

# Chapter 7

## Mains Interference

Facts Worth Knowing about Frequency Converters



## 7 Mains Interference

### 7.1 What are Harmonics?

#### 7.1.1 Linear Loads

On a sinusoidal AC supply a purely resistive load (for example an incandescent light bulb) will draw a sinusoidal current, in phase with the supply voltage.

The power dissipated by the load is:  $P = U \times I$

For reactive loads (such as an induction motor) the current will no longer be in phase with the voltage, but will lag the voltage creating a lagging true power factor with a value less than 1. In the case of capacitive loads the current is in advance of the voltage, creating a leading true power factor with a value less than 1.

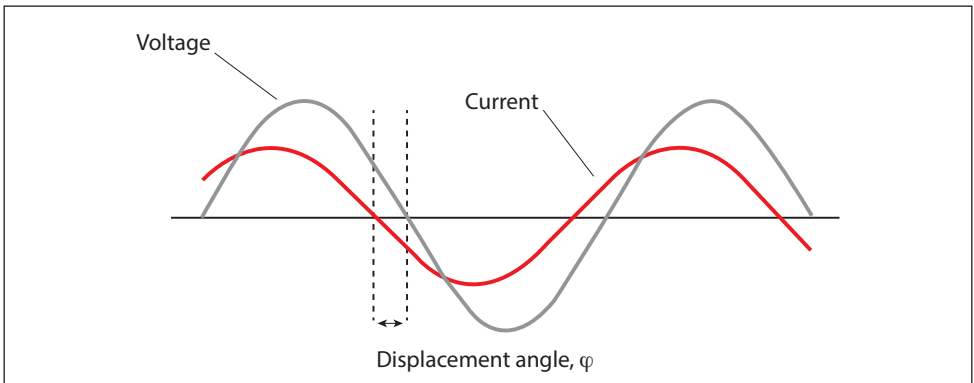


Fig. 7.1 Linear Load

In this case, the AC power has three components: real power ( $P$ ), reactive power ( $Q$ ) and apparent power ( $S$ ).

The apparent power is:  $S = U \times I$

In the case of a perfectly sinusoidal waveform  $P$ ,  $Q$  and  $S$  can be expressed as vectors that form a triangle:

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

Units:  $S$  in [kVA],  $P$  in [kW] and  $Q$  in [kVAR].

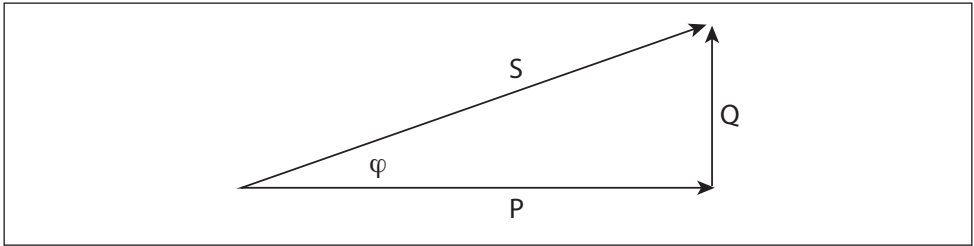


Fig. 7.2 Components of AC Power: Real Power (P), Reactive Power (Q) and Apparent Power (S)

The displacement angle between current and voltage is  $\phi$ .

The displacement power factor is the ratio between the active power (P) and apparent power (S):

$$DPF = \frac{P}{S} = \cos(\phi)$$

### 7.1.2 Non-linear Loads

Non-linear loads (such as diode rectifiers) draw a non-sinusoidal current. Fig. 7.3 shows the current drawn by a 6-pulse rectifier on a three phase supply.

A non-sinusoidal waveform can be decomposed in a sum of sinusoidal waveforms with periods equal to integer multiples of the fundamental waveform.

$$f(t) = \sum a_h \times \sin(h \omega 1t)$$

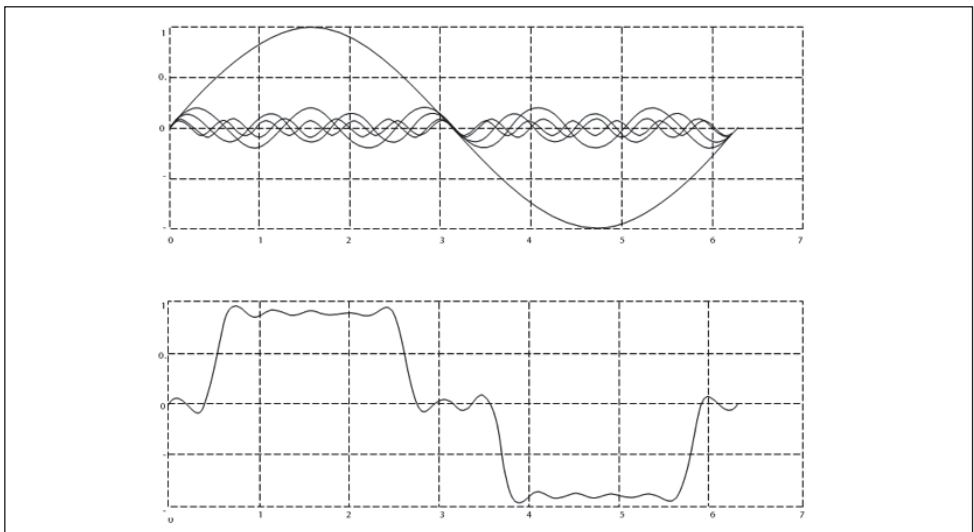


Fig. 7.3 Non-linear Load: Current drawn by a 6-pulse rectifier on a 3-phase supply

The integer multiples of the fundamental frequency  $\omega_1$  are called harmonics. The RMS value of a non-sinusoidal waveform (current or voltage) is expressed as:

$$I_{\text{RMS}} = \sqrt{\sum_{h_1}^{h_{\text{max}}} I(h)^2}$$

The amount of harmonics in a waveform gives the distortion factor, or total harmonic distortion (THD), represented by the ratio of RMS of the harmonic content to the RMS value of the fundamental quantity, expressed as a percentage of the fundamental:

$$\text{THD} = \sqrt{\sum_{h_2}^{h_{\text{max}}} \left(\frac{I_h}{I_1}\right)^2} \times 100 \%$$

Using the THD, the relationship between the RMS current  $I_{\text{RMS}}$  and the fundamental current  $I_1$  can be expressed as:

$$I_{\text{RMS}} = I_1 \times \sqrt{1 + \text{THD}^2}$$

The same applies for voltage.

The true power factor PF ( $\lambda$ ) is:

$$\text{PF} = \frac{P}{S}$$

In a linear system the true power factor is equal to the displacement power factor:

$$\text{PF} = \text{DPF} = \cos(\varphi)$$

In non-linear systems the relationship between true power factor and displacement power factor is:

$$\text{PF} = \frac{\text{DPF}}{\sqrt{1 + \text{THD}^2}}$$

The power factor is decreased by reactive power and harmonic loads. Low power factor results in a high RMS current that produces higher losses in the supply cables and transformers.

In the power quality context, the total demand distortion (TDD) term is often encountered. The TDD does not characterise the load, but it is a system parameter.

TDD expresses the current harmonic distortion in percentage of the maximum demand current  $I_L$ .

$$THD = \sqrt{\sum_{h_2}^{h_{max}} \left(\frac{I_h}{I_L}\right)^2} \times 100 \%$$

Another term often encountered in literature is the partial weighted harmonic distortion (PWHd). PWHd represents a weighted harmonic distortion that contains only the harmonics between the 14th and the 40th, as shown in the following definition.

$$PWHd = \sum_{h=14}^{40} h \left(\frac{I_h}{I_1}\right)^2 \times 100 \%$$

### 7.1.3 The Effect of Harmonics in a Power Distribution System

The picture below shows an example of a small distribution system. A transformer is connected on the primary side to a point of common coupling PCC1, on the medium voltage supply. The transformer has impedance  $Z_{xfr}$  and feeds a number of loads. The point of common coupling where all loads are connected together is PCC2. Each load is connected through cables that have respective impedance  $Z_1, Z_2, Z_3$ .

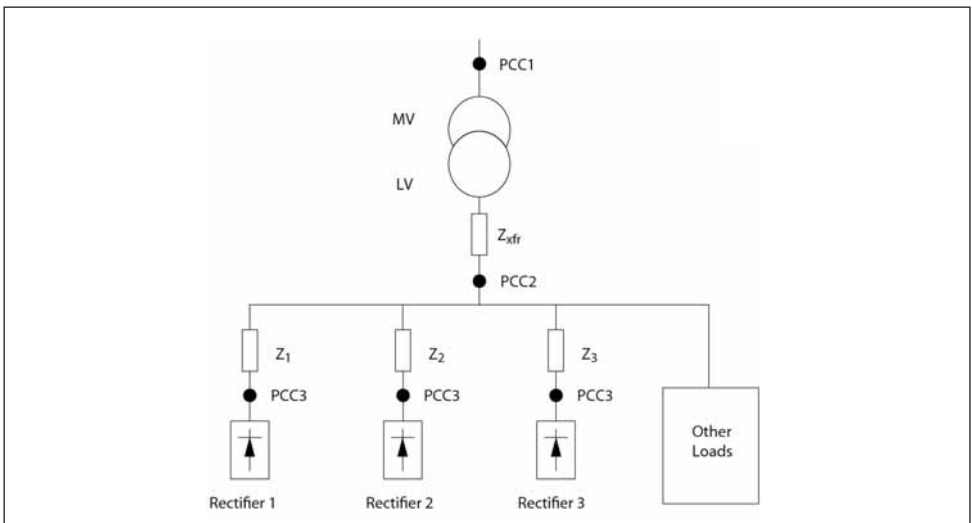


Fig. 7.4 Example of Distribution System

Harmonic currents drawn by non-linear loads cause distortion of the voltage, due to the voltage drop on the impedances of the distribution system. Higher impedances result in higher levels of voltage distortion.

Current distortion relates to apparatus performance and it relates to the individual load. Voltage distortion relates to system performance. It is not possible to determine the voltage distortion in the PCC knowing only the harmonic performance of the load. In order to predict the distortion in the PCC the configuration of the distribution system and relevant impedances must be known.

A commonly used term for describing the impedance of a grid is the short circuit ratio  $R_{sce}$ , defined as the ratio between the short circuit apparent power of the supply at the PCC ( $S_{sc}$ ) and the rated apparent power of the load ( $S_{equ}$ ).

$$R_{sce} = \frac{S_{sc}}{S_{equ}}$$

$$\text{where } S_{sc} = \frac{U^2}{Z_{supply}} \quad \text{and} \quad S_{equ} = U \times I_{equ}$$

The negative effect of harmonics is twofold

- Harmonic currents contribute to system losses (in cabling, transformer)
- Harmonic voltage distortion causes disturbance to other loads and increase losses in other loads

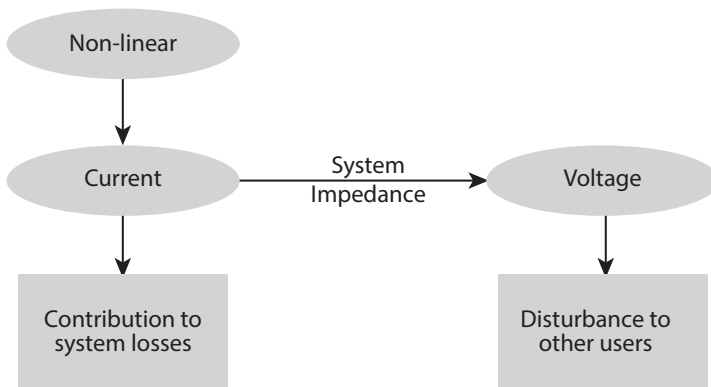


Fig. 7.5 Negative Effects of Harmonics: System Losses and Disturbance

## 7.2 Harmonic Limitation Standards and Requirements

The requirements for harmonic limitation can arise from:

- Application-specific requirements
- Requirements for compliance with standards

The application-specific requirements are related to a specific installation where there are technical reasons for limiting the harmonics.

Example: 250 kVA transformer with two 110 kW motors connected.

Motor A is connected directly to mains supply, and Motor B is supplied through Frequency Converter B. There is a need to retrofit FC A, so that Motor A is supplied through its own FC, but the transformer will, in this case, be undersized. Solution: In order to retrofit without changing the transformer, mitigate the harmonic distortion from FC's A and B using harmonic filters.

There are various harmonic mitigation standards, regulations and recommendations. Different standards apply in different geographical areas and industries. The most common are the following:

- IEC/EN 61000-3-2, Limits for harmonic current emissions ( $\leq 16A$  per phase)
- IEC/EN 61000-3-12, Limits for harmonic currents ( $>16A$  and  $\leq 75A$ )
- IEC/EN 61000-3-4, Limitation of emission of harmonic currents ( $> 16A$ )
- IEC/EN 61000-2-2 and IEC/EN 61000-2-4 Compatibility levels for low frequency conducted disturbances
- IEEE519, IEEE recommended practices and requirements for harmonic control in electrical power systems
- G5/4, Engineering recommendation, planning levels for harmonic voltage distortion and the connection of nonlinear equipment to transmission systems and distribution networks in the United Kingdom

## 7.3 Harmonic Reduction Methods in Frequency Converters

The line current of unmitigated diode rectifiers has a total harmonic distortion (THD) of at least 80%. This high distortion value is unacceptable in most applications with FC's. Therefore it is necessary to have some harmonic mitigation. The level of harmonic mitigation depends, as explained earlier, on the specific installation and the harmonic standards the installation needs to comply with.

An overview of the various harmonic mitigation methods is shown in Table 7.1 – Harmonic Mitigation Methods.

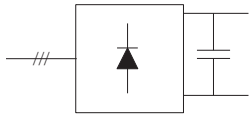
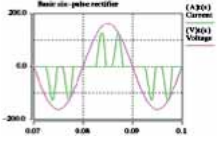
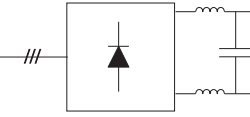
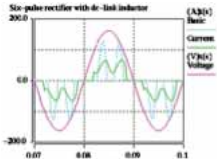
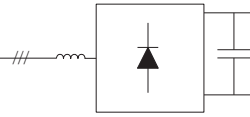
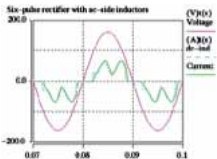
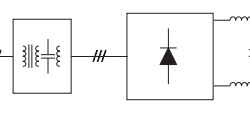
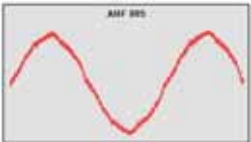
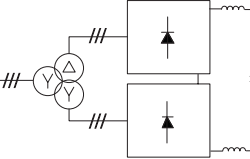
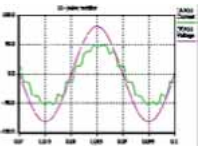
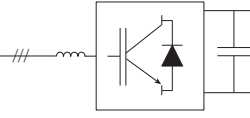
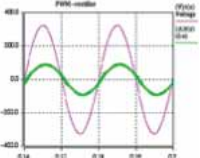
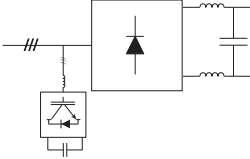
Mitigation method	Circuit diagram	Typical current waveform
No mitigation THD > 80%		
DC inductors THD < 40%		
AC inductors THD < 40%		
Passive harmonic filter THD < 10%		
Multi-pulse rectifier (12/18) THD < 10%		
Active front end THD < 5%		
Active filter THD < 5%		Waveform similar to AFE

Table 7.1 Harmonic Mitigation Methods

Harmonic mitigation can be achieved by using either passive or active circuits.

### 7.3.1 Passive Harmonic Mitigation

#### DC inductors

DC inductors are placed in the DC link between the rectifier and the bulk DC capacitor. It is possible to use a single inductor in either the + or the – side or use two inductors. This solution reduces THDi to values between 35 and 45%.

#### AC inductors

AC inductors are placed on the line side of the rectifier. Their harmonic performance is similar to DC inductors and reduce THDi to typical values of between 35 and 45%, depending on the size of the inductor.

#### DC vs. AC inductors

Since DC and AC inductors have similar harmonic performance levels the question about the differences between the two solutions often arises. First of all, even if the THD value is similar, the effect of the two solutions on the components of the harmonic spectrum is different. DC inductors attenuate more the low frequency components (5th, 7th, 11th harmonic) while the AC inductors have a better performance for higher harmonic orders.

Across inductors an AC voltage drop occurs. In the case of AC inductors, a voltage drop will occur, typically around 4%. In the case of DC inductors, the DC current does not cause a voltage drop. The only voltage drop across DC inductors results from the current ripple of the rectifier. Consequently, using DC inductors will result in a higher DC link voltage, thus the ability to provide more torque at the motor shaft. This is the major advantage of DC inductors. The main advantage of AC inductors is that they protect the rectifier against transients from the mains.

#### Passive harmonic filters

Passive harmonic filters are connected in series with the mains supply. They can be realised with various circuit topologies that typically consist of combinations of inductors (L) and capacitors (C), sometimes also damping resistors R. The filter circuit can be a low-pass circuit, tuned to specific harmonics (5th, 7th, etc.) or slightly de-tuned, to avoid the risk of resonances. The performance of passive filters depends on the specific frequency converter's DC link configuration (with/without DC chokes, value of capacitance) and a performance level can be assured for a specific configuration. Danfoss Advanced Harmonic Filters (AHF) are designed specifically for Danfoss VLT® frequency converters and can reduce THD to 10 % (AHF10 series) or even 5% (AHF 5 series). These filters use a proprietary topology with a two-stage de-tuned LC harmonic- absorbing circuit.

Passive filters have the disadvantage of being quite bulky (comparable in size with the FC). They have a capacitive power factor that needs to be considered during system level design for avoiding resonances.

### **Multi-pulse rectifiers**

Multi-pulse rectifiers are fed from phase-shift transformers. The most common solutions are with 12 pulses (2 x 3 phases) or 18 pulses (3 x 3 phases). Through phase-shifting, low order harmonics are in 180° opposition, cancelling each other. For example, in the case of 12 pulse rectification the phases of the secondary have a 30° phase offset (the offset between the D and Y windings). In this configuration the 5th and 7th harmonics are cancelled and the largest harmonics will be the 11th and 13th. Multi-pulse harmonic mitigation requires large transformers – larger than the FC. Another disadvantage is that the performance is reduced in non-ideal conditions such as voltage imbalance.

## **7.3.2 Active Harmonic Mitigation**

### **Active Front End (AFE)**

The diode rectifier can be replaced with an inverter with active switches (usually IGBT transistors), similar to the inverter at the motor side. The grid-side inverter is pulse-width modulated and the input current is nearly sinusoidal. The harmonics of the mains frequency are not present. On the other hand the switching frequency components are injected to the mains grid. In order to reduce the switching noise a passive filter is used, usually in a low-pass L-C-L topology (two inductors and capacitors between the inductors).

The main advantage of the AFE is that it allows four-quadrant operation: that means that the energy flow is bi-directional and in the case of regenerative braking the energy can be injected back to the grid. This is advantageous in applications with frequent braking or long-time braking such as cranes or centrifuges.

The disadvantage of the AFE solution is a relatively low efficiency and a high complexity. When the application does not require bi-directional energy flow the energy efficiency of the AFE is inferior to an active filter solution.

### **Active filters**

Active filters (AF) consist of an inverter that generates harmonic currents in anti-phase with the harmonic distortions on the grid thus achieving a 180° cancellation effect. The operation principle is illustrated in the illustration below, where the AF cancels the harmonic currents from a diode rectifier.

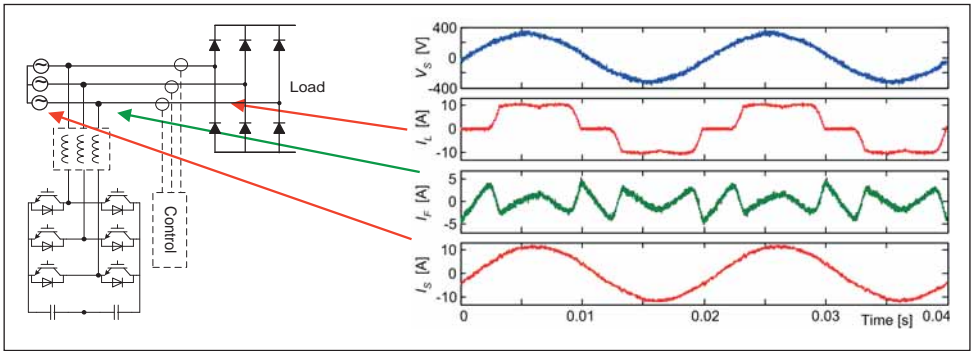


Fig. 7.6 Operation Principle of an Active Filter

As in the case of AFE, an LCL filter is needed to eliminate the noise at the switching frequency.

Active filters are connected in parallel with the non-linear (harmonic generating) load. This allows for several harmonic mitigation possibilities:

- Individual compensation of non-linear loads: an active filter compensates harmonics from a single load. Danfoss offers an optimised filter + FC package called “Low Harmonic Drive (LHD)”
- Group compensation: harmonics from a group of several loads (for example FC’s) are compensated by a single filter
- Central compensation: harmonics are compensated directly at the point of common-coupling of the main transformer

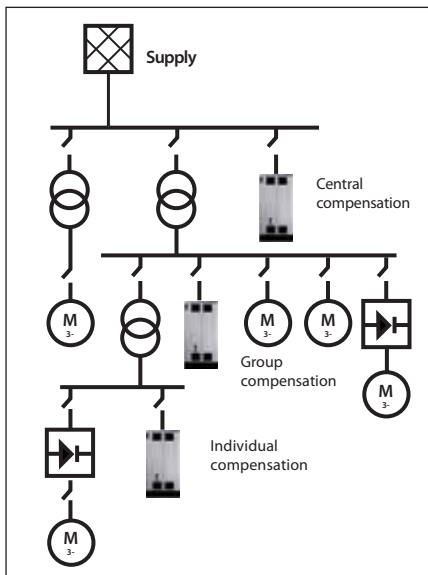


Fig. 7.7 Harmonic compensation can take place in different areas of the network

## 7.4 Harmonic Analysis Tools

Harmonic analysis tools can be used to calculate harmonics in a system and design the optimal harmonic mitigation solution to meet specific requirements. The advantage of software tools is that different solutions can be compared, allowing the selection of the best solution.

There are a variety of commercially available software tools ranging from simple calculation tools for a non-linear load to complex software packages that allow the design of an entire power system.

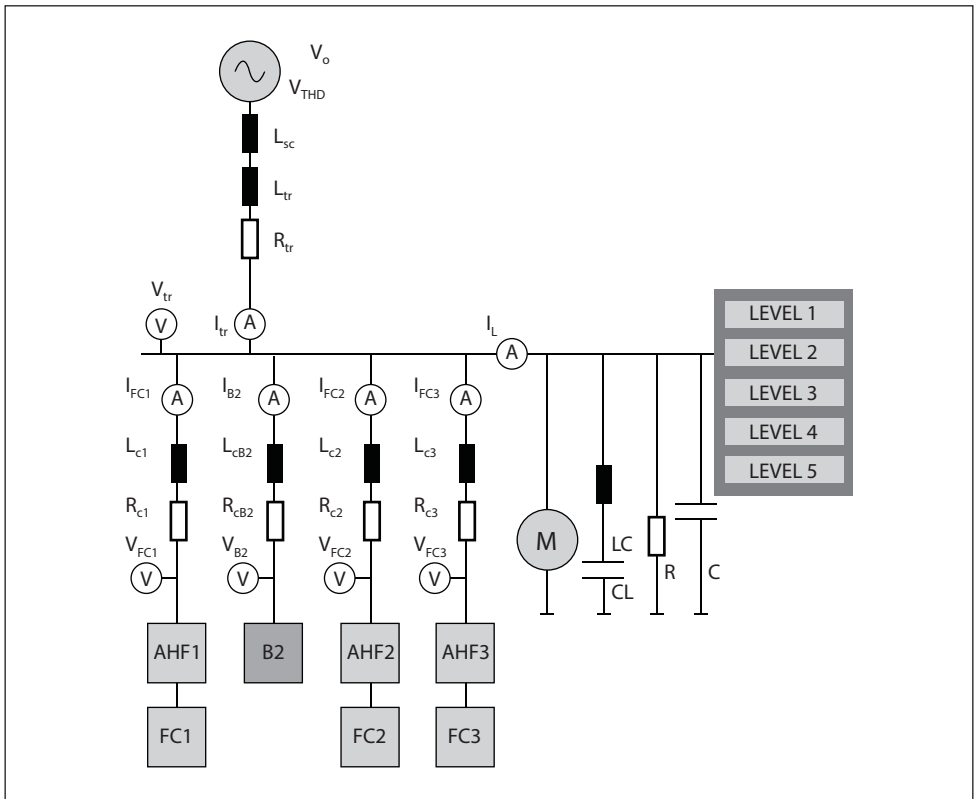


Fig. 7.8 Calculation model with current and voltage measurement points

Danfoss offers two software tools:

- the offline tool VLT® Motion Control Tool MCT 31 and
- the on-line tool HCS (Harmonic Calculation Software)

### 7.4.1 VLT® Motion Control Tool MCT 31

MCT 31 is an off-line software package used to calculate harmonics based on polynomial interpolation between pre-defined simulation results. The advantage of this method is speed and the disadvantage is that it is less precise compared to a simulation.

MCT 31 enables simulations with all Danfoss products, including mitigation solutions such as AHF passive filters and AAF active filters. Generic, non-Danfoss frequency converters can be simulated as well. MCT 31 can generate harmonic reports.

### 7.4.2 Harmonic Calculation Software (HCS)

The HCS tool can be accessed on-line at [www.danfoss-hcs.com](http://www.danfoss-hcs.com). It is available in two levels: basic for simple calculations and expert for more complex system level calculations.

Behind the web interface of the HCS tool there is a powerful circuit simulator that performs a simulation of the specific system designed by the user. Therefore it is more precise than the interpolation-based MCT 31.

HCS has a vast library containing Danfoss FC's, AHF passive filters, AAF active filters. It also features the time-domain and frequency domain graphical visualisation of the voltages and currents in a system and comparing the harmonics to different limit lines. HCS can also generate reports in HTML or PDF format.