Module 7
Filtering of harmonics

Content

- Filtering of the output of an inverter
- Filtering of line currents
    - Passive filters
    - Active filters
- Filtering of dc-link
    - Six-pulse rectifier
        - Load is resistance
        - Load is voltage sourced inverter

Learning outcomes of the module

After the module, you will be able to:

- understand the basics of filtering of harmonics in
  - the output of voltage sourced converter
  - the input of line-commuted rectifier (line-current harmonics)
  - Dc-bus

Why filtering

- Converters are producing both voltage and current harmonics
  - Filters are based on inductors and capacitors
  - Efficiency as high as possible
    - Filter resistances should be small
    - Risk for not wanted resonances
- Filters are enhancing voltage and/or current properties of the converter

Voltage Filter

- Output voltage of self-commutated inverters contains harmonics (PWM)
- When the voltage is sinusoidal enough?
  - THD less than 10%
  - Often required less than 5% or even 3 %

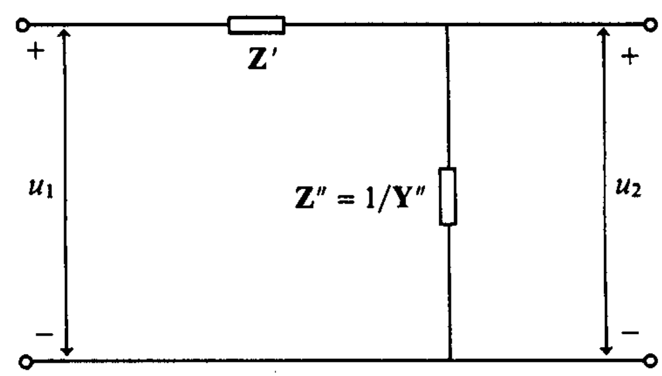
Filtering factor (damping)

$$f_{(n)} = \left| \frac{\boldsymbol{U}_{2(n)}}{\boldsymbol{U}_{1(n)}} \right| = \left| \frac{\boldsymbol{Z}''_{(n)}}{\boldsymbol{Z}''_{(n)} + \boldsymbol{Z}'_{(n)}} \right| = \left| \frac{1}{1 + \boldsymbol{Z}'_{(n)} \boldsymbol{Y}''_{(n)}} \right|$$

- Voltage divider
  - Phase-shift is not often interesting => RMS value is enough
  - At fundamental there should be no damping
  - At harmonics high damping

$$f_{(1)} \approx 1$$

$$f_{(n)} \to \infty$$



Series and parallel resonance

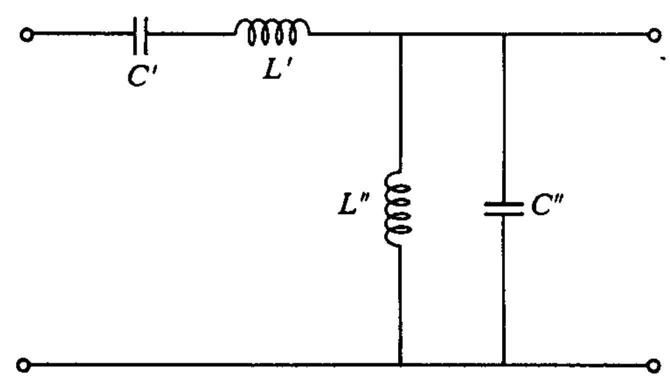
- Fundamental
  - Series impedance must be zero
  - Parallel impedance must be infinite
- At harmonics *n*

$$X' = L'\omega = \frac{1}{C'\omega}$$

$$Y'' = C''\omega = \frac{1}{L''\omega}$$

$$\boldsymbol{Z}'_{(n)} = \mathrm{j}L'n\omega - \mathrm{j}\frac{1}{C'n\omega} = \mathrm{j}X'\left(n - \frac{1}{n}\right)$$

$$\boldsymbol{Y}''_{(n)} = \mathrm{j}C''n\omega - \mathrm{j}\frac{1}{L'''n\omega} = \mathrm{j}Y''\left(n - \frac{1}{n}\right)$$



Filtering

- Using the previous impedances

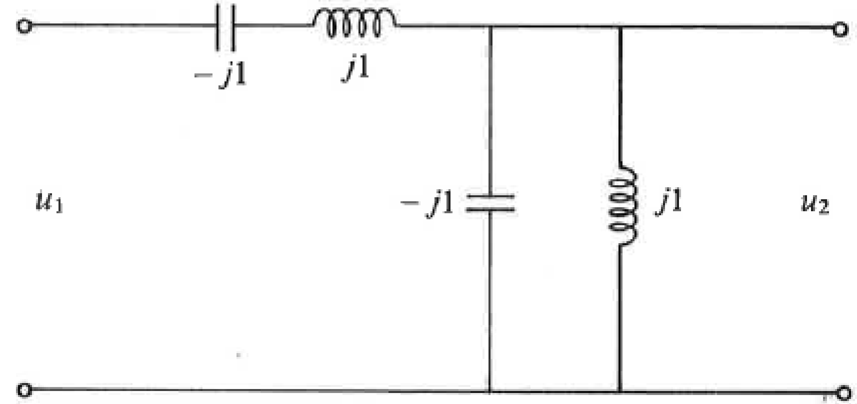
$$f_{(n)} = \left| \frac{1}{1 + \mathrm{j}X' \left(n - \frac{1}{n} \right) \mathrm{j}Y'' \left(n - \frac{1}{n} \right)} \right| = \left| \frac{1}{1 - \left(n - \frac{1}{n} \right)^2 X' Y''} \right|$$

- Results is infinite if

$$1 - \left(n - \frac{1}{n} \right)^2 X' Y'' = 0 \Rightarrow n = \frac{1}{2} \left(\sqrt{\frac{1}{X' Y''}} + \sqrt{\frac{1}{X' Y''} + 4} \right)$$

- Harmonics at these frequencies are amplified

Example



For $X' = Y'' = 1$:

$$f_{(n)} = \left| \frac{1}{1-(n-1/n)^2} \right| = \frac{n^2}{(n^2-1)^2 - n^2}$$

$$f_{(3)} = \frac{9}{64-9} = 0.164$$

$$f_{(5)} = \frac{25}{576-25} = 0.045$$

$$f_{(7)} = \frac{49}{2304-49} = 0.021$$

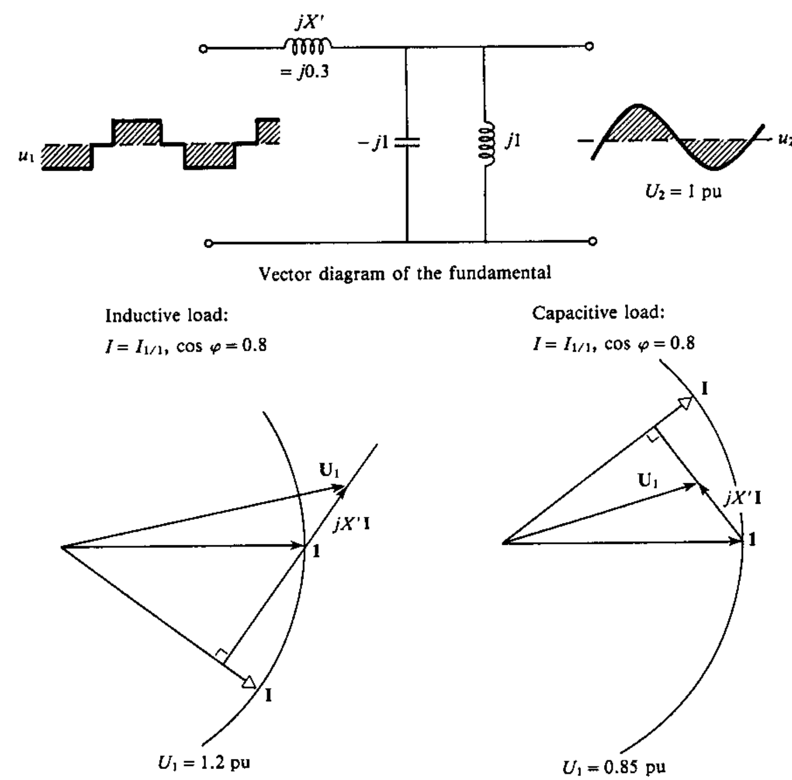
Input voltage: $U_{(1)} = 1$, $U_{(3)} = 1/3$, $U_{(5)} = 1/5$, $U_{(7)} = 1/7$ etc.

Output voltage: $U_{(1)} = 1$, $U_{(3)} = 0.164/3 = 0.055$,

$U_{(5)} = 0.045/5 = 0.009$, $U_{(7)} = 0.021/7 = 0.003$ etc.

Filter without series resonance

- Series capacitor is a risk for resonances if load is inductive
- Without series capacitor
  - Output voltage depends on load current
  - To compensate this converter output voltage must be changes according to the load current



Filtering of line-current harmonics

Content

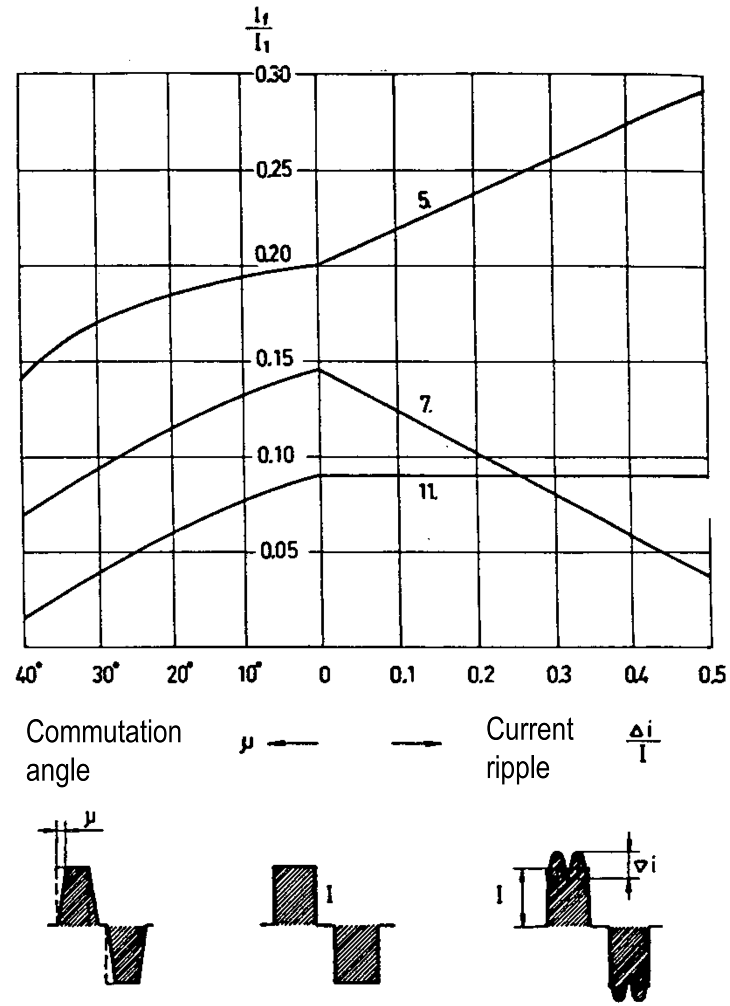
- Source of current harmonics
- Filtering of currents
  - Passive harmonic filters
  - Series and parallel resonances
- Active filters

Thyristor rectifiers

- Rectifiers are causing harmonics based on the pulse number of the converters
  - $n = pk \pm 1$ (k = 1, 2, ...)
  - Amplitude $I_{(n)} = I_{(1)}/n$
- Commutation is assumed to be infinitely fast and dc current ideally smooth

Commutation angle and ripple

- In practice current is not ideal
  - y-axis
- Commutation reduces harmonics in line current
  - left from y-axis, increasing commutation angle
- Ripple in dc-current increases fifth harmonic in line current
  - right from y-axis



Harmonic voltages

- Converter (rectifiers) are sources of current harmonics for the supply system
  - Harmonic voltage is created by the harmonic impedance and current

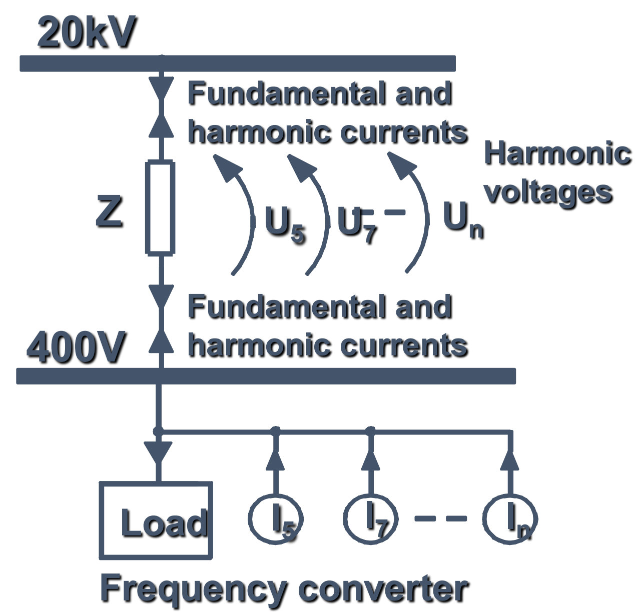
$$U_{(n)} = Z_{N(n)} I_{(n)}$$

- Defining the ac system impedance exactly is difficult
  - Often approximated by a reactance $Z_{N(n)} \approx nX_{(1)}$
  - Fundamental reactance is calculated from the short-circuit power

$$X_{(1)} = \frac{U^2}{S_k}$$

Voltage distortion

- Supply system and the transformer are creating harmonic impedance Z_h
- Load creates harmonic current I_h
- Voltage distortion



$$U_{THD} = \frac{U_h}{U_{rms}} * 100\%$$

$$U_h = \sqrt{U_3^{\,2} + U_5^{\,2} + U_7^{\,2} + \ldots + U_n^{\,2}}$$

$$U_{rms} = \sqrt{U_1^{\,2} + U_3^{\,2} + U_5^{\,2} + U_7^{\,2} + \ldots + U_n^{\,2}}$$

Voltage distortion, example

<u>**Initial values:**</u>

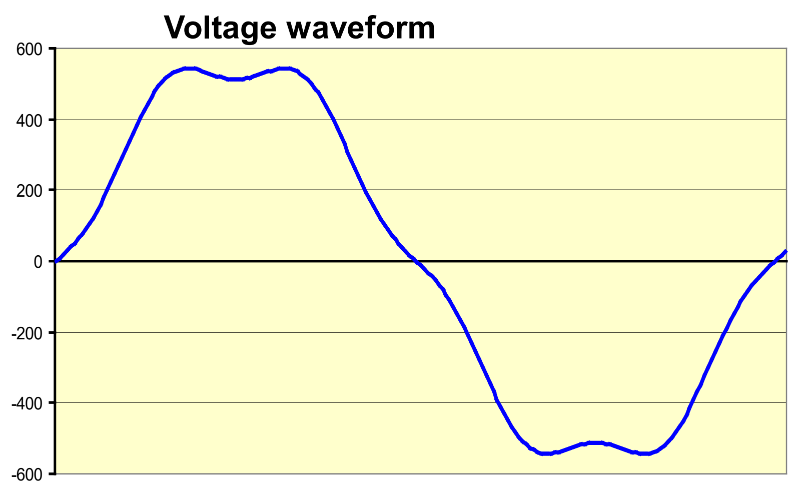
5. Harmonic current: 500 A
Transformer values :
U_n = 20/0,4 kV
S_n = 1000 kVA
Z_k = 5,5 %

Transformer impedance at 250 Hz is 44 mΩ

$$U_5 = \sqrt{3} Z_5 I_5 = \sqrt{3} \cdot 44\text{m}\Omega \cdot 500\text{A} = 38\text{V}$$

$$\text{U}_{rms} = \sqrt{U_1^2 + U_5^2} = \sqrt{400^2 + 38^2}\,\text{V} = 402\text{V}$$

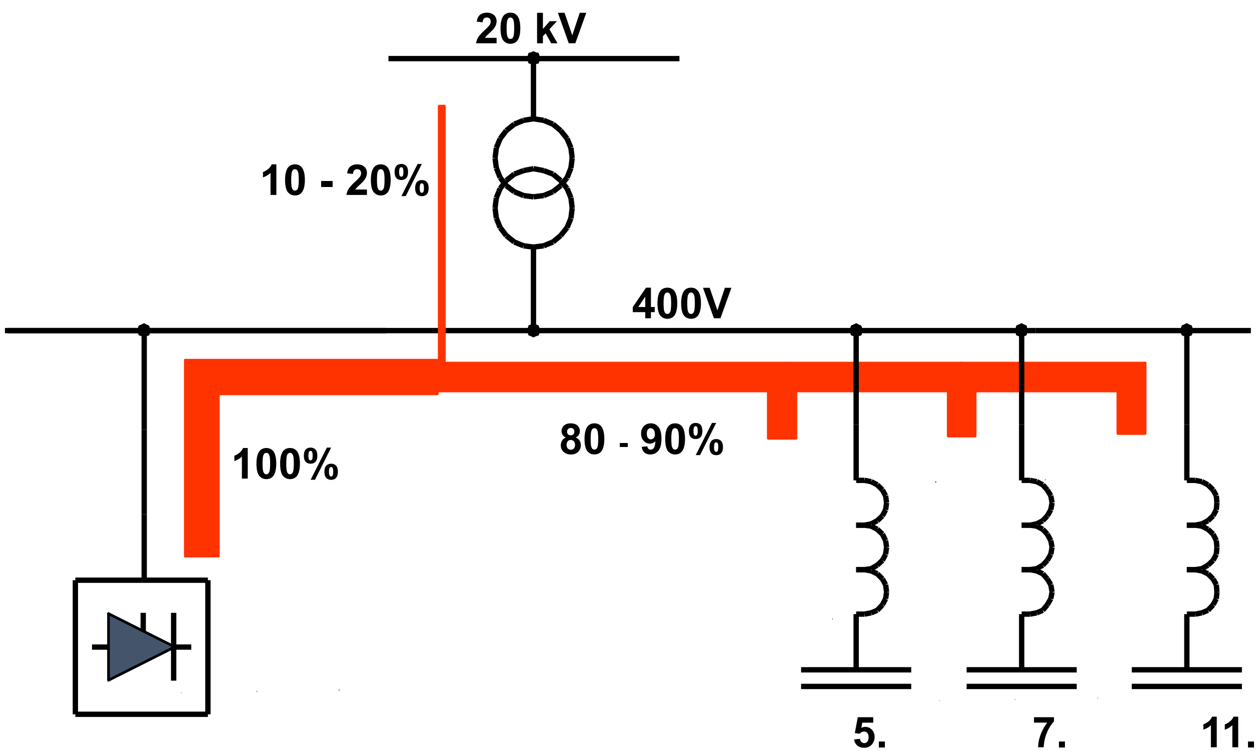
$$U_{5thTHD} = \frac{U_5}{U_{rms}} \cdot 100\% = \frac{38}{402} \cdot 100\% \approx 9,5\%$$



Harmonic filters

- Current filtering is done with LC-circuits tuned to specific frequencies
  - o Normally parallel connected circuits for different frequencies
  - o Additionally, a wide band filter for higher harmonics
  - o Single- and three-phase connections

Principle of filter bank



Impedance of the harmonic component is smallest in the filter and therefore major part of current is flowing there and not in to the 20 kV network

Tuning

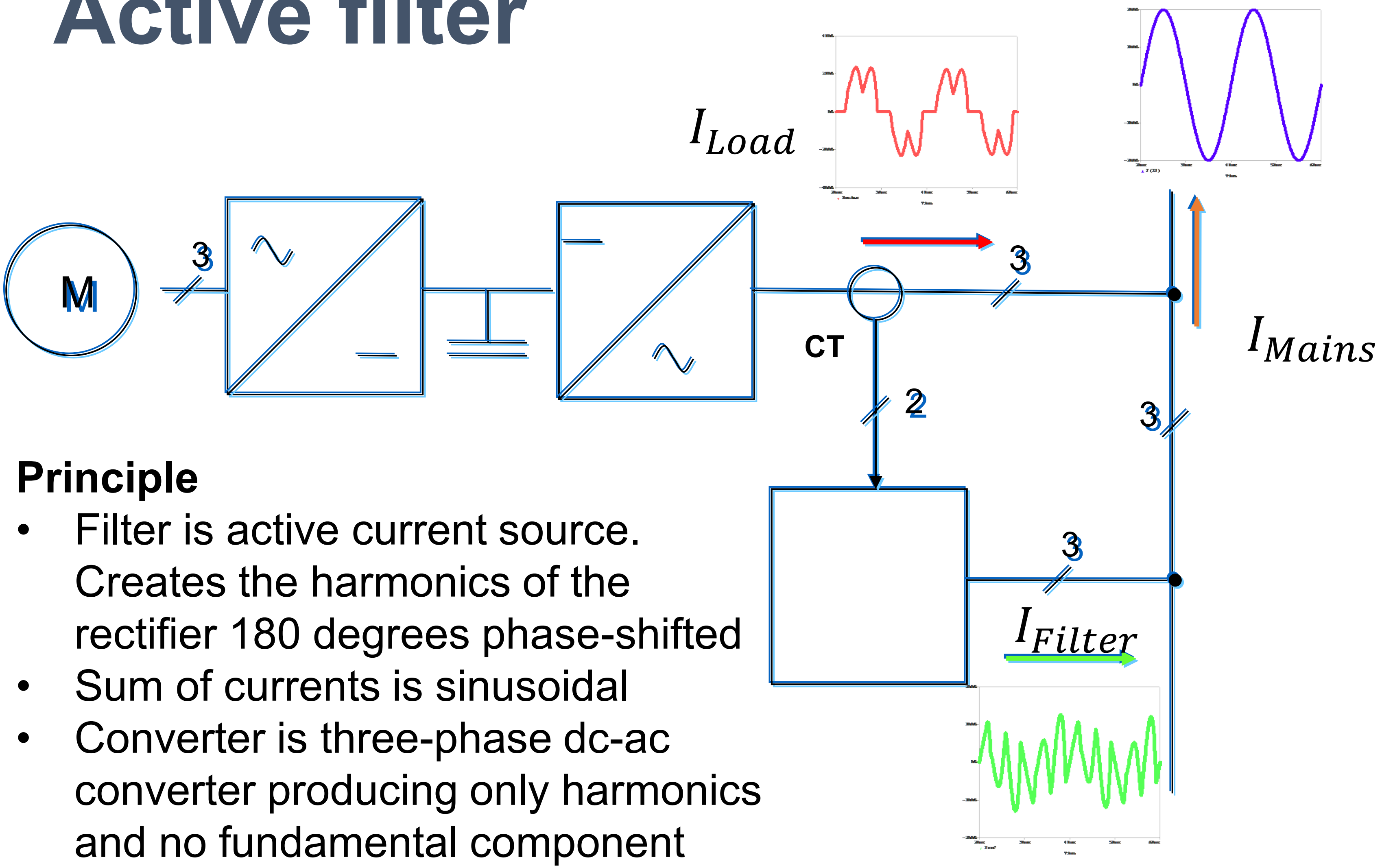
$$Z_{F(n)} = \mathrm{j}n\omega L + \frac{1}{\mathrm{j}n\omega C}$$

- Capacitor
  - At fundamental frequency filter produces reactive power, impedance of capacitor dominant as $n\omega$ is smaller than the tuning frequency
  - Size is selected based on the required compensation,i.e. reactive power
- Inductance is selected based on the series resonance, i.e. so that $Z = \mathrm{j}n\omega L + \frac{1}{\mathrm{j}n\,\omega\,C}$ = 0 at the selected frequency $n\omega$
  - Low impedance circuit for 5., 7., 11. etc harmonics
- Over-current protection of the filter is needed

Active filters

- Active filters are dc-ac converter that are connected in parallel with network and rectifier
- Current reference is based on the fundamental component and harmonics of the rectifier
  - Active filter produces harmonics of the current, reversed
  - Ideally total current is sinusoidal

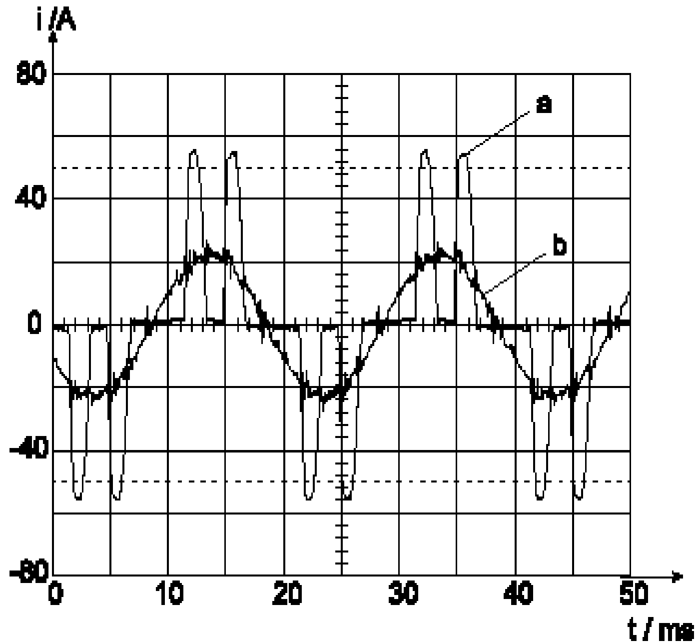
Active filter



Principle

- Filter is active current source. Creates the harmonics of the rectifier 180 degrees phase-shifted
- Sum of currents is sinusoidal
- Converter is three-phase dc-ac converter producing only harmonics and no fundamental component

Result

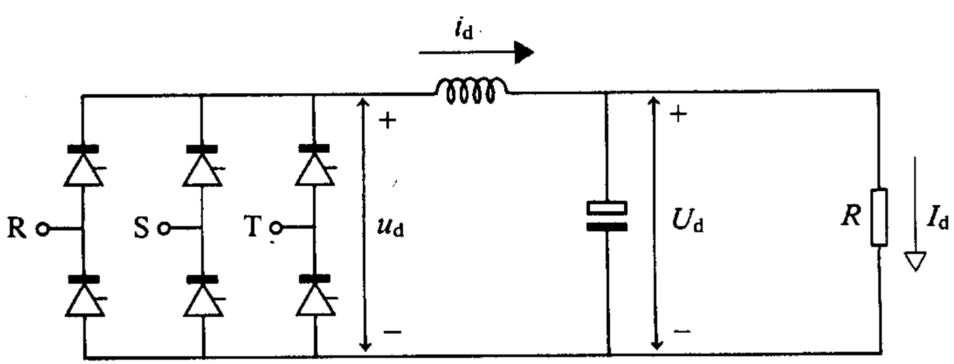


Network current of a DC-motor drive a) without active filter and b)with active filter

Filtering of dc-voltage

Six-pulse recitifier with passive load

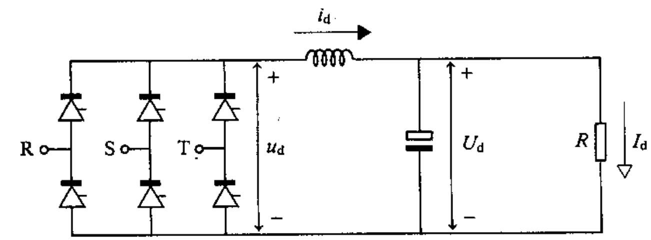
- Six-pulse rectifier
  - Filtering of current, inductoc
  - Filtering of voltage, capacitor
    - Together a low-pass filter, -40 dB/decade



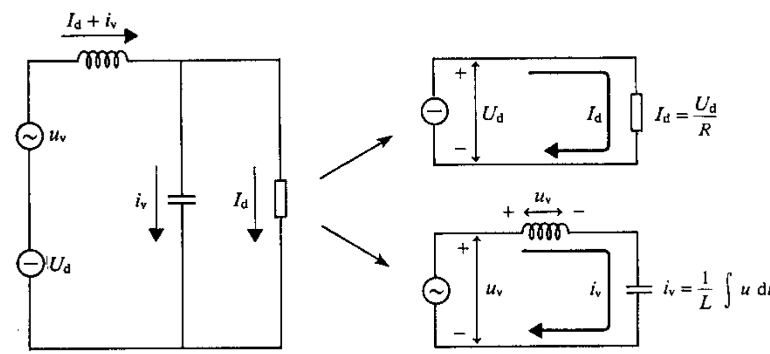
(a) Connection

Equivalent circuit, superposition

- For simplicity load is assumed to be a resistor
  - No harmonics because of load
  - Circuit divided to dc and ac



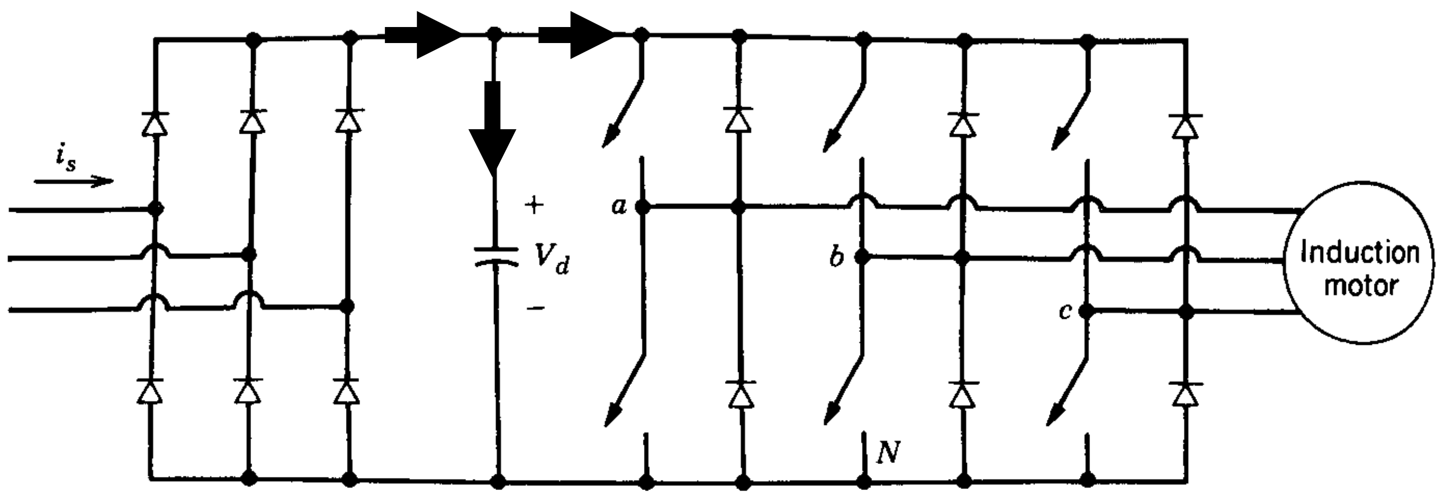
(a) Connection



(b) Equivalent diagram

Frequency converter as a load

- DC-bus is combining both the rectifier and inverter currents

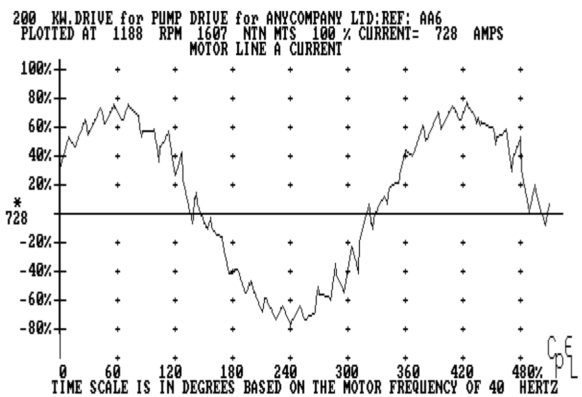


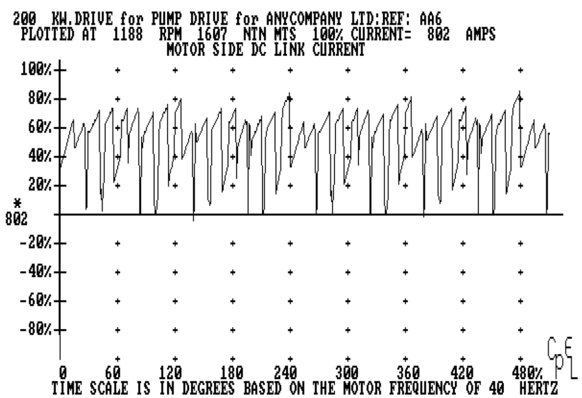
Current in dc-bus

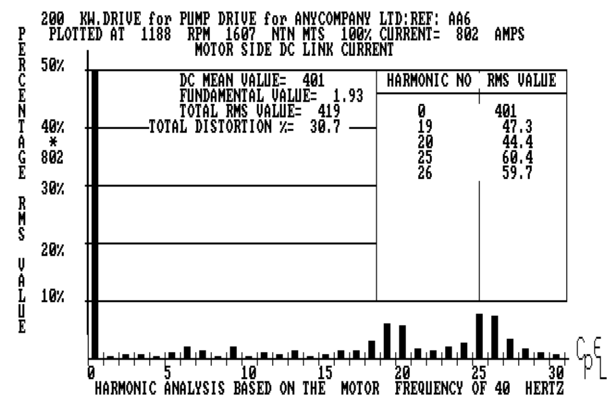
- Three different currents
  - Supply side dc link current
  - Motor side dc link current
    - Average corresponds to the transferred power, harmonics are from the PWM
  - Dc link capacitor current
    - Harmonics caused by the rectifier and by the inverter
- Next pages show these currents

Output current and motor side dc-link current, PWM-harmonics

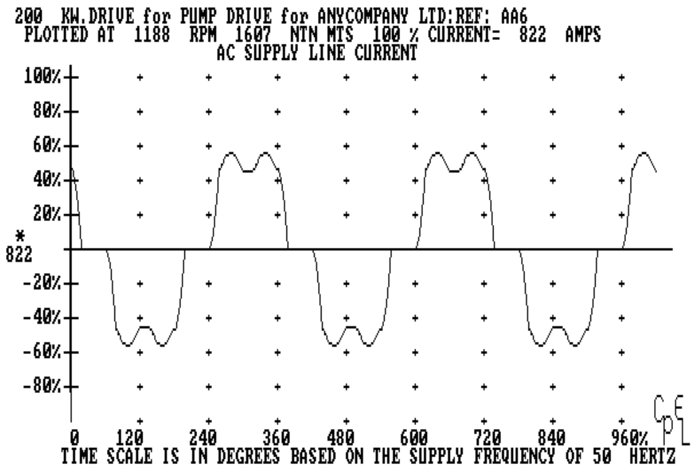
- Average dc current corresponds to the power

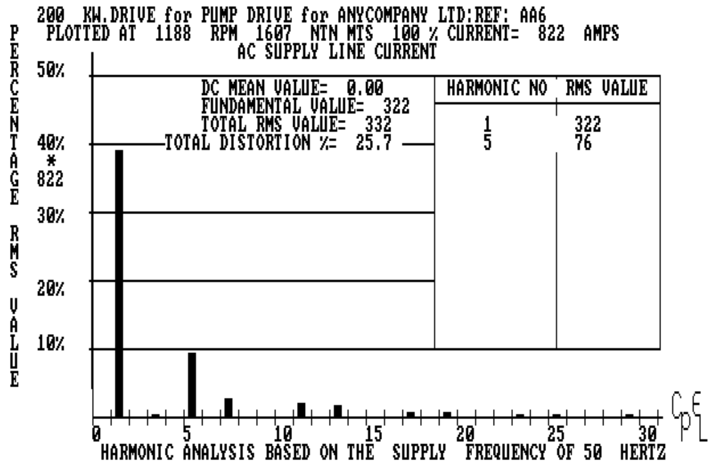


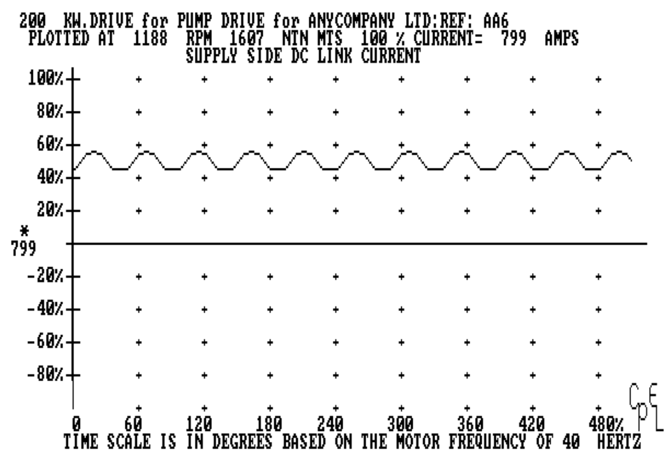




Line-current and supply side dc-link current

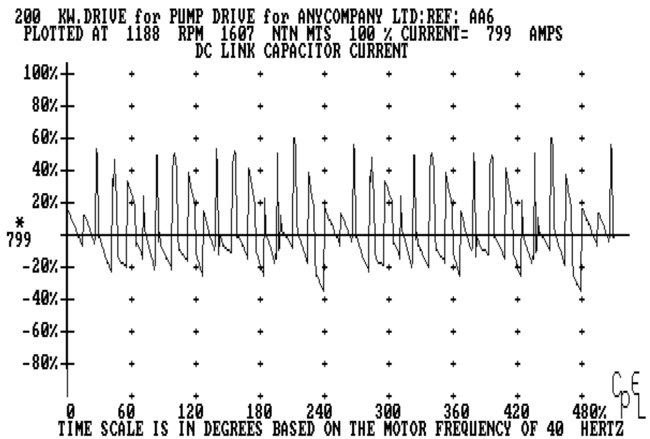


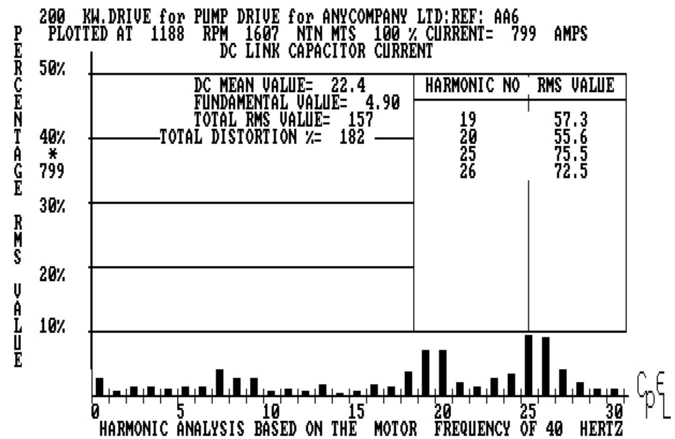




Capacitor current

- No dc component
- Harmonics
  - Switching frequency harmonics from motor currents
  - Line-frequency harmonics from rectifier





Summary of the module

- Converters are producing waveforms that are not ideal, they include different harmonics
  - Filters can be used to remove these or to provide an alternative path
- Filters are resonant circuits, including inductor and capacitor and as small series resistance as possible
  - Most simple filter is parallel connected capacitor, which provides a low impedance path for harmonics
- Filters are used in the input and output side of converters but also in dc-bus