Compensation of harmonic currents and reactive power with Shunt Active Filters

There is increasing number of electrical equipment with non-linear voltage-current characteristic connected to public and industrial networks. Harmonic currents produced by them cause harmonic voltages in network impedances, which add to the fundamental system voltage resulting in voltage distortion. Sensitive electronic control systems are likely not to operate properly when supplied with distorted voltage. The Shunt Active Filter described in following chapters is able to compensate harmonic currents and reactive power simultaneously with very high dynamic and with relative low control equipment cost. In Figure 1 there is a Shunt Active Filter delivered for compensation of the lift drives.

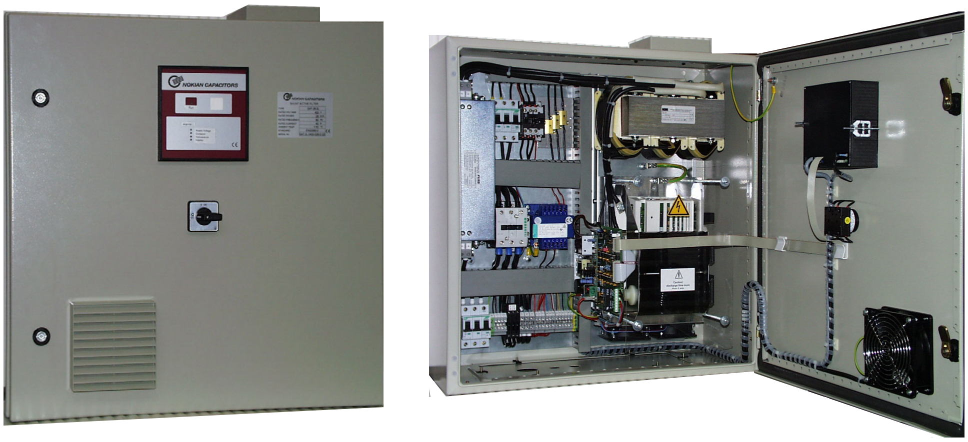

Figure 1. Shunt Active Filter having an output of 50kVA at 400V.

Introduction

A big number of modern electrical equipment like variable speed drives with diode or thyristor rectifier drawn non-sinusoidal currents from supplying network. Nowadays this kind of drives can be found in all kind of industries and in office buildings. Also the currents of office equipment and of the ballast for the fluorescent lamps are highly distorted containing up to 80% of 3rd harmonic. The non-sinusoidal currents of all those devices result in harmonic voltage drops in network impedances, which add to the fundamental voltage causing voltage to be distorted.

This voltage distortion is experienced by all electrical equipment connected to the network leading to higher thermal loading of motors, transformers, capacitors, switchgear and cabling. Some of the electrical equipment develops more audible noise when supplied with distorted voltage. Additionally malfunctioning of protection, control and ripple control systems can occur.

Mathematical background

According to FOURIER all periodical functions can be split into DC-component together with a sum of sinusoidal waves with whole multiples of the fundamental frequency. Ignoring DC-component the following equation for a non-sinusoidal current can be written as follows:

$$i(t) = \hat{i}_1 \bullet \sin(\omega_1 t + \varphi_1) + \sum_{n>1}^{\infty} \hat{i}_n \bullet \sin(n\omega_1 t + \varphi_n) \tag{1}$$

or

$$i(t) = i_1(t) + \sum_{n>1}^{\infty} i_n(t) \tag{2}$$

According to (1) and (2) a non-sinusoidal current can be split in a sinusoidal fundamental current $i_1(t)$ and a sum of sinusoidal harmonic currents as follows:

$$\sum_{n>1}^{\infty} i_n(t)$$

For example the frequencies of the harmonic currents in the supply current of a typical 3-phase 6-pulse rectifier can be calculated as follows:

$$f_n = (6m \pm 1) f_1 \qquad m = 1,2,3... \tag{3}$$

$$f_1 = 50 Hz$$

$$f_n = 250 Hz,\ 350 Hz,\ 550 Hz,\ 650 Hz, ...$$

Assuming a sinusoidal voltage and a non-sinusoidal current some important indices for definition of Active, Reactive and Distortion Reactive powers. The quality of the supply current can be characterized with its fundamental content

$$g_i = \frac{I_1}{I} \tag{4}$$

where

I_1 = RMS value of the fundamental current
I = RMS value of the total current including harmonics

or with k_i (THD)

$$k_i = \frac{\sqrt{\sum_{n>1}^{\infty} I_n^2}}{I} \tag{5}$$

where

I_n = RMS value of the harmonic current with order "n"

The relationship between g_i and k_i is

$$k_i^2 + g_i^2 = 1\,. \tag{6}$$

For the apparent power S of a 1-phase equipment can be written

$$S = U \cdot I = \sqrt{P^2 + Q_1^2 + D^2} \tag{7}$$

where

P = Active power
Q_1 = Fundamental reactive power
D = Harmonic reactive power

It is known that active power can be arise only from voltage and current having same frequency. Because the assumption that the voltage does not contain any harmonics can only the fundamental component of the current contribute to the active power. Therefore can be written:

$$P = U \cdot I_1 \cdot \cos\varphi_1 \tag{8}$$

where

$\cos\varphi_1$ = power factor for fundamental or displacement factor.

Therefore the fundamental reactive power is:

$$Q_1 = U \cdot I_1 \cdot \sin\varphi_1\,. \tag{9}$$

The distortion reactive power can be calculated from RMS value of the system voltage and from harmonic currents as follows:

$$D = U \cdot \sqrt{\sum_{n>1}^{\infty} I_n^2} = k_i \cdot S \tag{10}$$

For the total reactive power there is a definition:

$$Q = \sqrt{Q_1^2 + D^2}\,. \tag{11}$$

Taking into account total reactive power the power factor is:

$$\lambda = \frac{P}{S} = g_i \cdot \cos\varphi_1 = \sqrt{1 - k_i^2} \cdot \cos\varphi_1\,. \tag{12}$$

With sinusoidal voltage and current: $g_i = 1$, $k_i = 0$ and therefore $\lambda = \cos\varphi_1 = \cos\varphi$.

Compensation method

According to Figure 2 there is a controlled current source connected parallel to a harmonics producing load. This controlled current source produce same harmonic currents than those produced by the load but with opposite phase. Therefore the supply system is loaded with almost fundamental current only.

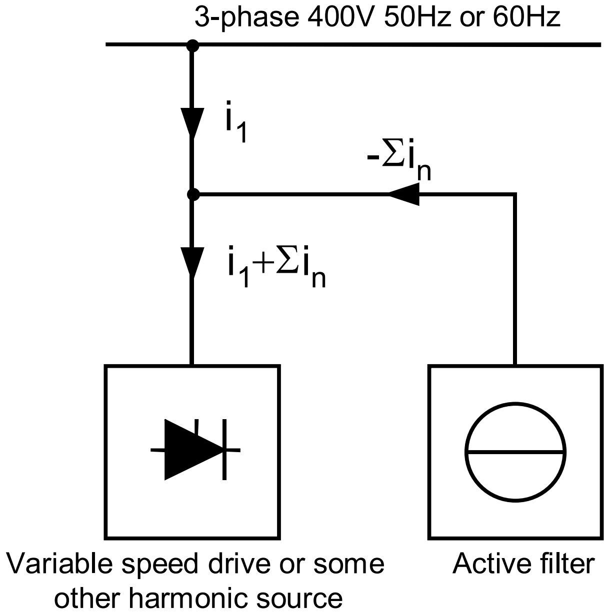

Figure 2. Harmonic source wit Shunt Active Filter

The realization of the current source in Figure 2 takes place with artificial commutated converter with phase current control. In Figure 3 there is an ideal equivalent circuit for one-phase converter.

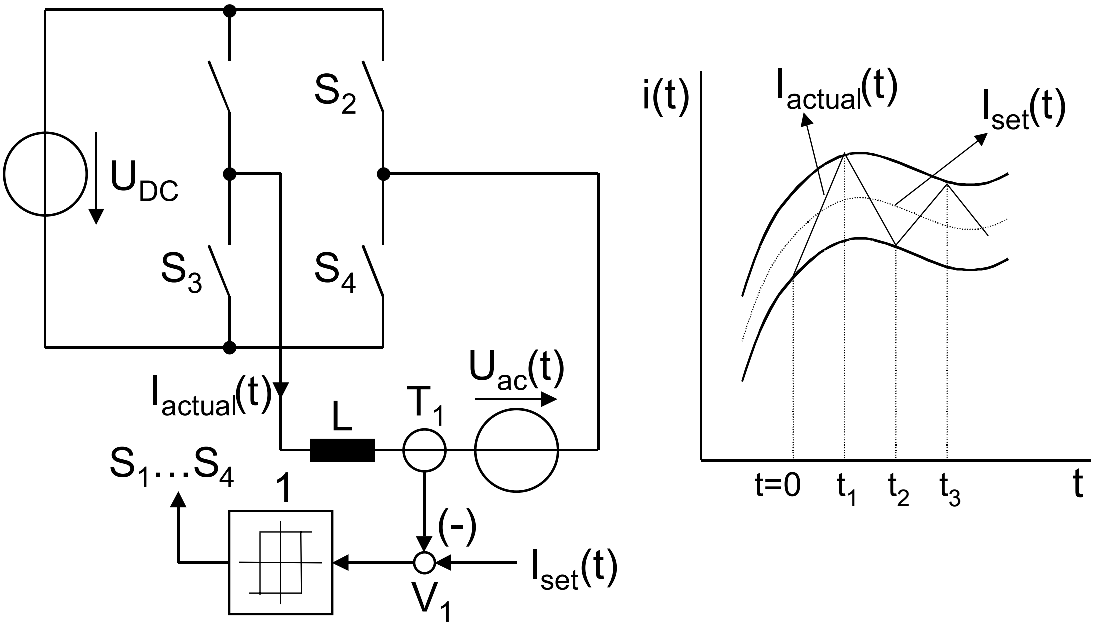

Figure 3. Ideal converter with phase current control

An ideal DC-voltage source with the voltage U_{DC} will be connected through the switches $S_1 – S_4$ and through the coupling reactor with an inductance L on the network with the voltage $u_{ac}(t)$. The current supplied into the network I_{actual} will be compared at V_1 with the current I_{set} measured by current transformer T_1. The difference of these currents is the input signal for the two-point regulator. The output signal of the two-point regulator controls switches $S_1 – S_4$. The current from the DC-voltage source can take place only if the switches S_1 and S_4 or
$S_2 – S_3$ are closed and within that time $U_{DC} > \hat{u}_{ac}$ is.

If switches S_1 and S_4 are closed at the time t=0 (see Figure 3) the voltage $+U_{DC} - u_{ac}(t)$ across the inductance causes a positive increase of the output current :

$$\frac{di_{actual}(t)}{dt} = \frac{+U_{DC} - u_{ac}(t)}{L} \tag{13}$$

When at the time t_1 the output current reaches the upper limit of the hysteresis of the two-point regulator, the regulator switches off S_1 and S_4 and switches on S_2 and S_3. When on S_2 and S_3 are closed the voltage $-U_{DC} - u_{ac}(t)$ across the inductance causes a decrease of the output current :

$$\frac{\mathrm{di}_{\mathrm{actual}}(\mathrm{t})}{\mathrm{dt}} = \frac{-\mathrm{U}_{\mathrm{DC}} - \mathrm{u}_{\mathrm{ac}}(\mathrm{t})}{\mathrm{L}} \tag{14}$$

When the output current reaches the lower limit of the hysteresis of the two-point regulator, the regulator switches off S_2 and S_3 and switches on S_1 and S_4. The switching frequency depends on value of the DC-voltage, hysteresis of the two-point regulator and on the inductance L. The current supplied by the converter follows all current curve forms with small deviation, which is due to the hysteresis of the two-point regulator.

Current source in Figure 3 becomes a Shunt Active Filter when the target value of the output current is the negative sum of the all harmonics of the harmonics producing load. In Shunt Active Filters The ideal DC-voltage source In Figure 3 is replaced with capacitor, which is charged using special control system.

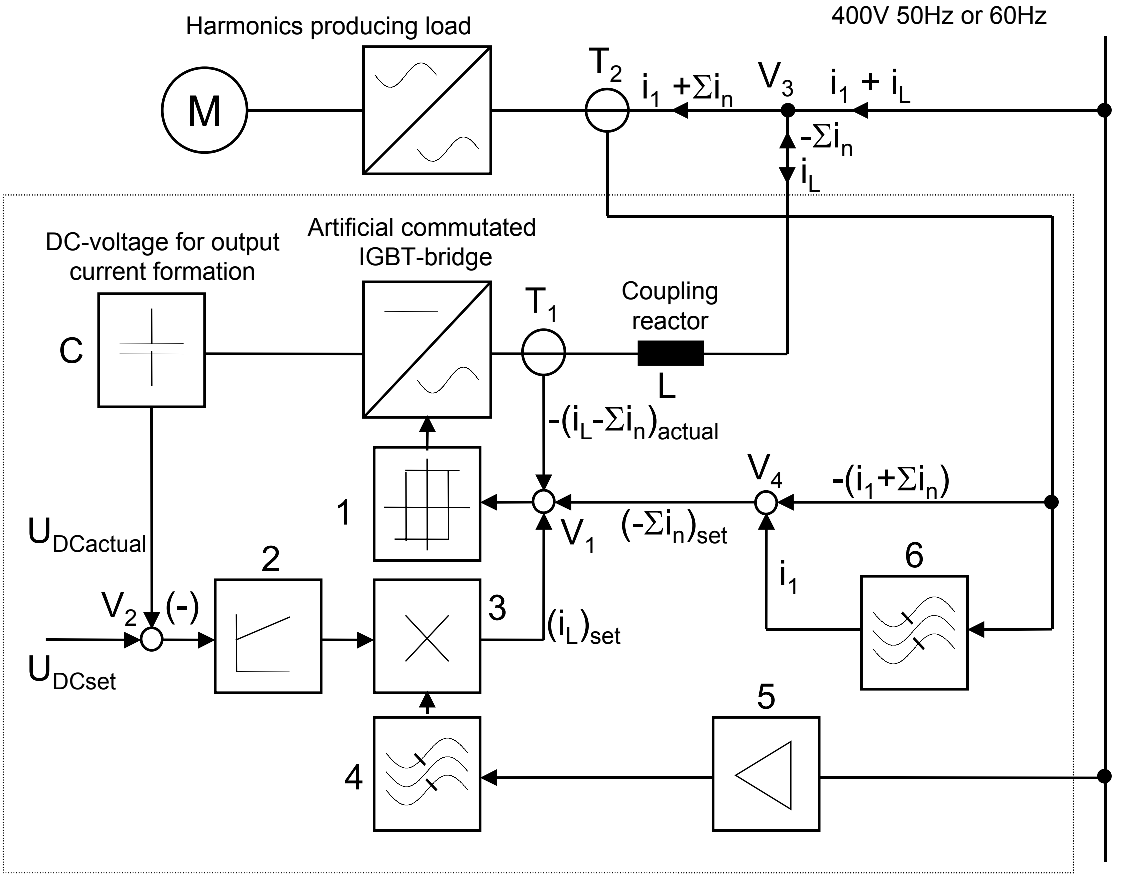

Figure 4. Block diagram of a shunt active filter.

In Figure 4 there is the block diagram of the Shunt Active Filter. Its power circuit consists of capacitor C for required DC-voltage, of artificial commutated IGBT-bridge with high switching frequency and of coupling reactor L.

DC-voltage regulation of the capacitor C

To be able to provide compensation the capacitor C must be kept properly charged. With ideal components without any losses this capacitor could be charged only once but due to the losses in reactor L, in IGBT-bridge and in capacitor C a continuously operating voltage regulator is needed.

At V_2 the capacitor voltage $U_{DCactual}$ is compared with U_{Dcset} and difference controls the voltage regulator 2. The output of the voltage regulator 2 is connected to one of the inputs of the multiplier 3, which other input is the pure sinusoidal voltage from the output of the band-pass filter 4. That results in such output voltage of the multiplier 3, which amplitude is controlled by voltage regulator 2 and it strictly is in phase with the network voltage. This voltage forms the set value for charge current I_{Lset} and it is compared with $I_{Lactual}$ at V_1. The output of V_1 is connected to the two-point regulator 1, which controls the IGBT-bridge in such a way that the capacitor is continuously properly charged.

Control circuit for harmonic currents and reactive power

The current of the harmonics producing load is measured with current transformer T_2. The corresponding voltage is formed and the fundamental component of the current is separated in band-pass filter 6. At V_4 fundamental component is deducted from the total current and inverted. This inverted voltage without the fundamental component at the output of V_4 corresponds to the negative sum of all harmonic currents $-\Sigma i_{nset}$ produced by the load. At V_1 the set value $-\Sigma i_{nset}$ is compared with the $-(i_L-\Sigma i_n)_{actual}$. The difference of $-\Sigma i_{nset}$ and

$-(i_L-\Sigma i_n)_{actual}$ at the output of the V_1 controls with the two-point regulator the IGBT-bridge to produce an output current $-\Sigma i_n$, which cancels the harmonics of the load at V_3. Therefore the load current from the network with the charge current i_L of the capacitor C is almost sinusoidal containing some residual harmonics only due to the hysteresis of the two-point regulator. To compensate also fundamental reactive power the output of the band-pass filter 6 has to be disconnected at V_4. In this case at V_1 the current $-(i_1+\Sigma i_n)_{set}$ is compared with $-(i_L-\Sigma i_n)_{actual}$ and the difference, containing now also fundamental component, representing reactive power, is used for the control. This control method forces the output current of the shunt active filter to compensate the fundamental reactive power too.

Experiences with shunt active filter

To demonstrate the operation of shunt active filter measurement was made at a DC-drive without and with shunt active filter Figure 9. As can be seen the curve form of the supply current is almost fundamental current only when active filter is on. It should also be noted that the fast changes of the supply current can be easily followed.

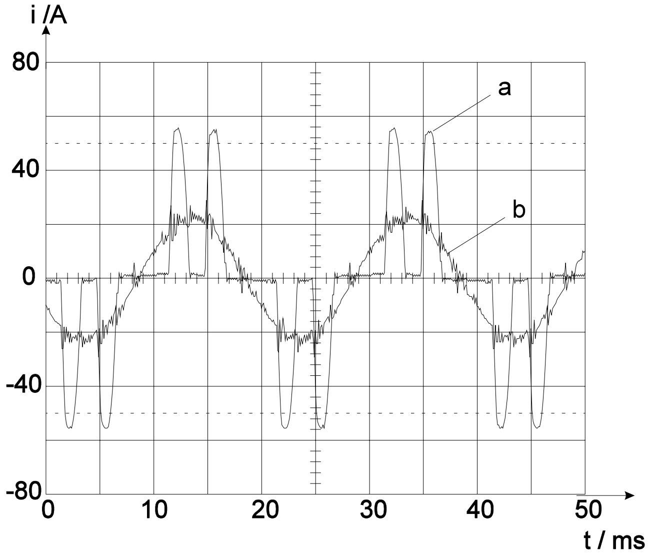

Figure 9. Network current of a DC-drive without active filter (a) and with shunt active filter (b).

An other example shows the high dynamics of the shunt active filter when compensating fast changing harmonic producing loads. In Figure 10 there is the current of a lift drive while accelerating without shunt active filter with the typical 6-pulse rectifier current curve form. In Figure 11 there is the same current when active filter is on. Comparison of the Figures 10 and 11 reveals that harmonics are effectively compensated and the system is loaded with fundamental current only.

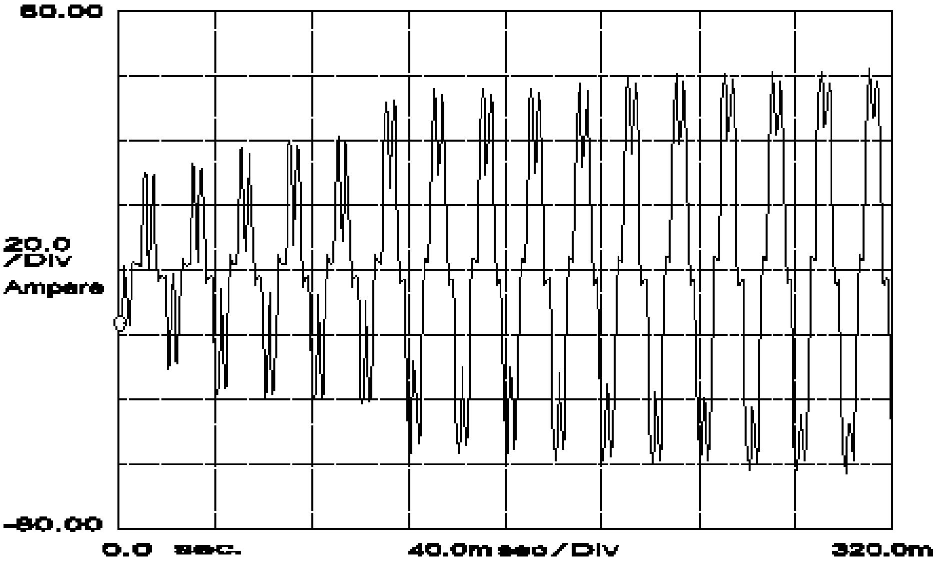

Figure 10. Supply current of a lift drive while accelerating without active filter.

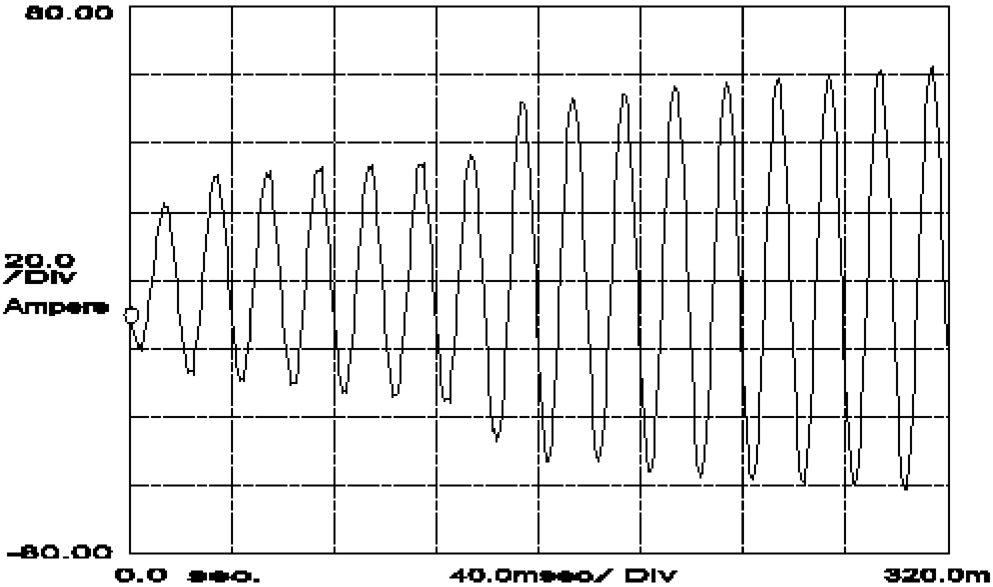

Figure 11. Supply current of a lift drive while accelerating with active filter.

Comparison of shunt active and passive filters.

When there is a need to compensate significant fundamental reactive power of relatively stabile harmonic producing loads the passive filters have turned out to be economically justified. With passive filters both reactive power compensation and harmonic filtering can be made at the same time.

When there is a need to compensate fast changing harmonic currents and fundamental reactive power shunt active filters are the right solution. Very short response time of the shunt active filters allows the better utilization of the supply system in respect of the voltage fluctuations.