Power Quality

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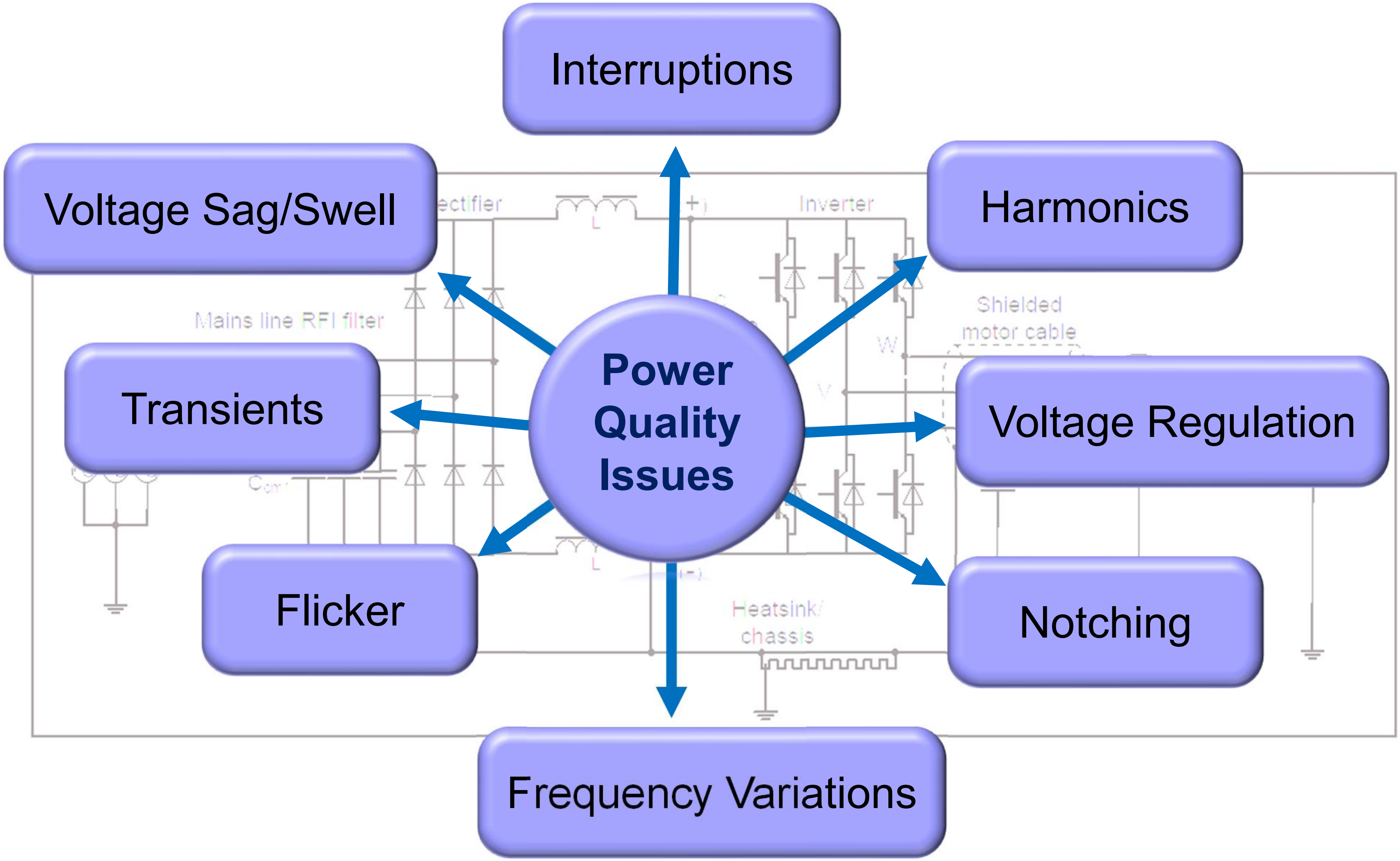
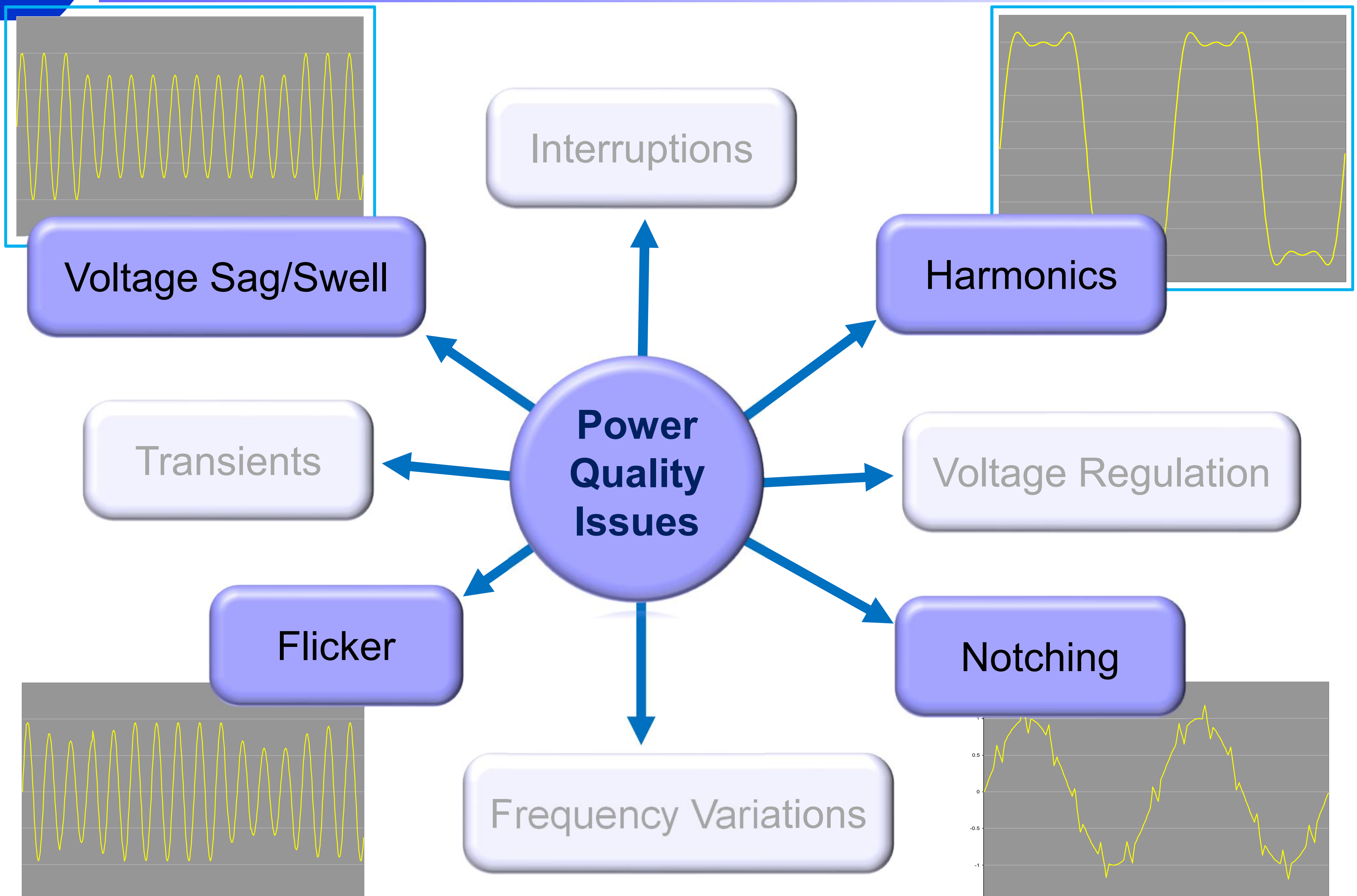
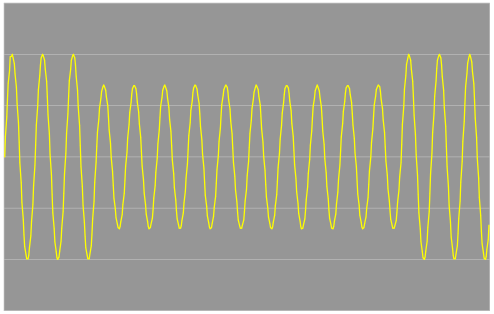
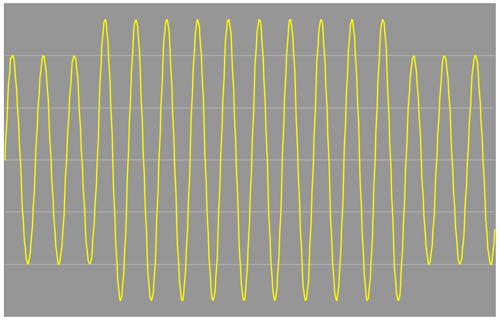

Interruptions
Voltage Sag/Swell
Harmonics
Transients
Power Quality Issues
Voltage Regulation
Flicker
Notching
Frequency Variations
Inverter
Mains line RFI filter
Shielded motor cable
Heatsink/ chassis


Power Quality Issues
Interruptions
Harmonics
Voltage Regulation
Notching
Frequency Variations
Flicker
Transients
Voltage Sag/Swell

Impact of Sag/Swell

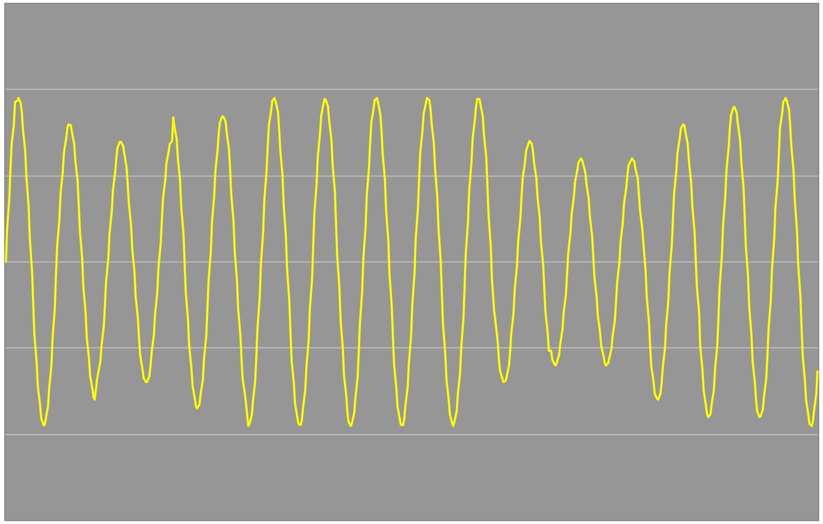




- Duration:
  0.5 to 30 Cycles
- Voltage variation:
  0.1 to 0.9 pu

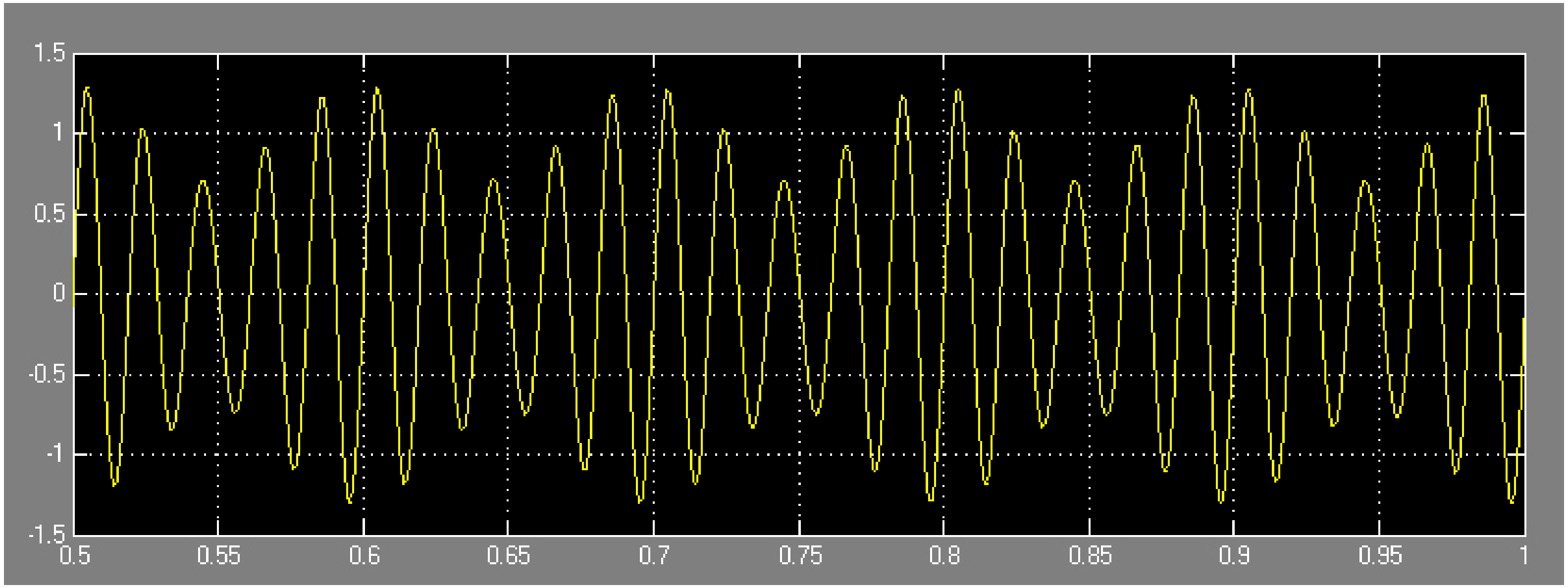
- Drive systems may trip on occurrence of sag/swell.
- Stored energy is not used or properly handled under such conditions
- *Ride through* methods are developed manage these conditions

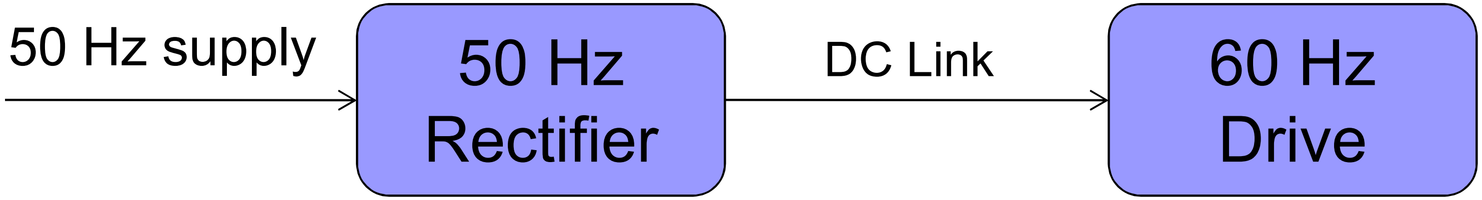
Flicker



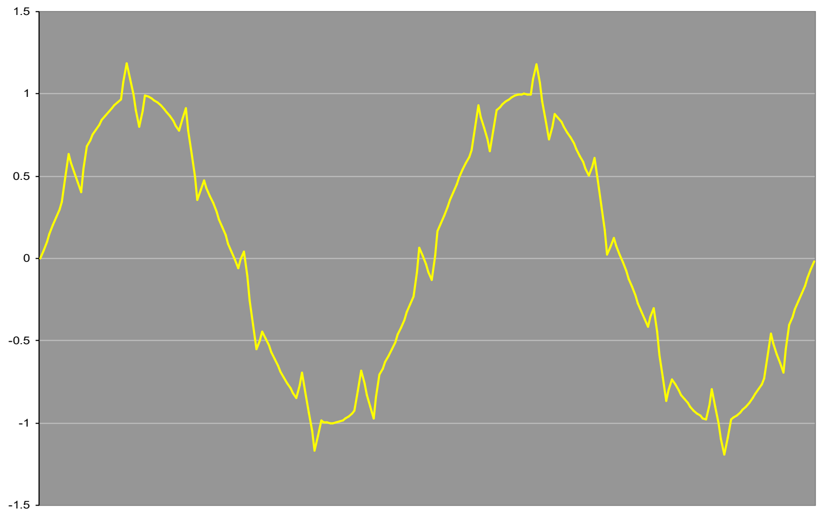
- Rapid on-off sensation of lamps as perceived by human eye
- Related to voltage fluctuations
- Caused by
  - Arc furnaces
  - Welding sets
  - Rapidly cycling loads
  - **Adjustable speed drives with inadequate dc-link filters**

Flicker Generation with VFD



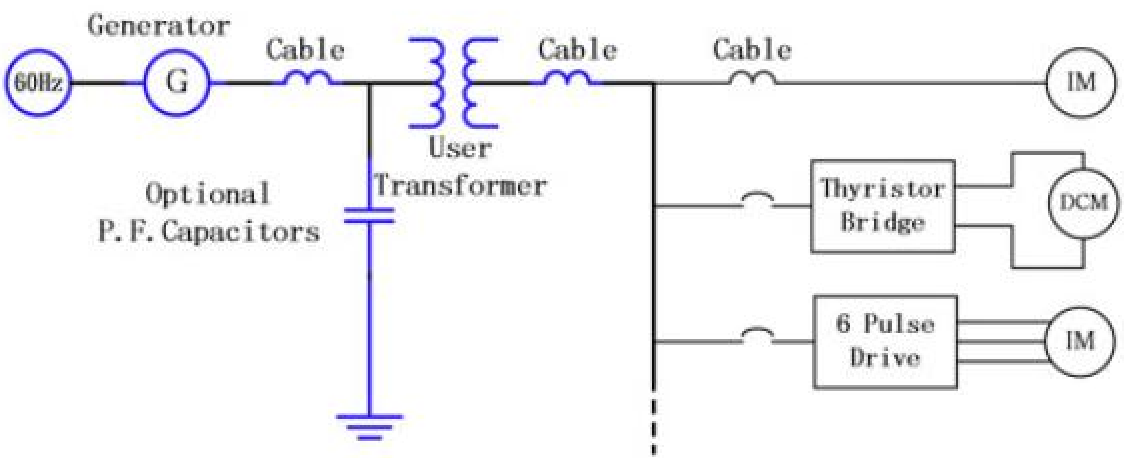


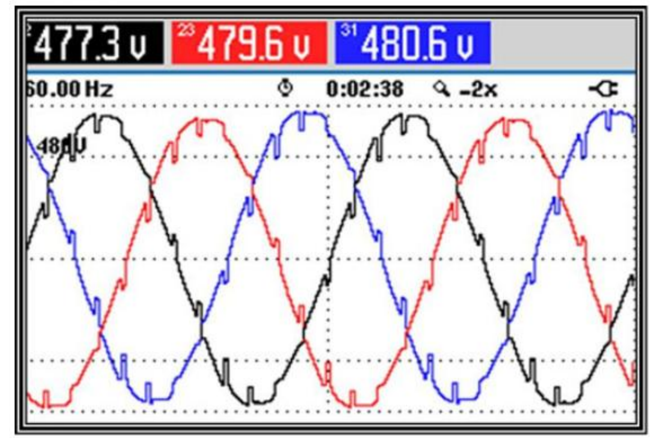
Notching



- Periodic voltage disturbance
- Caused by power electronic drives
  - Usually occurs when power is commutated from one phase to another
- Results in
  - Frequency detection errors
  - Zero crossing errors

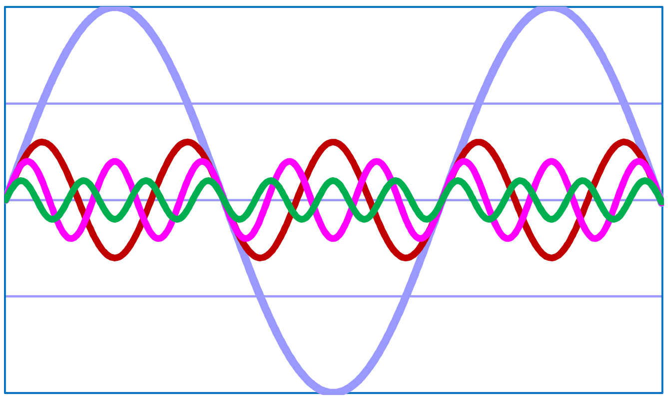
Impact of Notching

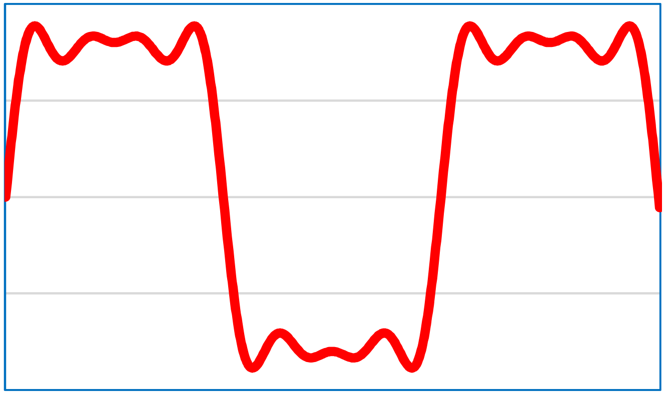




- Multiple dc drives operating at different speeds complicating maloperation and potential failure issues resulting from notches
- Appropriate filters are to be installed to reduce the effect of notching

Harmonics

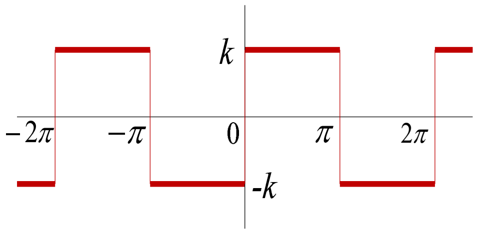


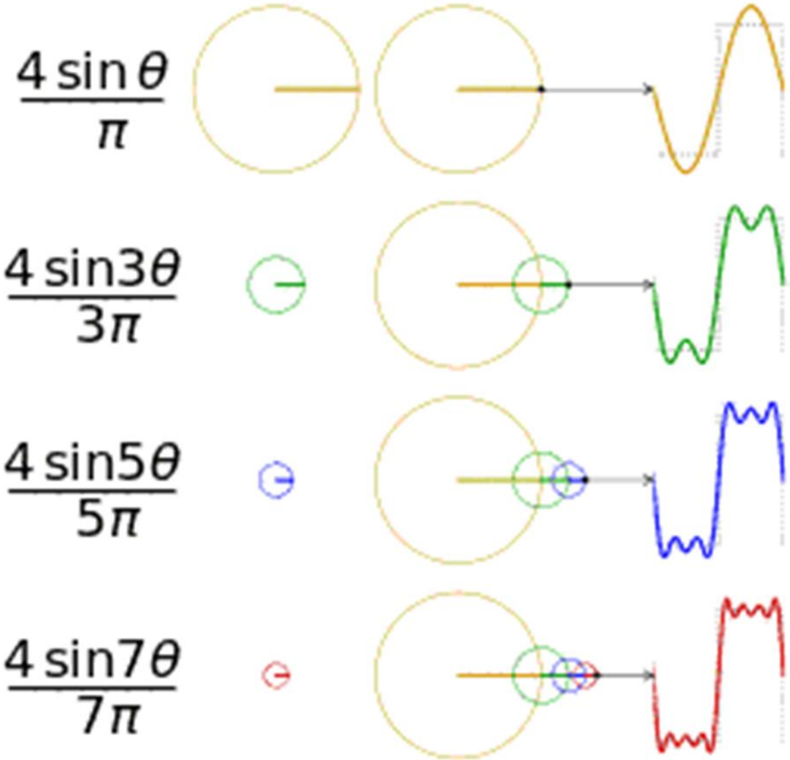


- Defined as sinusoidal voltages and currents at frequencies other than the fundamental frequency.
- Harmonic frequencies are integer multiples of the fundamental frequency
- Caused by
  - Nonlinear components in system
  - Power electronic controllers

$$f(x) = a_0 + \sum_{n=0}^{\infty}[a_n \cos(nx) + b_n \sin(nx)]$$

Phasor-waveform relation



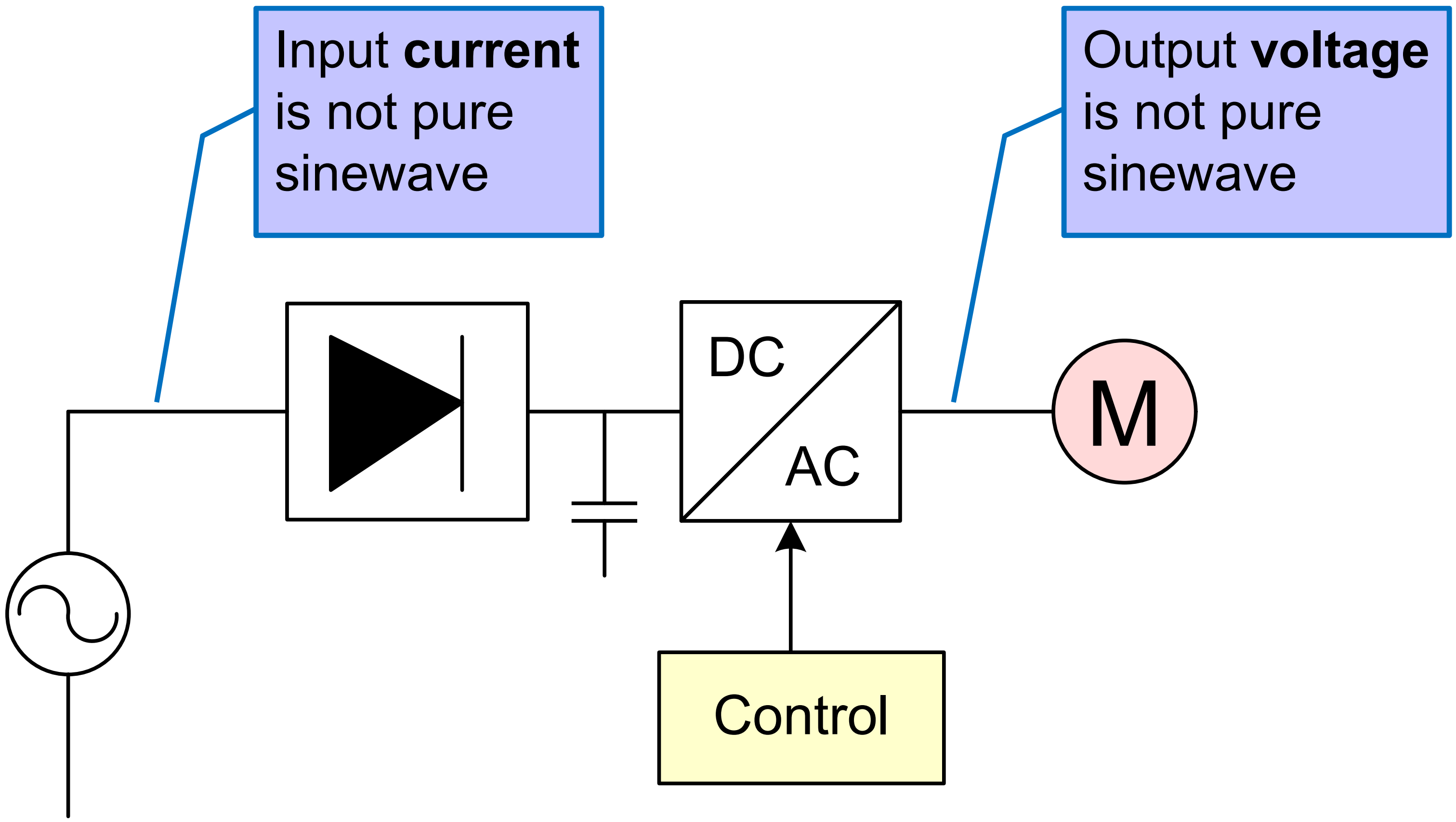


$$f(x) = \frac{4}{\pi}\sin x + \frac{4}{3\pi}\sin 3x + \frac{4}{5\pi}\sin 5x + \frac{4}{7\pi}\sin 7x + ..$$

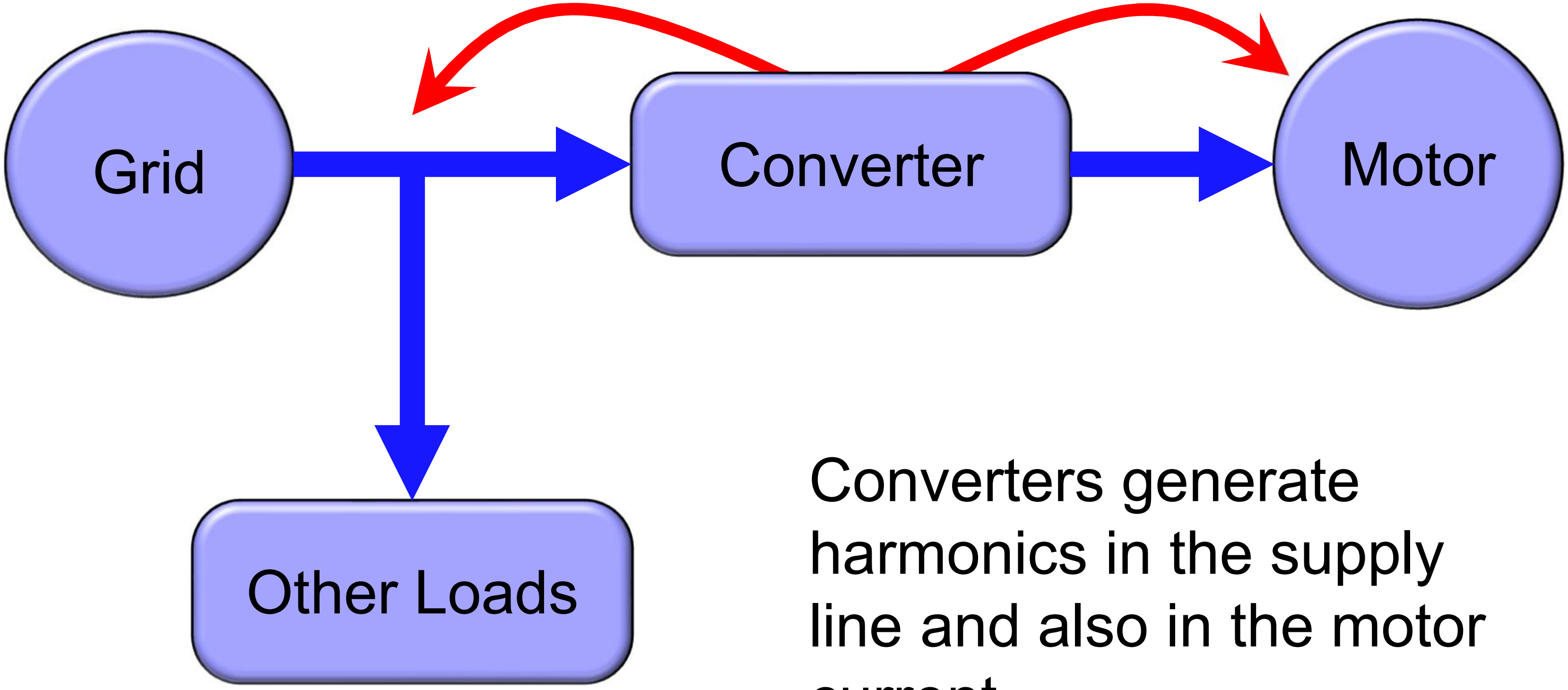
Sources of Harmonics

- DC power supplies including SMPS
- Transformer magnetisation nonlinearities
- Rotating machine harmonics
- Arcing devices
- Three phase adjustable speed drives
- Thyristor controlled reactors
- AC Regulators

How harmonics is generated in drives?

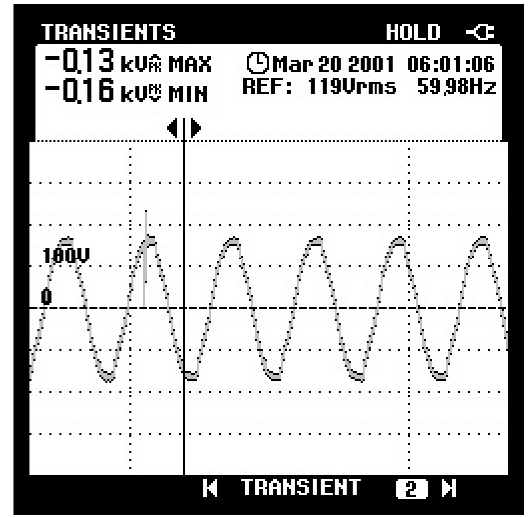


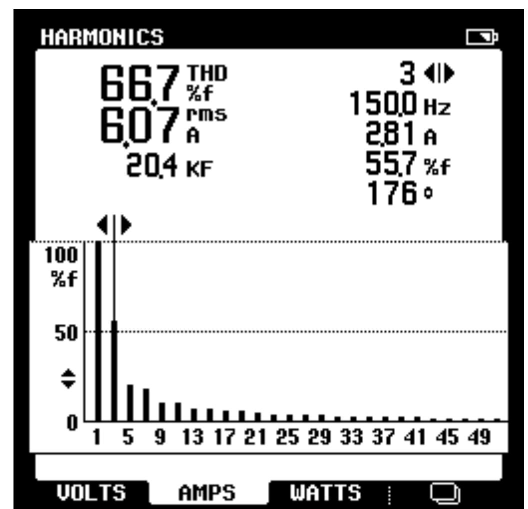
Harmonic Flows in Drive Systems



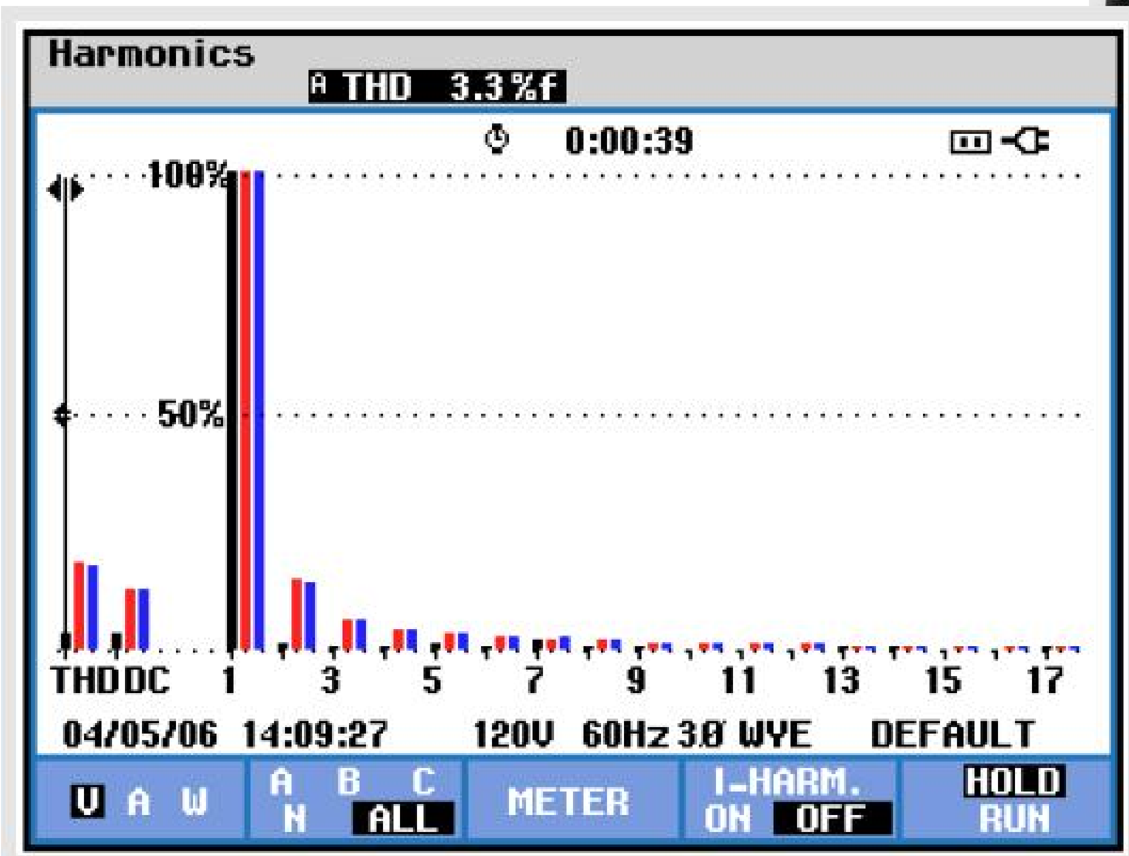
Converters generate harmonics in the supply line and also in the motor current

Single Phase Power Quality Monitor





Three Phase
Power Quality Monitor



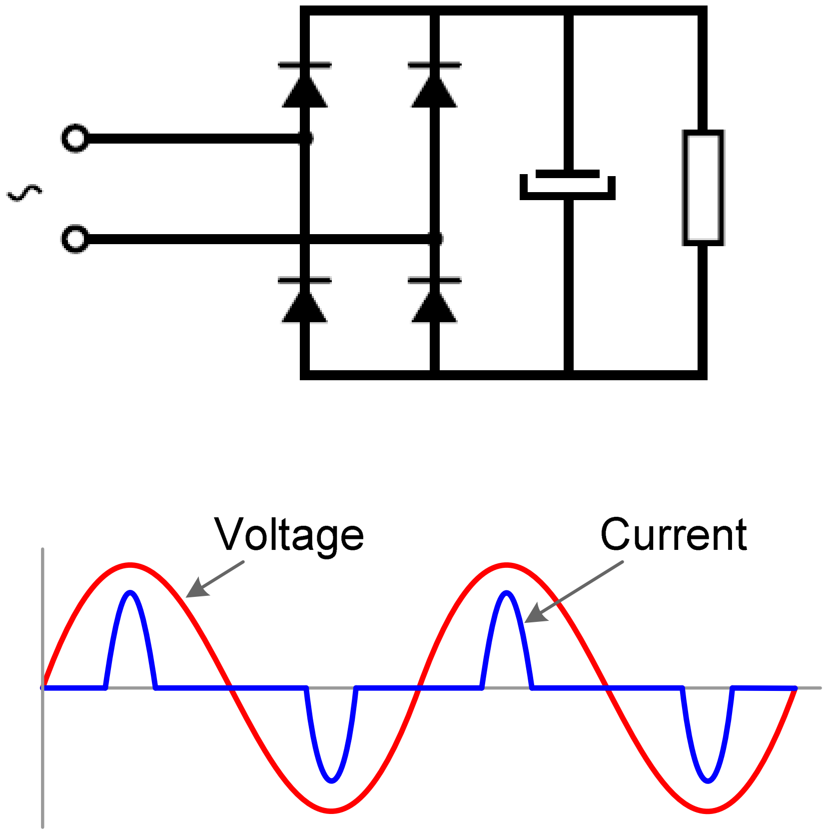
Effects of Harmonics ….1

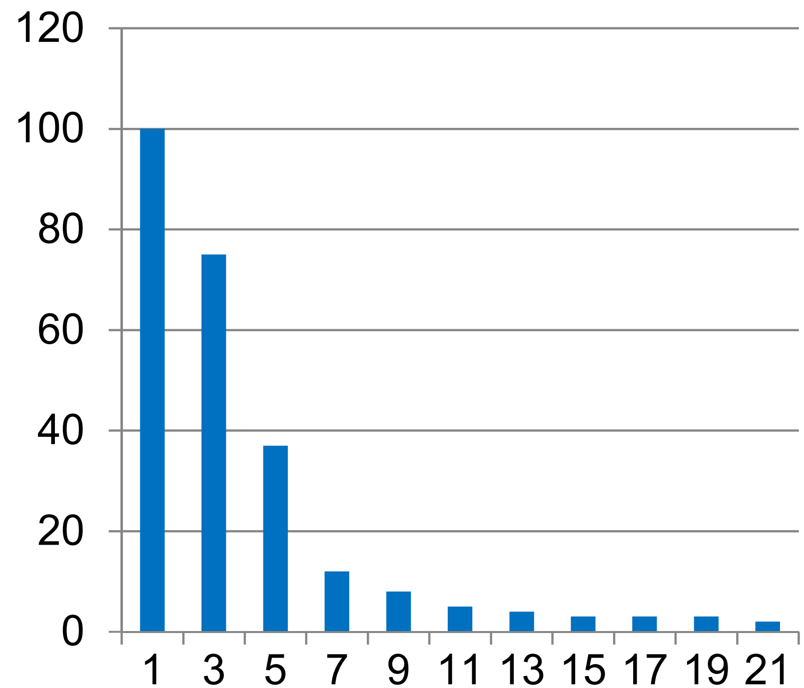
- Motor efficiency reduces with harmonics
- Transformer efficiency reduces with harmonics
- Harmonics may cause circulating current in delta side of transformers
- Harmonics results in de-rating of generator & transformer
- Harmonics may damage capacitors
- PF correction becomes ineffective with harmonics

Effects of Harmonics …2

- Harmonics causes increased heat loss in conductors due to skin effect
- Harmonics may result in resonant conditions and result in excessive current and voltage in system
- Overloads the distribution system
- Overloads the neutral conductor
- De-rating of system
- Disturbance on communication networks
- Nuisance tripping of circuit breakers due to harmonics

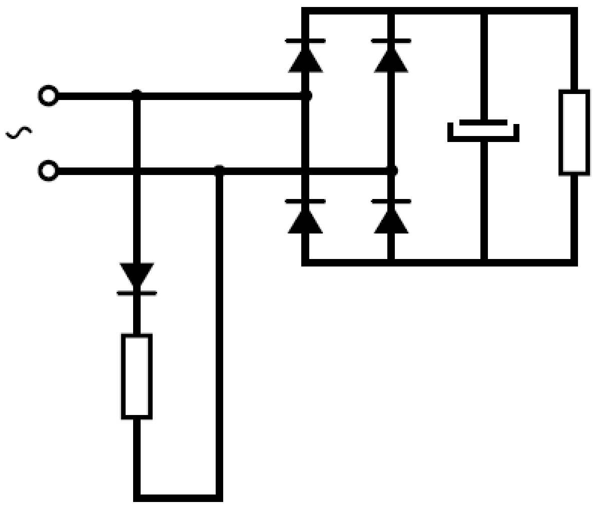
Harmonics Created by Single phase rectifier

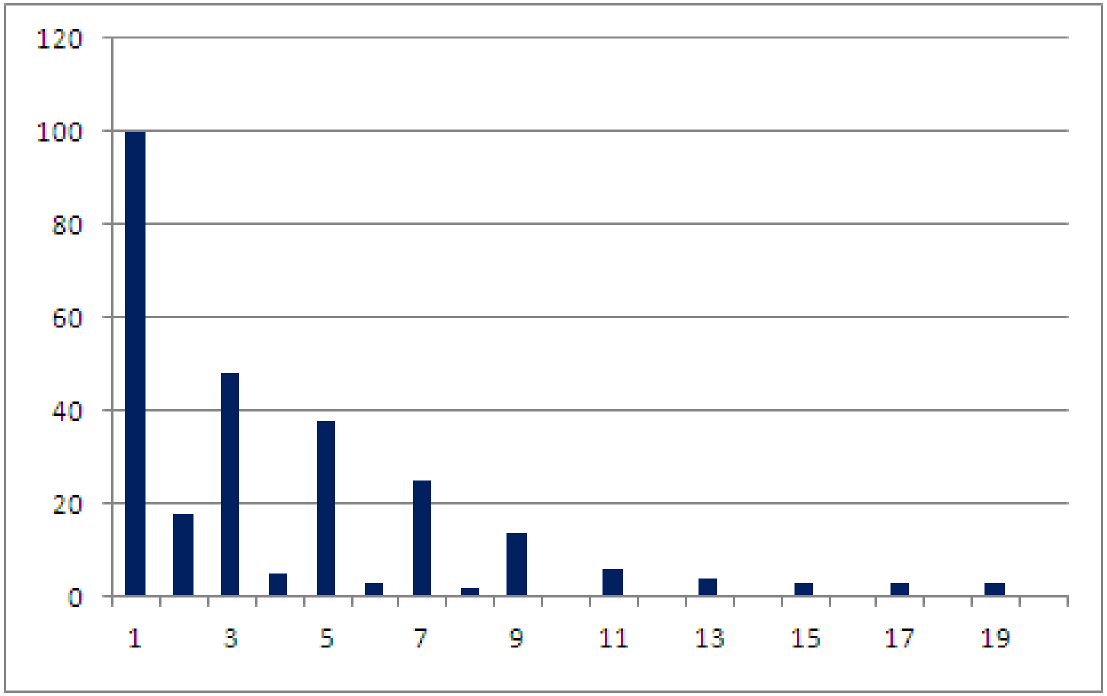


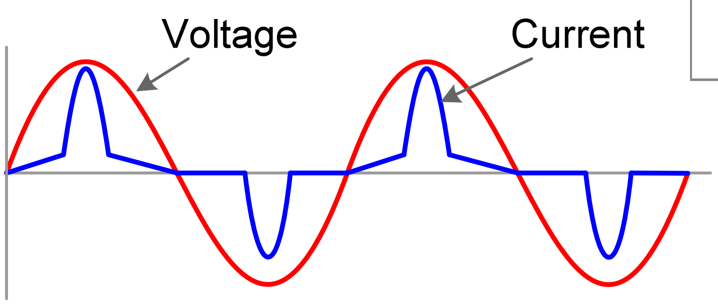


Third order harmonic is predominant

Rectifier with unsymmetrical current

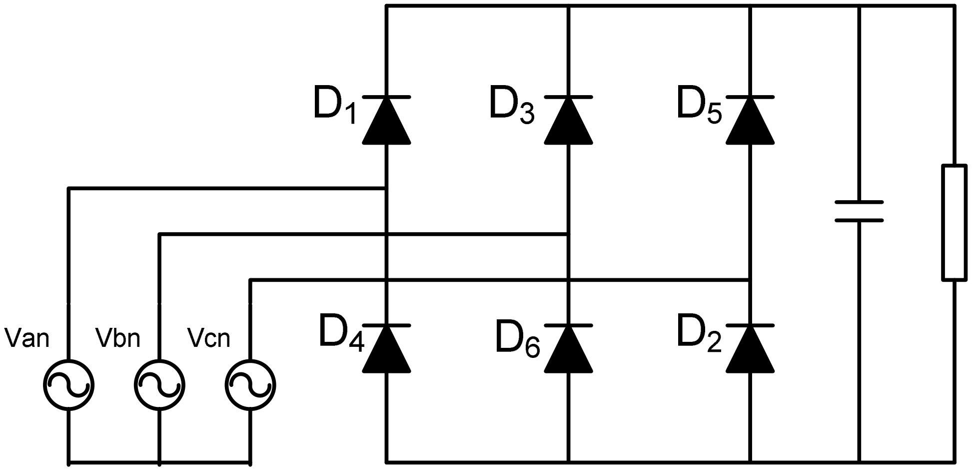


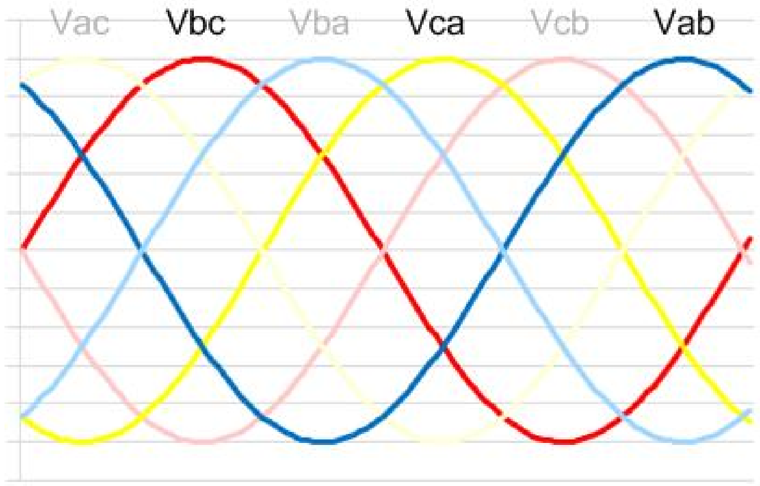


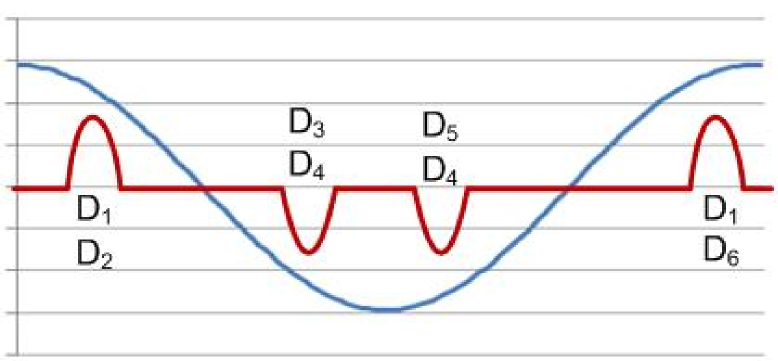


Even order harmonics are also present

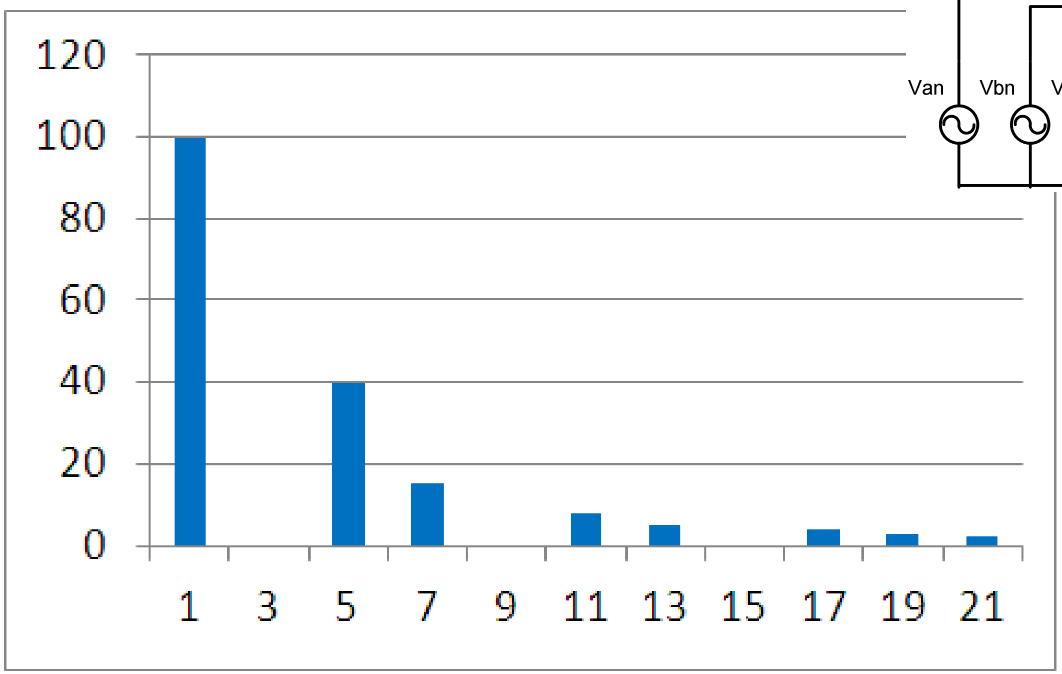
Three phase rectifier V and I

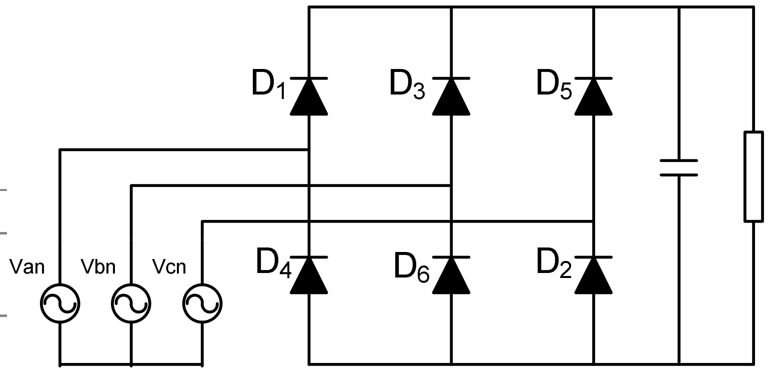






Harmonics Created by Three phase rectifier





THD and TDD

- Total Harmonic Distortion (Current)

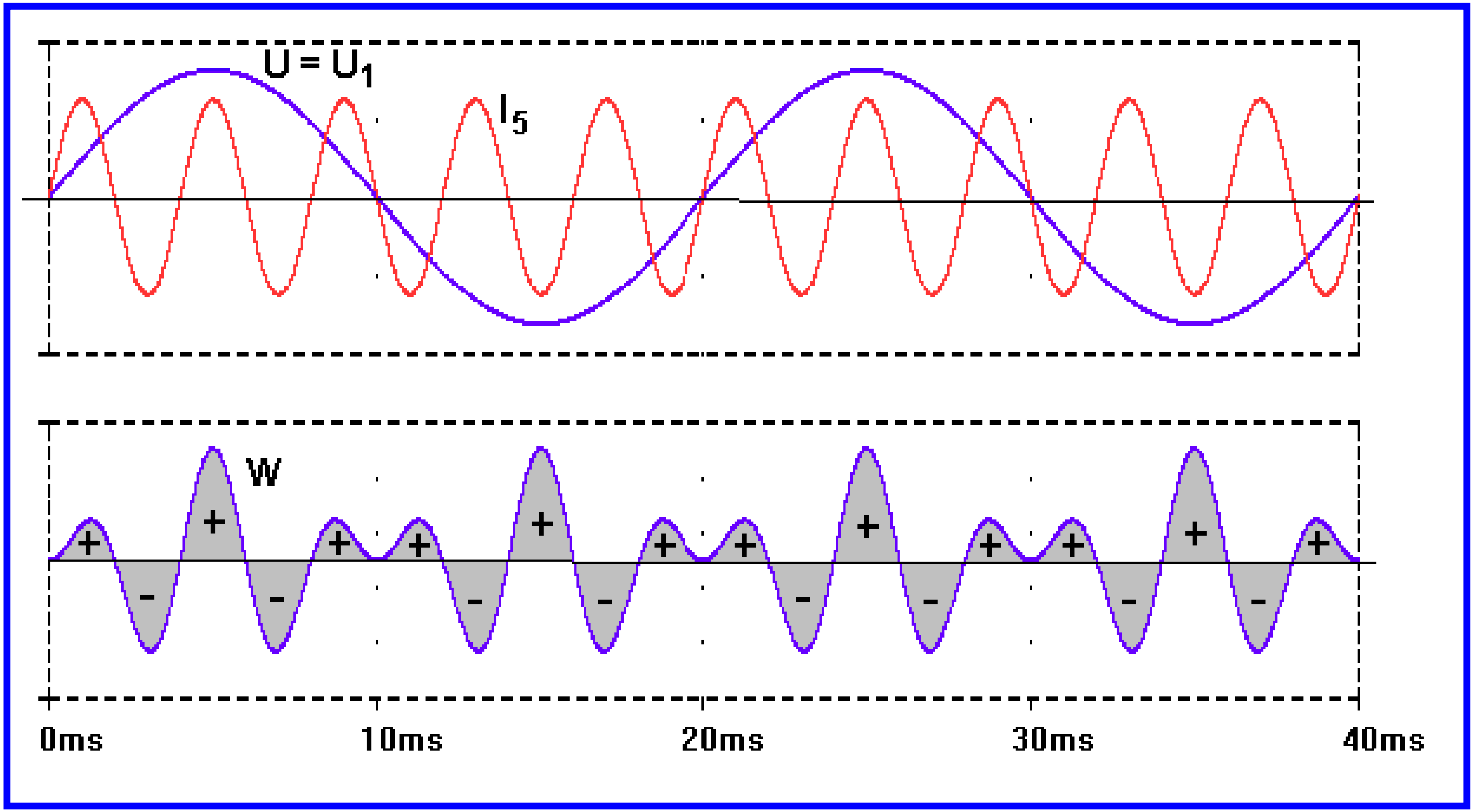
$$THD_I = \frac{\sqrt{\sum_{h=2}^{n} {I_h}^2}}{I_1}$$

- Total Demand Distortion

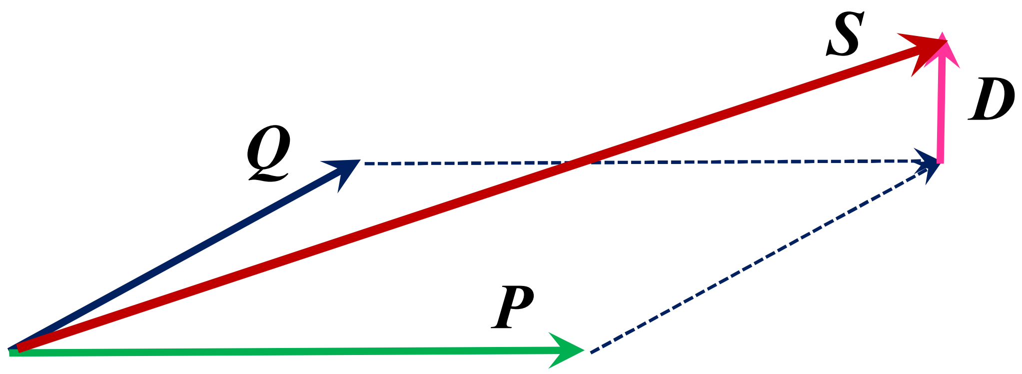
$$TDD = \frac{\sqrt{\sum_{h=2}^{n} {I_h}^2}}{I_{MD}}$$

Where $\boldsymbol{I_{MD}}$ is current corresponding to Max. Demand

Distortion Power



Power factor under harmonic conditions



- Power equation takes into account a distortion power also

$$S^2 = P^2 + Q^2 + D^2$$

- The effective power factor ***P/S*** decreases due to harmonics

Standards Available

IEEE 1433	Power Quality definitions
IEEE 519	Harmonic control
IEEE P 1453	Voltage flicker
IEEE 1409	Distribution and custom power
ANSI-IEEE C62	Guide for surge voltage
IEEE 1459	Definitions for the measurement of power quantities
IEC 61000	Power quality monitoring
EN 50160	Voltage characteristics of electricity supplied by public distribution systems

IEEE Std 519 -2014

- Sets limits for voltage and current harmonics in terms of Total Harmonic Distortion
- List out recommended practices for reduced level of harmonics

$$THD_V = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1}$$

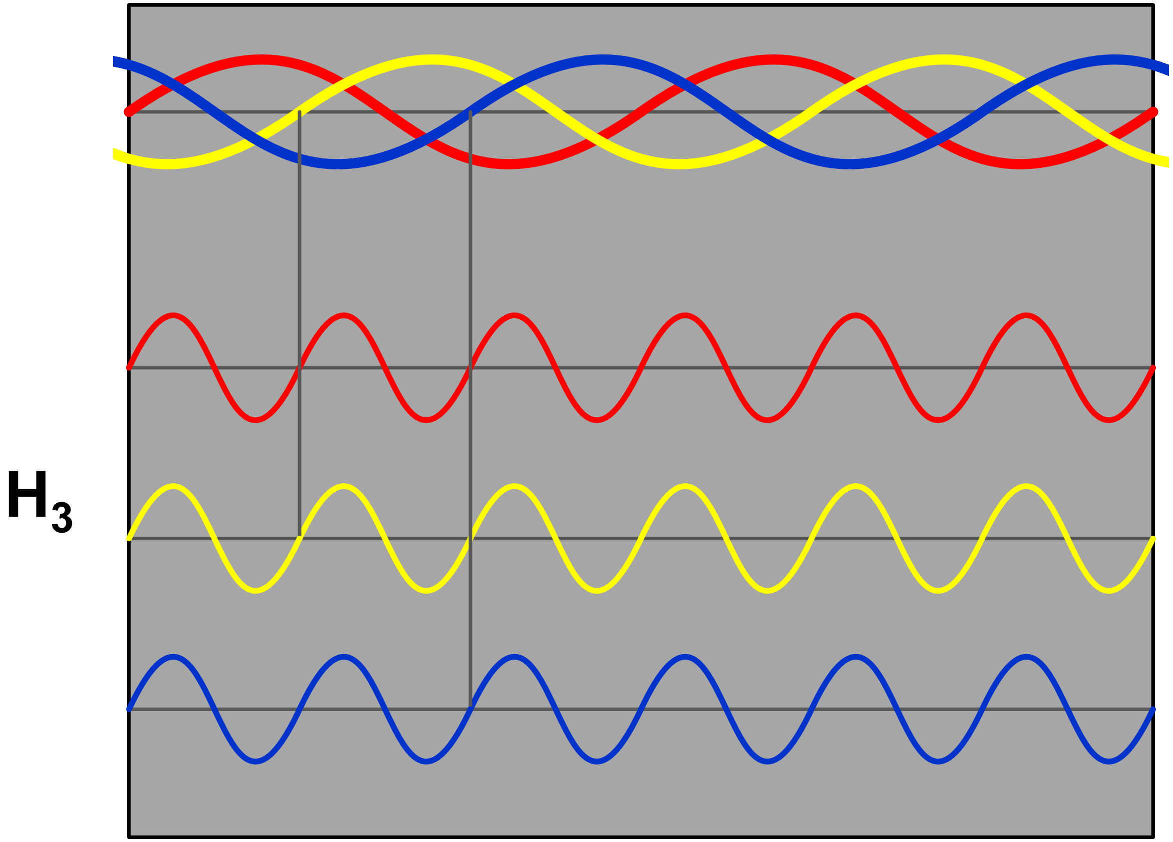
$$THD_I = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1}$$

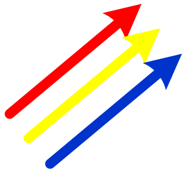
Limits on Voltage THD	
Upto 1 kV	8%
1kV to 69 kV	5 %
69kV to 161 kV	2.5 %
Above 161 kV	1.5%

Limits on Current TDD For systems upto 69kV

I_{SC} / I_L	Current
Below 20	5 %
20 to 50	8 %
50 to 100	12 %
100 to 1000	15 %
Above 1000	20 %

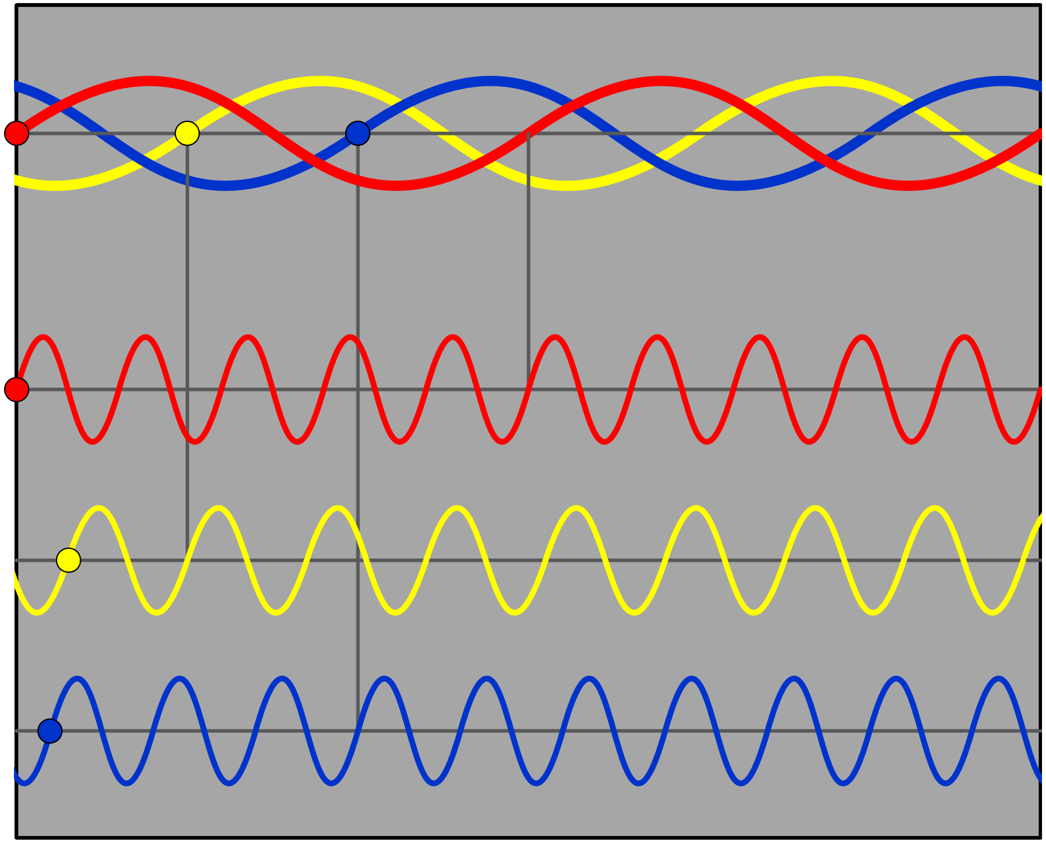
Zero Sequence Harmonics

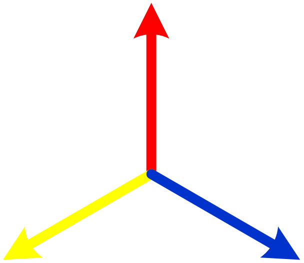




Negative Sequence Harmonics

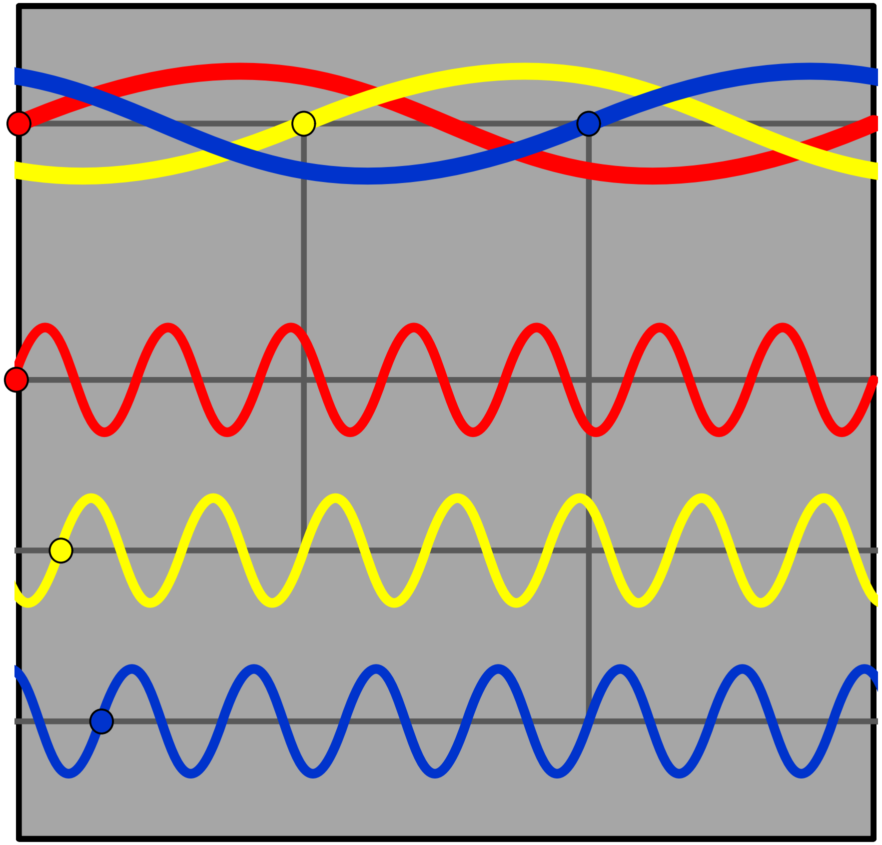
H$_5$

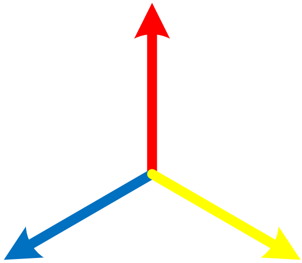




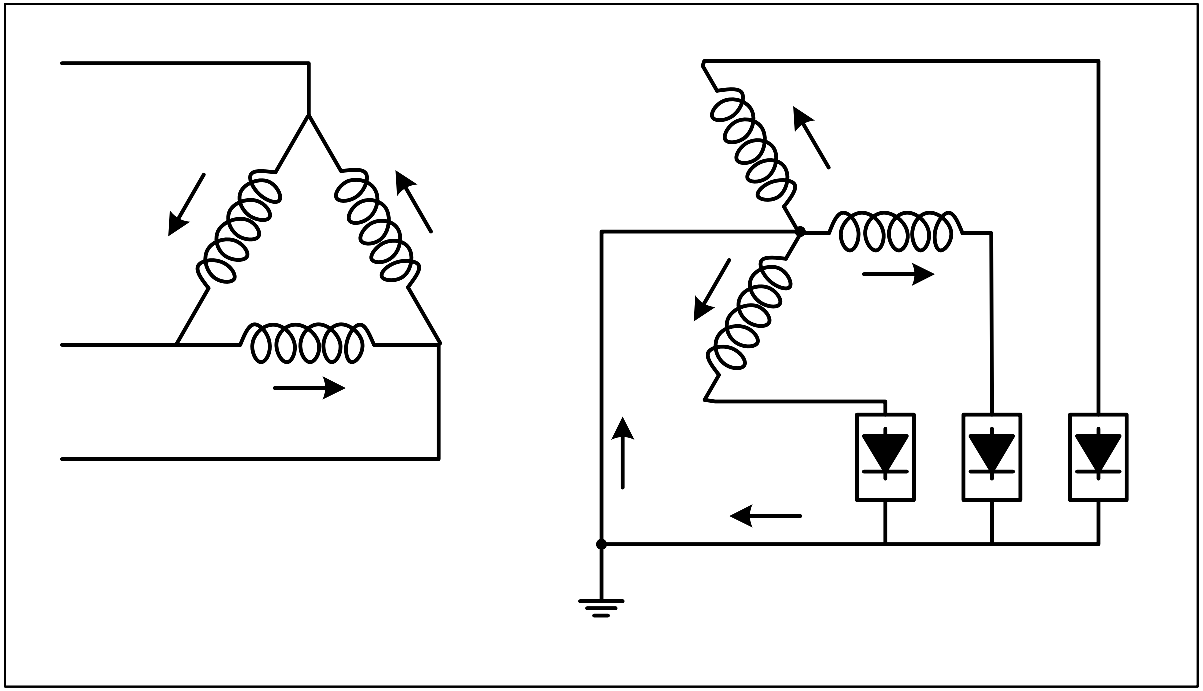
Positive Sequence Harmonics

H7

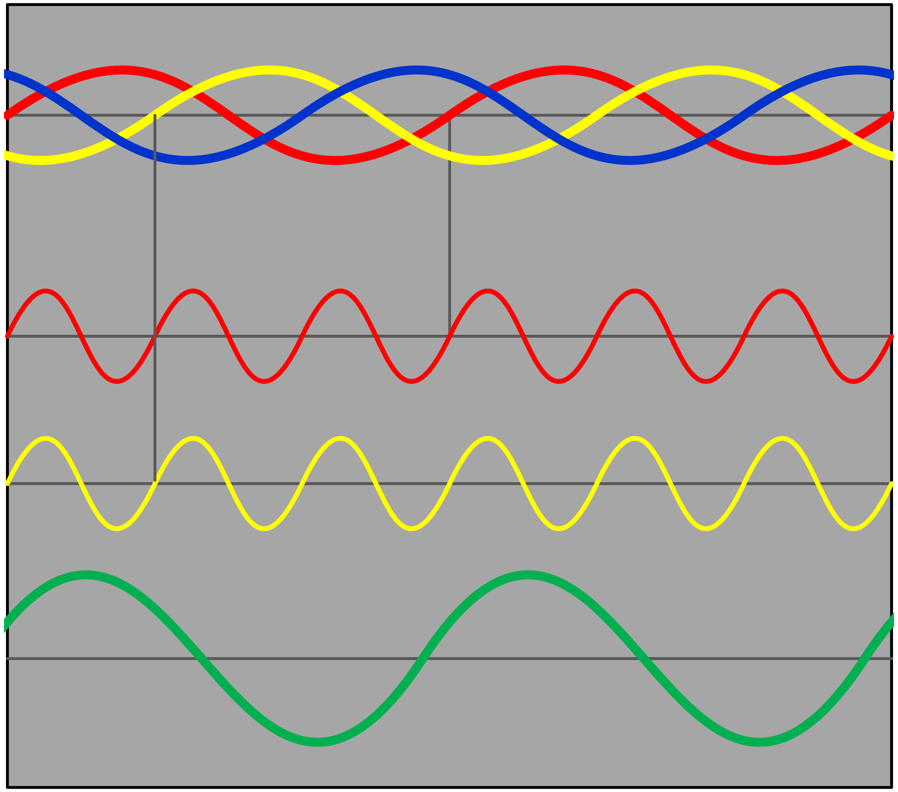




Neutral current in Y connection



Line Voltage with Harmonics

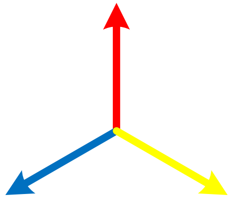


$$V_{RY} = V_R - V_Y$$

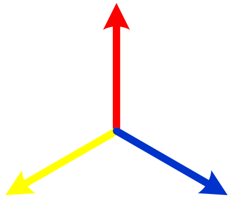
Zero sequence harmonics cancel in line voltage

Harmonic order classification

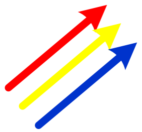
- Positive sequence: 1, 4, 7, 10, 13, …



- Negative sequence: 2, 5, 8, 11, 14, …



- Zero sequence: 3, 6, 9, 12, 15, … (called triplen)



K Factor

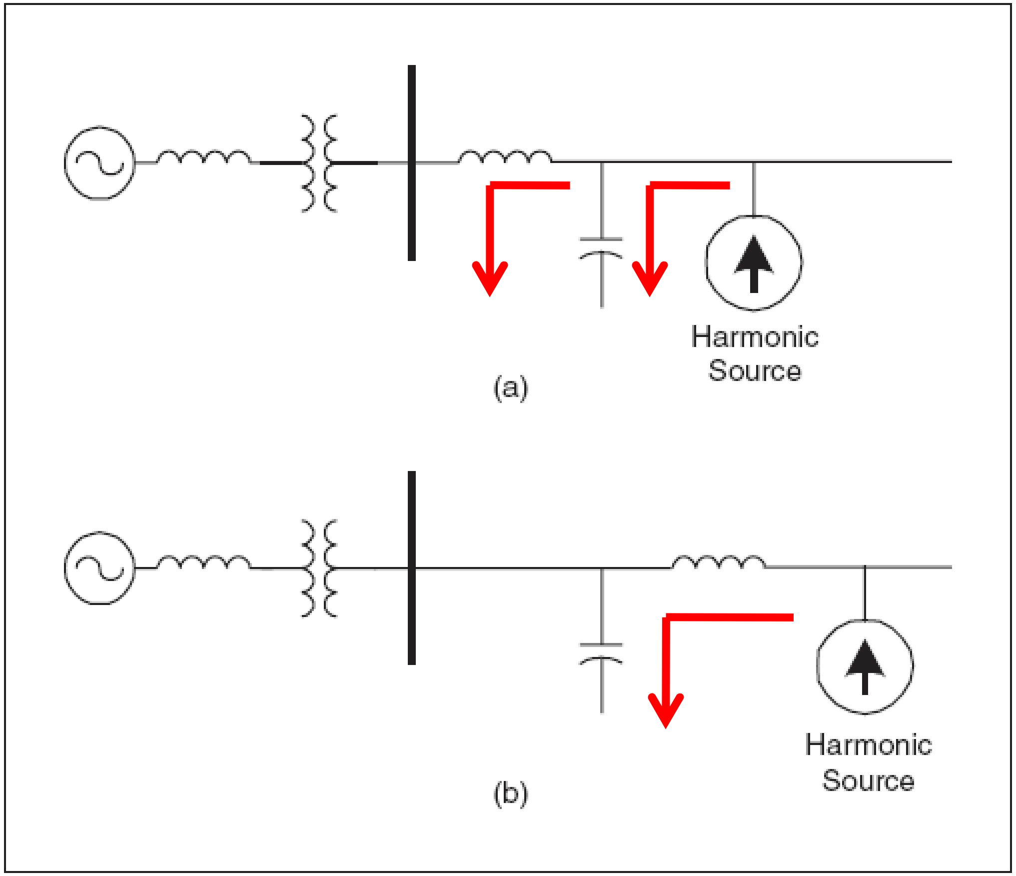
- Is an indication of possible heating up and de-rating of transformers due to harmonics
- Specified by the equation:

$$K = \frac{\sum I_h^{\,2} \times h^2}{\sum I_h^{\,2}}$$

  - Where I_h is in PU

- K rated transformers have design modifications to meet the harmonic conditions

Resonance



Parallel Resonance

Series Resonance

Interharmonics

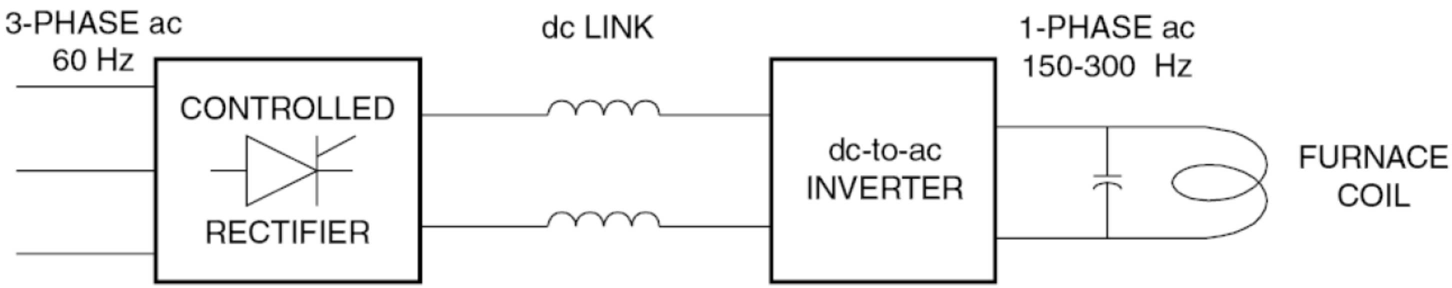
Noninteger multiple of the fundamental frequency is commonly known as an *interharmonic frequency*

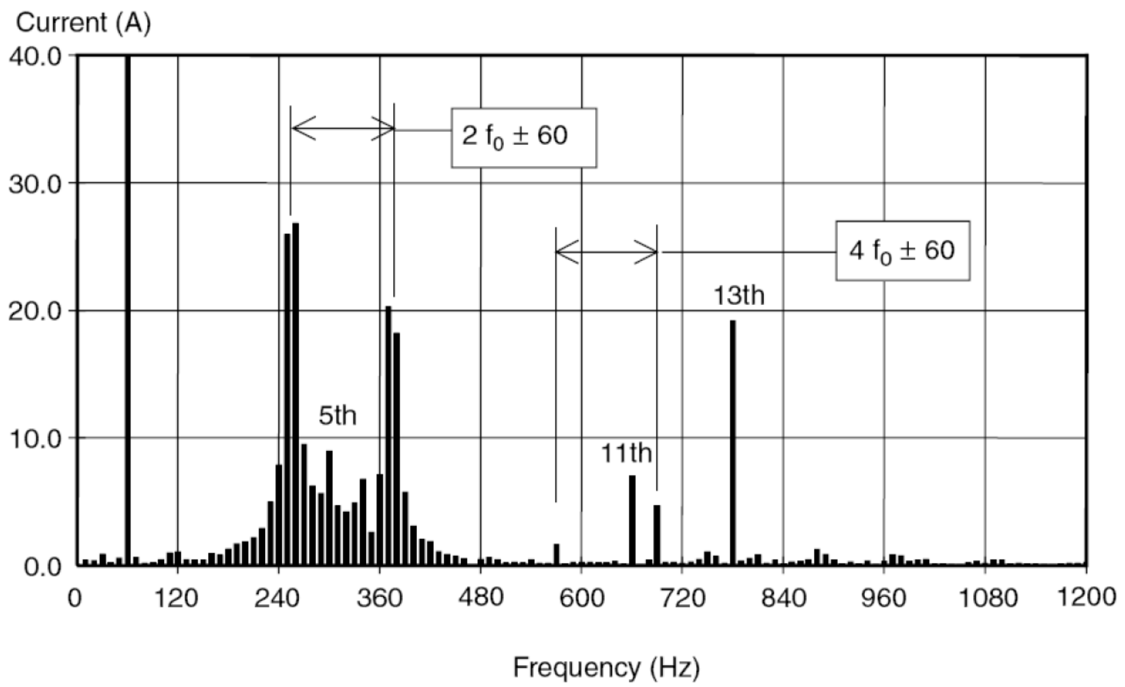
Sum of Interharmonic frequencies does not necessarily result in a periodic waveform

It is possible to have interhamonics in variable speed drives and rapidly changing loads

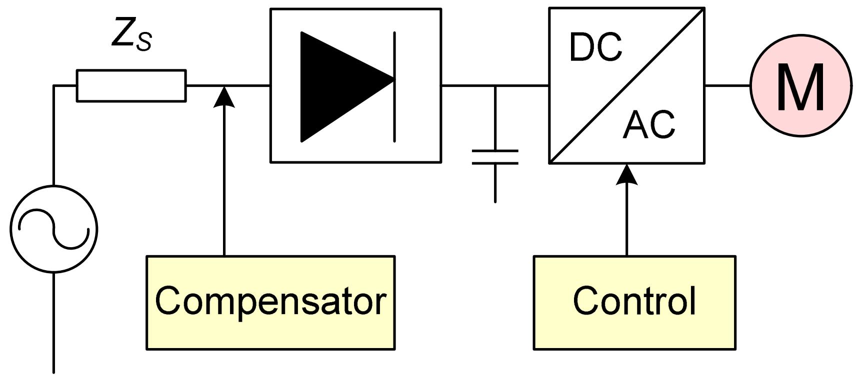
Longer sampling interval is required to capture interharmonics. Sampling 10 cycles of 50 Hz result in a resolution of 5 Hz

Interharmonics Example



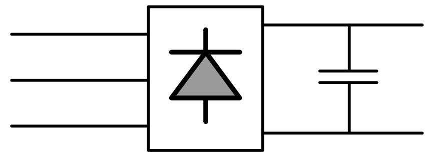
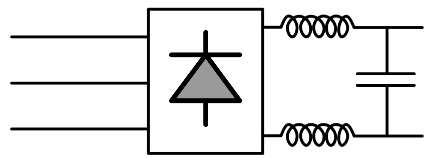
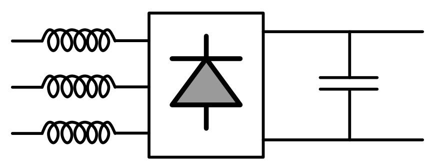
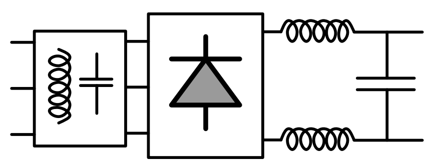


Factors affecting impact of drives

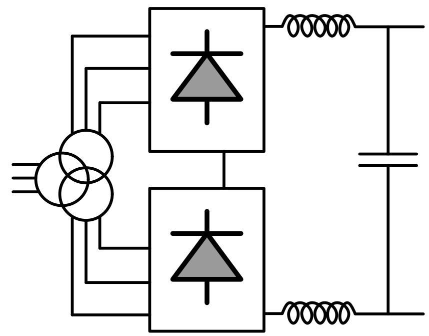
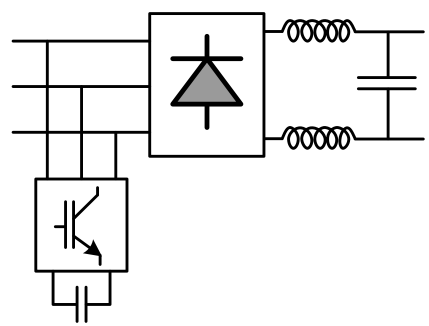


- Pulse number of the front-end rectifier of the VSD
- Compensation circuits
- Magnitude of the power system (source) impedance at PCC

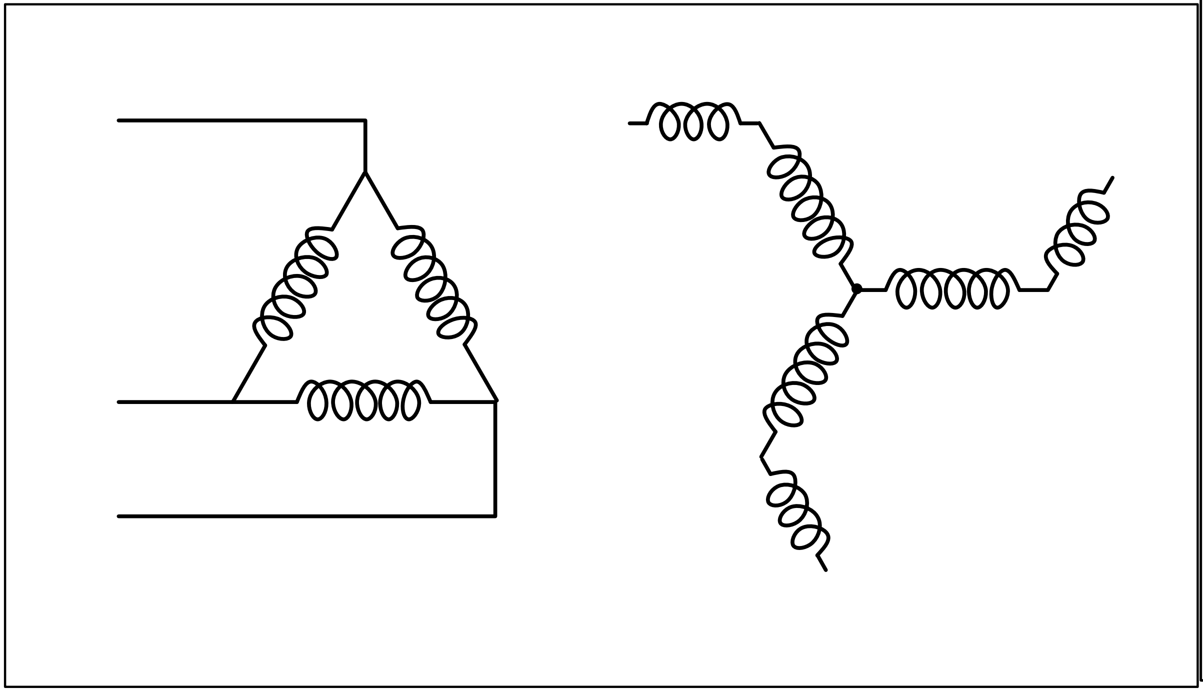
Mitigation Methods for Harmonics

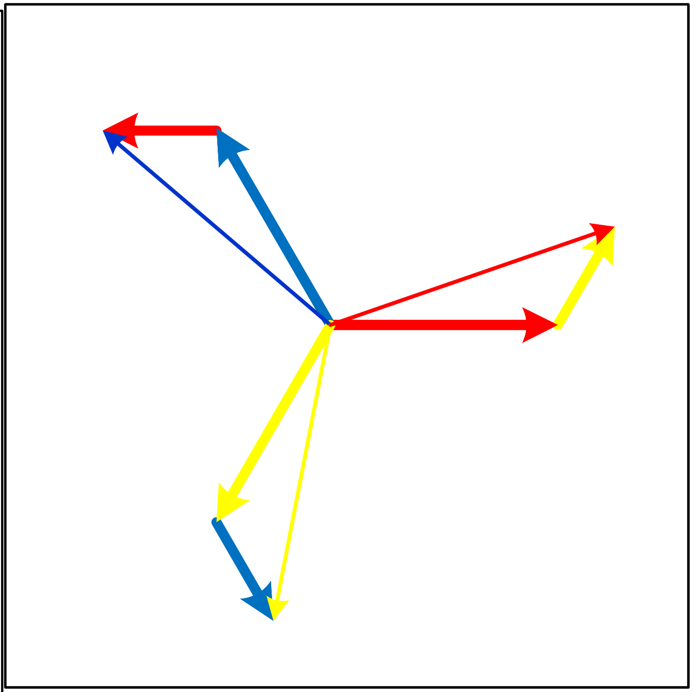
Method	Schematic	THD Range
No mitigation		THD > 80%
DC Inductor		THD < 40%
AC Inductor		THD < 40%
Passive Filter		THD < 10%

Mitigation Methods for Harmonics

Method	Schematic	THD Range
Multi-pulse Rectifier		THD < 10%
Active Filter		THD < 5%

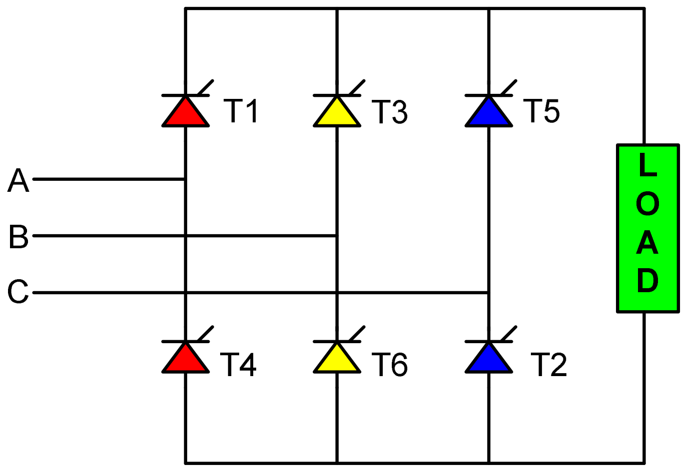
Zigzag Transformers

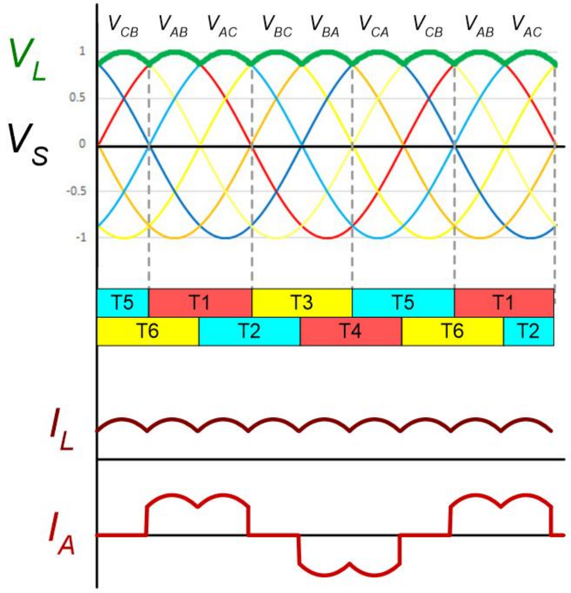




- Phase Shifting in different angles possible
- Can selectively block certain harmonic order

6 Pulse converter

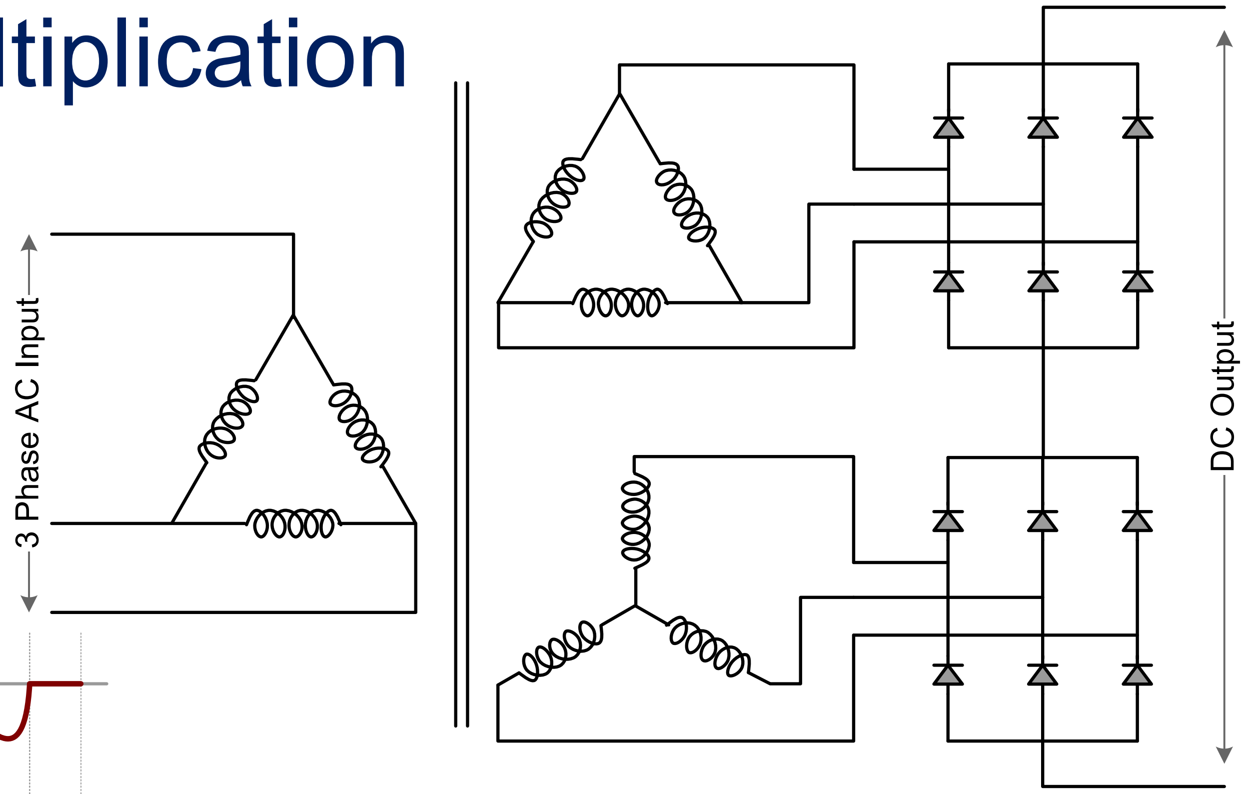


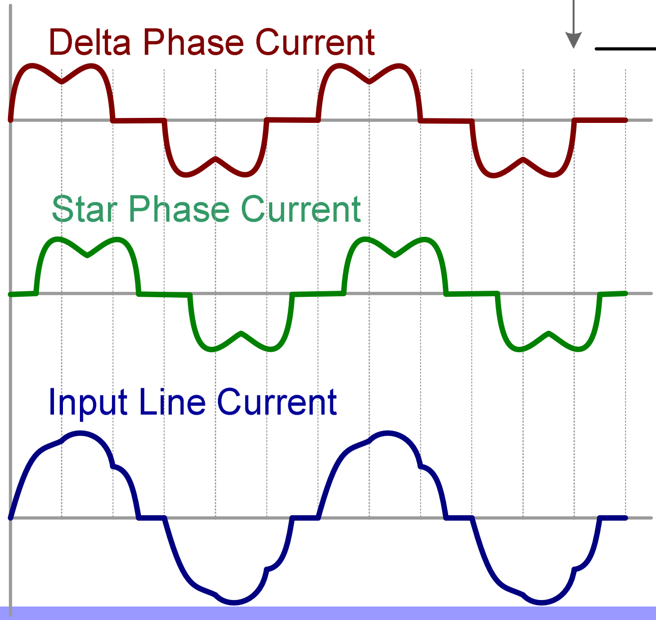


6 pulse inverter has considerable amount of waveform distortion in the input current

Phase Multiplication

12 pulse
Series Connected
Converter

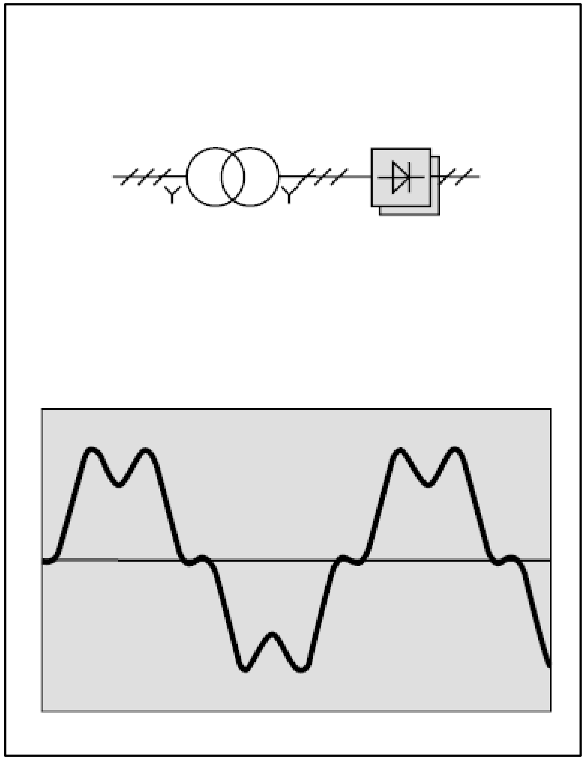




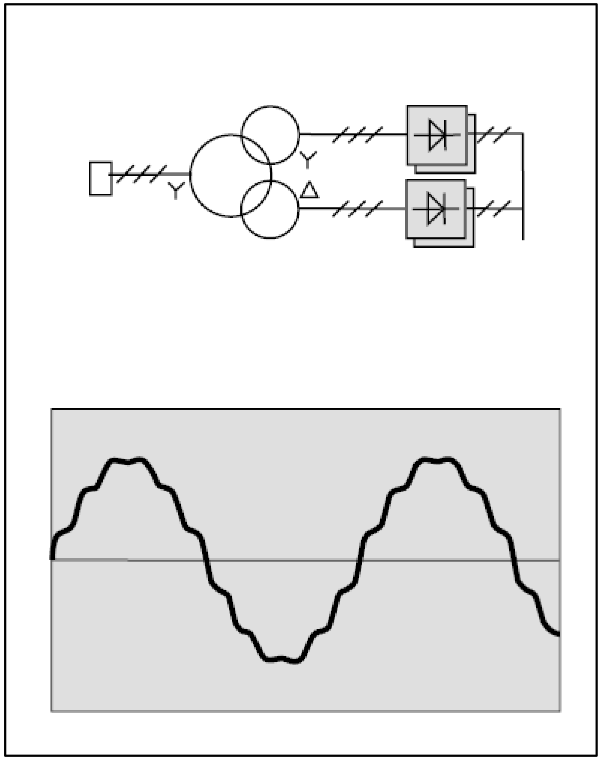
Input harmonics in much less compared to 6 pulse converter

Converter Types and Harmonics

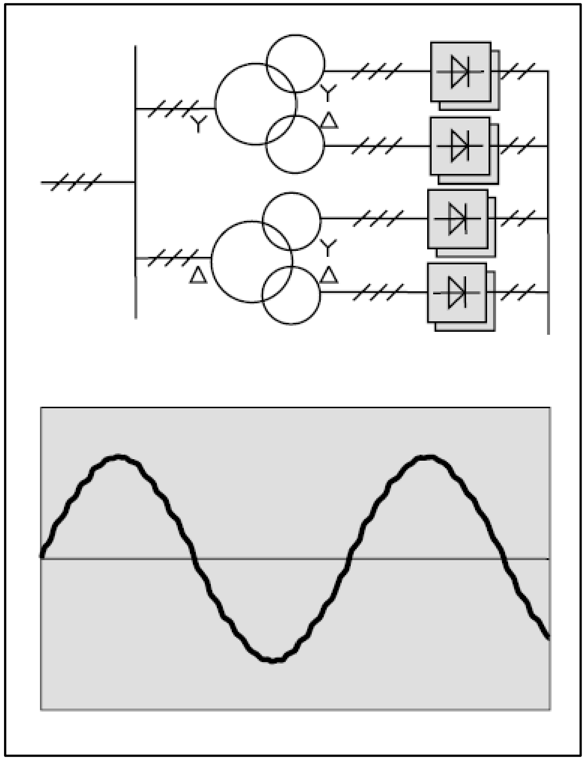
6 Pulse



12 Pulse



24 Pulse



Harmonics in input current

$$h = n \cdot p \pm 1 \qquad\qquad p = 1, 2, 3, \ldots$$

h	Number of Rectifier Pulses, *p*			
	6	12	18	24
5	X			
6	X			
11	X	X		
13	X	X		
17	X		X	
19	X		X	
23	X	X		X
25	X	X		X

Remedies for Harmonic Problem

- Harmonic filters
  - Active, passive or hybrid
- Selection of nonpolluting equipment
- Good distribution network
- Stipulate power quality standards for consumer equipment
  - Already introduced in many countries
  - Implementation may be difficult
- Introduce a penalty/incentive scheme
- Good PQ monitoring System

Thank you