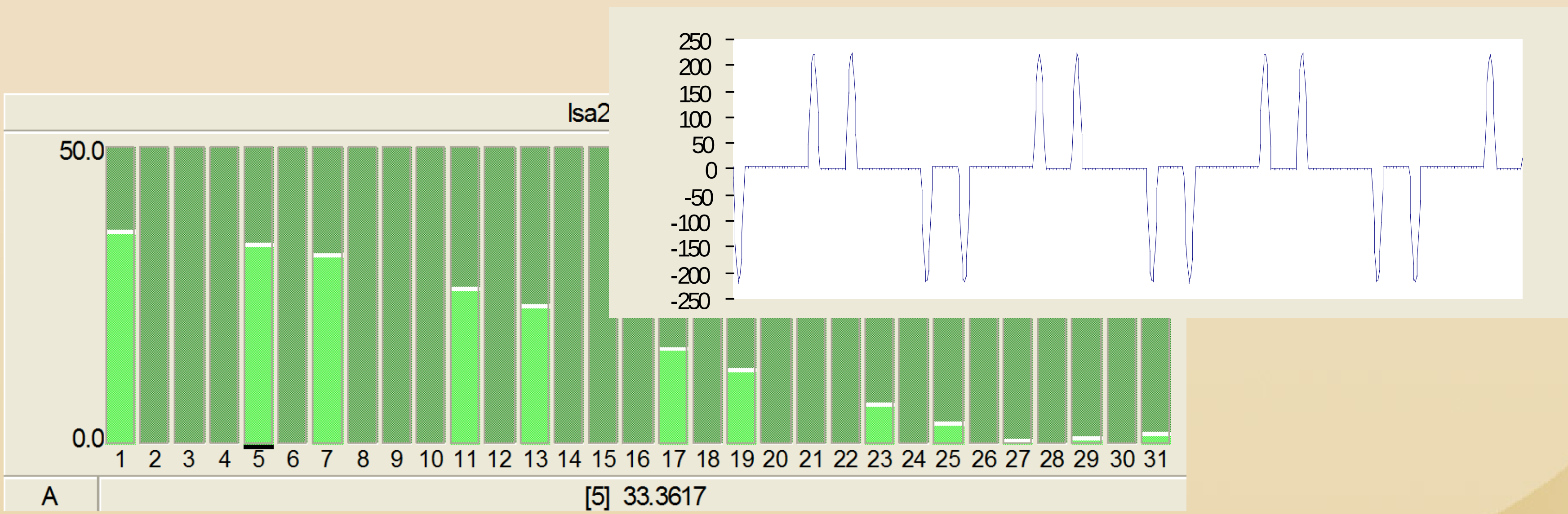




Controlled voltage source conversion

- Controlled input and output at low frequencies
  - Operate at system frequency
  - Narrow current pulses
  - Higher percentage of harmonics, depending on the firing angle e.g. with 60° α





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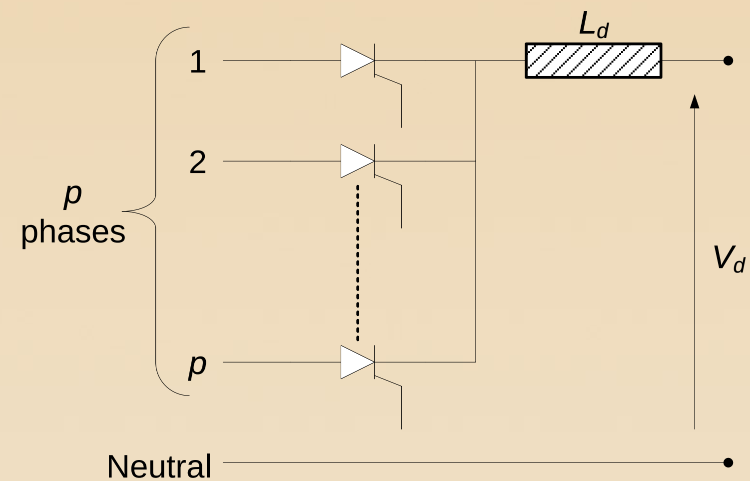
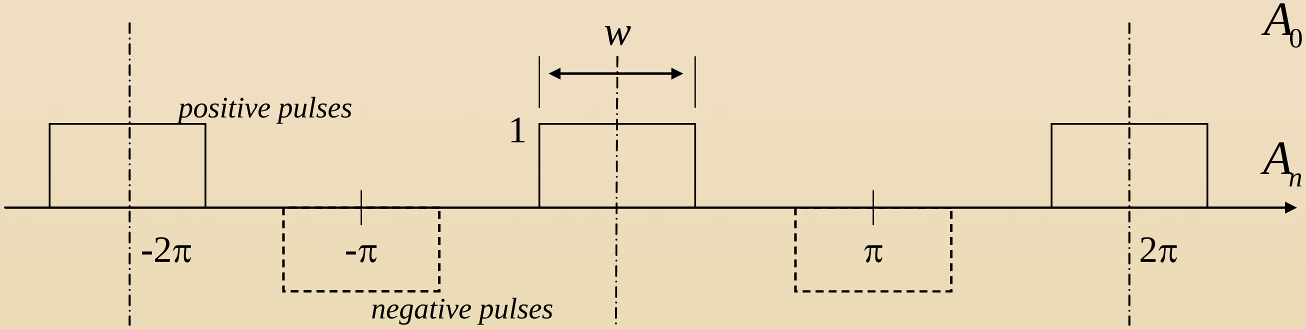
Current source conversion harmonics

- Ideal *p*-phase one-way converter
  - Zero ac system impedance
  - Infinite dc side smoothing inductance
  - ac phase current consists of periodic positive rectangular pulses of width $w = 2\pi/p$, repeating at supply frequency
    - Even function ➔ only cosine terms
    - Fourier series w.r.t. 1 p.u. dc current





$$A_0 = \frac{1}{2\pi}\int_{-w/2}^{w/2} d(\omega t) = \frac{w}{2\pi} = \frac{1}{p}$$

$$A_n = \frac{1}{\pi}\int_{-w/2}^{w/2} \cos(n\omega t)\, d(\omega t)$$

$$= \frac{2}{n\pi}\sin\left(\frac{nw}{2}\right) = \frac{2}{n\pi}\sin\left(\frac{n\pi}{p}\right)$$

  - Fourier series of positive current pulses is

$$F_p = \frac{2}{\pi}\left(\frac{w}{4} + \sin\left(\frac{w}{2}\right)\cos(\omega t) + \frac{1}{2}\sin\left(\frac{2w}{2}\right)\cos(2\omega t) + \frac{1}{3}\sin\left(\frac{3w}{2}\right)\cos(3\omega t)\right.$$
$$\left. + \frac{1}{4}\sin\left(\frac{4w}{2}\right)\cos(4\omega t) + \cdots\right)$$

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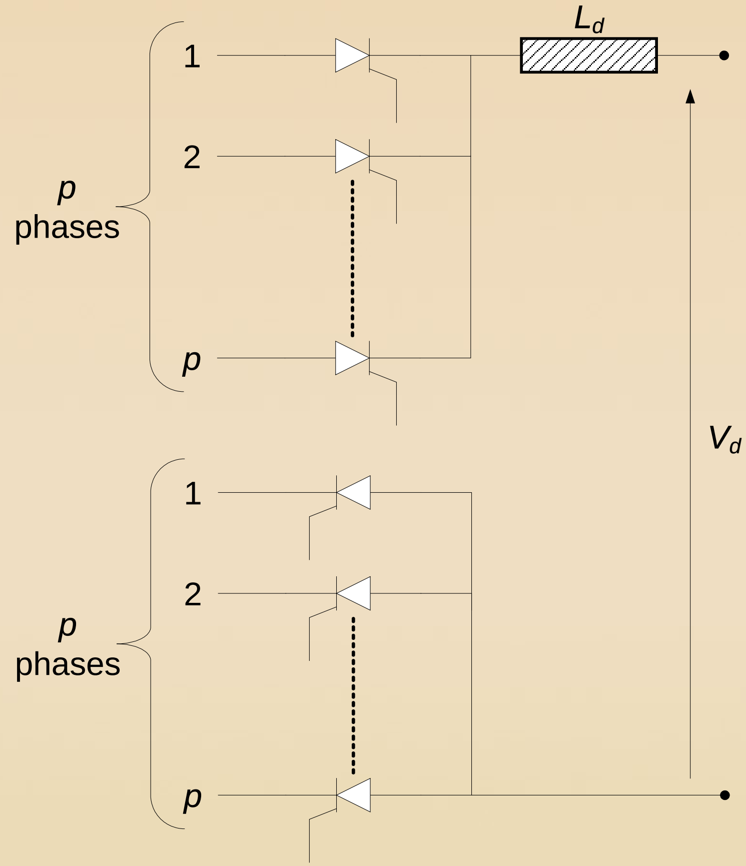
Current source conversion harmonics

- Ideal *p*-phase two-way converter
  - Positive and negative current pulses
  - Fourier series of negative pulses

$$F_n = \frac{2}{\pi}\left(-\frac{w}{4} + \sin\left(\frac{w}{2}\right)\cos(\omega t) - \frac{1}{2}\sin\left(\frac{2w}{2}\right)\cos(2\omega t)\right.$$
$$\left. + \frac{1}{3}\sin\left(\frac{3w}{2}\right)\cos(3\omega t) - \frac{1}{4}\sin\left(\frac{4w}{2}\right)\cos(4\omega t) + \cdots\right)$$



  - Each phase current consists of alternate positive and negative pulses such that $F(\omega t+\pi) = -F(\omega t)$ (half-wave symmetry)
  - Fourier series is a combined F_p and F_n

$$F = F_p + F_n$$
$$= \frac{4}{\pi}\left(\sin\left(\frac{w}{2}\right)\cos(\omega t) + \frac{1}{3}\sin\left(\frac{3w}{2}\right)\cos(3\omega t) + \frac{1}{5}\sin\left(\frac{5w}{2}\right)\cos(5\omega t) + \cdots\right)$$

- dc component and even harmonics are eliminated

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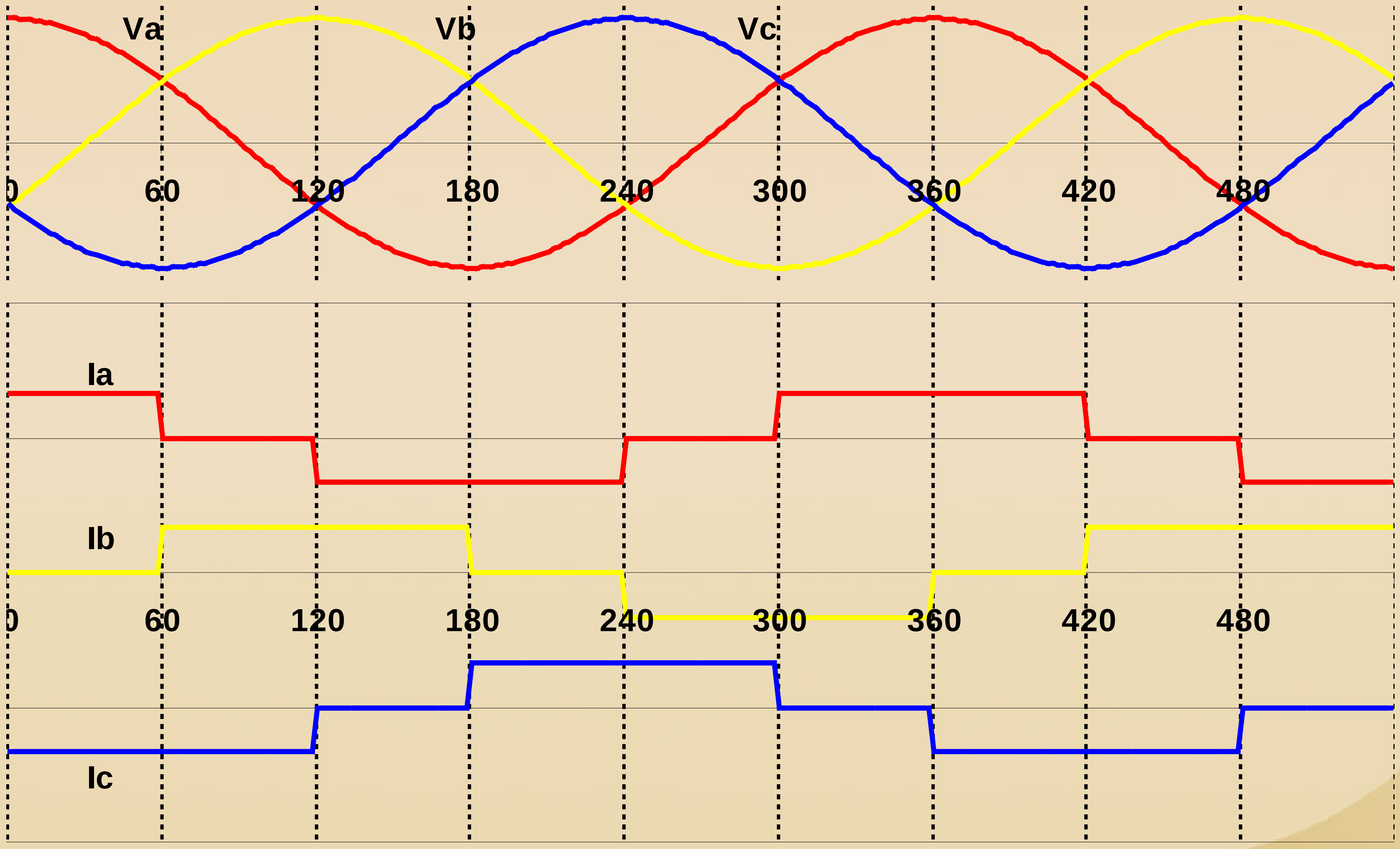
Basic 6-pulse configuration



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Basic 6-pulse configuration - harmonics

- Three-phase two-way configurations
  - Each phase conducts for 2/3 cycle (1/3 positive pulse and 1/3 negative pulse)
  - $w = 2\pi / 3$ with a dc current of I_d

$$i_a = \frac{2\sqrt{3}}{\pi} I_d \left(\cos(\omega t) - \frac{1}{5}\cos(5\omega t) + \frac{1}{7}\cos(7\omega t) - \frac{1}{11}\cos(11\omega t) + \frac{1}{13}\cos(13\omega t) - \frac{1}{17}\cos(17\omega t) + \frac{1}{19}\cos(19\omega t) \cdots \right)$$

- Some useful observations
  - Absence of triplen harmonics
    - Harmonic orders that are multiples of three (3rd, 9th, 15th, etc.)
  - Presence of harmonics of order $6k\pm1$, k are integers
  - Those harmonics of orders $6k+1$ are of positive sequence (7th, 13th, 19th, etc.)
  - Those harmonics of orders $6k-1$ are of negative sequence (5th, 11th, 17th, etc.)
  - The r.m.s. magnitudes of the fundamental frequency and the n^{th} harmonic are,

$$I_1 = \frac{1}{\sqrt{2}} \times \frac{2\sqrt{3}}{\pi} I_d = \frac{\sqrt{6}}{\pi} I_d \quad ; \quad I_n = \frac{I_1}{n}$$

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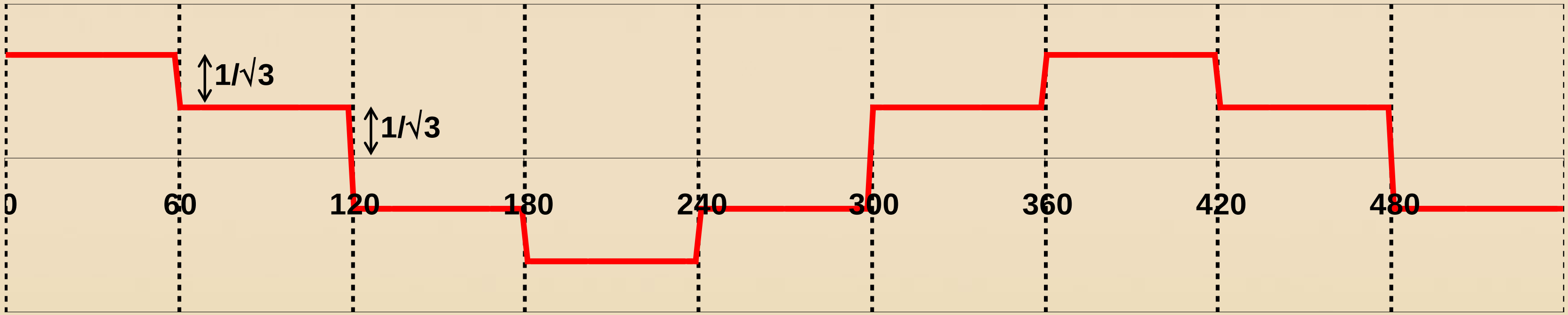
Effect of transformer delta connection

- Either the primary or secondary three-phase windings of converter transformer is connected in delta
  - ac side current waveforms consist of instantaneous differences between two rectangular current pulses of the star-star connection
  - A factor of √3 is incorporated in the transformer ratio to maintain the same primary and secondary voltages as for the star-star connection



  - Fourier series of this waveform is found by superimposing the results of two component pulses of widths π and π/3, respectively
  - For $w = \pi$,

$$F_1 = \frac{4}{\pi}\left(\sin\left(\frac{\pi}{2}\right)\cos(\omega t) + \frac{1}{3}\sin\left(\frac{3\pi}{2}\right)\cos(3\omega t) + \frac{1}{5}\sin\left(\frac{5\pi}{2}\right)\cos(5\omega t) + \cdots\right)$$

$$= \frac{4}{\pi}\left(\cos(\omega t) - \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) + \cdots\right)$$

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Effect of transformer delta connection

– For $w = \pi / 3$,

$$F_2 = \frac{4}{\pi}\left(\sin\left(\frac{\pi/3}{2}\right)\cos(\omega t) + \frac{1}{3}\sin\left(\frac{3\pi/3}{2}\right)\cos(3\omega t) + \frac{1}{5}\sin\left(\frac{5\pi/3}{2}\right)\cos(5\omega t) + \cdots\right)$$

$$= \frac{4}{\pi}\left(\frac{1}{2}\cos(\omega t) + \frac{1}{3}\cos(3\omega t) + \frac{1}{5}\cdot\frac{1}{2}\cos(5\omega t) - \frac{1}{7}\cdot\frac{1}{2}\cos(7\omega t) + \cdots\right)$$

– Incorporating the √3 factor and the dc current I_d

$$i_a = (F_1 + F_2) \times \frac{I_d}{\sqrt{3}} = \frac{4}{\pi}\left(\frac{3}{2}\cos(\omega t) + \frac{1}{5}\cdot\frac{3}{2}\cos(5\omega t) - \frac{1}{7}\cdot\frac{3}{2}\cos(7\omega t) + \cdots\right) \times \frac{I_d}{\sqrt{3}}$$

$$= \frac{2\sqrt{3}}{\pi} I_d \left(\cos(\omega t) + \frac{1}{5}\cos(5\omega t) - \frac{1}{7}\cos(7\omega t) - \frac{1}{11}\cos(11\omega t) + \frac{1}{13}\cos(13\omega t)\right.$$

$$\left. + \frac{1}{17}\cos(17\omega t) - \frac{1}{19}\cos(19\omega t) \cdots\right)$$

– Differences in the sign or sequence of the $6k\pm1$ harmonics with odd values of k from those of the star-star connection

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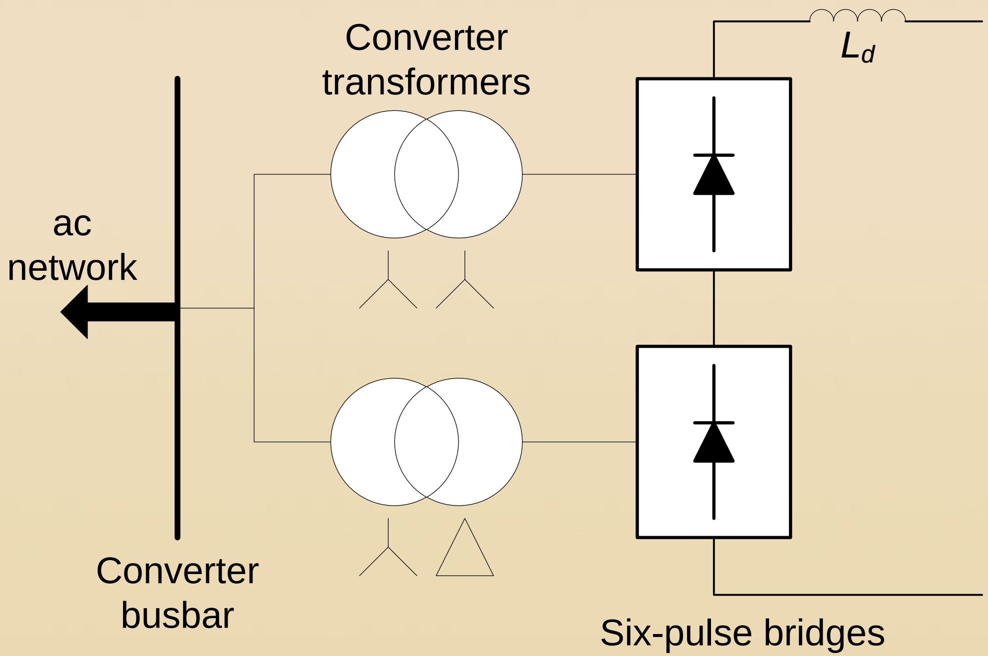
12-pulse configuration

- Consists of two 6-pulse groups
  - Fed from two sets of three-phase transformers in parallel
  - Same fundamental voltage magnitude and phase-shifted by 30°
  - Both 6-pulse groups operate with same control angle so that the fundamental frequency currents on ac side of both transformers are in phase



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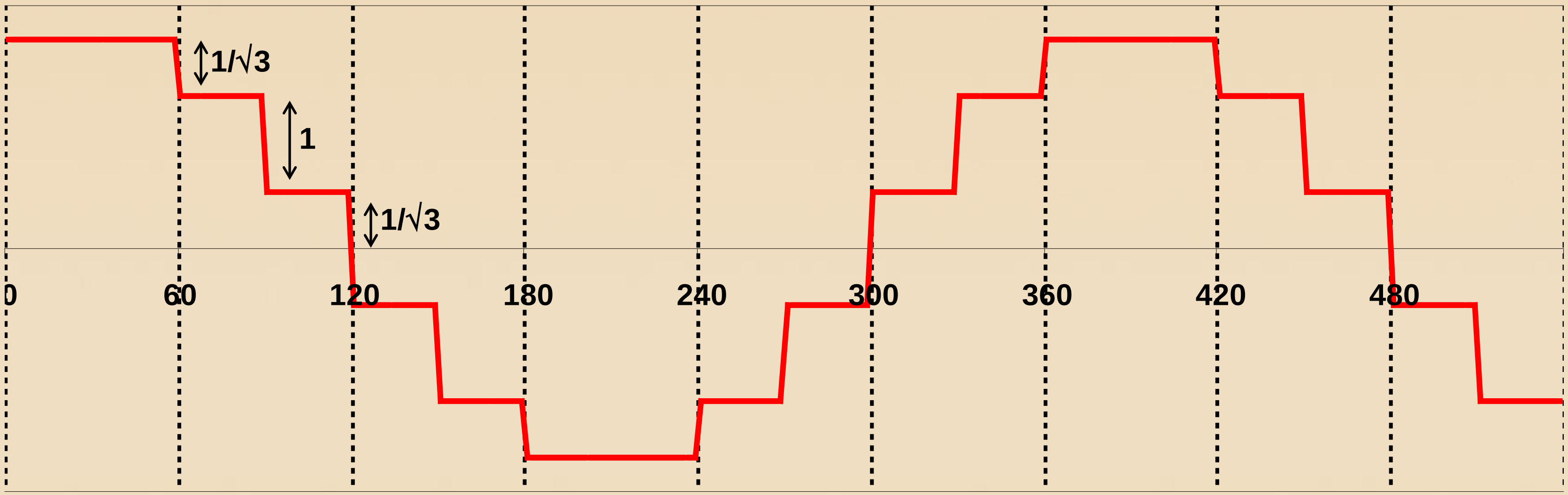
12-pulse configuration - harmonics

- Resultant waveform is sum of the two waveforms of the star-star and star-delta transformers



- Fourier series is the sum of those of star-star and star-delta

$$i_a = 2\left(\frac{2\sqrt{3}}{\pi}\right) I_d \left(\cos(\omega t) - \frac{1}{11}\cos(11\omega t) + \frac{1}{13}\cos(13\omega t) - \frac{1}{23}\cos(23\omega t) + \frac{1}{25}\cos(25\omega t) \cdots\right)$$

  – Harmonics of order $12k\pm1$, k are integers
  – Harmonic currents of order $6k\pm1$ with odd k, circulate between the transformers but do not penetrate the ac network

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Harmonics and sequences

- AC currents (fundamental and harmonics) are all rotating vectors
  - Harmonics with higher frequency rotate faster than fundamental component
  - For every degree of rotation or phase shift at the fundamental frequency, the length of time corresponds to *n* degrees for the n^{th} harmonic component

	Fundamental	3^{rd} harmonic	5^{th} harmonic	7^{th} harmonic
Phase A	$0°$	$0°\times3=0°$	$0°\times5=0°$	$0°\times7=0°$
Phase B	$-120°$	$-120°\times3=-360°=0°$	$-120°\times5=-600°=+120°$	$-120°\times7=-840°=-120°$
Phase C	$+120°$	$+120°\times3=+360°=0°$	$+120°\times5=+600°=-120°$	$+120°\times7=+840°=+120°$

  - Under **balanced** condition, each harmonic comprises of a particular sequence (ignoring the possible effect from delta-star transformer connections)

Positive	**Fund**	4^{th}	7^{th}	10^{th}	13^{th}	16^{th}	19^{th}
Negative	2^{nd}	5^{th}	8^{th}	11^{th}	14^{th}	17^{th}	20^{th}
Zero	3^{rd}	6^{th}	9^{th}	12^{th}	15^{th}	18^{th}	21^{st}

  - Under **unbalanced** conditions, each harmonic would comprise of all sequences
    - e.g. 3^{rd} harmonic in unbalanced situation would comprise primarily of zero sequence but with a certain level of positive and negative sequences

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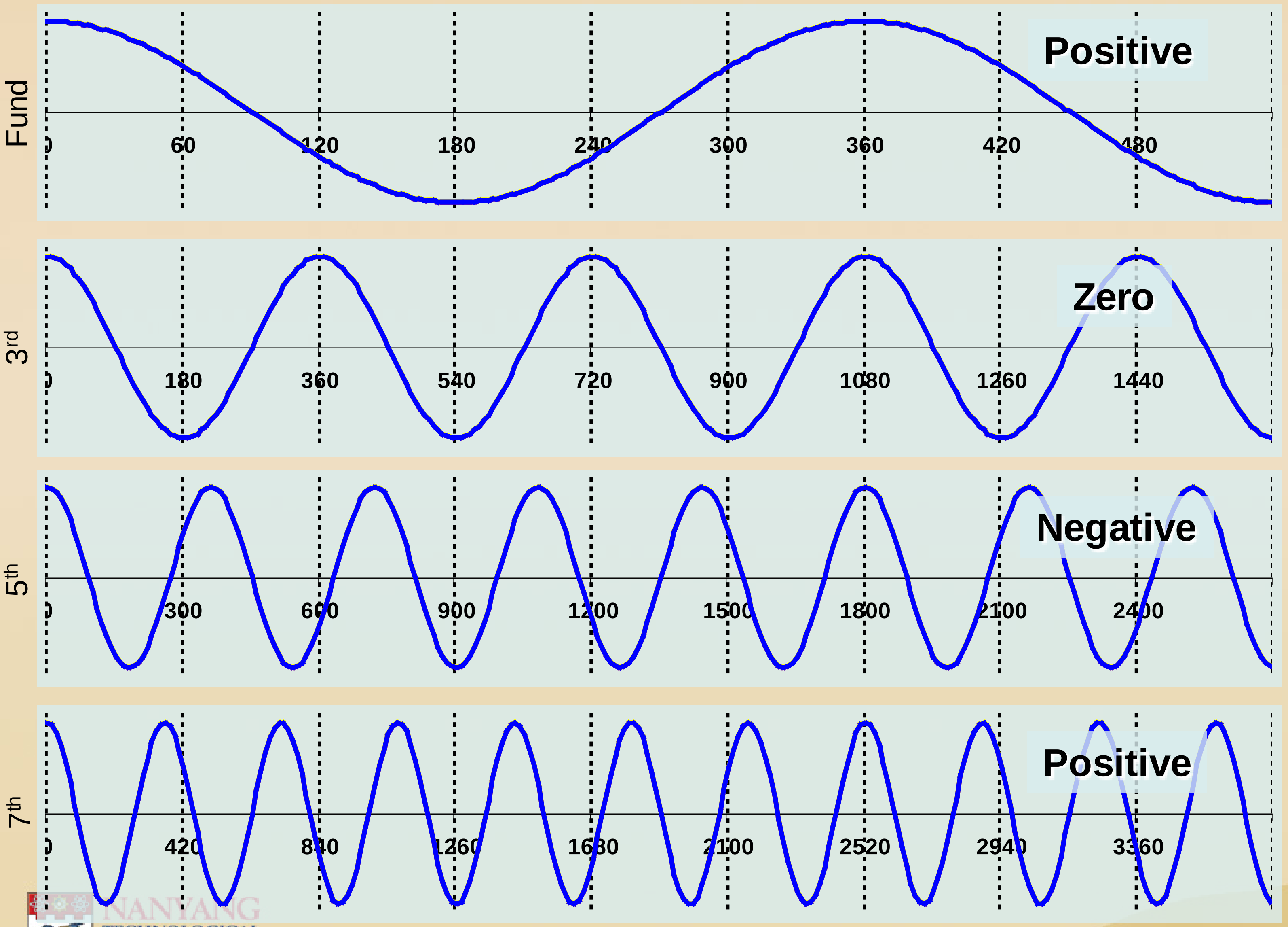
Harmonic sequences



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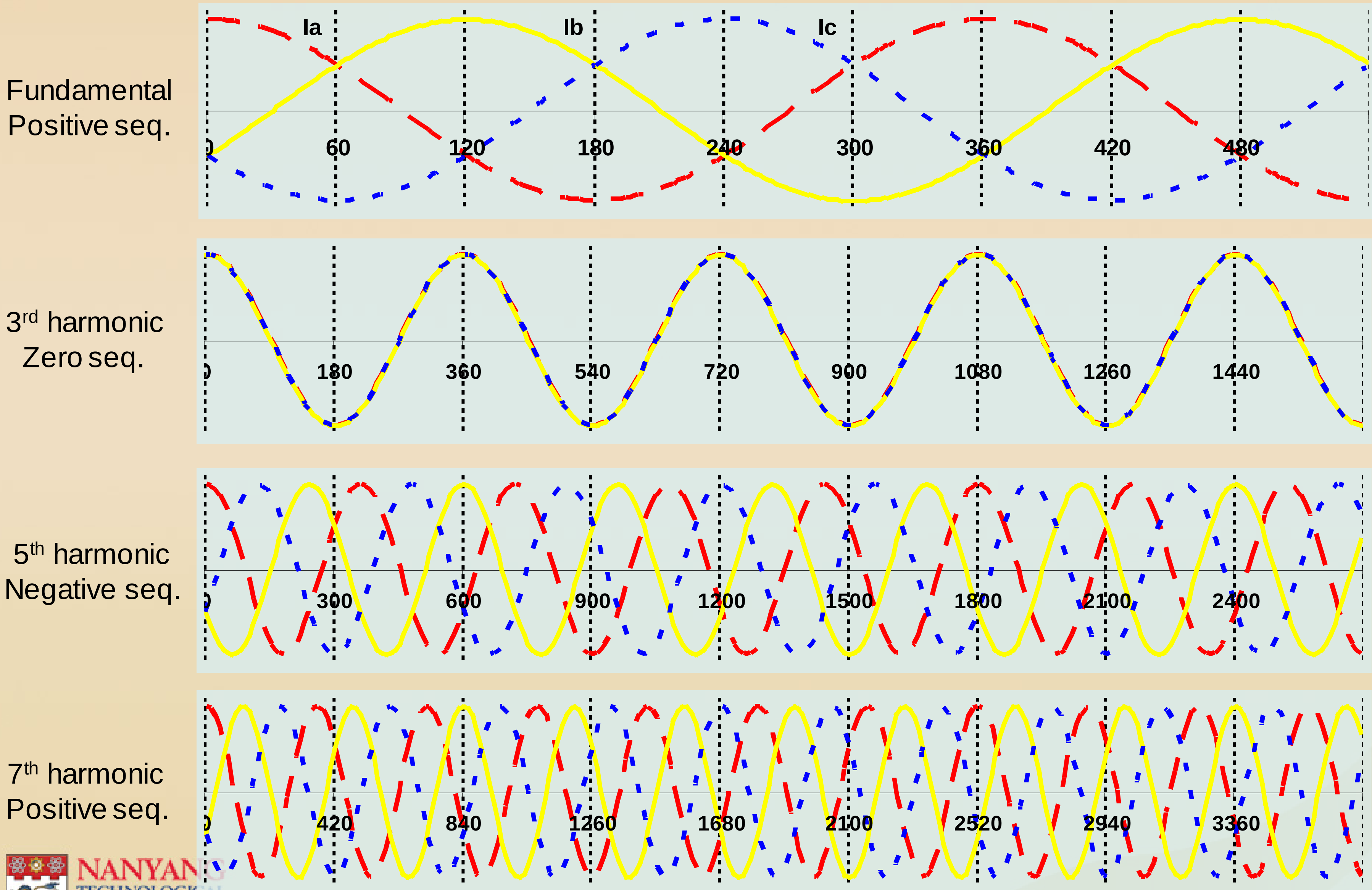
Harmonic sequences



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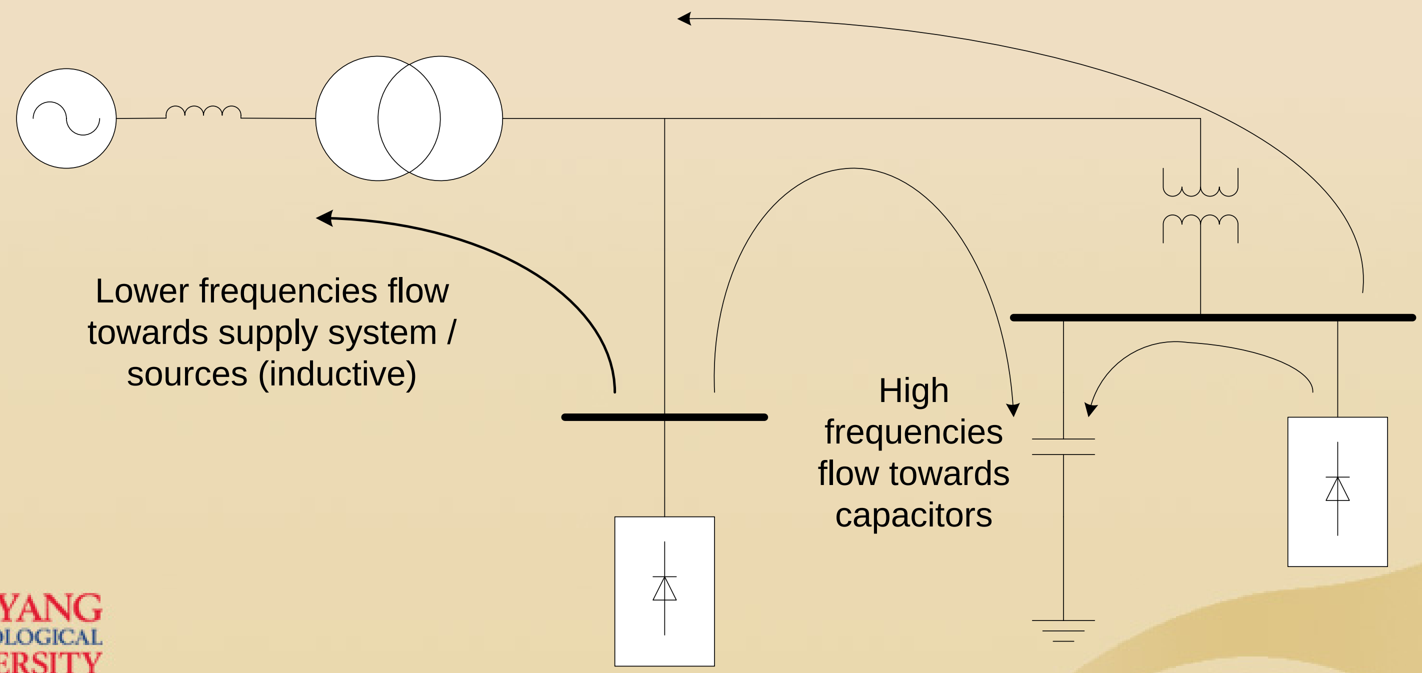
System response to harmonics

- Distorting load behaves as harmonic current sources injecting harmonic currents back into the supply system
- Flow of harmonic current depends on impedance of parallel paths provided by the loads and supply source
  - Low frequency harmonics flow towards inductive system or ac source
  - High frequency harmonics are drawn / attracted by low impedance of capacitors
  - Depends on the impedance at the harmonic frequency and for three-phase system, the sequence impedance



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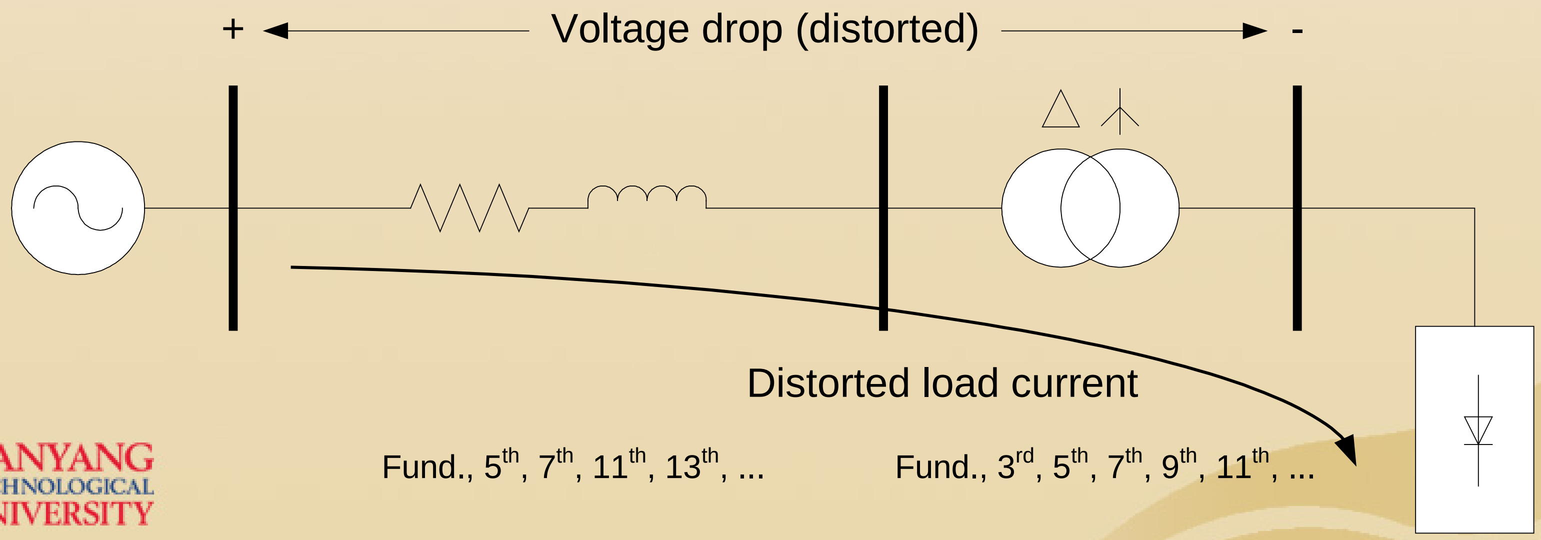
Harmonic voltage distortions

- As distorted currents flow through system impedances, voltages at various nodes in the system become distorted
- Magnitude of harmonic voltages
  - Size of harmonic currents – load characteristics
  - Size of harmonic impedances – length of the current flow path
- Effects of sequences and transformer connections
  - Triplen harmonics that are predominantly zero sequence are confined to the low voltage distribution system only
  - No or little triplen harmonics are found in the medium-voltage or high-voltage distribution and transmission systems



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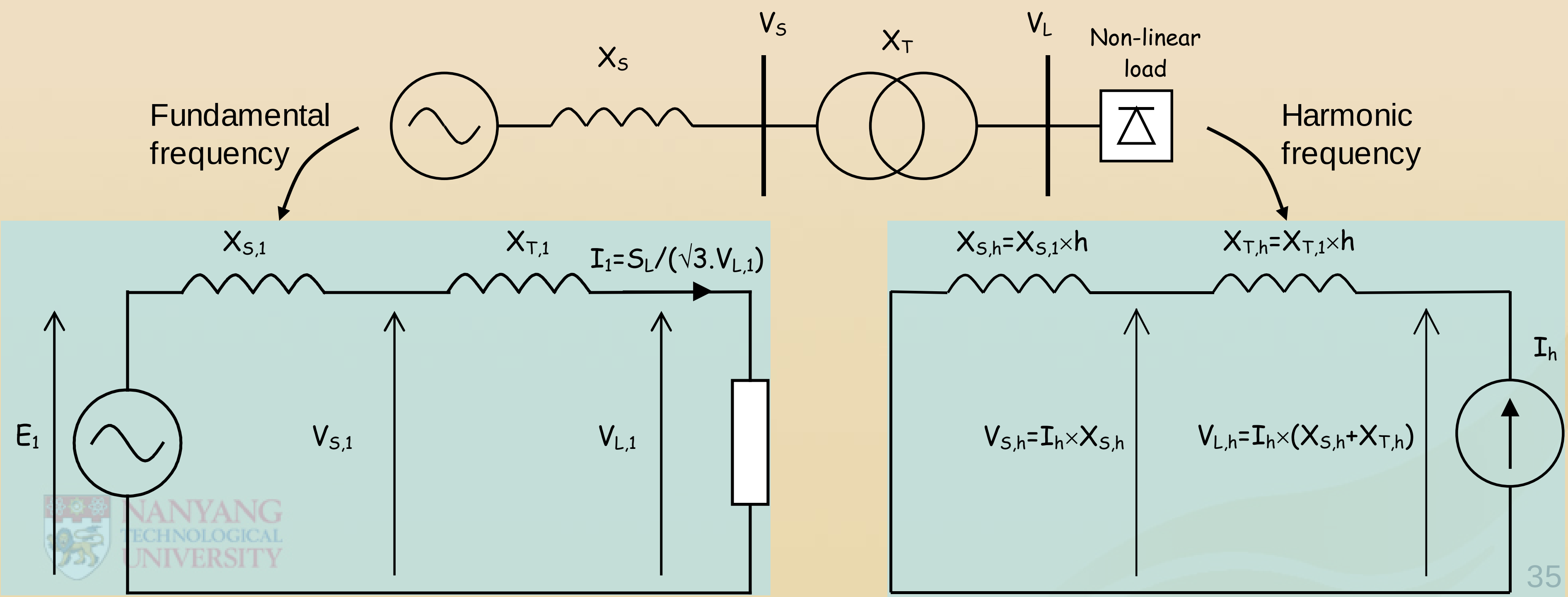
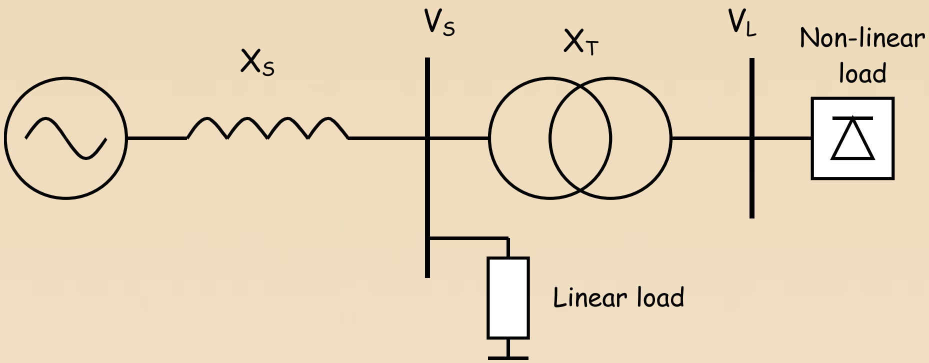
Visualizing system response to harmonics

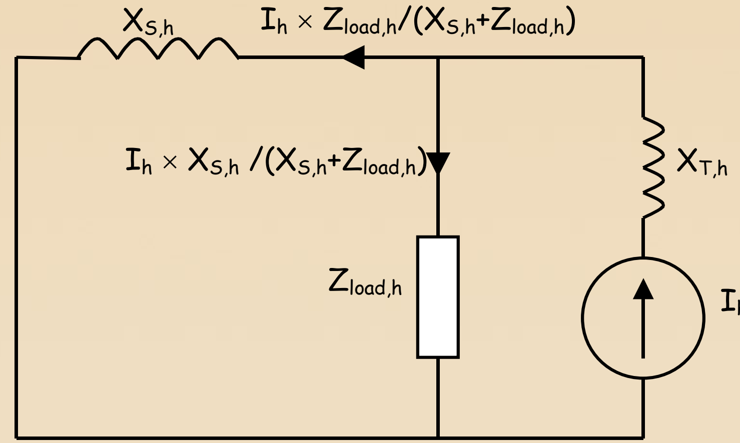
- System responds differently to currents and voltages of different frequencies
  - Separate individual harmonic responses from the fundamental response
  - At fundamental frequency, voltages are dependent on the voltage drops across system impedances due to the power or current flow as drawn by the load
  - At a harmonic frequency, non-linear load acts as harmonic current source, injecting harmonic current into the supply system
    - Results in harmonic voltage as the current flows through the system impedance



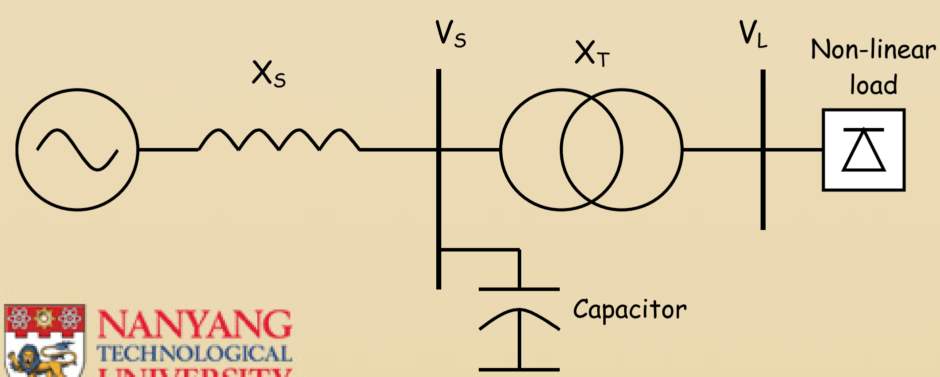
Flow of harmonic currents

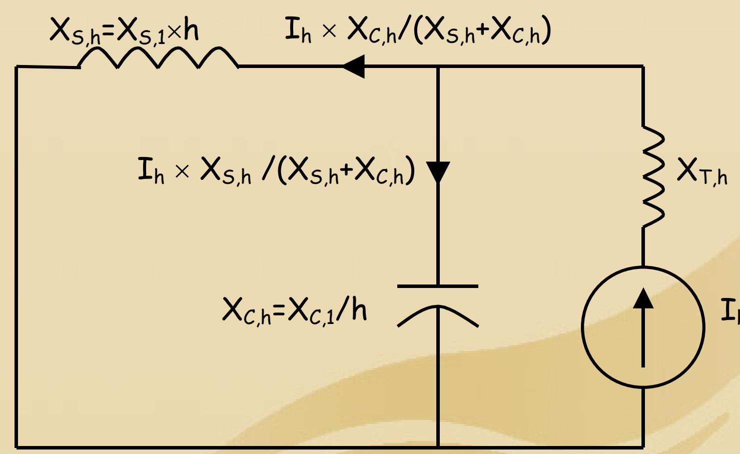
- Linear loads form alternative paths for the harmonic current





  - Low frequency harmonic currents tend to flow back towards the predominantly inductive supply system
  - High frequency harmonic currents tend to flow towards the local capacitor used for voltage support or reactive compensation





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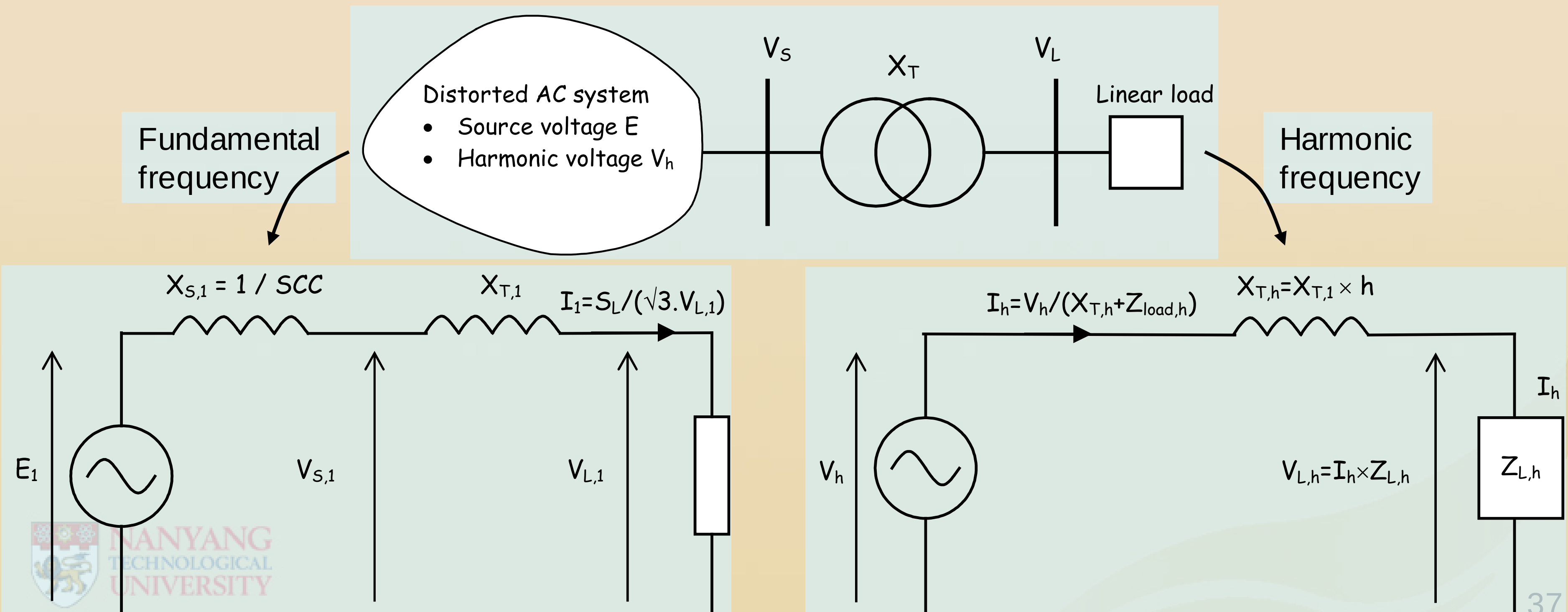
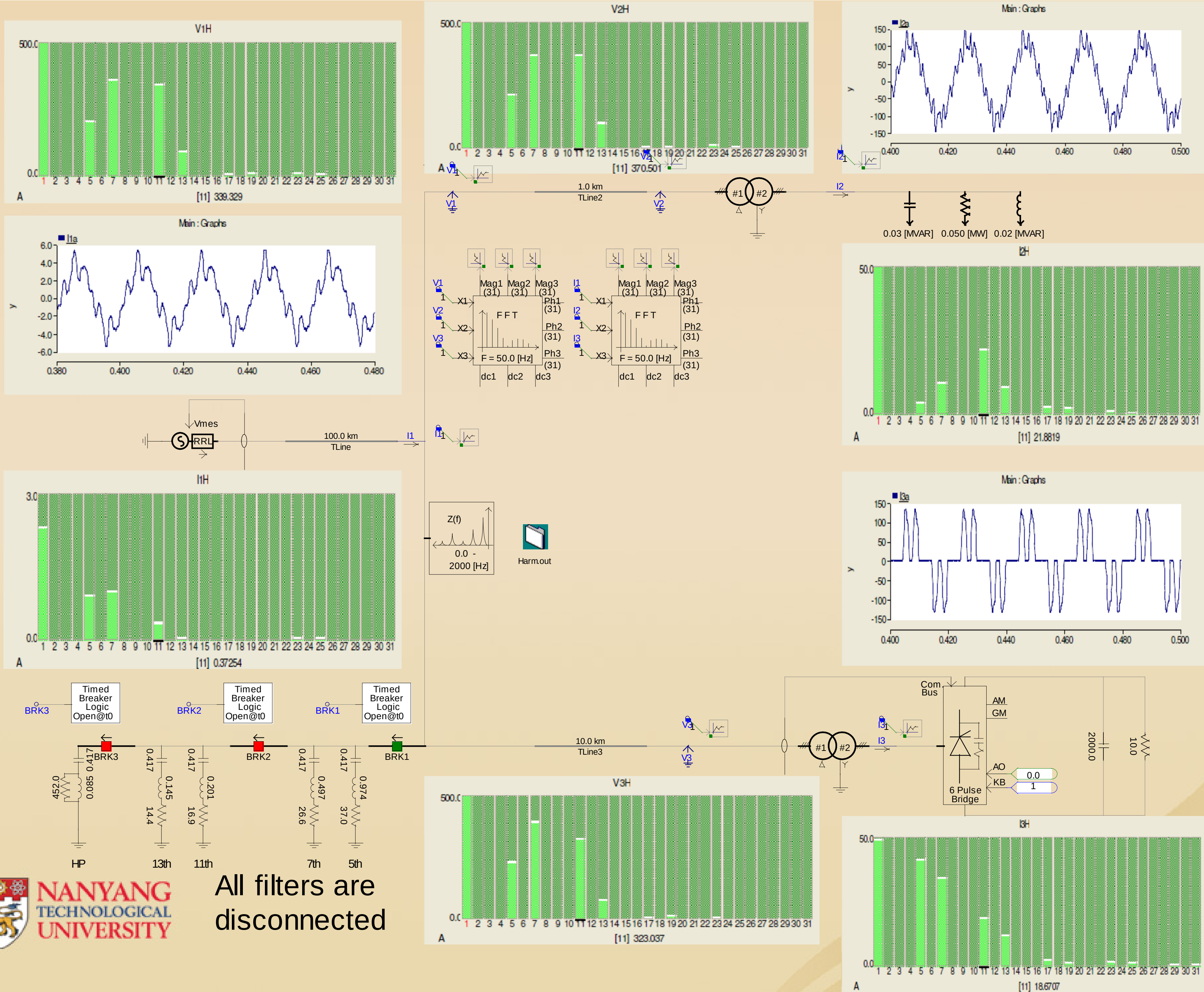
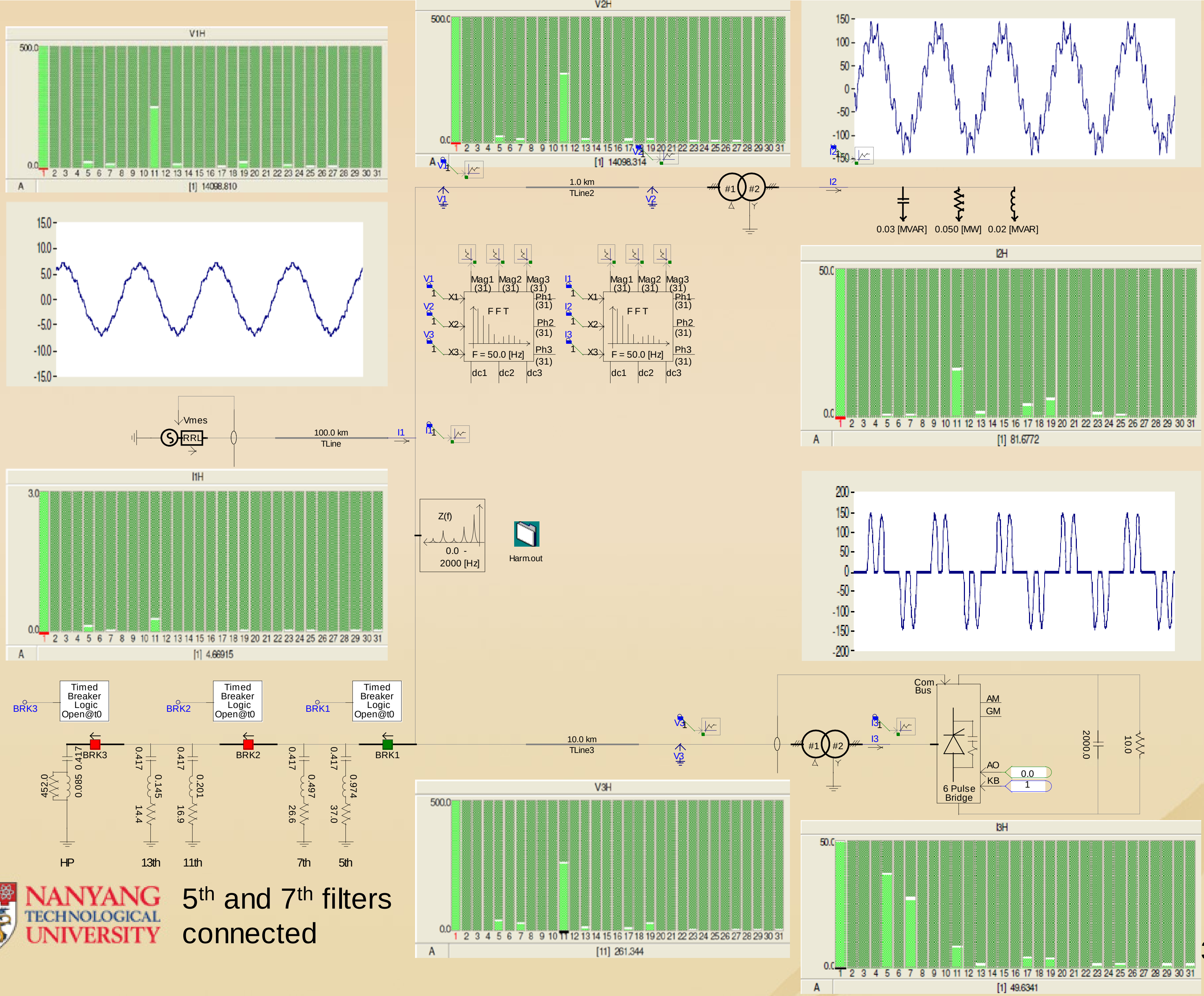
Analyzing effect of distorted system voltage on loads

- System voltage may already be distorted
  - Combined effect of system impedance and harmonic currents from non-linear loads of other customers
  - All loads including linear load would be subjected to a distorted supply voltage
    - At fundamental frequency, load terminal voltage is less than source voltage E due to voltage drop across the system impedance caused by flow of load power/current
    - At a harmonic frequency, harmonic voltage would appear across the load, resulting in flow of harmonic current into the load





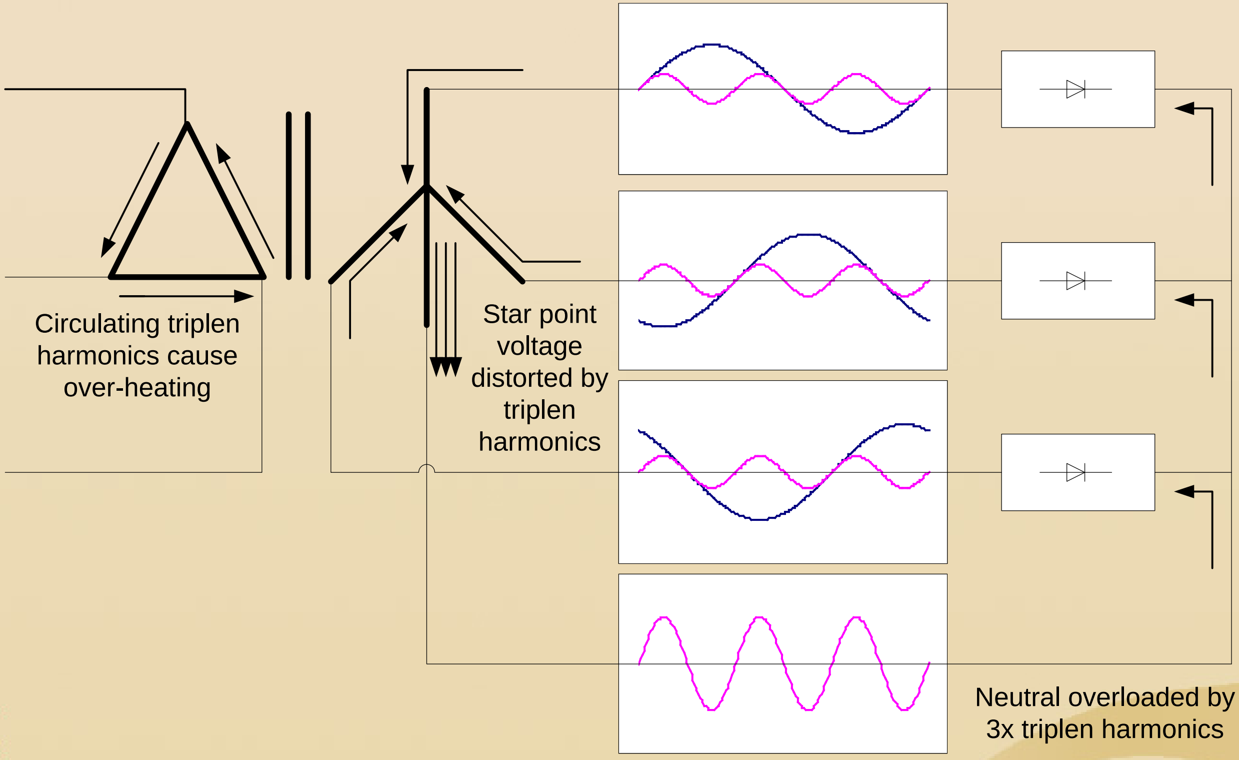
All filters are disconnected



5th and 7th filters connected

Triplen harmonics

- Odd multiples of 3rd harmonic, e.g. 3rd, 9th, 15th, 21st
  - Zero sequence if the system and load are balanced
- Zero sequence triplens sum up at neutral
  - Neutral overloading
  - Transformer overheating
  - Distorted star point (neutral) voltage



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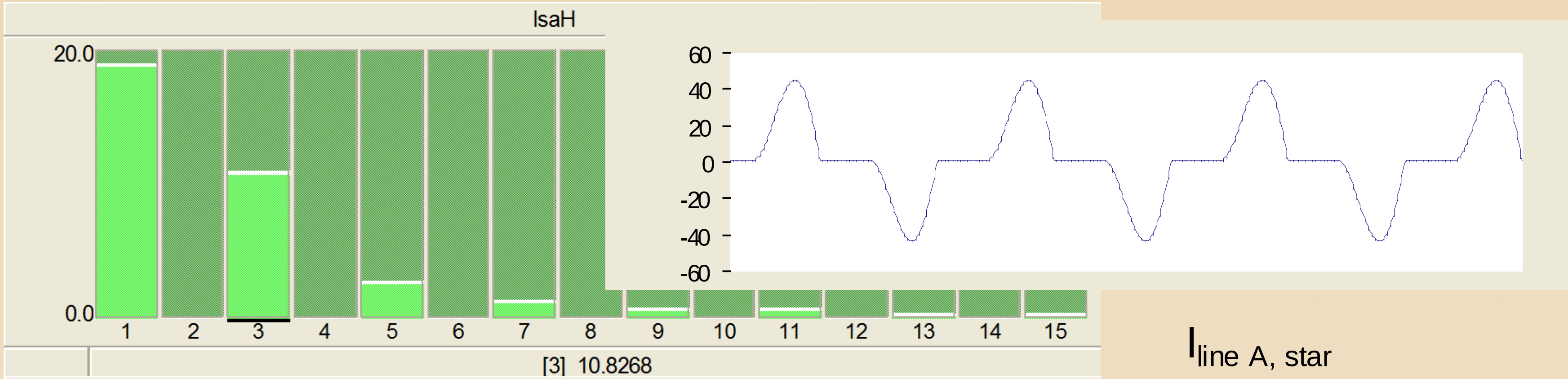
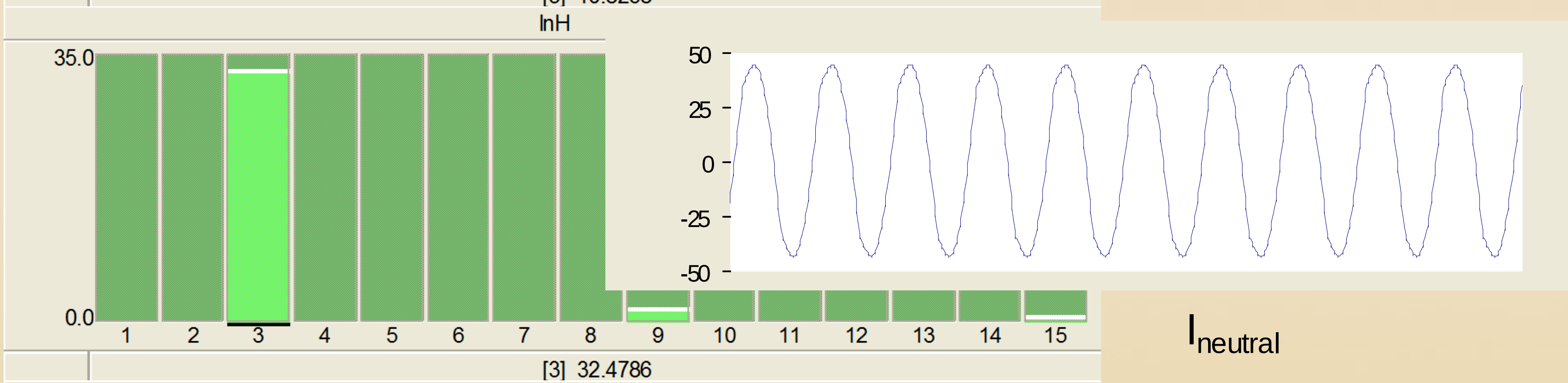
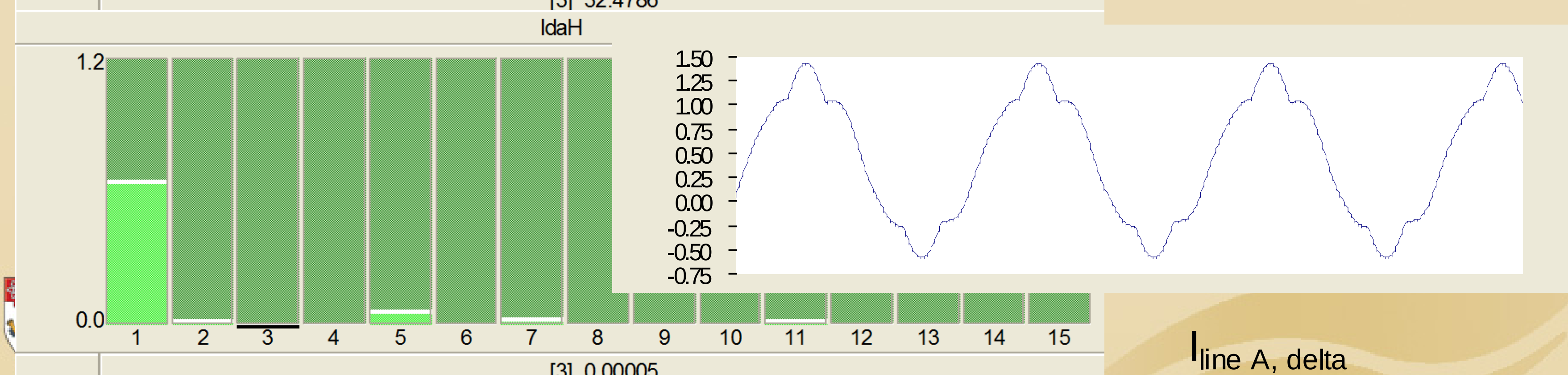
Transformer line currents



$I_{\text{line A, star}}$



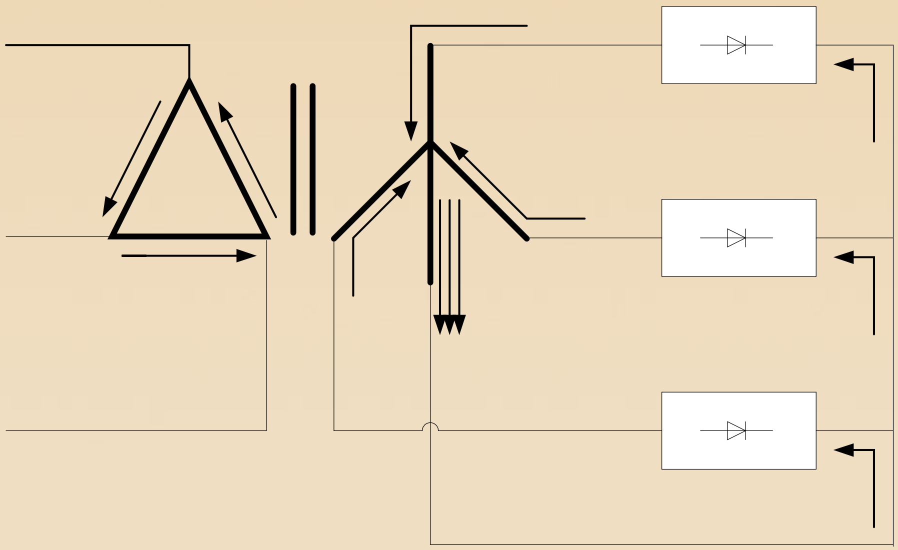
I_{neutral}



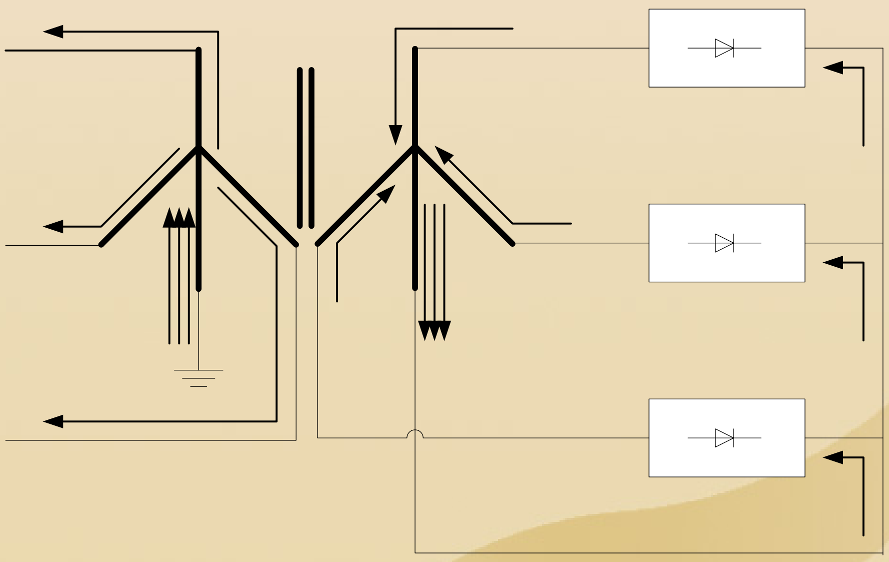
$I_{\text{line A, delta}}$

Transformer effect on triplens

- Zero sequences are trapped, circulating in delta winding
  - Do not propagate into supply system
  - Harmonic problem confined within the distribution network
  - Overloading/overheating not obvious from line side measurements



- Wye-ground connection allows zero-sequence to penetrate upstream into the ac supply system
  - Harmonic problem is extended into the supply networks



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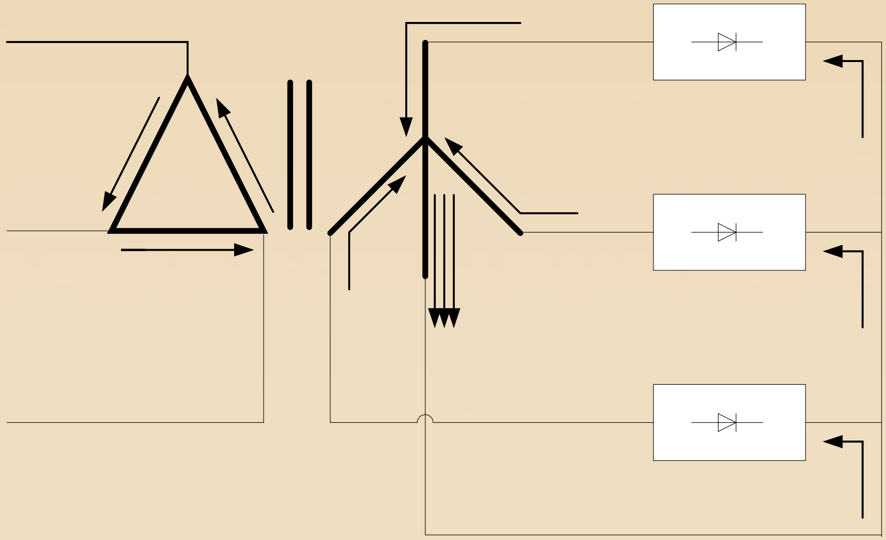
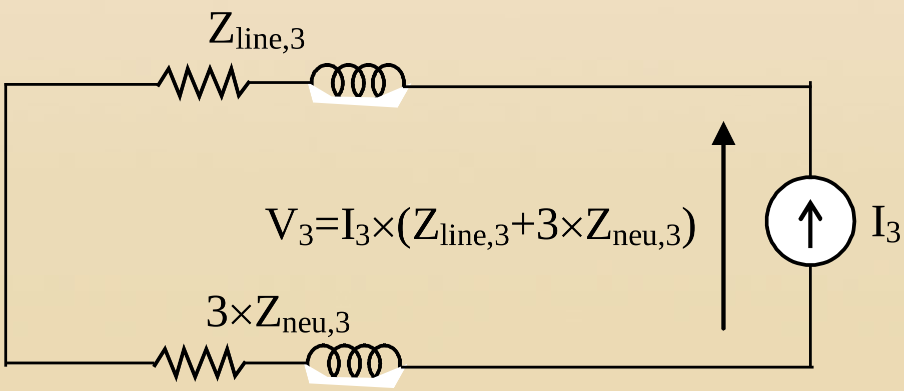
Triplen harmonic voltages

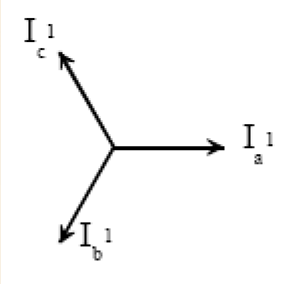




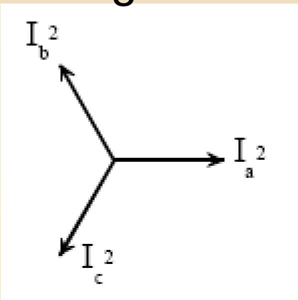
Fundamentals of symmetrical components

- In 1918, Fortescue developed the idea of breaking up asymmetrical three-phase voltages and currents into three sets of symmetrical components
  - Positive sequence currents and voltages (known also as the "abc" and often denoted by the superscript "1" or " + ") shown on the right.
  - Negative sequence currents and voltages (known also as the "acb" and often denoted by the superscript "2" or " - ".)
    - Note the sequence of the phasors is the opposite direction from the positive sequence (acb instead of abc.)
  - Zero sequence components of currents and voltages (often denoted by the superscript "0".)
    - Note that these zero sequence phasors are all in-phase and equal in magnitude.

Positive



Negative

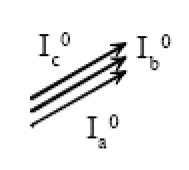


$$I_a^1 = I_a^1\angle 0° = I_a^1 \qquad I_a^2 = I_a^2\angle 0° = I_a^2$$

$$I_b^1 = I_a^1\angle 240° = a^2 I_a^1 \qquad I_b^2 = I_a^2\angle 120° = aI_a^2 \qquad I_a^0 = I_b^0 = I_c^0$$

$$I_c^1 = I_a^1\angle 120° = aI_a^1 \qquad I_c^2 = I_a^2\angle 240° = a^2 I_a^2$$

Zero



$$a = 1\angle 120° \quad ; \quad a^2 = 1\angle 240°$$

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Symmetrical component transformation

- An unbalanced current is made up of all symmetrical components

$$I_a = I_a^0 + I_a^1 + I_a^2 = I_a^0 + I_a^1 + I_a^2$$
$$I_b = I_b^0 + I_b^1 + I_b^2 = I_a^0 + a^2 I_a^1 + a I_a^2$$
$$I_c = I_c^0 + I_c^1 + I_c^2 = I_a^0 + a I_a^1 + a^2 I_a^2$$
$$I_n = I_a^0 + I_b^0 + I_c^0 = 3I_a^0$$

$$\begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \begin{pmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{pmatrix}$$

- Similarly, phase components can be transformed into symmetrical components

$$\begin{pmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix} \begin{pmatrix} I_a \\ I_b \\ I_c \end{pmatrix}$$

$$I_a^0 = \frac{1}{3}\left(I_a + I_b + I_c\right)$$
$$I_a^1 = \frac{1}{3}\left(I_a + aI_b + a^2 I_c\right)$$
$$I_a^2 = \frac{1}{3}\left(I_a + a^2 I_b + aI_c\right)$$

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Unbalanced system with harmonics

- When system is unbalanced or the non-linear loads are not balanced across the three phases
  - All harmonics comprise of all symmetrical components
    - Fundamental frequency would be made up of mainly positive sequence but with certain levels of negative and zero sequences
    - Third harmonic would be made up of mainly zero sequence component but with some positive and negative sequence components
    - Fifth harmonic would be made up of mainly negative sequence component but with certain levels of positive and zero sequences
- Irrespectively of the harmonic order (frequency)
  - Positive and negative sequence components would pass unimpeded through transformer of all configurations including those with delta or ungrounded star winding connections
  - Zero sequence components would be blocked by delta winding configuration
  - Systems without neutral connection will not have any zero sequence component at anywhere in the system

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Calculating unbalanced currents

- Non-linear single phase converter loads are not evenly distributed in a system supplied via a delta/star transformer

$$I_a = 1.6\angle 25^\circ, \quad I_b = 1.0\angle 180^\circ, \quad I_c = 0.9\angle 132^\circ$$

- Corresponding symmetrical components are

$$\begin{pmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{pmatrix}\begin{pmatrix} 1.6\angle 25^\circ \\ 1.0\angle 180^\circ \\ 0.9\angle 132^\circ \end{pmatrix} = \begin{pmatrix} 0.45\angle 96.45^\circ \\ 0.94\angle -0.06^\circ \\ 0.60\angle 22.32^\circ \end{pmatrix}$$

- Over at the transformer primary side
  - Only positive and negative sequence components exist

$$I_a = \frac{N_2}{N_1}\left(I_a^0 + I_a^1 + I_a^2\right) = \frac{N_2}{N_1}\left(0 + 0.94\angle -0.06^\circ + 0.60\angle 22.32^\circ\right)$$

- Neutral current on transformer secondary side
  - Only zero sequence component flows in the neutral

$$I_n = I_a + I_b + I_c = 3I_a^0 = 3\times 0.45\angle 96.45^\circ = 1.35\angle 96.45^\circ$$

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Effects of harmonic distortions

- Possibility of amplification of harmonic levels
  - Parallel resonance from amplification of harmonic currents
  - Series resonance from amplification of harmonic voltages
- Reduction in the efficiency of the generation, transmission and utilization of electric energy
  - Increased resistive losses due to additional flow of harmonic currents

$$P_{losses} = I_{rms}^2 R = \sum_{n=1,2\ldots n} I_n^2 \cdot R$$

  - Increased losses in magnetic core of all power equipment, due to additional magnetic flux at harmonic frequencies
- Ageing of insulation of electrical plant components with consequent shortening of their useful life
  - Higher potential difference across dielectric / insulation results in higher stress
- Malfunctioning of system or plant components
  - Many controls assume supply voltage is sinusoidal and use it as reference
  - Control instability if the feedback loop has resonance close to one of the harmonic frequencies

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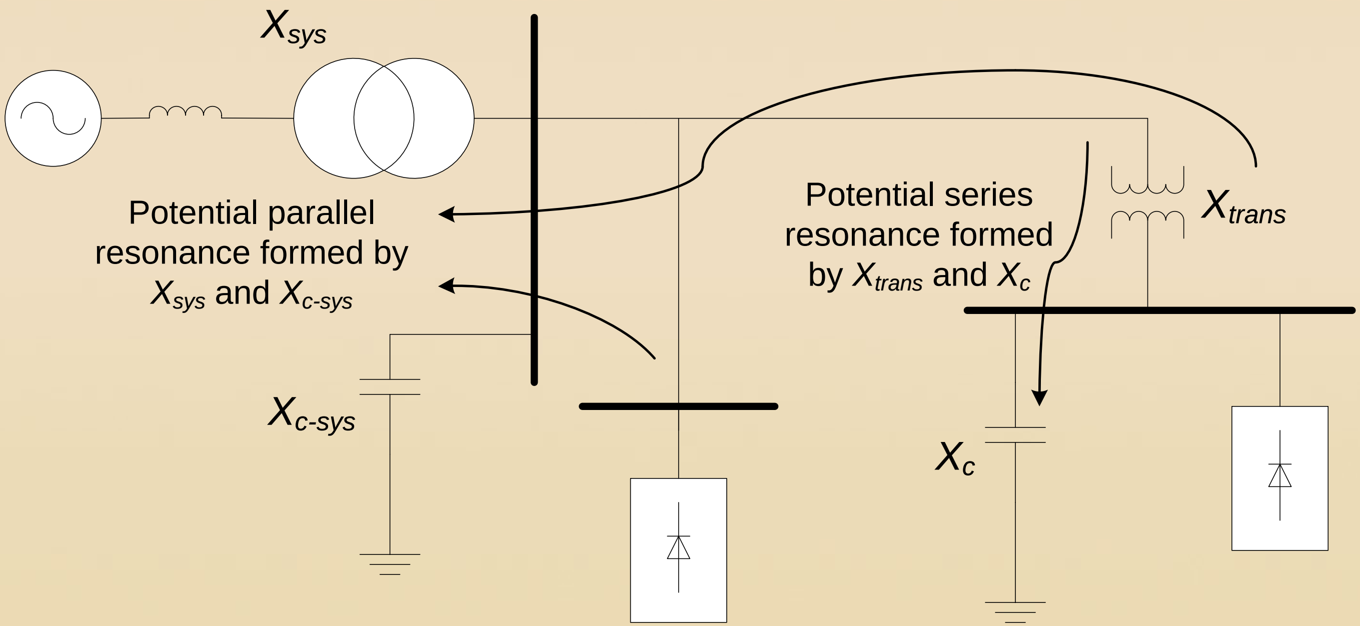
Parallel and series resonances

- Resonance occurs when an inductive reactance equal to a capacitive reactance at or near a characteristic harmonic frequency
  - Parallel resonance involving supply system and substation capacitors or supply system with power factor correction capacitor
  - Series resonance made up of distribution transformer and power factor improvement capacitor



- A resonance point becomes problematic only when there is a harmonic source that excites (kick-starts) the resonance effect
  - Harmonic frequency is close to or equal to the resonance frequency

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Visualizing harmonic resonances

- Viewed from the source of harmonic distortion
  - Potential parallel resonance when there is an inductive element connected in parallel to a capacitive element
  - Potential series resonance when these two elements are connected in series
- Resonance frequency
  - In terms of *L* and *C*,

$$\left.\begin{aligned} X_{L,r} &= X_{C,r} \\ 2\pi f_r L &= \frac{1}{2\pi f_r C} \end{aligned}\right\} \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

  - In terms of their fundamental reactance

$$\left.\begin{aligned} X_{s,h} &= X_{c,h} \\ X_{s,\,fund} \times h &= \frac{X_{c,\,fund}}{h} \end{aligned}\right\} \quad h = \sqrt{\frac{X_{c,\,fund}}{X_{s,\,fund}}}$$

  - In terms of the capacitor's power ratings and system short circuit capacity (assuming that capacitor voltage rating is equal to = system nominal voltage)

$$\left.\begin{aligned} X_{s,\,fund} &= \frac{1}{S_{scc}} \\ X_{c,\,fund} &= \frac{1}{S_{cap}} \end{aligned}\right\} \quad h = \sqrt{\frac{S_{scc}}{S_{cap}}}$$

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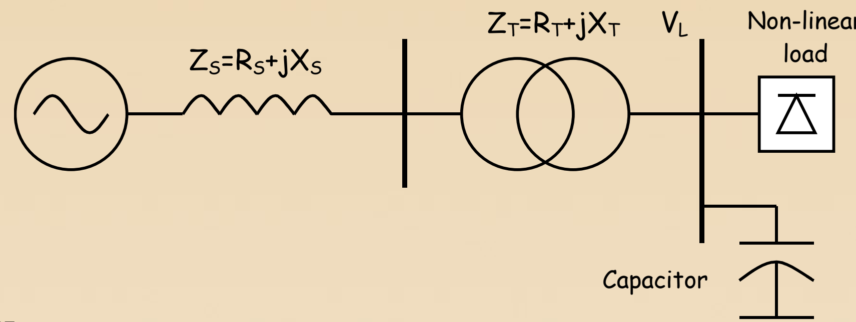
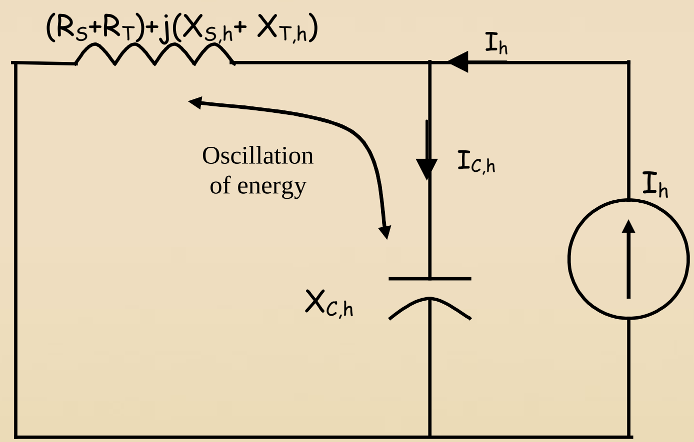
Parallel resonance and current amplification

$$Z_{sys,h} = R_{sys} + jX_{sys,h}$$
$$= \left(R_S + R_T\right) + j\left(X_{S,h} + X_{T,h}\right)$$
$$I_{c,h} = I_h \times \frac{\left(R_{sys} + jX_{sys,h}\right)}{\left(R_{sys} + jX_{sys,h}\right) + \left(-jX_{c,h}\right)}$$



- At or near resonant frequency, $X_{sys,h} = X_{c,h}$

$$\frac{I_{c,h}}{I_h} = \frac{\left(R_{sys} + jX_{sys,h}\right)}{R_{sys}} = 1 + j\frac{X_{sys,h}}{R_{sys}} \approx j\frac{X_{sys,h}}{R_{sys}}$$



- A high impedance at or near the resonance frequency being presented to the harmonic source, considered as a current source
  - Increased harmonic voltages at both load terminal and the entire supply system
  - High harmonic currents in each leg of the parallel impedance
    - Can be viewed as current amplification, which depends on the system X/R ratio

$$V_{L,h} = I_{ch} \times \left(-jX_{c,h}\right) = I_h \times \frac{\left(R_{sys} + jX_{sys,h}\right)\left(-jX_{c,h}\right)}{\left(R_{sys} + jX_{sys,h}\right) + \left(-jX_{c,h}\right)} \approx I_h \times \frac{\left(R_{sys} + jX_{sys,h}\right)\left(-jX_{c,h}\right)}{R_{sys}}$$

    - System resistance helps to damp oscillations and hence lower amplification

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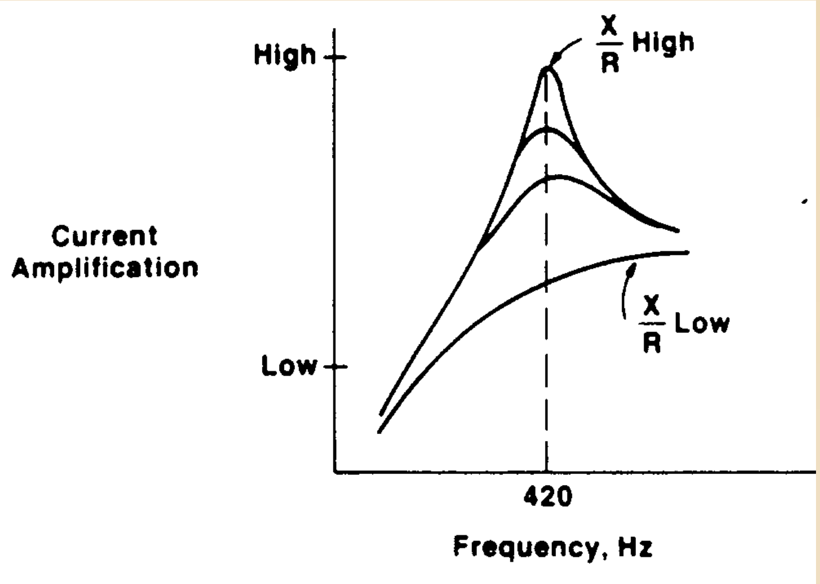
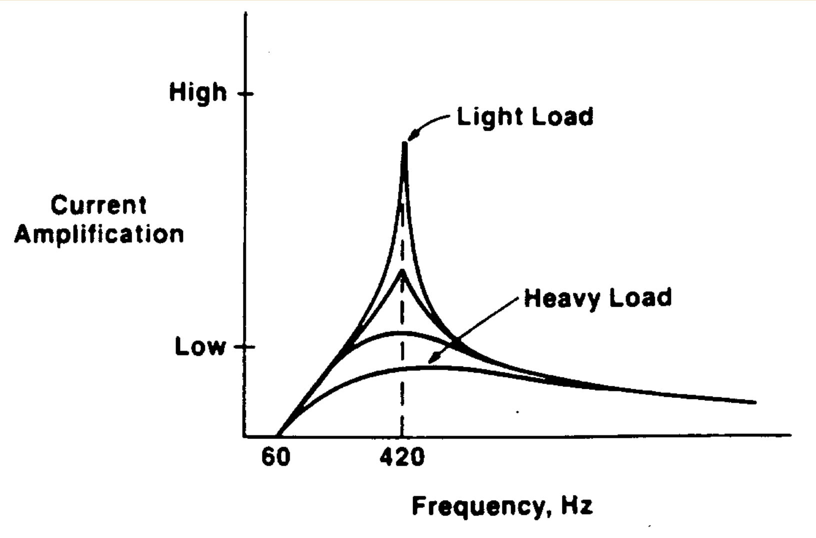
Severity of parallel resonance

- More resistance in the circuit will help to reduce the level of current amplification during parallel resonance condition



- Loads are connected in parallel to the capacitor and hence each additional load provides an alternative path for the harmonic current.
- Higher load levels resulting in more alternative path and hence lower level of current amplification



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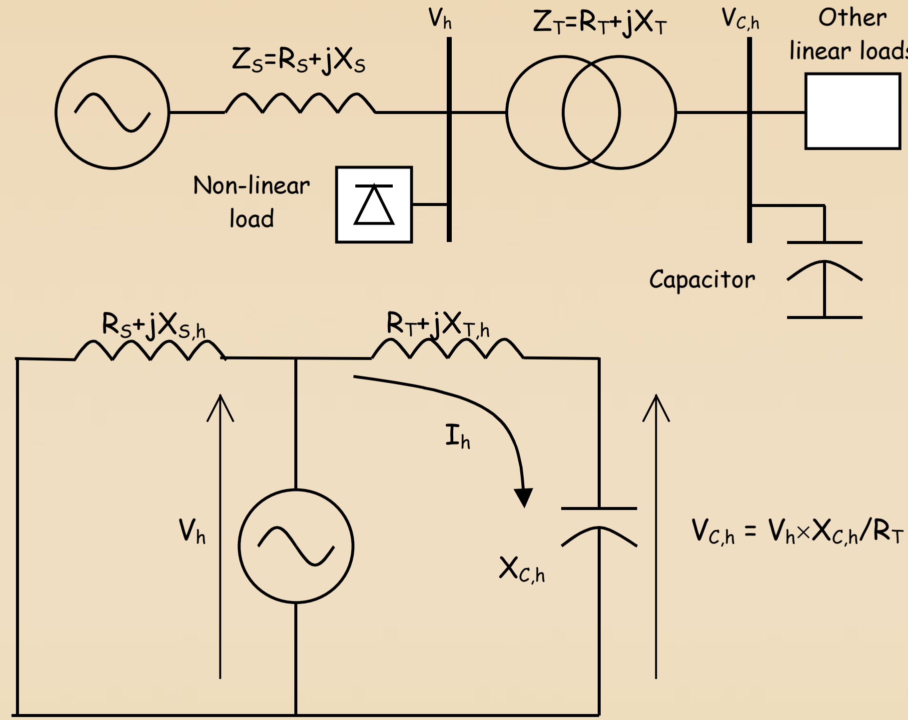
Series resonance and voltage amplification

- At high frequencies, load impedance can be ignored as $X_{c,h}$ reduces

$$
\begin{aligned}
I_h &= \frac{V_h}{\left(R_T + jX_{T,h}\right) + \left(-jX_{c,h}\right)} \\
V_{c,h} &= I_h \times \left(-jX_{c,h}\right) \\
&= \frac{V_h}{\left(R_T + jX_{T,h}\right) + \left(-jX_{c,h}\right)} \times \left(-jX_{c,h}\right) \\
&= V_h \times \frac{\left(-jX_{c,h}\right)}{\left(R_T + jX_{T,h}\right) + \left(-jX_{c,h}\right)}
\end{aligned}
$$

  - At or near resonant frequency,

$$
X_{T,h} = X_{c,h} \quad \Rightarrow \quad \frac{V_{c,h}}{V_h} = \frac{-jX_{c,h}}{R_T} = \frac{1}{j\omega_h C \cdot R_T}
$$



- Results in a near short-circuit (low impedance) at a resonant frequency
  - High capacitor current can flow for relatively small harmonic voltage
    - High current causes overloading and overheating to transformer and capacitor
    - High voltage distortion at load terminal
- Resonant frequency considering load ratings,

$$
f_s = f\sqrt{\left(\frac{S_t}{S_C Z_t} - \frac{S_l^2}{S_C^2}\right)}
$$

- S_t, Z_t : transformer rating and per unit impedance
- S_c, S_l : capacitor rating and load rating (resistive)

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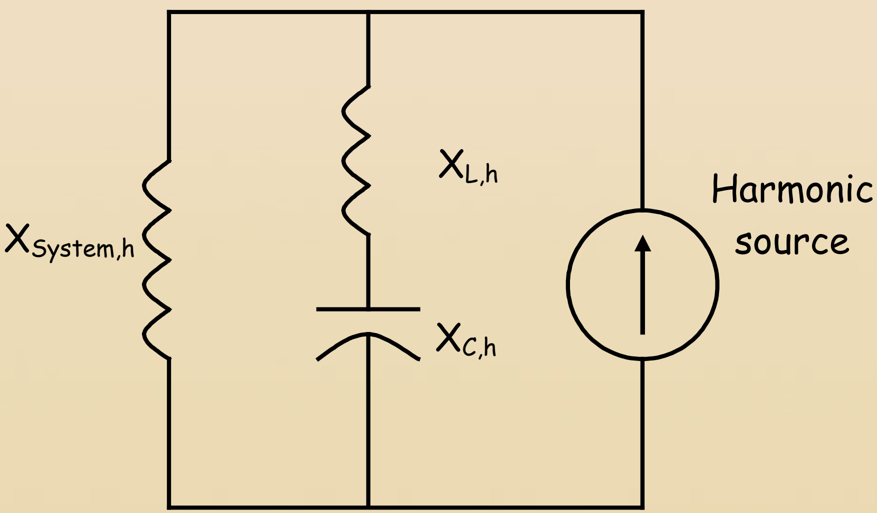
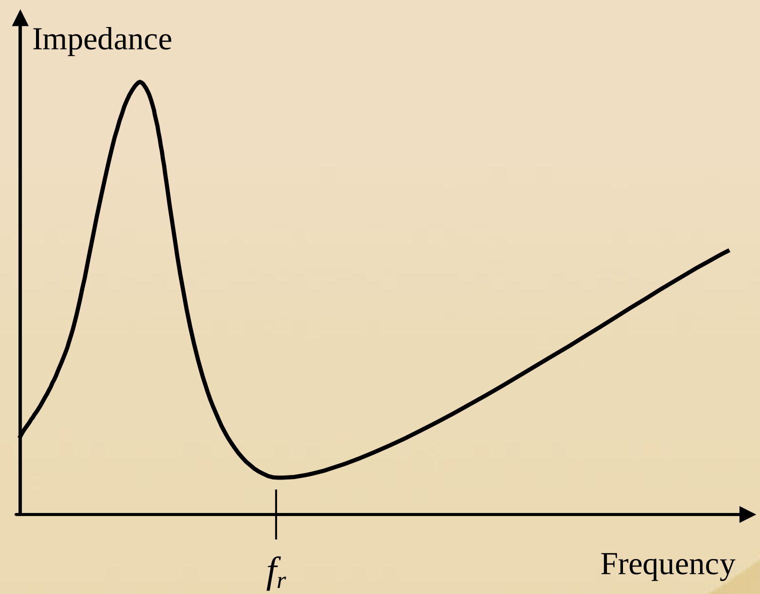
Concurrent parallel and series resonances

- At frequency lower than the series resonant frequency,
  - The series branch of transformer inductive impedance and capacitor reactance becomes capacitive as X_c increases with decreasing frequency
  - This branch will result in a parallel resonance with the system impedance (which is inductive) at a frequency slightly lower than the series resonant frequency

$$f_p = f_{fund}\sqrt{\frac{X_{C,fund}}{X_{S,fund} + X_{L,fund}}}$$





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Effect of harmonics on rotating machines

- Extra losses in stator windings, rotor circuits, stator / rotor laminations
  - Distorted voltages applied to electrical machines may cause overheating
    - Motors normally not derated if harmonic voltage remains below 5%
  - Stator / rotor conductor losses are greater due to eddy-currents and skin effect
  - Approximate assessment of the additional thermal stress of the coils can be achieved by a weighted distortion factor adapted to inductance, i.e.

$$THD_L = \frac{\sqrt{\sum_{n=2}^{N}\left(\frac{V_n^2}{n^{\alpha}}\right)}}{V_1}$$

  - α = 1 to 2
  - V_n is the single frequency rms voltage at harmonic n
  - N is the maximum order of harmonic to be considered
  - V_1 is the fundamental line to neutral rms voltage

  - Capability of machine to withstand harmonic currents depend on the effect of additional losses on machine overall temperature rise and local overheating (probably in the rotor)
- Harmonic torques
  - Harmonic currents in stator produce motoring action (positive slips)
    - Positive sequence harmonics develop shaft torques aiding shaft rotation
    - Negative sequence harmonics have opposite effect
    - Torques tend to be small and occur in pairs, canceling each other
  - Little effect upon mean torque but can produce significant torque pulsations

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Effect of harmonics on transmission system

- Additional power losses caused by increased rms current

$$\sum_{n=2}^{\infty} I_n^2 R_n$$

  - I_n is the n^{th} harmonic current
  - R_n is the system resistance at that harmonic frequency
  - Skin and proximity effects are function of frequency, raising the value of ac resistance of cable, increasing the conductor I^2R losses
- Harmonic current flow creates harmonic voltage drops across the circuit impedances
  - A weak system (large impedance and low fault level) will result in greater voltage distortions than a stiff system (low impedance and high fault level)
  - In transmission by cable, harmonic voltages increase the dielectric stress in proportion to their crest voltages
    - Shortening of useful life
    - Increase the number of faults
  - Corona starting and extinction levels are a function of peak-to-peak voltage
    - Peak voltage depends on phase relationship between harmonics and fundamental
    - Possible for peak voltage to be above the rating while rms voltage is well within limit

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Effect of harmonics on transformers

- Additional heat generated by the losses caused by harmonics
  - Presence of harmonic voltages increases hysteresis and eddy current losses in the lamination and stresses the insulation
  - Flow of harmonic currents increases copper losses
  - Converter transformers do not benefit from the presence of filters
    - Extra rating is necessary
    - Often develop unexpected hot spots in the tank
  - Delta winding overloaded by circulation of triplen frequency zero-sequence current, unless these extra currents are considered in the design
    - Additional heating in tanks, core clamps caused by zero-sequence harmonic fluxes
    - Derating factor,
      - I_R is fundamental rms current under rated load conditions
      - $P_{EC\text{-}R}$ is the ratio of eddy-current loss to rated I^2R loss

$$K = \sqrt{\frac{\sum_h \left(I_h^2 h^2\right)}{\sum_h I_h^2}} \Rightarrow I_{\max} = \sqrt{\frac{1+P_{EC-R}}{1+KP_{EC-R}}}\left(I_R\right)$$

- Other effects on transformer
  - Possible resonances between transformer inductance and system capacitance
  - Mechanical insulation stress (winding and lamination) due to temperature cycle
  - Possible small core vibrations

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Effect of harmonics on capacitor banks

- Presence of voltage distortion increases the dielectric loss

$$\sum_{n=1}^{\infty} C(\tan\delta)\omega_n V_n^2$$

  - $\tan\delta = R/(1/\omega C)$ is the loss factor
  - $\omega_n = 2\pi f_n$
  - V_n is the r.m.s. voltage of the nth harmonic
  - The additional thermal stress can be assessed approximately with the help of a special capacitor weighted THD factor,

$$THD_C = \frac{\sqrt{\sum_{n=1}^{N}\left(n \cdot V_n^2\right)}}{V_1}$$

- Series and parallel resonances with the rest of system
  - Overvoltages and high currents result in increased losses and overheating
  - PF correction capacitor is often tuned to about 3rd or 5th harmonic frequency by adding a small series inductance (about 9% or 4% respectively) to make it look inductive above these frequencies and thus avoid parallel resonance

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Capacitor operation under distorted condition

- Maximum continuous operating voltage, current, and kVAr (IEEE Std 18)
  - Capacitors shall be capable of continuous operation under contingency system and bank conditions provided that none of the following limitations are exceeded:
    - 110% of rated rms voltage
    - 120% of rated peak voltage, i.e. peak voltage not exceeding $1.2 \times \sqrt{2} \times$ rated rms voltage, including harmonics, but excluding transients
    - 135% of nominal rms current based on rated kVAr and rated voltage
    - 135% of rated kVAr
- When choosing capacitors for use in harmonic filter
  - Capacitor must be rated according to the above guideline

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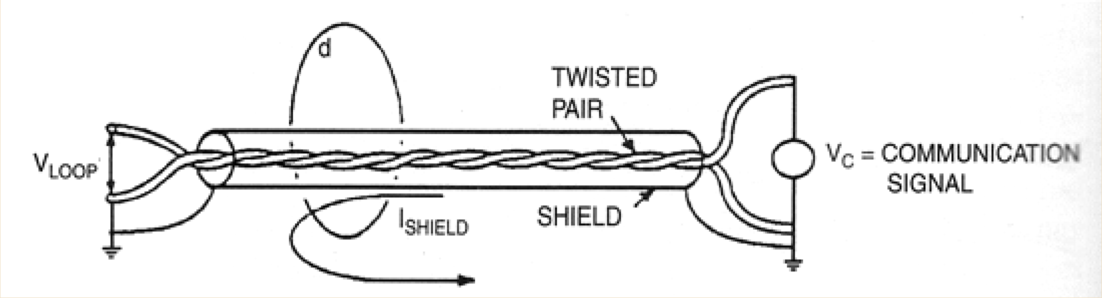
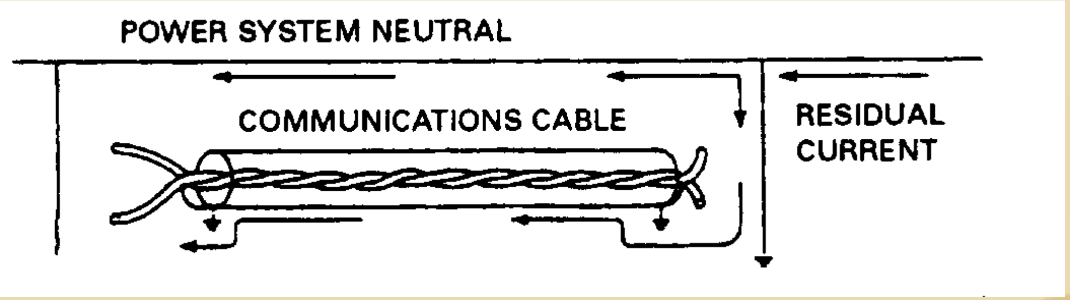
Harmonic currents flowing in the shield

- Even with shielded twisted-pair conductors for telephone circuit, inductive coupling can still be a problem
  - High harmonic current induced in the shield surrounding telephone conductors, resulting in IR voltage drop, which leads to potential difference in the ground references at ends of the telephone cable



- Direct conduction can also cause harmonic current flowing in the shield
  - Shield in parallel with power system ground path
  - High shield IR drop causes potential difference in ground references



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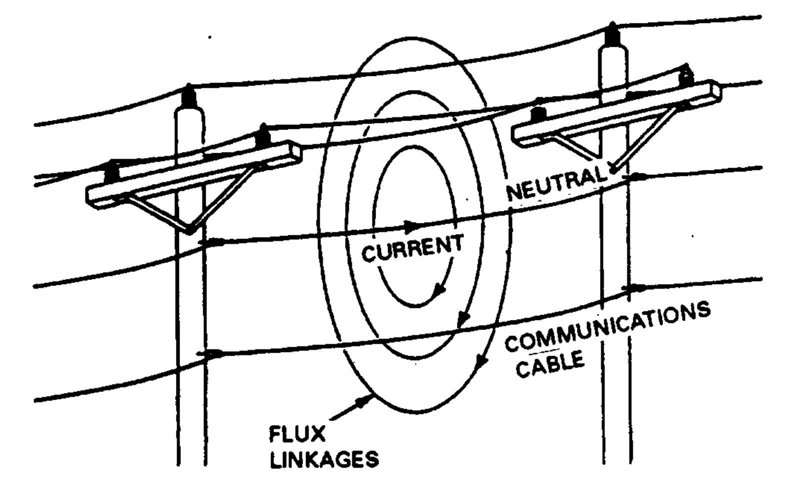
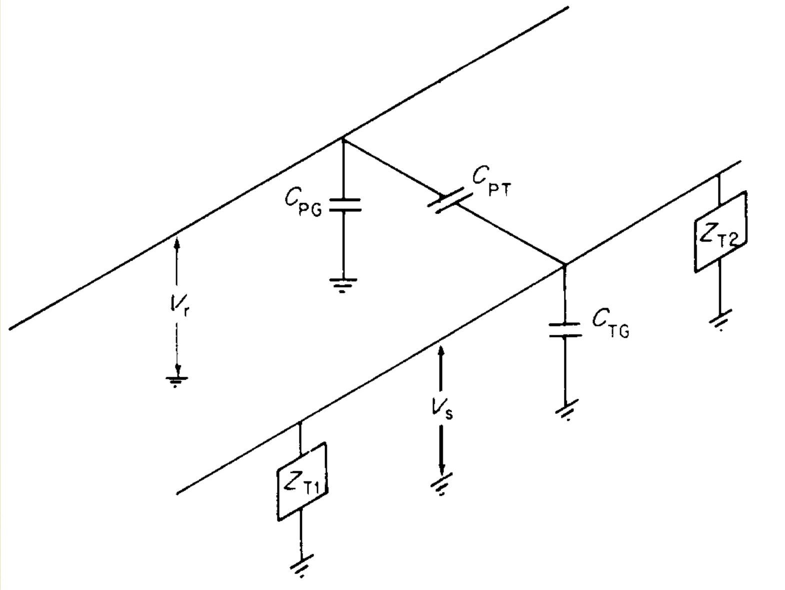
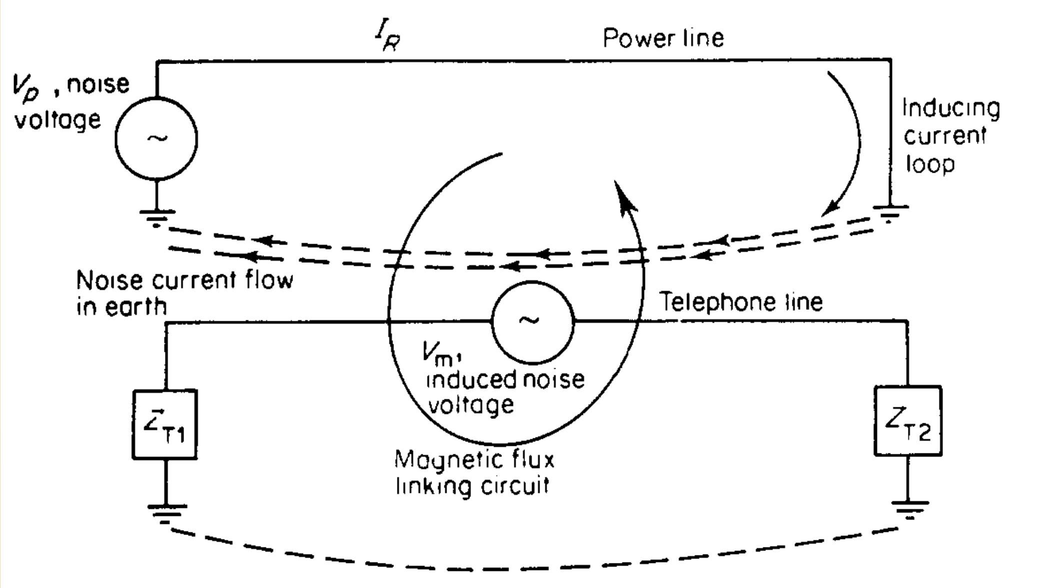
Telecommunication interference

- Residual voltages
  - electrostatic induction
- Residual currents
  - electromagnetic induction
- Important factors
  - Influence of power systems
  - Coupling to communication circuits
  - Susceptiveness of communication circuits







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Underlying concerns with harmonic distortions

- Large harmonic currents
  - Overloaded / overheated transformers and conductors
  - Nuisance breaker trippings
  - Increased losses
- Harmonic current flow path is too long
  - High voltage distortion,
  - High neutral to ground voltages
  - Electronic equipment failures, interferences
- Badly distorted voltage
  - Additional stress on insulation and dielectrics
  - Additional iron core losses
- System resonance magnifies one or more harmonics
  - Damages to system equipments that are in the path of resonance

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Harmonic solution working principles

- Reduce harmonic currents from the source
  - Correct or modify distorted current waveform such that it appears sinusoidal to the system
    - Phase multiplication to cancel low-order characteristic harmonics, leaving only those of high frequencies, with lower magnitudes and lower likelihood to excite resonance
    - Shunt active filters to alter the current waveshape
  - Series blocking filter at transformer neutral to prohibit 3rd harmonic current flow
- Provide alternative path for harmonic currents
  - Minimize the amount of currents penetrating into the ac system
  - Divert harmonic current from over-loaded equipment
  - Shorten harmonic current path by introducing alternative path of lower impedance
    - Passive shunt filters: tuned filters or damped high-pass filters
    - Zigzag transformer close to loads to shorten return path of 3rd harmonic current
- Modify system response frequency to be away from typical (characteristic) harmonic frequencies, avoiding resonances
  - Adding a reactor to power factor correction capacitor making it a filter
  - Shift location of the capacitor, typically into the customer systems
  - .

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Coping with harmonic distortions

- Design equipment to cope with or live with the harmonic distortions
  - Over-sizing or derating of supply equipment
    - Transformer K-factor derating
  - Individual neutral conductor for each phase or double the neutral conductor size
  - Specification of equipment to meet harmonic limits
- Protect sensitive loads from voltage distortions
  - Series active filters to correct the distorted supplied voltage so that it appears as sinusoidal to the load

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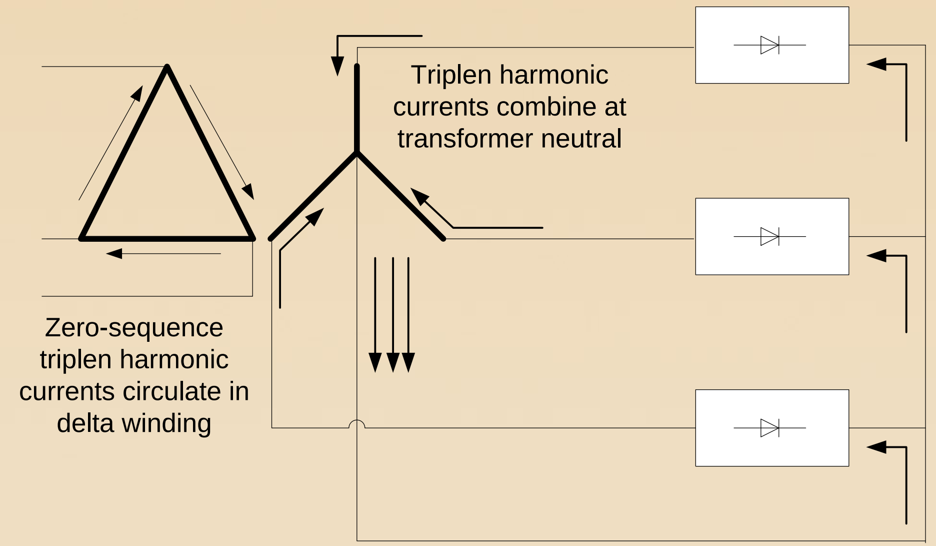
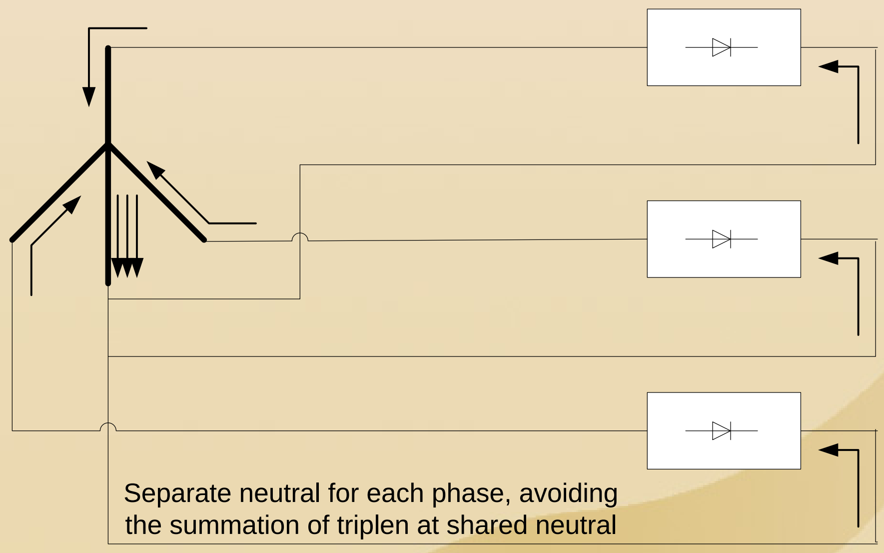
Solving neutral / transformer overloading

- Zero-sequence triplen harmonics
  - Harmonic currents from three phases sum up at the neutral since they are in-phase with each other
  - Overloading and overheating of neutral conductors
  - Zero-sequence currents circulate in transformer delta winding, raising losses and temperature
- Separate / individual neutral for each phase
  - Avoid the summing effect of zero-sequence currents at the neutral
  - Avoid overloading and overheating of the neutral conductor
  - Unchanged overloading and overheating effect at transformer



With ordinary delta-star transformer



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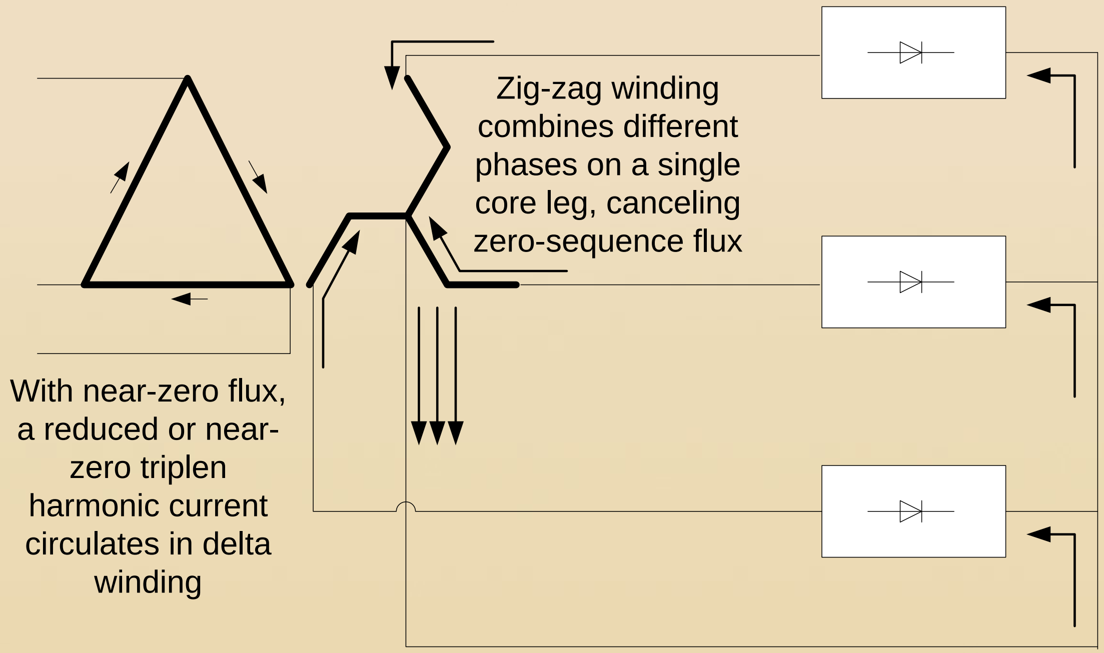
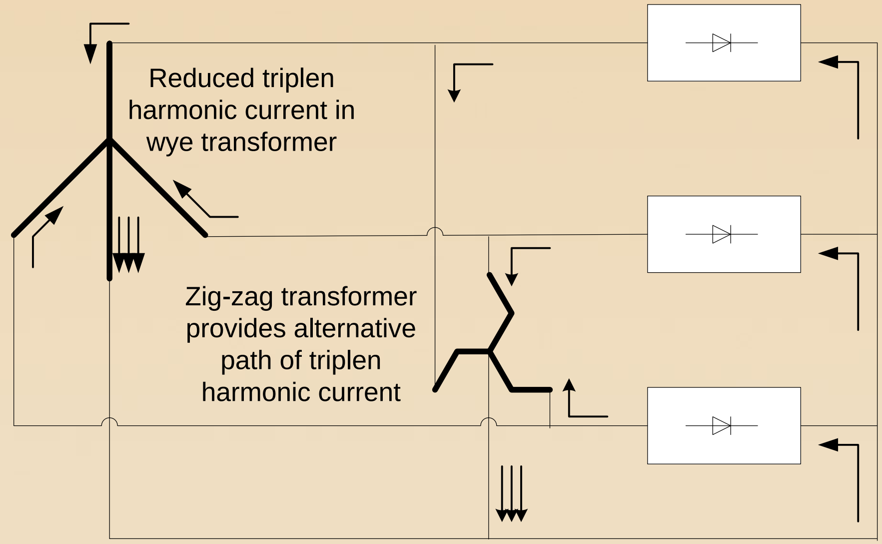
Harmonic mitigation using zig-zag transformer

- Attenuate triplen harmonics by using a zig-zag winding on transformer secondary
  - Half of the turns of each phase is wound around two legs of transformer core
  - Cancellation of magnetic flux established by triplen harmonic currents, so little or none is transferred to the primary windings
  - Flux cancellation also results in much lower impedance to the zero-sequence currents, and hence lower voltage distortions at these frequencies



With harmonic mitigation zig-zag transformer

Third-harmonic shunt filter



- Three-phase dry-type zig-zag autotransformers
  - Wound on a common core
  - Designed for very low zero-sequence impedance (usually < 1%)
  - Installed in parallel at panel or bus duct close to harmonic loads
  - Forms alternative and shorted path of 3rd harmonic current
  - Confine zero-sequence current to conductors that are close to non-linear loads only
- Advantages
  - No capacitor ➔ no harmonic resonance
  - Reduce 3rd harmonic currents in both phase and neutral conductors upline of zig-zag transformer
    - reduces neutral conductor loading and losses
    - reduces transformer heating and the need for k-rated transofmer
    - improve voltage regulations
  - Reduce voltage distortion with lower harmonic currents

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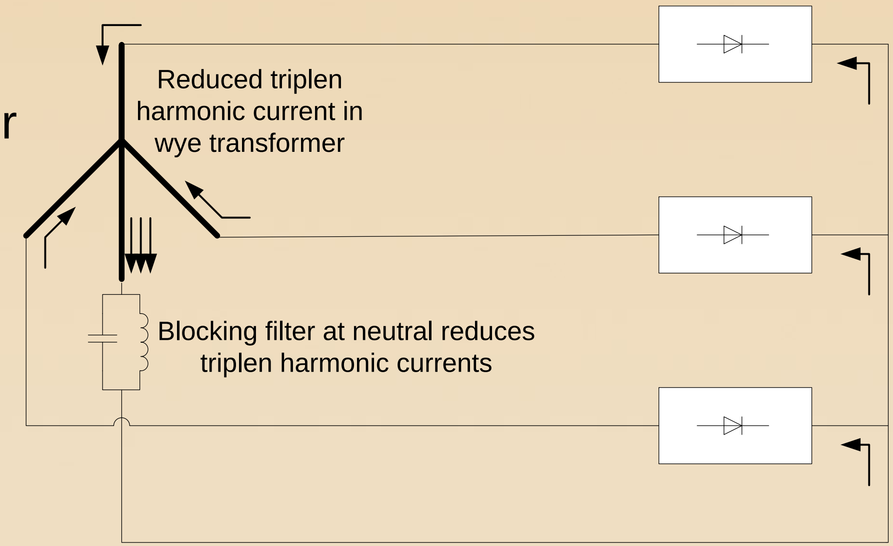
Neutral third-harmonic blocking filter

- RLC band pass filter
  - Installed close to system transformer
  - Tuned to parallel-resonate (high impedance) at triplen frequency, normally at 3rd harmonic, but low impedance at fundamental 50Hz
  - High impedance impedes flow of zero-sequence currents



- Advantages
  - Installed at step-down transformer, thereby limit the 3rd harmonic currents for entire distribution system
- Disadvantages
  - Increased voltage distortion due to the high impedance
  - Voltage distortions change the current characteristics so that the level of 5th and 7th harmonic currents increase
  - Take extra care to make sure it does not affect the fault protection integrity of the system

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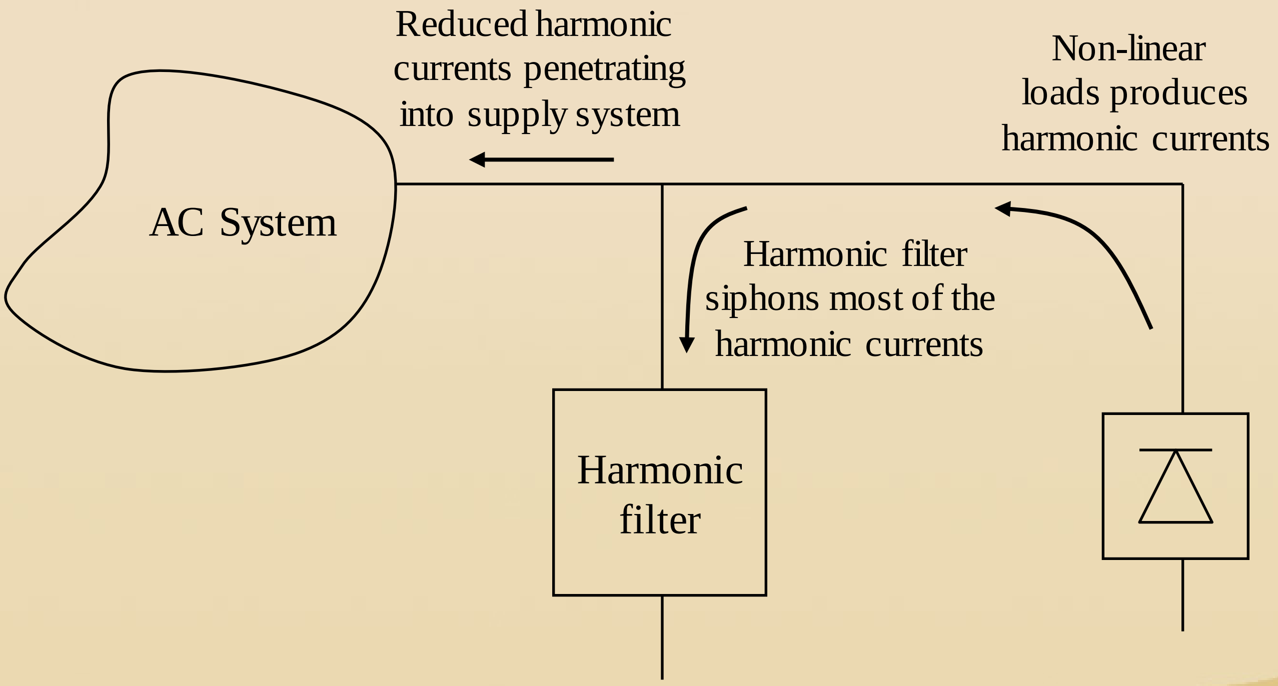
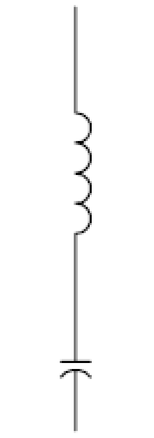
Harmonic filter

- Control harmonic distortions by placing a passive filter close to harmonic producing load/s
  - Harmonic producing device is generally viewed as a harmonic current source
  - Filter is to shunt some of the harmonic currents from the load into the filter
  - Reducing the amount of harmonic current that flows into the power system
  - Filters may involve multiple LC circuits, some may include resistor



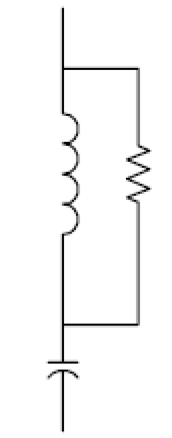
Types of commonly applied harmonic filters

- Band-pass or single-tuned filter
  - Simplest type and widely applied.
  - Almost zero impedance at the resonant frequency, yielding almost perfect filtering at this frequency
  - A drawback is the high value of parallel resonance with the network at some frequency below the tuning point, which may seriously amplify other harmonics, possibly creating a new harmonic problem.
  - Poor filtering of harmonics above the tuning point



(a) Bandpass or Notch

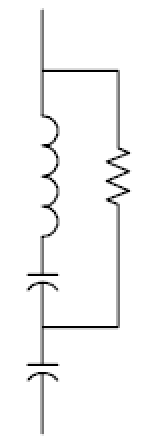
- High-pass harmonic filter
  - Effective compromise between filtering a target frequency and all others above it
  - Typically suitable for tuning at 7^{th} or 11^{th} and higher harmonics
  - Resistor can effectively dampen high frequency notch-type oscillations and lower order parallel resonance
  - Resistor may consume substantial fundamental power; therefore, it is not usually applied at or below the 5^{th} harmonic (see C-type filter)



(b) Highpass or First order

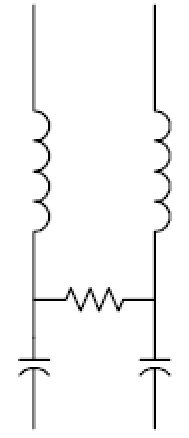
Types of commonly applied harmonic filters

- C-type harmonic filter
  - very similar performance characteristics to the high-pass filter
  - The advantage is that the resistor consumes no fundamental losses
  - For this reason, it is mainly applied where substantial damping is required on filters tuned at or below the 5th harmonic
  - often used in electric arc furnace or cycloconvertor applications to avoid amplifying low-order and noninteger harmonics.



(c)
C-type

- Pi-type harmonic filter
  - Essentially two band-pass harmonic filters tied at the midpoints with a resistor
  - Main advantage is good filtering performance at both resonant frequencies, with very good parallel resonance damping.
  - Typically the resistor can have a lower power rating than a high-pass or C-type harmonic filters
  - Save one resistor as compared to installing two high-pass or C-type harmonic filters.
  - A restriction is that the two harmonic filter legs must be switched as one filter group.



(d)
Pi-type
or
Bridge-type

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Harmonic filter design procedure

- Requires basic information on power system
  - System configurations
  - Impedances of system components (e.g. transformers, lines, sources, capacitors, harmonic filters and shunt reactors)
  - Nominal and maximum voltage
  - Load power ratings and power factors
- Information on local harmonic generation
  - Harmonic measurements at the site are the most accurate
  - If loads are not installed, equipment manufacturers should supply the information
- Divided into 4 steps
  - Step 1: Determine harmonic filter bank kVAr size
  - Step 2: Select initial harmonic filter tuning
  - Step 3: Optimize harmonic filter configuration to meet harmonic guidelines
  - Step 4: Determine the component ratings

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Harmonic filter design - example

- A 30 MVA industrial load is supplied from a 60 Hz 34.5 kV bus
  - Three-phase fault level at the bus is 10.0 kA rms symmetrical
  - The load has a power factor of 0.85 lagging and it is desired to improve the power factor to 0.95
- Step 1: Determine filter bank reactive power (var) size
  - Power factor improvement (or voltage control) requirement determines the “effective kVAr” size of harmonic filter
    - Effective kVAr of filter is less than nameplate kVAr of filter capacitor because of the subtraction effect of the filter reactor

$$Q_{eff}\left(\text{in kVAr}\right)=\left(\text{multiplying factor}\right)\left(\text{load power in kW}\right)\quad\left\{\text{Based on IEEE Std 1036}\right\}$$

$$Q_{eff}=\left(0.291\right)\left(30,000\right)\left(0.85\right)=7420\text{ kVAr}$$

  - Load need 7.4 MVAr from filter bank to raise power factor to 0.95
- Step 2: Select initial filter tuning
  - Typically tuned to the lowest frequency of the most significant harmonics
  - Often not tuned to exact harmonic frequency but 3-15% below the frequency
    - Low impedance at resonance resulting in nearly all harmonic current at that frequency being absorbed by the filter
    - Larger and more expensive filter than necessary to meet harmonic requirement

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– Harmonic filter interact with system impedances to result in a parallel resonance at a frequency just lower than the tuned frequency
  - Variations in system or filter (failure or manufacturing tolerance) could detune the filter resulting in parallel resonance at or near the tuned frequency

$$X_{eff} = \frac{V_{\text{sys,LL}}^2}{Q_{eff}} = X_C - X_L$$

$$X_C = \left(\frac{h^2}{h^2 - 1}\right) X_{eff}$$

$$X_L = \frac{X_C}{h^2}$$

– X_{eff} effective reactance of harmonic filter
– Q_{eff} effective reactive power (MVAr) of filter
– V_{sysLL} nominal system line-to-line voltage (kV)
– X_C reactance of filter capacitor at fundamental frequency
– X_L reactance of filter reactor at fundamental frequency
– h harmonic number (usually non-integer)

– 5th harmonic filter is tuned to 6% below 300Hz

$$h = \frac{0.94 \times 300\ \text{Hz}}{60\ \text{Hz}} = 4.7$$

$$X_{eff} = \frac{(34.5\ \text{kV})^2}{7.4\ \text{MVAr}} = 160.8\ \Omega$$

$$X_C = \left(\frac{4.7^2}{4.7^2 - 1}\right) \times 160.8 = 168.4\ \Omega$$

$$X_L = \frac{X_C}{h^2} = \frac{168.4}{4.7^2} = 7.62\ \Omega$$

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- Step 3: Optimize filter configuration to meet harmonic guidelines
  - Harmonic analysis performed to determine if the design adequately controls the harmonics to meet the limits
    - Finalize the number of harmonic filters, filter tunings and locations
    - Number of filter steps to be switched
    - Contingency of outage of a filter when multiple filters are used
    - Range of system voltage variation, load variation and system configuration changes
    - Detuning of filter by changes to fundamental frequency, component tolerances, and capacitor unit or element outages
    - Characteristic, uncharacteristic and system background harmonics
  - Special care to ensure parallel resonance does not occur, even during switching of individual filter in a multiple filter design
  - Outcome of the analysis is the harmonic spectra for voltage across and current through each filter component
- Estimating harmonic filter current
  - Harmonic measurement over a certain period of time to consider all possible operating conditions is the most accurate way of determining harmonic currents from loads
  - When three-phase (6-pulse) rectifier dominate the harmonic generation
    - Principal harmonics generated are 5^{th}, 7^{th}, 11^{th}, 13^{th} and so on
    - Magnitude of harmonic current is $1/h$ of the fundamental current

– Not all generated harmonic current flows through the harmonic filter

- Some is absorbed by parallel load and some will go into the utility source
- Worst case (highest current through filter) is with negligible parallel load and a high impedance (low fault current) source

			Harmonic order			
System	**Fundamental**		**5th**	**7th**	**11th**	**13th**
System voltage	34.5	kV (phase to phase)				
Short circuit current	10	kiloamperes				
Impedance	1.992	Ohms				
X/R ratio	10					
System reactance	1.982	Ohms				
System resistance	0.198	Ohms				
Filter						
Size	7420	rated kvar				
Current	124.2	Amperes				
Impedance	160.4	Ohms	4.4	29.2	68.4	86.0
Tuning	4.7	Harmonic order				
Capacitive reactance	168.0	Ohms	33.6	24.0	15.3	12.9
Inductive reactance	7.6	Ohms	38.0	53.2	83.7	98.9
Rectified load						
Total including factor of safety	30000	kva				
Current	502.0	Amperes	100.4	71.7	45.6	38.6
System						
Parallel impedance		Ohms	3.07	9.45	16.61	19.92
Voltage (line to ground)	19918.6	Volts	308.0	677.9	758.1	769.2
Filter Harmonic current		Amperes	69.6	23.2	11.1	8.9
Total harmonic voltage	1311.7	Volts (rms)				
Voltage THD	6.59	Percent				

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- Step 4: Determine component ratings
  - Capacitors are rated by voltage and kVAr

$$V_r = \sum_{h=1}^{\infty} I(h) X_C(h) = V_C(1) + \sum_{h=2}^{\infty} V_C(h)$$

$$V_C(1) = I_f(1) X_C$$

$$V_C(h) = I_f(h) \frac{X_C}{h}$$

  - $V_C(h)$ harmonic voltage across filter capacitor
  - $I_f(h)$ harmonic current flowing through filter
  - $V_C(1)$ fundamental voltage across filter capacitor
  - $I_f(1)$ fundamental frequency current flowing through filter
  - X_C capacitive reactance at fundamental frequency

  - Fundamental frequency current, V_S is the voltage across filter LC circuit

$$I_f(1) = \frac{V_S}{(X_C - X_L)} = \frac{\left(34.5\text{ kV}/\sqrt{3}\right)}{(168.4 - 7.62)} = 124\text{ A}$$

  - Total rms current in the harmonic filter,

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I(h)^2} = \sqrt{I_{f1}^2 + I_{f5}^2 + I_{f7}^2 + I_{f11}^2 + I_{f13}^2}$$

$$= \sqrt{124^2 + 69.6^2 + 23.2^2 + 11.1^2 + 8.9^2} = 144.8\text{ A}$$

    - Total rms current < 135% of capacitor unit nominal current based on the rated kVAr and the rated voltage
    - It should be kept within the capability of capacitor fuses

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– Total harmonic voltage across the capacitor,

$$V_C\left(1\right) = I_f\left(1\right) X_C = 124 \times 168 = 20{,}832 \text{ V}$$

$$V_C\left(h\right) = \sum_h I_f\left(h\right)\left(\frac{X_C}{h}\right) = 69.6 \times \frac{168}{5} + 23.2 \times \frac{168}{7} + 11.1 \times \frac{168}{11} + 8.9 \times \frac{168}{13} = 3{,}180 \text{ V}$$

– Voltage rating of the capacitor,

$$V_r = V_C\left(1\right) + V_C\left(h\right) = 20{,}832 + 3{,}180 = 24{,}012 \text{ V}$$

– Design should rate capacitor voltage at 100%, and reserving the 110% rms voltage and 120% peak voltage margins for contingency operation

– Based on line-to-line rated voltage and its impedance, the rated three-phase MVAr of the capacitor bank,

$$Q_{\text{rated}} = \frac{\left(\sqrt{3}V_r\right)^2}{X_C} = \frac{\left(\sqrt{3} \times 24.012\right)^2}{168.4} = 10.27 \text{ MVAr}$$

- Capacitor rated MVAr is significantly larger than the filter effective reactive power (7.4 MVAr) because capacitor voltage rating is higher than nominal system voltage

– Nominal capacitor current based on rated voltage and MVAr,

$$I_{\text{nom}} = \frac{Q_{\text{rated}}}{\sqrt{3}V_{\text{rated}}} = \frac{10.27 \text{ MVAr}}{\sqrt{3} \times \left(\sqrt{3} \times 24 \text{ kV}\right)} = 142.6 \text{ A}$$

The calculated filter current of 144.8 A is only 101.5% of this nominal current, and thus complying with IEEE Std 18 (<135%)

– Dielectric heating of the capacitor must be acceptable,

$$\left|\sum_h \left(V(h)\,I(h)\right)\right| \le \left|1.35 Q_{\text{rated}}\right|$$

$$\left|3\times\left(20.83\times124+2.34\times69.6+0.56\times23.2+0.17\times11.1+0.12\times8.9\right)\right| \le \left|1.35\times10270\right|$$

$$8,285 \le 13,865$$

– Filter capacitor is conservatively designed and meets all requirements

– Good to build certain contingency for harmonics from unidentified sources or new non-linear loads

– Filter reactor can be located at the source side of the capacitor or the neutral side

– If located at the source side, it should be rated to withstand a short circuit to ground at the junction between reactor and capacitor,

$$X_S = \frac{V_{\text{ll,nom}}}{\sqrt{3}I_{\text{SCBUS}}} = \frac{34.5\ \text{kV}}{\sqrt{3}\times10\ \text{kA}} = 1.99\ \Omega$$

$$I_{SC} = \frac{V_{\text{ll,nom}}}{\sqrt{3}\left(X_S + X_L\right)} = \frac{34.5\ \text{kV}}{\sqrt{3}\times\left(1.99+7.63\right)} = 2.07\ \text{kA}$$

– $V_{\text{ll,nom}}$ nominal system line-to-line voltage
– I_{SCBUS} available short-circuit current at bus
– I_{SC} symmetrical short-circuit rating of reactor

– The quality factor *Q* (*X*/*R* ratio) of harmonic filter is not critical in most application, but is usually above 50

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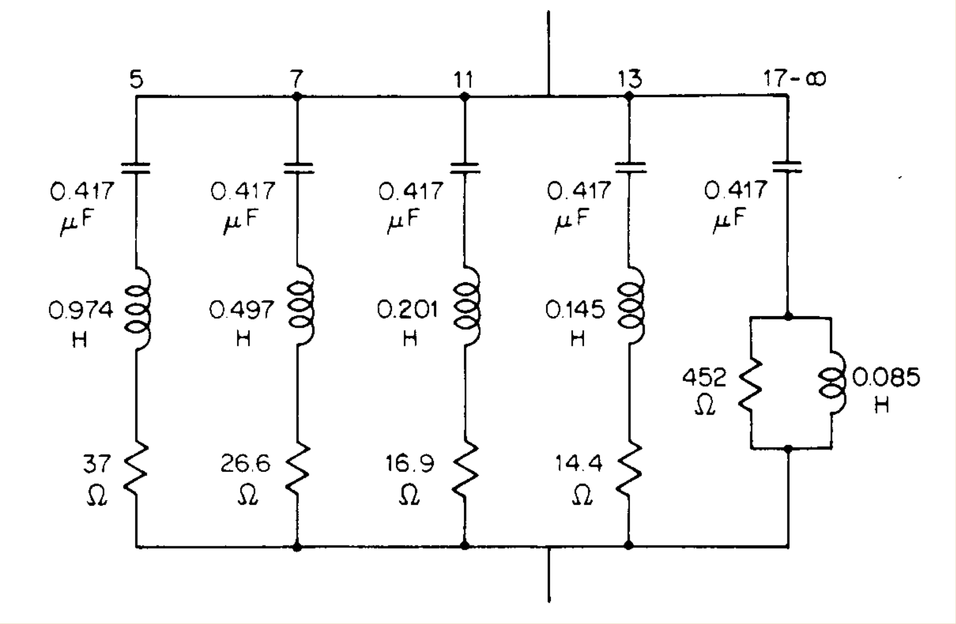
Typical filter bank

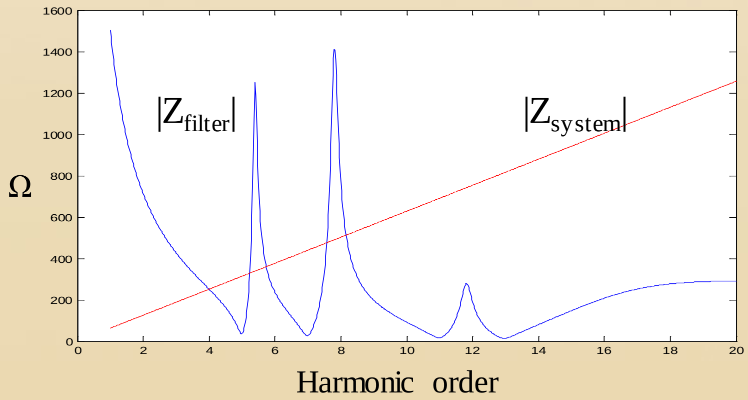
- Several tuned filters to eliminate lower order harmonics at 5th, 7th, 11th and 13th
- A damped high-pass filter for filtering higher order harmonic current, > 17th

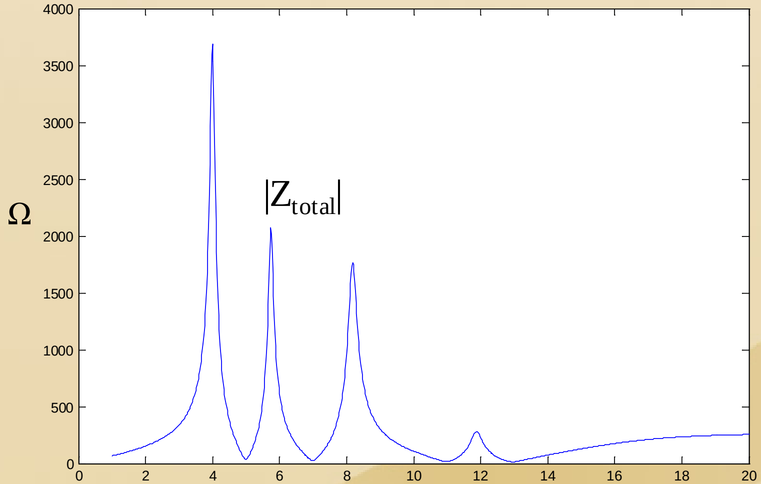
$$Z_{filter} = Z_5 // Z_7 // Z_{11} // Z_{13} // Z_{17+}$$

$$Z_{system} = R_{system} + jX_{system}$$

$$Z_{total} = Z_{system} // Z_{filter}$$







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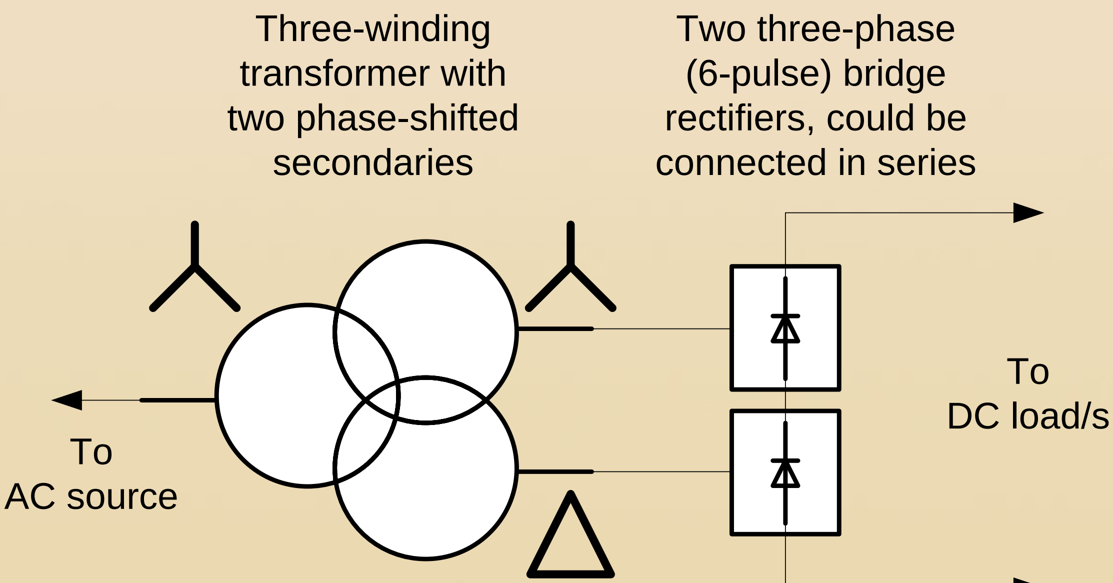
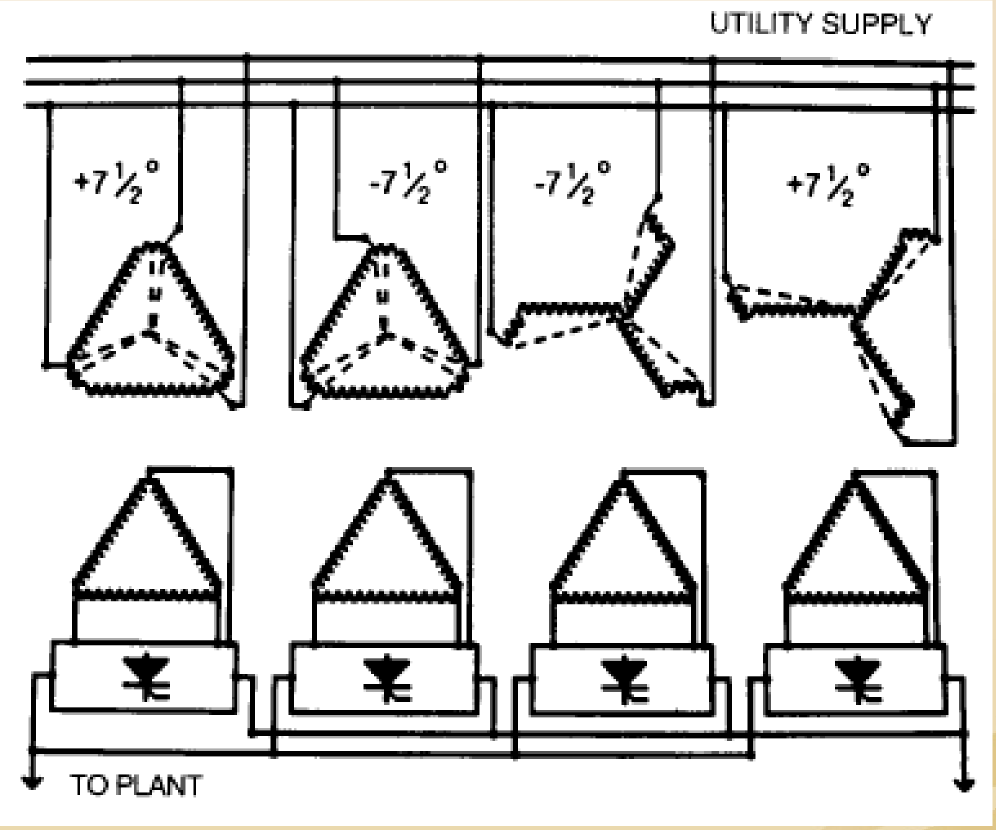
Three-phase harmonic mitigating transformers

- Specially designed transformers to deal with commercial and industrial facilities of power quality problems associated with harmonic currents
  - Targetted at 5th, 7th, 11th, 13th, etc. harmonics
  - Uses dual secondary or pairs of transformers to achieve substantial attenuation of the problematic harmonics
  - The two secondaries are electrically phase-shifted relative to each other
  - Targeted harmonic currents from one secondary are close to or equal to 180° out of phase with those from the other secondary and thus result in cancellations



Phase multiplication

- Arrangement of converter loads such that some harmonics cancel each other and do not penetrate into supply system
  - Two 6-pulse units phase-shifted from each other by 30° will result in a 12-pulse system, eliminating 5th, 7th, 17th, 19th, etc…
  - Four 6-pulse units phased-shifted by 15° result in a 24-pulse system
- Significant reduction in the amount of filtering required



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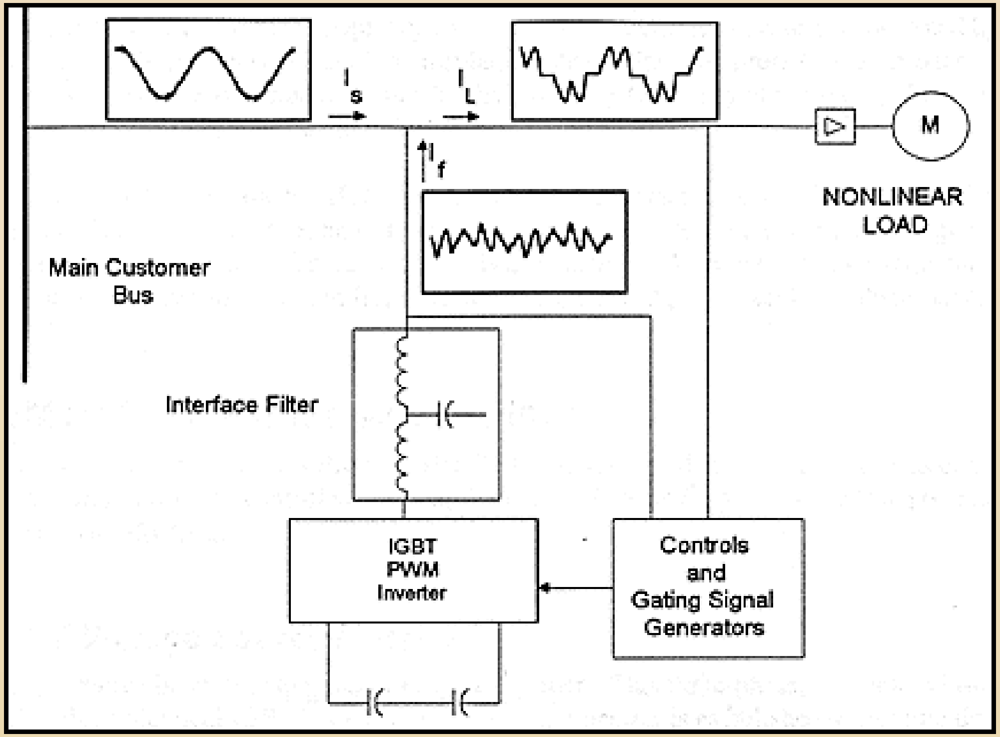
Active filter

- Made of power electronic devices which switch in current portions so as to make the load current sinusoidal when flowing in the supply system
  - Injected currents contain harmonic components which cancel out the original harmonic components in the load current



IEEE 519-1992 Harmonic control

- Divided into two main parties of compatibility relationship
  - Harmonic current limits that apply to individual consumers of electrical energy
  - Harmonic voltage limits that define the quality of electrical power furnished by the utility to the consumers
- Focuses on Point of Common Coupling (PCC), consumer-utility interface
  - Excludes HVDC (High Voltage Direct Current) and SVC (Static Var Compensator) installations that are generally large in MVA ratings
    - Substantial impacts on power system operation, and thus justify more extensive studies and a more conservative approach to harmonic control
- Practicality issues concerning harmonic control
  - Impractical to control harmonics to such an extent that harmonic effects caused by connection of harmonic producing loads are nil at every points in power network, including consumer's own circuit, utility and other consumers' circuits
  - Economic factors and effectiveness of harmonic control must be balanced
  - Some harmonic effects are unavoidable at some points in the system
  - Attempts to reduce harmonic effects by establishing limits on certain harmonic indices at PCC, a point accessible by consumer and utility for measurement

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Remarks on harmonic control

- Choice of PCC
  - Location on the system where another customer can be served
  - Can locate at either primary or secondary of a supply transformer
- Harmonic effects differ substantially depending on characteristics of the equipment affected
  - Severity of harmonic effect cannot be perfectly correlated to a few simple indices
  - Indices are useful as general guidelines
    - Physically meaningful and strongly correlated to severity of harmonic effects, simple, practical and measurable for determining if limits are encroached
    - Notch depth, total notch area and distortion of bus voltage by commutation notches
    - Individual and total voltage distortion
    - Individual and total current distortion
- Strict adherence to recommended harmonic limits will not always prevent problems from arising, particularly when limits are approached
  - Reexamination and measurement should be performed from time to time, especially when there are system changes and to confirm the following,
    - Capacitors or harmonic filters are not being overstressed by excessive harmonics
    - Harmful series and parallel resonance is not occurring
    - Level of harmonics at PCC and utilization points is not excessive

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Establishing current distortion limits

- Philosophy of developing harmonic current limits
  - Limit the harmonic injection from individual customers so that they will not cause unacceptable voltage distortions for normal system characteristics
  - Limit overall harmonic distortion of utility system voltage
- Conservative approach (worst case condition)
  - System is completely characterized by a short-circuit impedance
  - Effect of capacitor (at filtering high frequency harmonics) is neglected
  - Effect of paralleled loads (provide damping near resonance frequencies and alternative path for harmonic current) is ignored
- Harmonic voltage distortion is a function of total injected harmonic current and system impedance at each harmonic frequency
  - Total injected current depends on number of customers and their sizes
  - Diversity between harmonic currents injected by different customers
    - Different harmonic components being injected
    - Differences in the phase angles of the individual harmonic components
    - Differences in the harmonic injection versus time profiles

Current distortion limits

- Objective of current limits is to limit to a maximum of 3% for individual harmonic voltage and 5% for voltage THD, without major parallel resonance at any harmonic frequency
- Maximum allowable harmonic current for a single consumer
  - Based on size of load with respect to size of connected power system
  - SCR (Short Circuit Ratio) – ratio of short circuit current available at PCC to customer's maximum fundamental load current I_L

Maximum harmonic current distortion in percent of I_L (general distribution system 120V-69kV)						
	Individual harmonic order (Odd harmonics)					THD
I_{SC} / I_L	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above						

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Current distortion limits

- Limits is inversely proportional to the customer loadings
  - Large customers (small SCR) have more stringent limits as they represent a larger portion of total system load
  - If load is small compared to system, higher injection limits are allowed
- Used as system design values for “worst case” conditions lasting > 1 hour
  - May exceed limits by 50% for shorter periods like start-ups or unusual conditions
- More stringent limits at higher voltage levels
  - Limits at sub-transmission systems (69kV-161kV) is 50% of distribution systems

Maximum harmonic current distortion in percent of I_L (general transmission system >161kV, dispersed generation and cogeneration)						
	Individual harmonic order (Odd harmonics)					THD
I_{SC}/I_L	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75
Even harmonics are limited to 25% of the odd harmonic limits above						

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Applying current distortion limits

- Determination of I_{SC}
  - Normal system conditions that result in minimum short circuit capacity
  - Not recommended to use the rare contingency conditions
- Computation of I_L
  - Average of maximum monthly demand currents for the previous 12 months
  - Estimated from measurements or based on predicted load profiles
- Probabilistic consideration
  - Probability distribution plot be developed from measurements
  - Considered acceptable if limits are only exceeded for a short period of time
- Transformer heating considerations
  - These limits are permissible provided that the transformer connecting user to utility system is not subjected to harmonic currents in excess of 5% of transformer rated current (IEEE C57.12.00). Otherwise,
    - Derating or use of larger unit is necessary
    - Designed to withstand additional heating according to IEEE C57.110
- Relax limits if converters have pulse number q > 6: limits raised by $\sqrt{\frac{q}{6}}$
  - Incentive for customers to use higher pulse number converters
  - Provided non-characteristic harmonics are less than 25% of limits

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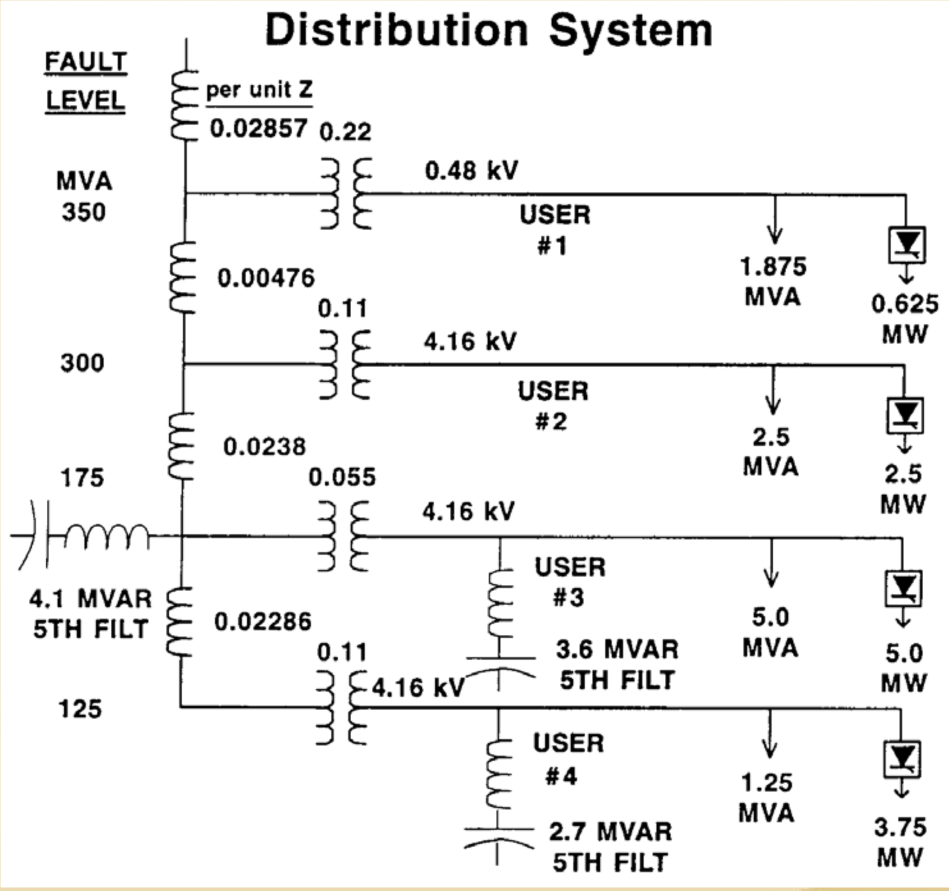
Example of meeting harmonic limits

- A utility distribution feeder with four users along the feeder
  - Evaluate if meeting limit requirements and effectiveness of harmonic filter
  - Each user sees a different short circuit level or system size
  - User 1 @ I_{sc} / I_L ratio of 140
    - 350MVA, 14.6kA system
    - 2.5MVA, 104A load
    - 25% is converter with 26A
  - User 2 @ I_{sc} / I_L ratio of 60
    - 300MVA, 12.55kA system
    - 5MVA, 209A load
    - 50% is converter with 105A
  - User 3 @ I_{sc} / I_L ratio of 17.5
    - 175MVA, 7.32kA system
    - 10MVA, 418A load
    - 50% is converter with 209A
  - User 4 @ I_{sc} / I_L ratio of 25
    - 125MVA, 5.2kA system
    - 5MVA, 209A load
    - 75% is converter with 157A



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Cases with harmonic filters

Arrangement of Harmonic Filters

Case	Filter Size (Mvar)	Location
A	None	—
B	4.1	At user #3 13.8 kV Bus
C	3.6	At user #3 4.16 kV Bus At user #4 4.16 kV Bus
D	5.8	At user #3

- Case A - Existing conditions without any harmonic filter
- Case B - Utility installs a harmonic filter near user #3
  - To absorb harmonic currents from larger sources of users #3 and #4
  - Approximately 4MVAr of capacitors are needed to furnish the reactive power requirement
- Case C - Users #3 and #4 furnish harmonic filters in their own systems
  - Filters improve power factor above penalty point and keep current distortion within limits
- Case D - Increase the size of the utility filter of Case B
  - 40% increase in the size

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User #1

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	4.99	3.43	1.90	1.48	0.91	0.70	0.52	0.42	0.36	0.31	0.29	
% Distortion	4.80	3.33	1.83	1.42	0.87	0.67	0.50	0.40	0.35	0.30	0.28%	6.42%
Case B To System	2.49	2.49	1.49	1.18	0.73	0.56	0.42	0.34	0.29	0.25	0.23	
To Filter	2.49	0.94	0.40	0.30	0.18	0.14	0.10	0.08	0.07	0.06	0.05	
% Distortion	2.39	2.39	1.43	1.13	0.70	0.54	0.40	0.33	0.28	0.24	0.22%	4.00%
Case C To System	3.50	2.67	1.53	1.20	0.74	0.57	0.43	0.34	0.30	0.25	0.24	
To Filter	1.48	0.76	0.37	0.28	0.17	0.13	0.09	0.08	0.06	0.06	0.05	
% Distortion	3.77	2.57	1.47	1.15	0.71	0.55	0.40	0.33	0.29	0.24	0.23%	4.76%
Case D To System	2.50	2.36	1.42	1.12	0.70	0.53	0.40	0.32	0.28	0.24	0.22	
To Filter	2.49	1.08	0.48	0.36	0.22	0.16	0.12	0.10	0.08	0.07	0.07	
% Distortion	2.40	2.26	1.36	1.07	0.67	0.51	0.38	0.31	0.27	0.23	0.21%	3.04%
IEEE Std 519 Limits	12%		5.5%		5.0%		2.0%				1.0%	15%

User #2

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	20.2	13.9	7.66	5.99	3.68	2.84	2.10	1.68	1.47	1.26	1.16	
% Distortion	9.67	6.65	3.67	2.87	1.76	1.36	1.00	0.80	0.70	0.60	0.56%	13.0%
Case B To System	8.42	9.44	5.76	4.56	2.84	2.20	1.63	1.31	1.14	0.98	0.90	
To Filter	11.8	4.41	1.90	1.43	0.84	0.64	0.47	0.37	0.32	0.28	0.25	
% Distortion	4.03	4.52	2.76	2.18	1.36	1.05	0.78	0.63	0.55	0.47	0.44%	7.35%
Case C To System	13.2	10.3	5.94	4.68	2.89	2.24	1.66	1.33	1.16	1.00	0.92	
To Filter	7.01	3.6	1.72	1.31	0.79	0.60	0.44	0.35	0.31	0.26	0.24	
% Distortion	6.32	4.93	2.84	2.24	1.38	1.07	0.79	0.64	0.56	0.48	0.45%	9.1%
Case D To System	8.43	8.79	5.38	4.27	2.66	2.06	1.53	1.23	1.07	0.92	0.85	
To Filter	11.8	5.07	2.28	1.72	1.02	0.78	0.57	0.45	0.39	0.34	0.31	
% Distortion	4.03	4.21	2.57	2.04	1.27	0.99	0.73	0.59	0.51	0.44	0.41%	7.0%
IEEE Std 519 Limits	10%		4.5%		4.0%		1.5%				0.7%	12%

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User #3

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	40.1	27.6	15.3	11.9	7.31	5.64	4.18	3.34	2.93	2.5	2.3	
% Distortion	9.59	6.60	3.66	2.85	1.75	1.35	1.00	0.80	0.70	0.60	0.55%	12.8%
Case B To System	0.01	12.5	8.78	7.03	4.44	3.45	2.58	2.07	1.82	1.56	1.44	
To Filter	40.1	15.1	6.52	4.87	2.87	2.19	1.60	1.27	1.11	0.94	0.86	
% Distortion	0.00	2.99	2.10	1.68	1.06	0.83	0.62	0.50	0.44	0.37	0.34%	4.37%
Case C To System	0.02	9.73	7.10	5.73	3.64	2.83	2.12	1.70	1.50	1.28	1.18	
To Filter	40.1	17.9	8.20	6.17	3.67	2.81	2.06	1.64	1.43	1.22	1.12	
% Distortion	0.00	2.33	1.70	1.37	0.87	0.68	0.51	0.41	0.36	0.31	0.28%	3.48%
Case D To System	0.04	10.3	7.50	6.05	3.84	2.99	2.24	1.80	1.58	1.35	1.25	
To Filter	40.1	17.3	7.80	5.85	3.47	2.65	1.94	1.54	1.35	1.15	1.05	
% Distortion	0.00	2.46	1.79	1.45	0.92	0.72	0.54	0.43	0.38	0.32	0.30%	3.68%
IEEE Std 519 Limits	4%		2.0%		1.5%		0.6%				0.3%	5.0%

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User #4

Harmonic Currents (Amperes)

	5	7	11	13	17	19	23	25	29	31	35	THD
Case A To System	30.1	20.7	11.5	8.95	5.50	4.24	3.14	2.51	2.20	1.88	1.72	
% Distortion	14.4	9.90	5.50	4.28	2.63	2.03	1.50	1.20	1.05	0.90	0.82%	19.3%
Case B To System	0.00	9.39	6.60	5.30	3.34	2.59	1.94	1.56	1.37	1.17	1.07	
To Filter	30.1	11.3	4.90	3.66	2.16	1.64	1.20	0.96	0.83	0.71	0.65	
% Distortion	0.00	4.49	3.16	2.54	1.60	1.24	0.93	0.75	0.66	0.66	0.51%	6.57%
Case C To System	0.01	6.17	4.64	3.76	2.40	1.87	1.40	1.12	0.99	0.85	0.78	
To Filter	30.1	14.5	6.86	5.19	3.10	2.37	1.74	1.39	1.21	1.03	0.94	
% Distortion	0.00	2.95	2.22	1.81	1.14	0.89	0.67	0.54	0.47	0.41	0.37%	4.50%
Case D To System	0.03	7.72	5.64	4.55	2.89	2.25	1.68	1.35	1.19	1.02	0.93	
To Filter	30.1	13.0	5.86	4.40	2.61	1.99	1.46	1.16	1.01	0.86	0.79	
% Distortion	0.01	3.69	2.70	2.18	1.38	1.08	0.80	0.65	0.57	0.49	0.45%	5.53%
IEEE Std 519 Limits	7%		3.5%		2.5%		1.0%				0.5%	8.0%

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Meeting harmonic voltage limits

User	Case	V_5	V_7	V_{11}	V_{13}	V_{17}	V_{19}	V_{23}	V_{25}	V_{29}	V_{31}	V_{35}	THD
#1	A	3.26	3.14	2.73	2.51	2.02	1.74	1.56	1.36	1.38	1.26	1.31	7.13
	B	0.37	1.62	1.70	1.60	1.32	1.14	1.03	0.90	0.92	0.84	0.87	3.93
	C	0.57	1.18	1.24	1.18	0.97	0.85	0.77	0.67	0.68	0.62	0.65	2.94
	D	0.38	1.39	1.50	1.42	1.17	1.02	0.92	0.80	0.82	0.75	0.78	3.48
#2	A	3.77	3.63	3.16	2.91	2.34	2.02	1.81	1.57	1.60	1.46	1.51	8.25
	B	0.41	1.86	1.96	1.85	1.52	1.32	1.19	1.04	1.06	0.97	1.01	4.53
	C	0.64	1.34	1.43	1.35	1.12	0.97	0.88	0.77	0.78	0.72	0.75	3.37
	D	0.41	1.60	1.72	1.63	1.35	1.17	1.06	0.92	0.94	0.86	0.90	3.99
#3	A	5.77	5.55	4.84	4.45	3.58	3.08	2.77	2.40	2.44	2.23	2.31	12.62
	B	0.00	2.52	2.78	2.63	2.18	1.89	1.71	1.49	1.52	1.39	1.44	6.39
	C	0.39	1.64	1.87	1.78	1.49	1.29	1.17	1.03	1.05	0.96	1.00	4.34
	D	0.00	2.07	2.37	2.26	1.88	1.64	1.48	1.29	1.32	1.21	1.26	5.47
#4	A	6.59	6.35	5.53	5.09	4.09	3.52	3.16	2.75	2.79	2.55	2.64	14.43
	B	0.82	3.31	3.47	3.27	2.69	2.33	2.10	1.03	1.87	1.71	1.77	8.02
	C	0.33	1.73	2.02	1.94	1.62	1.41	1.28	1.12	1.14	1.04	1.09	4.69
	D	0.83	2.86	3.07	2.90	2.39	2.08	1.88	1.64	1.67	1.53	1.59	7.12

A = System with no filters
B = System with 4.1 Mvar fifth harmonic filter at User #3, 13.8 kV bus
C = System with fifth harmonic filter at User #3 and #4, 4.16 kV bus
D = System with 5.8 Mvar fifth harmonic filter at User #3, 13.8 kV bus

Note: All values are in percent

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Effectiveness of harmonic solutions

- Case A
  - User #1 is well within the limits while user #2 is marginal
  - Users #3 and #4 are both well over the recommendations
  - For each user, voltage distortion is above the 5% limit
- Case B
  - Voltage distortion is within limits for users #1 and #2 but still above 5% for users #3 and #4
  - Individual current harmonics and current THD are all within limits except for users #3 and #4 with some marginal ones
- Case C
  - Voltage distortion values and current distortion values are all within recommended limits
- Case D
  - Even a 40% increase in utility harmonic filter still leaves the voltage distortion on users #3 and #4 above the limits
- Conclusion
  - The most effective way to correct harmonic distortion is at the source of the harmonic current or at user's point of common coupling with the utility

Application of IEEE 519 for industrial facility

- Most harmonic problems are associated with harmonics from nonlinear loads used in industrial facilities
  - Adjustable speed motor drives, large rectifiers for dc processes such as aluminum pot lines, induction furnaces, arc furnaces, and dc drives.
  - These loads form a significant portion of the total facility load
  - Industrial facilities often have power factor correction capacitors, creating resonance conditions that can magnify harmonics
  - Industrial motors and other loads do not provide much resistive damping of resonance conditions at harmonic frequencies.
- Most harmonic problems show up within the industrial facility before they create problems on the utility supply system
  - Resonance conditions within an industrial plant will result in high voltage distortion levels at the customer's low voltage bus where power factor correction capacitors are applied
  - Problems are likely to show up in the plant with motors overheating, transformer heating, and misoperation of electronic equipment
  - It is in the customer's best interest to understand the possible harmonic problems and make sure the harmonic distortion levels are not excessive

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Application of IEEE 519 for industrial facility

- IEEE 519-1992 recommends that voltage distortion at the PCC be limited to 5% for most medium voltage systems.
  - This provides some margin allowing for higher voltage distortion levels within customer facility
  - Voltage distortion levels should be less than 8% to prevent excessive motor heating, probably the most important concern for most industrial customers
  - This 8% voltage distortion level is specified as the compatibility level in IEC 1000-2-2
- Evaluation of harmonic concerns for industrial facilities requires an understanding of the different types of loads that are used in the facility
  - Most integrated industrial plants have many different sources of harmonics (nonlinear loads) and the combined effect of these different sources may be difficult to calculate.
  - Measurements are required to characterize these sources and their interaction.
  - At the design stage, evaluations often require conservative assumptions in order to estimate expected harmonic levels.

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Harmonic evaluation procedure for industrial facility

- Step 1: Choose PCC
  - Normally at high voltage side of step-down transformer
- Step 2: Characterize harmonic producing loads
  - Harmonics from individual non-linear loads are available
  - Combined effects may be difficult to determine without measurements
- Step 3: Determine power factor correction needs (installing capacitors)
  - Potential of absorbing harmonics from the supply system
  - Possible resonances that could magnify harmonic currents from facility
- Step 4: Calculate expected harmonic currents at the PCC
  - Evaluate compliance from harmonic generation characteristics and system response characteristics
- Step 5: Design harmonic control equipment, if necessary
  - Usually coordinated with power factor correction needs (passive harmonic filter)
  - Active filter may be more economical if only small filter is needed, as it avoids the possibility of overloading due to voltage distortion on the supply system
- Step 6: Verify harmonic performance (within limits) with measurements
  - Measurements are to be conducted over selected period that adequately characterizes the time-varying and statistical characteristics of the harmonics

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Controlling utility voltage distortion

- Maximum voltage distortion at PCC with each customer
  - Used in system design as “worst case” values for conditions lasting > 1 hr
    - Shorter periods during start-up or unusual condition, limits may be exceeded by 50%

Bus voltage at PCC	Individual voltage distortion (%)	Total voltage distortion THD (%)
69 kV and below	3.0	5.0
69 kV through 161 kV	1.5	2.5
161 kV and above	1.0	1.5

- If limits are exceeded, the following steps may be taken:
  - Enforcing harmonic current limits on all connected customers
  - Install filters to control the harmonics
  - Install new feeder to stiffening the source and isolating harmonic problems
- Addition of harmonics
  - Diversity in harmonic order, phase angle and time profile
  - Instead of vigorous summation of phasors of each harmonic frequency, a simple, approximate and conservative method is recommended
    - Solve circuit to determine branch currents and node voltages caused by each harmonic source separately
    - Arithmetically adding up the branch currents and node voltages
    - Coincidence factors of converter loads can be used to refine the addition
    - Extrapolate the results for assessment of the effects of new converters

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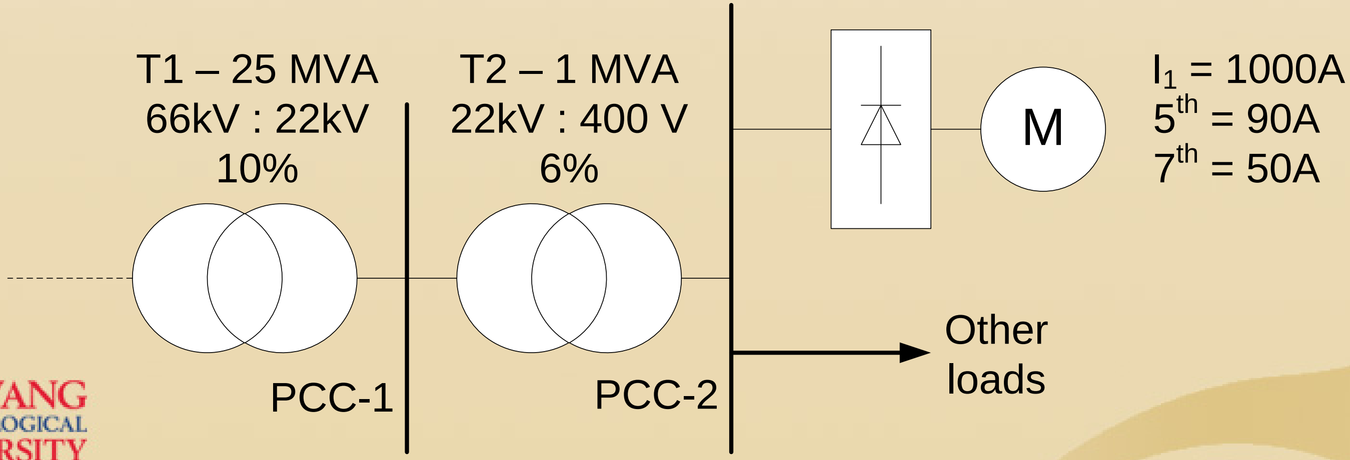
Meeting IEEE 519-1992 harmonic limits

- Most effective way to meet harmonic distortion limits
  - Filter harmonics at each individual load
  - Measure them at the PCC
- Enforcing harmonic limits on each individual load is difficult
  - Currently available technology may be incapable or inadequate
  - Need very costly equipment to achieve the required performance
- IEEE 519-1992 is meant to apply the limits to system harmonic distortion rather than to individual load distortion
  - Significant effect from the location or selection of PCC, the electrical connecting point or interface between utility distribution system and the customer's or user's electrical distribution system



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Effect of selection of PCC

- Load characteristics

$$I_L = \sqrt{\sum_{n=1}^{\infty} I_n^2} = \sqrt{1000^2 + 90^2 + 50^2} = 1005.3\text{ A} \quad ; \quad \text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} = \frac{\sqrt{90^2 + 50^2}}{1000} = 10.3\%$$

$$5^{\text{th}}\ \text{harmonic} = \frac{90}{1000} \times 100\% = 9\% \quad ; \quad 7^{\text{th}}\ \text{harmonic} = \frac{50}{1000} \times 100\% = 5\%$$

- Using PCC-1,

$$I_{sc,PCC-1} = \frac{I_{rated,T1}}{X_{\%,T1}} = \frac{\frac{25{,}000\text{ kVA}}{22\text{ kV} \times \sqrt{3}}}{0.1} = \frac{656.1}{0.1} = 6561\text{ A}$$

$$SCR = \frac{I_{sc,PCC-1}}{I_1} = \frac{6561\text{ A}}{1000\text{ A} \times \frac{400\text{ V}}{22{,}000\text{ V}}} = 361$$

  - As SCR of 361, limits are 15% THD and 12% for 5th and 7th harmonics
  - Within the limits
  - Relatively stiff system (25 MVA) feeding a relatively small load

- Using PCC-2,

$$I_{sc,PCC-2} = \frac{I_{rated,T2}}{X_{\%,T2}} = \frac{\frac{1{,}000\text{ kVA}}{0.4\text{ kV} \times \sqrt{3}}}{0.06} = \frac{1443.4}{0.06} = 24056\text{ A}$$

$$SCR = \frac{I_{sc,PCC-2}}{I_1} = \frac{24056\text{ A}}{1000\text{ A}} = 24$$

  - With SCR of 24, limits are 8% THD and 7% for 5th and 7th harmonics
  - Exceed limits of THD and 5th harmonic
  - Small load on a system that is only adequate for one of that size

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