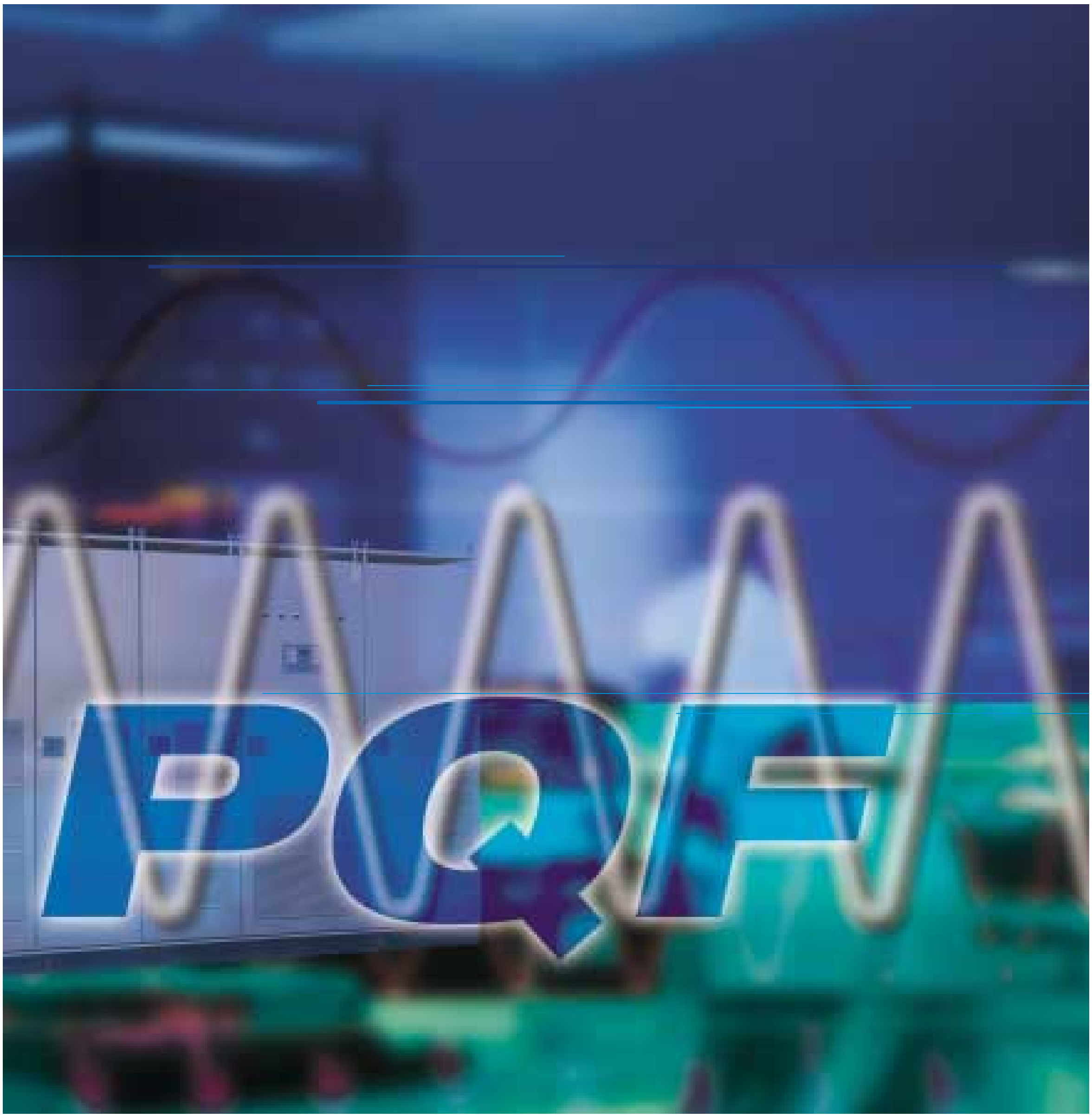
Power Quality Filter

Active Filtering Guide



Contents

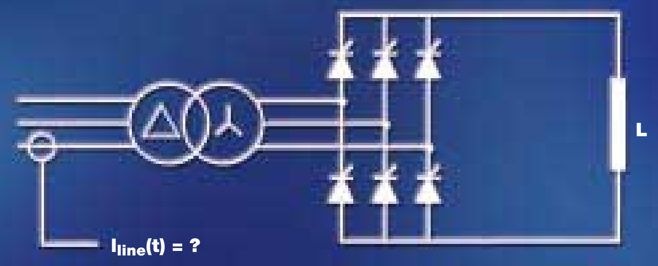
PQFL

Part I: Harmonics and Power Quality

1. Introduction to harmonics.

Power system generators normally produce a clean sinusoidal waveform at their terminals. This sinusoidal waveform is regarded as the pure form of the AC voltage and any deviation from it is described as distortion. More and more types of loads absorb non-sinusoidal current from the power system. As an example consider figure I.1 which shows a six-pulse thyristor bridge feeding a purely inductive load.

Figure I.1 *Example of a load drawing a non-sinusoidal current from the supply.*



Imagine that the thyristor bridge is connected through a transformer to a clean sinusoidal supply system. The frequency of this sinusoidal voltage waveform is referred to as the fundamental frequency f_{fund}. Upon connection of the load to the supply, a line current, denoted as $I_{line}(t)$, will flow. Figure I.2 shows an approximation of the current waveform.

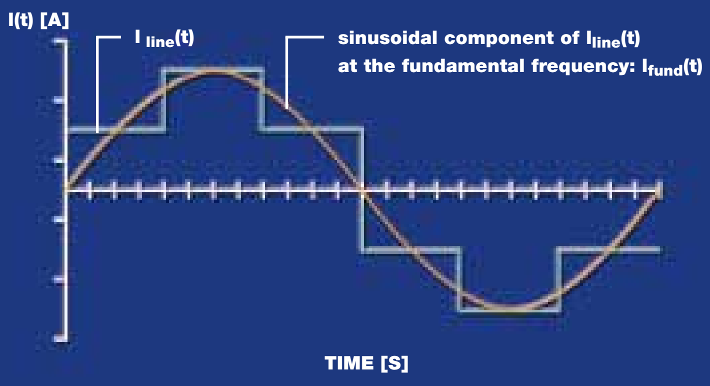


Figure I.2 *Line current $I_{line}(t)$ flowing in the supply branch of the six-pulse thyristor bridge of figure I.1*

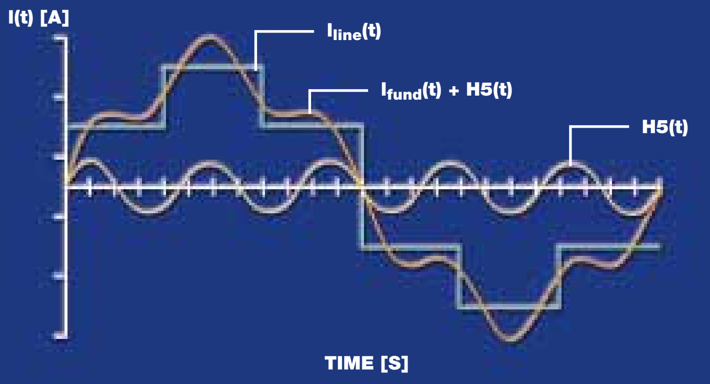


Figure I.3 *Comparison of the current waveform $I_{line}(t)$ with the waveform ($I_{fund}(t)$ + H5(t))*

From figure I.2 it may be seen that the current $I_{line}(t)$ deviates strongly from the sinusoidal current waveform $I_{fund}(t)$ and thus 'something' needs to be added to this sinusoidal component to obtain the current really flowing.

In order to derive what this 'something' is, consider figure I.3 which shows the resulting current waveform obtained by adding a component H5(t) with a frequency equal to five times the fundamental frequency to $I_{fund}(t)$.

It can be seen in figure I.3 that the resulting waveform $I_{fund}(t)$ + H5(t) resembles closer to the line current waveform $I_{line}(t)$ than the waveform $I_{fund}(t)$ alone (Cf. figure I.2). Continuing this approach, one can also add a current waveform H7(t) to the already existing waveform $I_{fund}(t)$ + H5(t).

In this, H7(t) refers to a current component with a frequency equal to seven times the fundamental frequency. Figure I.4 shows the waveforms $I_{line}(t)$ and H7(t) and the waveform obtained by adding the current components $I_{fund}(t)$, H5(t) and H7(t).

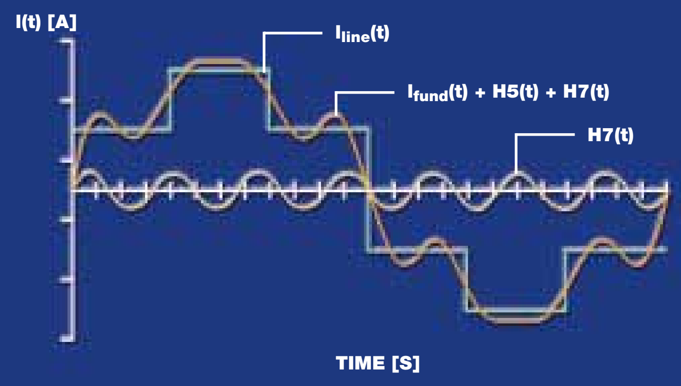
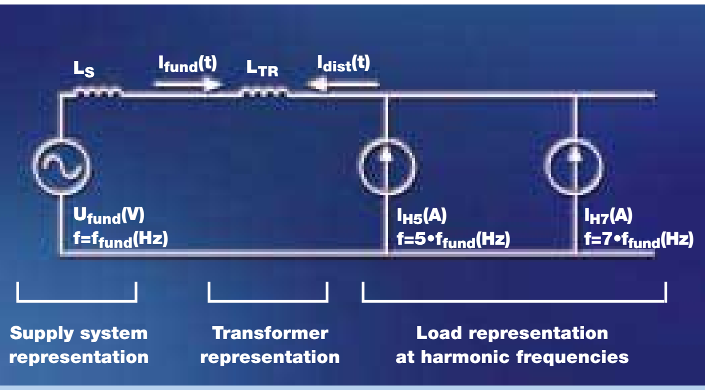


Figure I.4 *Comparison of the current waveform $I_{line}(t)$ with the waveform ($I_{fund}(t) + H5(t) + H7(t)$)*



$I_{line}(t)$: *The line current flowing between the supply and the load*
$I_{line}(t) = I_{fund}(t) + I_{dist}(t)$
$I_{fund}(t)$: *The load current at the fundamental frequency, determined by the supply system impedance, the transformer impedance and the load impedance at the fundamental frequency.*
$I_{dist}(t)$: *The distortion current (i.e. harmonics) generated by the load*

Figure I.5 *Schematic representation of the harmonic flow for the thyristor bridge load of figure I.1*

By adding the waveform H7(t) to the waveform $I_{fund}(t)$ + H5(t), the resulting waveform resembles even more to the line current $I_{line}(t)$ than it was the case for the addition of only Ifund(t) and H5(t). It may be shown that by adding still more current components Hi(t), each at a particular integer multiple of the fundamental frequency, to the sinusoidal component $I_{fund}(t)$ one may obtain the same waveform as the measured line current $I_{line}(t)$.

The current components H5(t), H7(t), ... which have to be added to the fundamental current $I_{fund}(t)$ in order to compose the line current actually flowing, $I_{line}(t)$, are referred to as the integer frequency harmonic components of the current or simply 'harmonics'. They exist at frequencies which are integer multiples of the fundamental frequency. Since it was assumed that the thyristor bridge is connected to a clean sinusoidal voltage at a fundamental frequency, it may be concluded that the load is the source of the harmonics. More specifically, the load is injecting current harmonics into the supply system. This is schematically represented in figure I.5.

It should be noted that not all type of loads inject harmonics into the supply system. Section 2 gives some characteristic load types and discusses typical harmonic components to be expected.

While in the preceding figures the line current and its harmonic components have been represented by time domain waveforms, it is easier and more common to represent the harmonics by means of the current spectrum. This spectrum shows for each harmonic frequency the magnitude of the corresponding harmonic component present in the current analysed. Possibly, the magnitude of the harmonic components is expressed as a percentage of the magnitude of the fundamental component. The horizontal axis shows generally the harmonic order, which is given by the ratio of the harmonic frequency over the fundamental frequency.

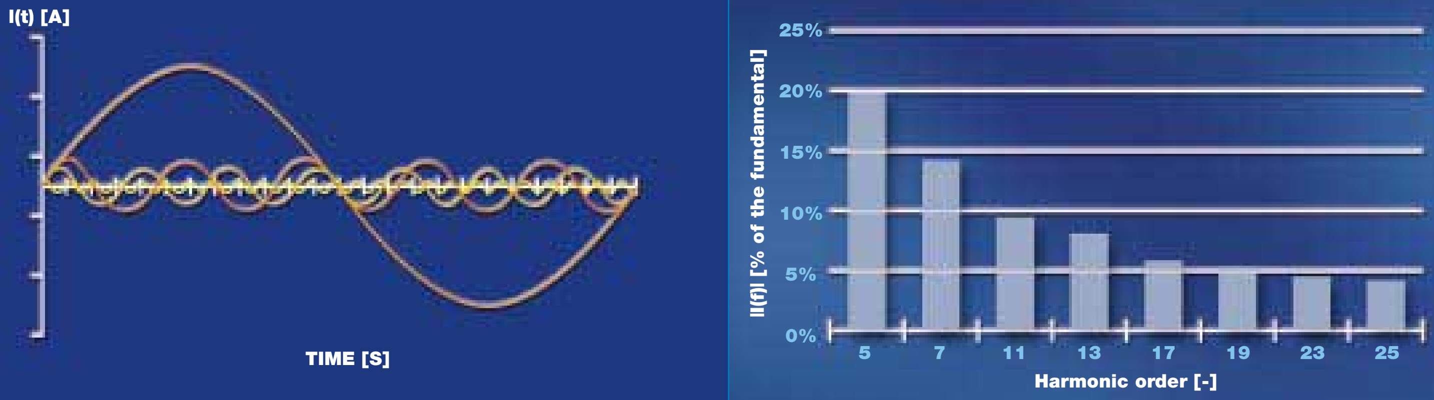


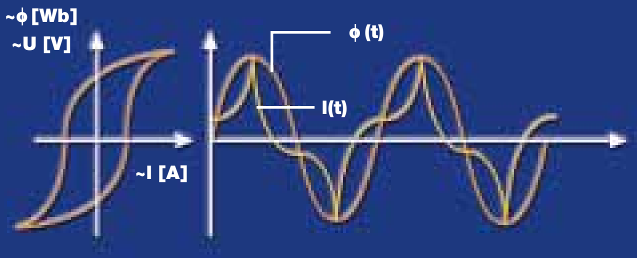
Figure I.6 *Representation of the current harmonics in the time domain (left) and in the frequency domain (spectrum) (right)*

Next to the integer frequency harmonic components discussed above, there also exists a class of harmonics which are not situated at integer multiples of the fundamental frequency. They are referred to as interharmonics. A typical example of a load producing interharmonics is a cycloconverter. This device generates at its output a waveform with a variable frequency which can be used to drive e.g. a synchronous motor. The cycloconverter output frequency is situated in the low frequency range, e.g. up to 15 Hz. It should be noted that in general the magnitude of the interharmonic components present in the low voltage networks is negligible. Therefore, they are not further discussed.

2. Harmonic sources.

Historically, harmonics were mainly caused by magnetisation non-linearities. As an example, figure I.7 shows the magnetisation characteristic of a transformer.

Figure I.7 *Illustration of the non-linear magnetisation characteristic of a transformer*



When applying a purely sinusoidal voltage source (and thus a purely sinusoidal flux) to a transformer operating in its non-linear region, the resulting magnetising current is not sinusoidal (Cf. I(t) in figure I.7). The resulting current waveform contains a variety of odd harmonics of which the third one is the most dominant. It should be noted that the magnetising current is in general a small percentage of the transformer's rated current and as such its effect becomes less pronounced as the transformer is more loaded.

At present, power electronics based equipment is the main source of the harmonic pollution in the low voltage network. Examples of such equipment include drives, UPS's, welders, PCs, printers etc. In general, the semiconductor switches in this equipment conduct only during a fraction of the fundamental period. This is how such equipment can obtain their main properties regarding energy saving, dynamic performance and flexibility of control. However, as a result a discontinuous current containing a considerable amount of distortion is drawn from the supply. Next are given some typical load arrangements and the resulting harmonic distortion.

- **Single-phase rectifier with smoothing capacitor (figure I.8).**

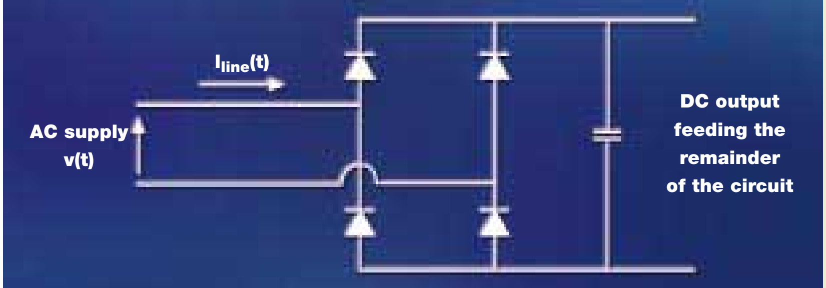


Figure I.8 *Single-phase rectifier with smoothing capacitor*

This circuit topology is present in many supplies of single-phase devices such as computers, printers and fluorescent lighting systems. The current drawn from the supply is characterised by a sharp current rise and fall during only a fraction of the fundamental period. Typical voltage and current waveforms are presented in figure I.9.

The current waveform contains a considerable amount of odd harmonics, the magnitude of which may be higher than the fundamental current component. While the devices using this circuit topology generally have a small power rating, an increasing number of them are being used. This may result in an excessive amount of harmonic current flowing in the feeding transformer and the supply lines.

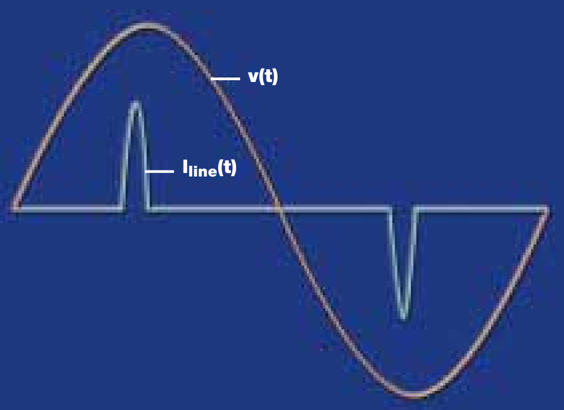


Figure I.9 *Supply voltage and current waveforms characterising the single-phase rectifier bridge with smoothing capacitor*

- **Six-pulse bridges.**

Six-pulse bridges are commonly used in three phase power electronic based equipment such as drives (AC and DC) and UPS's. The switches used can either be controllable (e.g. IGBTs, thyristors,...) or uncontrollable (diodes). Depending on the equipment, the DC side of the bridge is connected to a smoothing capacitor, a smoothing inductor or both. Figure I.10 (a) shows the circuit topology for a diode bridge with a smoothing reactor and figure I.10 (b) shows the topology for a diode bridge with a smoothing capacitor.

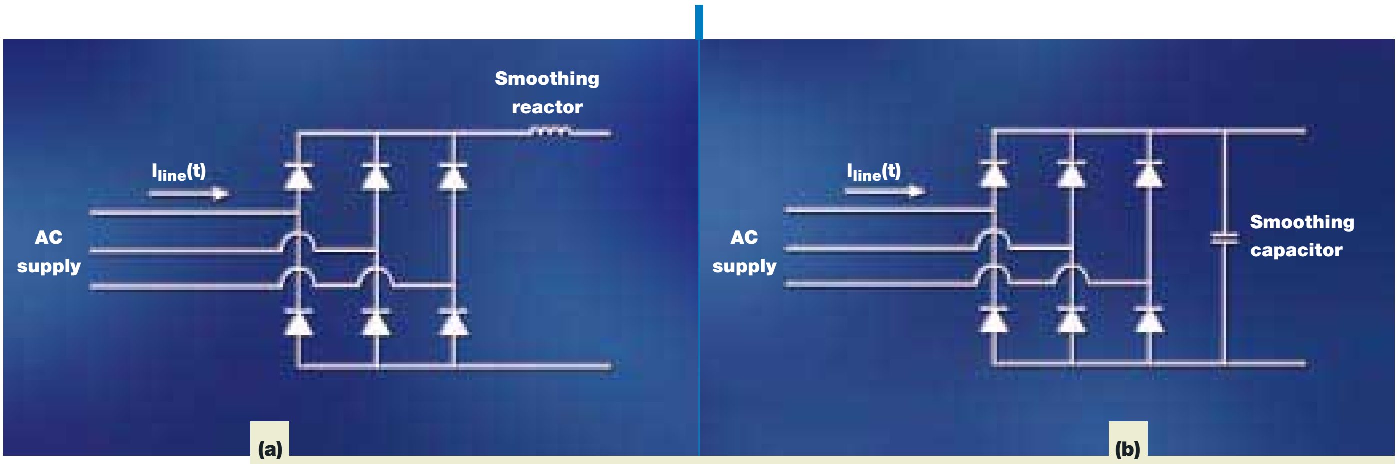


Figure I.10 *Circuit topology of a three phase diode bridge with (a) a smoothing reactor and with (b) a smoothing capacitor*

Figure I.11 (a) shows a typical waveform of the line current drawn by the circuit having a smoothing reactor and figure I.11 (b) shows a typical waveform of the line current drawn by the circuit with a smoothing capacitor.

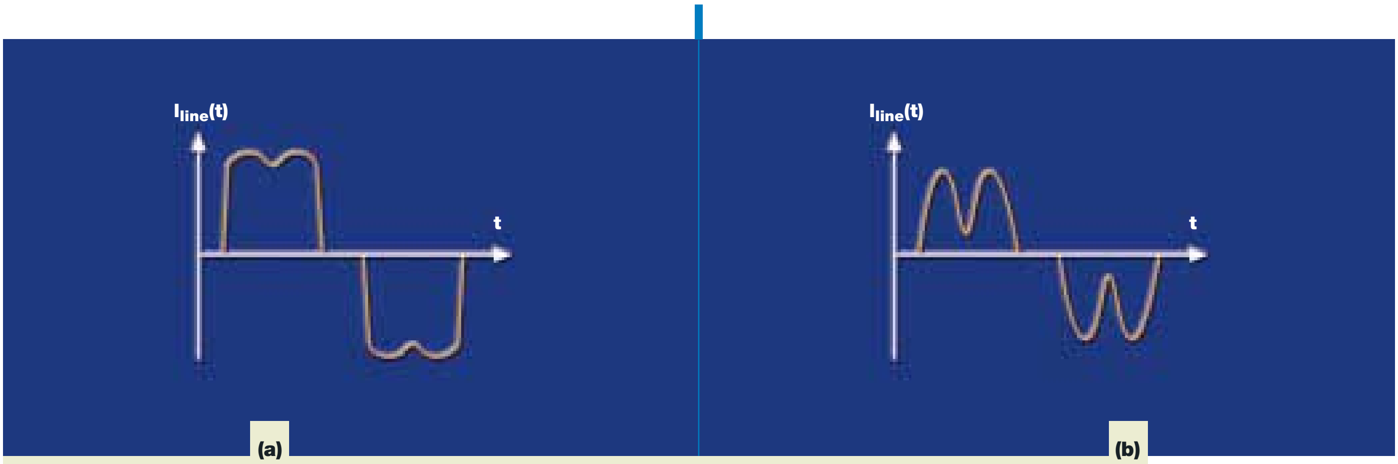


Figure I.11 *Line current waveforms of a six-pulse diode bridge with (a) a smoothing reactor and (b) a smoothing capacitor*

It may be shown that the current drawn by a six-pulse bridge contains harmonics of the order $n = (6 \cdot i \pm 1)$ where i is an integer greater or equal than 1. Thus the line current contains harmonics of the order 5, 7, 11, 13, ...

For a six-pulse diode bridge having a large smoothing reactor, the magnitude of the harmonics is approximated by the expression

$$|I_n| \approx \frac{|I_{fund}|}{n} \qquad (1)$$

where: $|I_n|$: The magnitude of the harmonic with order n
$|I_{fund}|$: The magnitude of the fundamental component
n : The order of the harmonic

E.g. the 5^{th} harmonic will have a magnitude equal to about 20 % of the fundamental component. Six-pulse bridges which do not have a smoothing reactor or a rather small one will produce much higher harmonic currents than predicted by Eqn. (1).

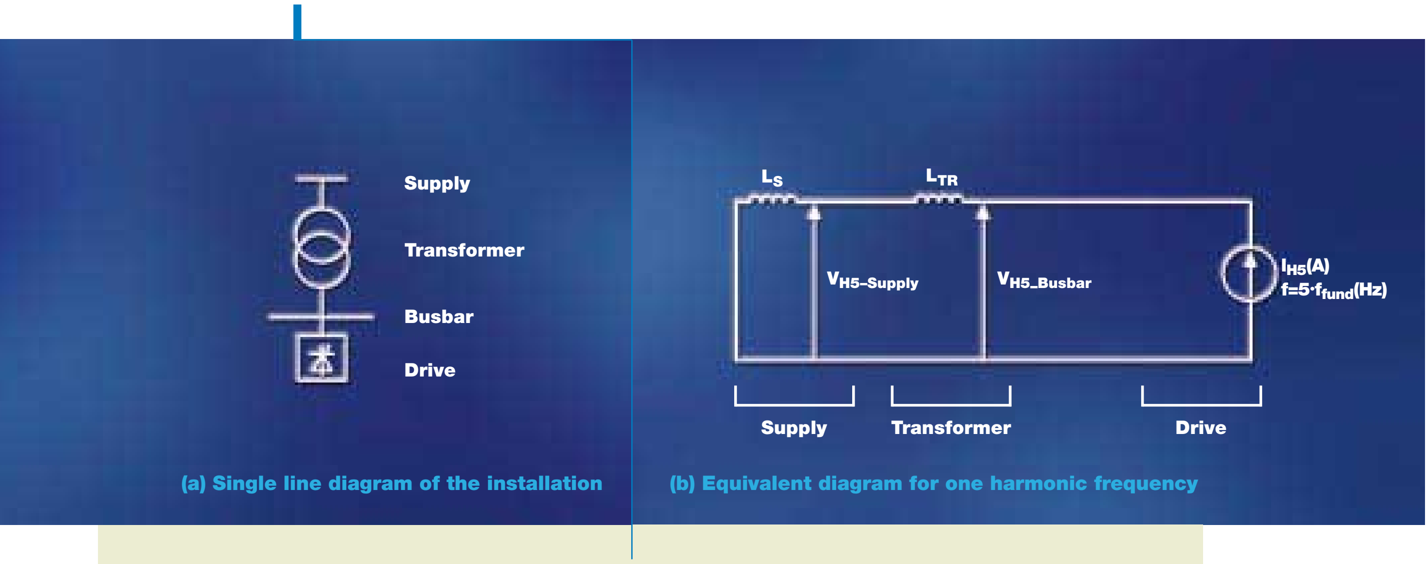
It should be noted that when the supply voltage is unbalanced, triplen harmonics will also be present in the line current.

- **Welders.**

A variety of welder types exist. Many of them are of the single-phase type and are connected between two phases. They are principally sources of odd harmonics, including the third.

3. Harmonics and resonance.

From the preceding sections it may be concluded that a lot of the equipment found in modern electrical installations can be considered as harmonic current sources. The currents are injected into the supply system and give rise to voltage harmonics. This can be understood by considering the following electrical installation and its equivalent diagram for one harmonic frequency. In the following discussion it is assumed that the supply voltage is initially not distorted.



(a) Single line diagram of the installation

(b) Equivalent diagram for one harmonic frequency

Figure I.12 *Single line diagram of an installation containing a drive and the corresponding equivalent diagram for one harmonic frequency*

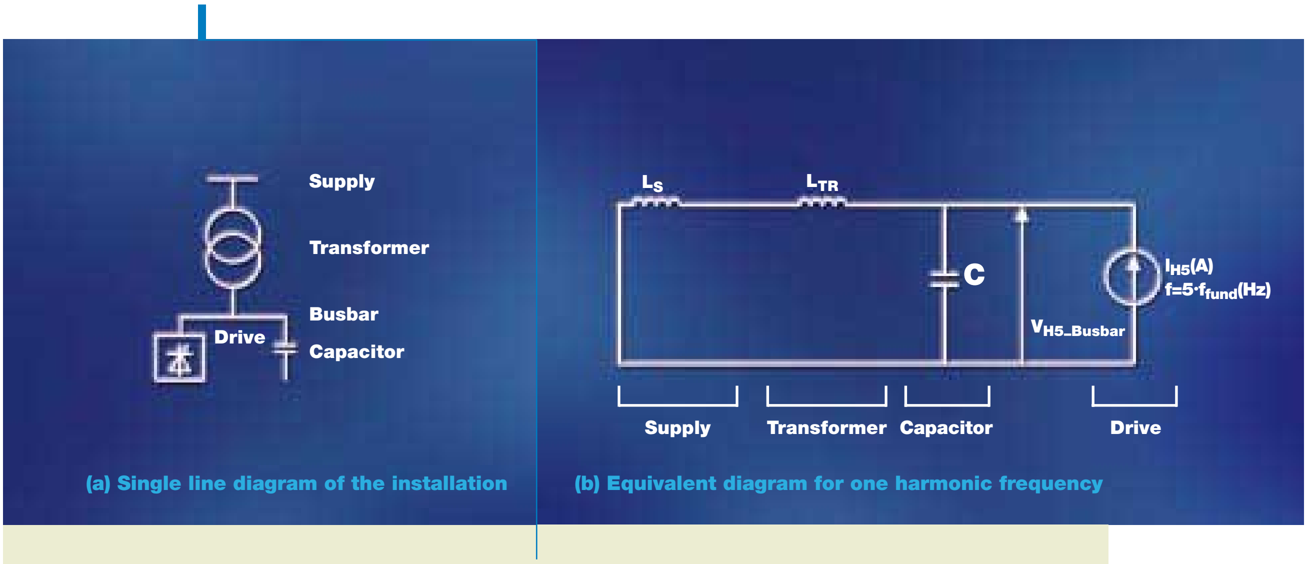
The plant considered in figure I.12 has one drive that is connected through a transformer to the medium voltage supply. In the equivalent scheme for the harmonic evaluation the supply is modelled by an impedance $Z_S = j\cdot\omega\cdot L_S$ where L_S is inversely proportional to the system fault level. The transformer is modelled by its an impedance $Z_{TR} = j\cdot\omega\cdot L_{TR}$. In these expressions j denotes the complex operator. For simplicity, the resistive part of the supply system and the transformer are ignored. The drive is injecting a 5th harmonic current I_{H5}. Applying Ohm's law to the equivalent circuit allows for the determination of the resulting harmonic voltage at the busbar V_{H5_Busbar} and at the primary of the transformer V_{H5_Supply}, i.e.

$$V_{H5\_Busbar} = (Z_{TR} + Z_S)\cdot I_{H5} \qquad (2)$$

$$V_{H5\_Supply} = Z_S\cdot I_{H5} \qquad (3)$$

From Eqs. (2) and (3) it may be concluded that the harmonic current injected by the drive gives rise to a distortion of the busbar voltage and the supply voltage. This may affect other loads that are connected to the same busbar or neighbouring plants which are connected to the same supply.

In many industrial plants capacitor banks are often present for reactive power compensation purposes. Imagine that this is the case in the plant discussed in figure I.12. Figure I.13 (a) shows the revised single line diagram and figure I.13 (b) shows the updated equivalent diagram.



(a) Single line diagram of the installation

(b) Equivalent diagram for one harmonic frequency

Figure I.13 *Single line diagram of an installation containing a drive, a capacitor bank and the corresponding equivalent diagram for one harmonic frequency*

In this case, the harmonic current is injected into an impedance which consists of a parallel circuit of reactors and a capacitor. The total parallel impedance is given by the expression

$$Z_{parallel} = \frac{(Z_S + Z_{TR}) \cdot Z_C}{Z_S + Z_{TR} + Z_C} \qquad (4)$$

where: $Z_{parallel}$: The parallel impedance of the reactors and the capacitor
Z_S, Z_{TR} : The supply and the transformer impedance respectively
Z_C : The capacitor impedance, $Z_C = \dfrac{1}{j \cdot \omega \cdot C}$

In many cases the supply impedance is negligible compared to the transformer impedance and can be omitted from Eqn. (4). In that case, the magnitude of the parallel impedance can be shown to be given by Eqn. (5).

$$|Z_{parallel}(\omega)| = \frac{\omega \cdot L_{TR}}{1 - \omega^2 \cdot L_{TR} \cdot C} \qquad (5)$$

From this expression it may be seen that there exists a frequency f_r (with $\omega_r = 2 \cdot \pi \cdot f_r$) for which the magnitude of the parallel impedance becomes theoretically infinite (denominator becomes zero). In practice the magnitude at this frequency will be limited by the resistance of the circuit. Figure I.14 shows an example of an impedance versus harmonic order graph for a parallel impedance topology.

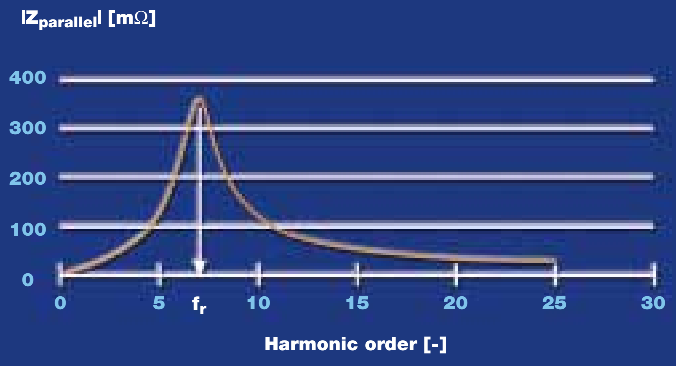


Figure I.14 *Impedance versus harmonic order graph for a parallel impedance topology*

In the example of figure I.14, the resonance frequency is situated near to the 7th harmonic. Noting that the resulting voltage distortion at a particular harmonic frequency is the product of the injected current and the impedance at that frequency, it may be concluded that the voltage distortion will be very high when the parallel resonance is situated in a frequency range at which a large amount of harmonic currents are injected. This is for instance the case for the application discussed (the drive injects a considerable amount of 5th and 7th harmonic current and the resonance frequency is situated around these frequencies). Since the voltage supply becomes heavily distorted, it may affect the proper operation of the equipment being connected to the same supply (e.g. overvoltage on the capacitors and the drives in the plant considered and possibly problems in neighbouring plants). In order to predict possible problems when harmonic generating equipment is installed in plants at which capacitors are present, it is useful to know the harmonic order at which a resonance exists. Eqn. (6) gives a good approximation of this harmonic order:

$$n_r \approx \sqrt{\frac{S_{scT}}{Q_C}} \qquad (6)$$

where: n_r : Harmonic order at which a resonance exists

S_{scT} : Short circuit power of the feeding transformer

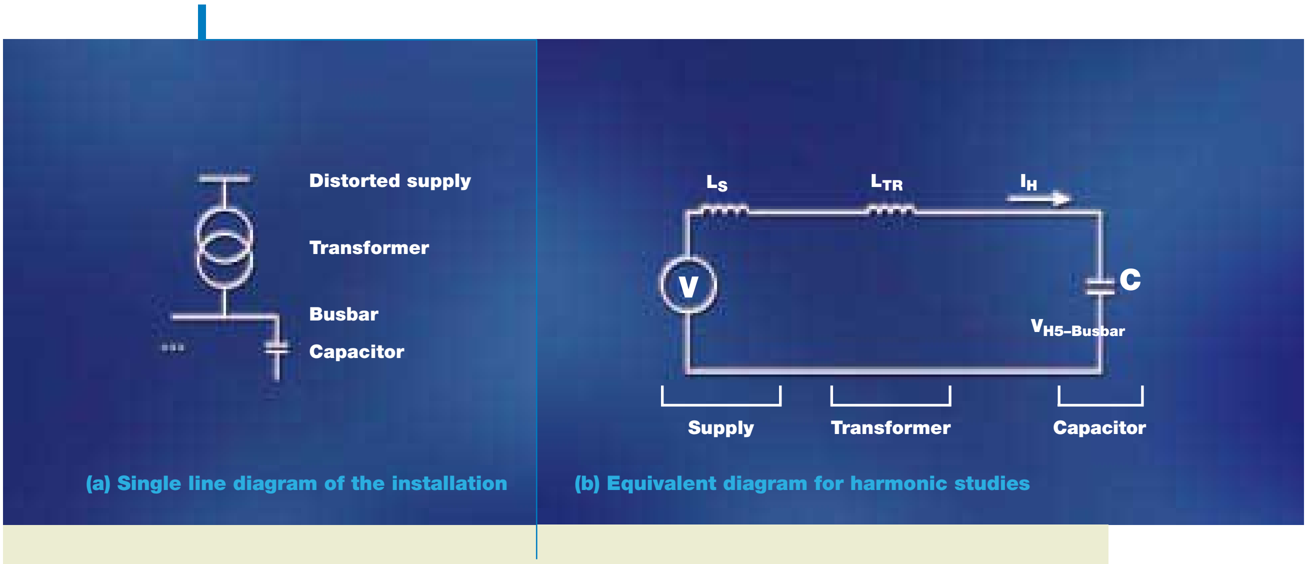
$S_{scT} = S_T/U_{cc}$

where S_T : Transformer power rating

U_{cc} : Transformer short circuit voltage

Q_C : The connected capacitive power

In the preceding discussion it was outlined that the harmonic currents generated by equipment in one plant introduce voltage distortion on the supply to the plant. This distortion will increase if a parallel resonance exists within the plant. Consider now another plant which is connected to the same distorted supply. Suppose that this plant does not have any loads which produce harmonic currents but it does have capacitor banks for reactive power compensation purposes. Figure I.15 (a) shows the single line diagram of the plant considered (omitting the linear loads) and figure I.15 (b) shows the equivalent diagram for harmonic studies, including the harmonic voltages present on the supply.



(a) Single line diagram of the installation

(b) Equivalent diagram for harmonic studies

Figure I.15 *Single line diagram of an installation connected to a distorted supply and which has a capacitor bank*

In Figure I.15 (b) it can be seen that the harmonic voltages present on the supply give rise to harmonic currents flowing into the plant. This current is given by Ohm's law:

$$I_H = \frac{V_H}{Z_{seriesH}} \qquad (7)$$

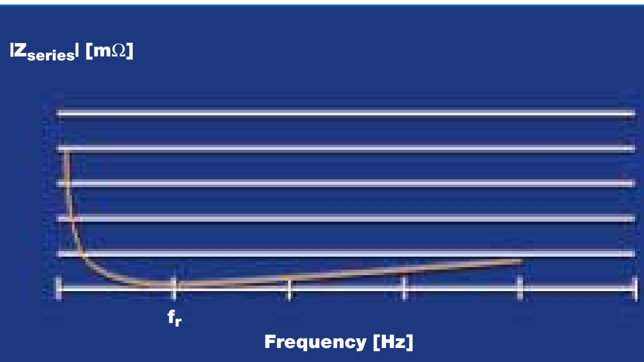
where: I_H : The current at harmonic frequency H
V_H : The voltage at harmonic frequency H
$Z_{seriesH}$: The impedance at harmonic frequency H

From Eqn. (7) it is clear that the harmonic current flowing into the capacitor becomes very high if the series impedance at the corresponding frequency is low. Eqn. (8) gives the expression of the impedance as a function of the frequency ignoring the supply impedance and the resistance of the circuit.

$$|Z_{series}(\omega)| = \sqrt{\left(\omega L_{TR} - \frac{1}{\omega C}\right)^2} \qquad (8)$$

This equation shows that a resonance frequency f_r exists at which the series impedance becomes theoretically zero. In practice, its value will be equal to the resistance of the circuit which tends to be small. The resonance considered is referred to as a series resonance. Figure I.16 shows an example of an impedance versus frequency graph for a series impedance topology.

Figure I.16 *Impedance versus frequency for a series impedance topology*



From the previous discussion it may be concluded that the presence of a series resonance in the frequency range at which harmonic voltage components are present is likely to give rise to excessive harmonic currents flowing into the busbar system and into the capacitors connected to this system. As a result, the capacitors and other elements of the installation may become overloaded and break down. The harmonic order at which a series resonance is introduced when installing a capacitor bank in a plant can be found with Eqn. (6).

4. Reasons for limiting harmonics.

In the previous sections it was outlined that many loads inject harmonic currents into the supply. These currents distort the supply voltage which may then give rise to harmonic currents at other locations, even when at these locations no harmonics generating equipment is present. It was also noted that resonance phenomena, e.g. introduced by the interaction between the (inductive) supply system and capacitor banks, amplify the harmonic distortion when they occur around harmonic frequencies.

Harmonic pollution causes a number of problems. A first effect is the increase of the RMS-value and the peak-value of the distorted waveform. This is illustrated in figure I.17 which shows the increase of these values as more harmonic components are added to an initially undistorted waveform.
The RMS-value and the peak-value of the undistorted waveform are defined as 100 %. The peaks of the fundamental component and the distortion components are assumed to be aligned. It may be seen that the distorted waveform which contains harmonics up to the 25th harmonic has a peak value which is more than twice the value of the undistorted waveform and an RMS-value which is 10 % higher.

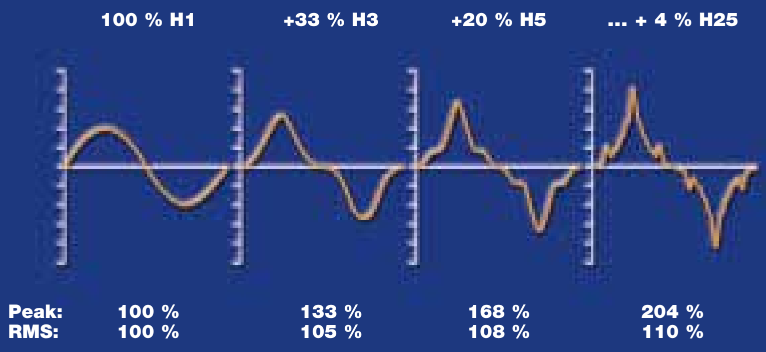


Figure I.17 *Evolution of the increase in peak-value and the RMS-value of a waveform as more harmonic components are added*

The increase in RMS-value leads to increased heating of the electrical equipment. Furthermore, circuit breakers may trip due to higher thermal or instantaneous levels. Also, fuses may blow and capacitors may be damaged. kWh meters may give faulty readings. The winding and iron losses of motors increase and they may experience perturbing torques on the shaft. Sensitive electronic equipment may be damaged. Equipment which uses the supply voltage as a reference may not be able to synchronise properly and either apply wrong firing pulses to switching elements or switch off. Interference with electronic communications equipment may occur.

In installations with a neutral, zero phase sequence harmonics may give rise to excessive neutral currents. This is because they are in phase in the three phases of the power system and add up in the neutral. Figure I.18 shows an example of this phenomenon.

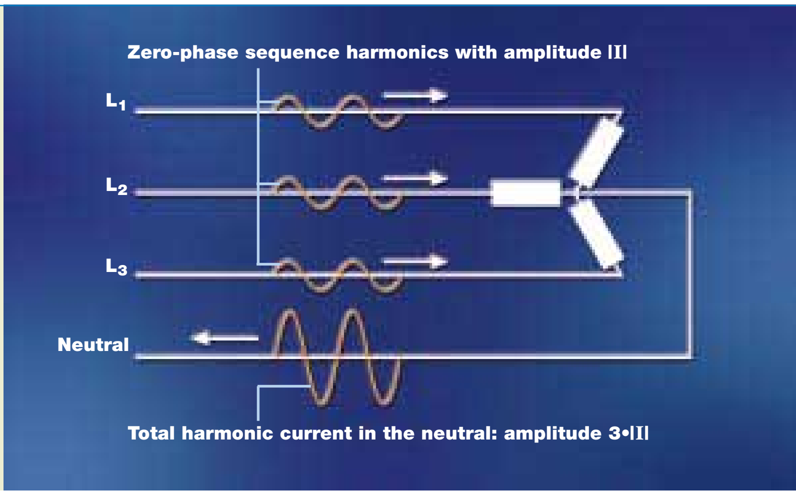


Figure I.18 *Illustration of the addition of zero phase sequence harmonics in the neutral*

The excessive neutral current problem is often found at locations where many single phase loads (e.g. PC's, faxes, dimmers, ...) are used. The triplen harmonics produced by these loads are of the zero phase sequence type.

Overall it may be concluded that an excessive amount of harmonics leads to a premature ageing of the electrical installation. This is an important motivation for taking action against harmonics.

The harmonic pollution may only affect equipment in the polluting plant but may also disturb equipment in other plants. In order to limit this disturbance, maximum allowable distortion limits have been defined in standards and recommendations ([1] , [2]). Also, the International Electrotechnical Commission (IEC) has issued technical reports (e.g. Ref. [3]) which outline assessment procedures to determine whether distorting loads may be connected to the supply system. In many cases, the regulations impose a limit for the total harmonic distortion (THD) of the voltage or current present at the point of common coupling (PCC). The PCC is the location at which the plant is connected to the public power system (generally at the primary of the main transformer(s)). The THD expresses the relative importance of the harmonics with respect to the fundamental component. It is calculated as

$$\mathrm{THD} = 100 \cdot \frac{\sqrt{\sum_{k=2} C_k^2}}{C_1} \qquad \text{(in \%)} \qquad (9)$$

where: THD : The total harmonic distortion of the waveform in %
C_1 : The magnitude of the fundamental component
C_k : The magnitude of the harmonic components (k = 2,3,...)

The utilities may impose penalties on users which introduce to much harmonic distortion on the supply. This is another motivation for taking action against harmonics.

5. Reducing the effects of harmonics.

A variety of solutions exist to limit the problems due to harmonics.

One approach is to make structural modifications within the plant. These include the connection of sensitive equipment to a clean part of the network. One could also choose twelve pulse drives rather than six pulse drives. These produce harmonics of which the order is given by the expression $n = (12 \cdot i \pm 1)$ where i is an integer greater or equal than 1. Thus the line current contains harmonics of the order 11, 13, 23, ... each with a magnitude

$$|I_n| \approx \frac{|I_{fund}|}{n}$$

which is an improvement over the spectrum generated by six pulse equipment.

A solution aimed at protecting power factor correction banks is to include reactors in the banks, this way increasing the total impedance of the units at harmonic frequencies and controlling the resonance frequency.

When the harmonic levels are too high, a harmonic filter solution is needed. Traditionally, passive filters have been used but some problems are associated with them.

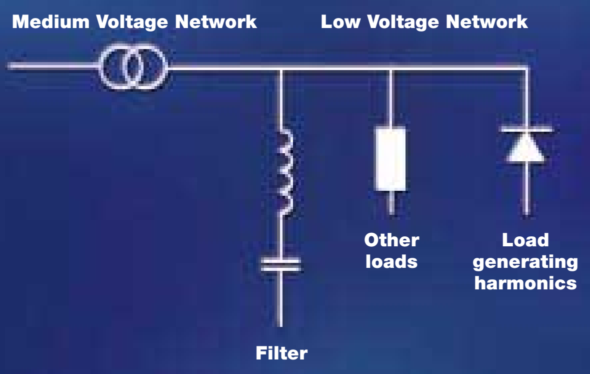


Figure I.19 *Passive filtering of harmonics*

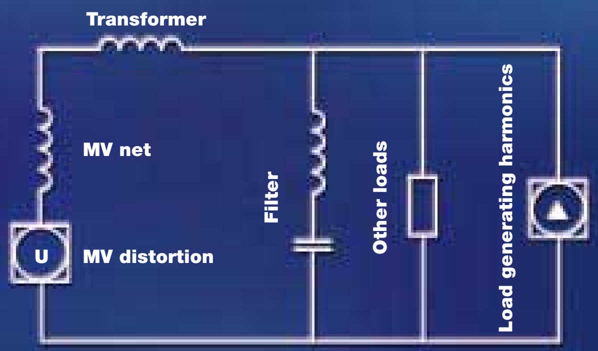


Figure I.20 *Equivalent circuit for passive harmonic filtering*

A passive filter consists of a series circuit of reactors and capacitors. Harmonic currents generated by, for example, a frequency converter are shunted by this circuit designed to have a low impedance at a given frequency compared to the rest of the network.

Figure I.19 illustrates schematically the described function with a harmonic generator, an impedance representing all other loads, a filter and a network. The equivalent circuit seen from the harmonic generator modeled as a harmonic current generator is shown in figure I.20. It includes the medium voltage network and some voltage distortion is represented by a harmonic voltage generator.

As the passive filters offer very low impedance at the resonance frequency, the corresponding harmonic current will flow in the circuit whatever its magnitude. Passive filters are then easily overloadable under which condition they will switch off or be damaged. The overload may be caused by the presence of unforeseen harmonics on the supply system or be caused by structural modifications in the plant itself (such as the installation of a new drive).

Passive filter provides always a certain amount of reactive power. This is not desirable when the loads to be compensated are AC drives which have already a good power factor. In that case the risk of overcompensation exists as a result of which the utility may impose a fine.

The degree of filtering of the passive filter is given by its impedance in relation to all other impedances in the network. As a result, the filtration level of a passive filter cannot be controlled and its tuning frequency may change in time due to ageing of the components or network modifications. The quality of the filtration will then reduce.

It is also important to note that a passive filter circuit may only filter one harmonic component. A separate filter circuit is required for each harmonic that needs to be filtered.

In order to overcome the problems associated with traditional passive filters and in order to answer to the continuing demand for a good power quality, ABB has developed an active filter for low voltage applications. The remainder of this document discusses this active filter, denoted as PQF.

References

*[1]	IEEE Standard 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", IEEE, New York, NY, USA, 1993.*

*[2]	Recommendation G5/3, "Limits for Harmonics in the UK Electricity Supply System", The Electricity Council Chief Engineers Conference, United Kingdom.*

*[3]	Technical Report IEC 1000-3-6, "ELECTROMAGNETIC COMPATIBILITY (EMC) - Part 3: Limits - Section 6: Assessment of emission limits for distorting loads in MV and HV power systems", International Electrotechnical Commission, October 1996.*

PQFA

Part II: The PQF

1. General principle of active filtering.

The principle of active filtering is fundamentally different from that of the passive filter. It was noted in part I that the passive filter is not controlled and that the filtering is a result of the impedance characteristics. The active filter does instead measure the harmonic currents and generates actively a harmonic current spectrum in opposite phase to the distorting harmonic current that was measured . The original harmonics are thereby cancelled. The principle is shown in Figure II.1.

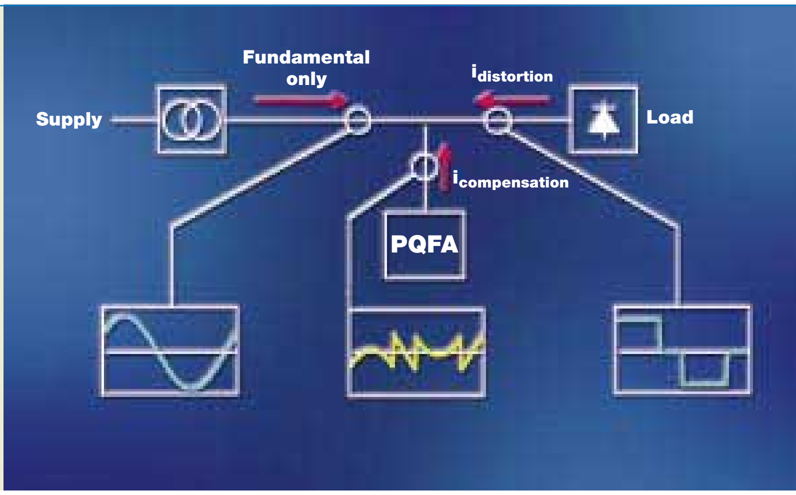


Figure II.1 *Principle of active filtering*

The control of the active filter in combination with the active generation of the compensating current allows for a concept that may not be overloaded. Harmonic currents exceeding the capacity of the active filter will remain on the network, but the filter will operate and eliminate all harmonic currents up to its capacity.
It can also be noted that the active filter we are considering here has a parallel topology. Active filters also exist in series topology but there do not offer the same advantage as the parallel topology: the connection is much less flexible, it has higher losses and is overloadable like the passive filter. From this point onwards, "active filter" will only refer to the parallel topology.

The principle of active filter showing currents and spectra is clarified in Figure II.2.

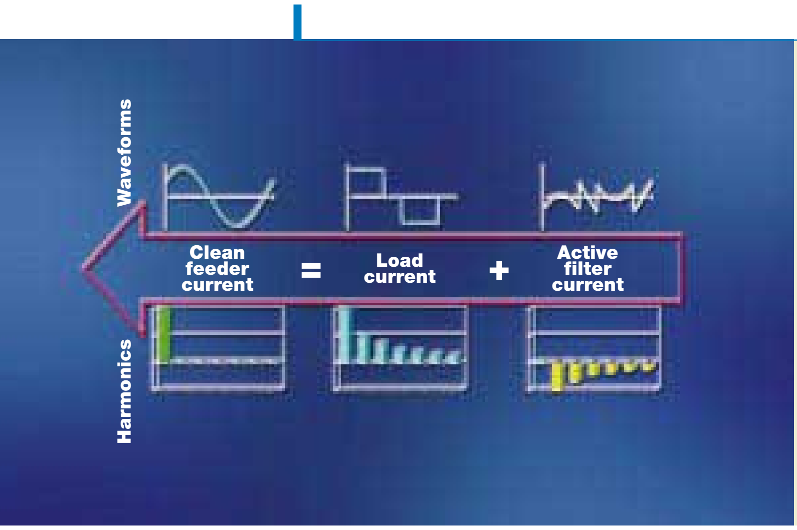


Figure II.2 *Active filter principle illustrated in the time and frequency domain*

2. The ABB Active filter: the PQF.

As we have just seen, the active filter is basically a compensating current generator. The most important parts are the current generator and the control system, which are detailed in the next sections.

2.1. The compensating current generator

The power circuit of the ABB active filter PQF is represented in figure II.3 hereafter.

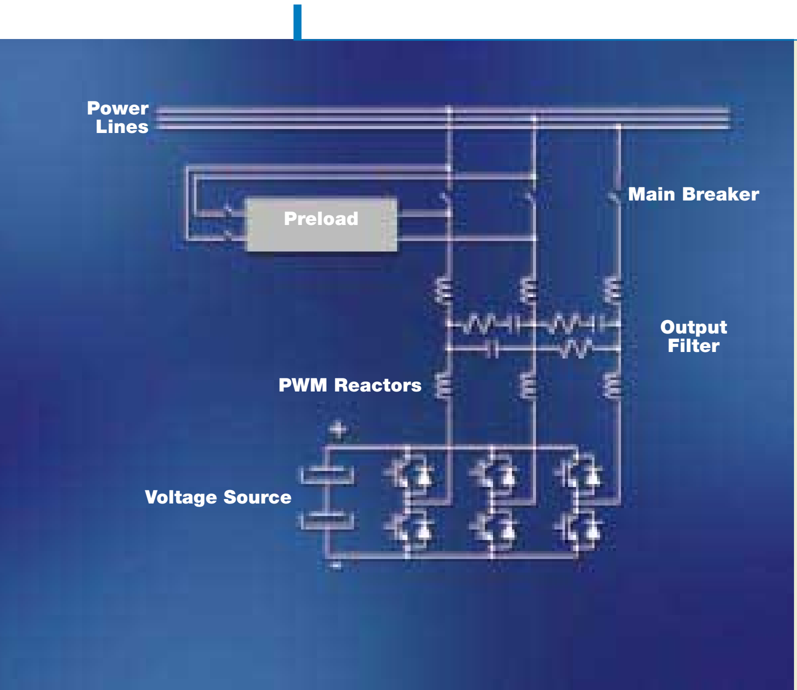


Figure II.3 *Electrical diagram of the PQF*

The compensating current is in a first step created by a three-phase Insulated Gate Bipolar Transistors (IGBT) inverter bridge that is able to generate any given voltage waveform with PWM (Pulse Width Modulation) technology. The IGBT bridge uses a DC voltage source realised in the form of a DC capacitor. The inverter bridge is in fact the same technology as the one used in AC drives. The generated voltage is coupled to the network via reactors and a small filter circuit. A good approximation to the desired ideal current generator is achieved.

Power semiconductors such as MOSFET's and GTO's might be considered, but today the practical solution is always IGBT's for the discussed application.

The main reason for this choice is that IGBT's offer now relatively high switching frequencies (smaller than MOSFET's but higher than GTO's) that allow the generation of high frequency harmonics currents, and relatively low on-state losses (much smaller than MOSFET's but higher than GTO's). Table II.1 summarises the principal characteristics of available power semiconductors and clearly shows that IGBT's are the best compromise between easy control and high power at present.

Table II.1 *Power semiconductors for active filters*

	GTO	MOSFET	IGBT
SWITCHING FREQUENCY	MEDIUM	HIGH	HIGH
GATE SIGNAL	CURRENT	VOLTAGE	VOLTAGE
POWER	VERY HIGH	MEDIUM	HIGH
SWITCHING LOSSES	HIGH	LOW	MEDIUM
CONDUCTION LOSSES	LOW	HIGH	MEDIUM

The DC capacitors are loaded actively through the inverter bridge and there is no need for an external power source. Obviously, the DC voltage level must always be higher than the peak value of the network voltage in order to be able to inject currents to the network.

The PQF is also fitted with a preloading circuit dedicated to the DC capacitors. The function of this preloading circuit is to avoid, at start-up when the capacitors are discharged, high inrush currents that could damage the power electronics or create transients in the network.

The PWM reactors transform the voltage source inverter into a current source.

Finally the output filter absorbs the high frequency components introduced by the PWM switching action.

2.2. PWM principle

As mentioned earlier, the control of the inverter bridge is based on PWM (Pulse Width Modulation). The PWM principle is explained step by step in this paragraph. It demonstrates how a DC voltage source may be used to generate an AC signal with a controlled frequency. The load considered is an RL circuit. In the case of the active filter, it is the PWM reactor.

Step 1

The RL circuit considered is first connected to a DC voltage source through a switch as shown in figure II.4. When the switch is closed, the current rises exponentially towards the DC value determined by the resistance of the circuit.

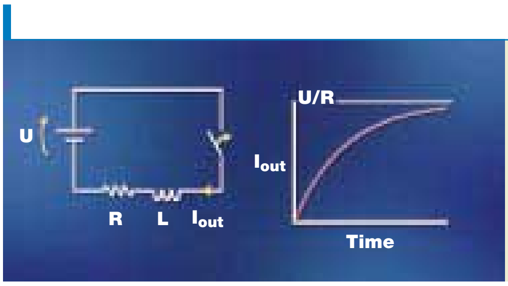


Figure II.4 *Pulse Width Modulation*

The circuit in figure II.5 is obtained by connecting a free wheeling diode across the load.
When the switch opens, the reactor ensures the continuation of the current, which starts to decrease exponentially through this diode.

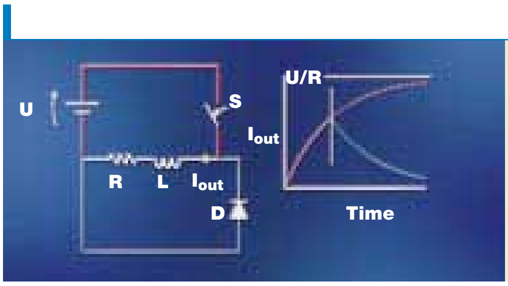
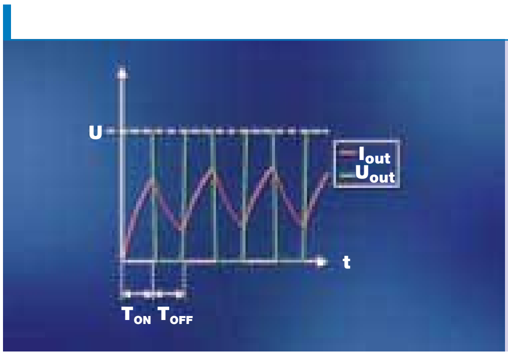


Figure II.5 *Pulse Width Modulation : Free Wheeling Diode*

If the switch is closed and opened in a controlled way, it is possible to control the average level of the DC current flowing through the load. In case the period over which the switch is opened and closed is constant, the duty cycle (δ) is defined as the time the switch is closed over the total period of time. The average voltage seen by the load is then easily calculated by multiplying this duty cycle by the DC voltage level as shown in figure II.6 for δ=0.5.



$$\delta = \frac{T_{ON}}{T_{ON} + T_{OFF}}$$

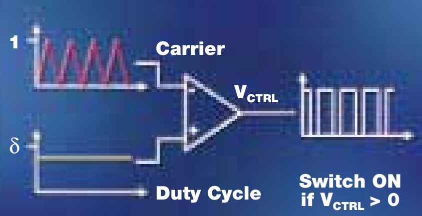
$$0 \leq \delta \leq 1$$

$$U_{out_{DC}} = \delta U$$

Figure II.6 *Pulse Width Modulation : Duty Cycle*

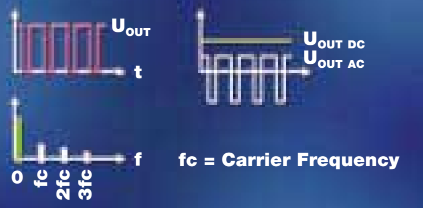
In order to control the switch, a control signal has to be generated. As illustrated in figure II.7, the control signal (in this case a voltage since IGBTs are voltage controlled) is obtained by comparing a triangular waveform having a frequency f_c (this signal is called the carrier) with the duty cycle δ. Whenever δ has a higher value than the carrier, the control voltage is positive and the switch is on. Whenever δ has a smaller value than the carrier, the control voltage is zero and the switch is off. If δ is zero, the switch is always off and the output voltage (voltage on the load) is zero. If δ is 1, the switch is always on and the output voltage is U. For values of δ between 0 and 1, the average DC voltage on the load is δU.

Figure II.7 *Pulse Width Modulation : Control signal*



The frequency analysis of the output voltage (figure II.8) shows that harmonics of the carrier frequency (or switching frequency) are added to the DC component (the average value).

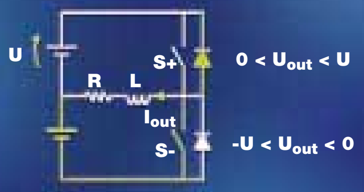
Figure II.8 *Pulse Width Modulation : Output voltage*



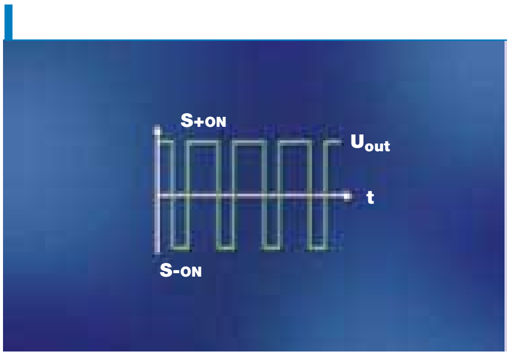
Step 2

It has been shown that it is possible to control the output voltage between 0 and U. With the extension indicated in green in figure II.9, it is also possible to control the voltage between –U and U.

Figure II.9 *Pulse Width Modulation : Improvements*



The average value of the DC voltage depends now on the working cycles of the two switches. A new definition of the duty cycle (δ) has to be considered and is specified in figure II.10. Let T_{S+on} be the time the positive polarity switch is on and T_{S-on} the time that the negative polarity switch is on. The two switches are never on or off together. If the positive switch is always on, δ equals 1 and the average output voltage is U. If the negative switch is always on, δ equals –1 and the average output voltage is –U. If the working cycles of the two switches are identical, δ equals 0 as is the average output voltage. For any value of $\delta \in [-1, 1]$, the average output voltage is $\delta U \in [-U, U]$.



$$\delta = \frac{T_{S+ON} - T_{S-ON}}{T_{S+ON} + T_{S-ON}}$$

$$\Downarrow$$

$$-1 < \delta < 1$$

$$\Downarrow$$

$$-U < U_{out} = \delta U < U$$

Figure II.10

Duty Cycle : Improvements

As illustrated in figure II.11, the control signal of the switches is now generated by comparing the duty cycle δ as defined above with a carrier having a triangular shape but values between –1 and 1. For values of δ superior to the carrier, the voltage signal is positive and the positive polarity switch is on. For values of δ inferior to the carrier, the voltage signal is negative and the negative polarity switch is off.

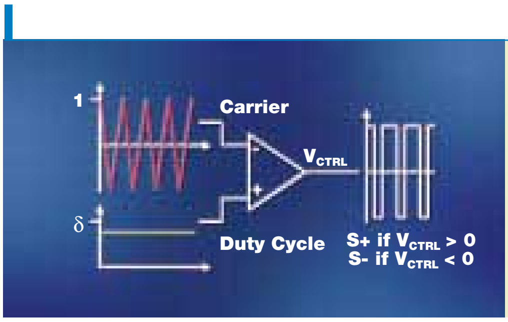


Figure II.11 *Control signal : Improvements*

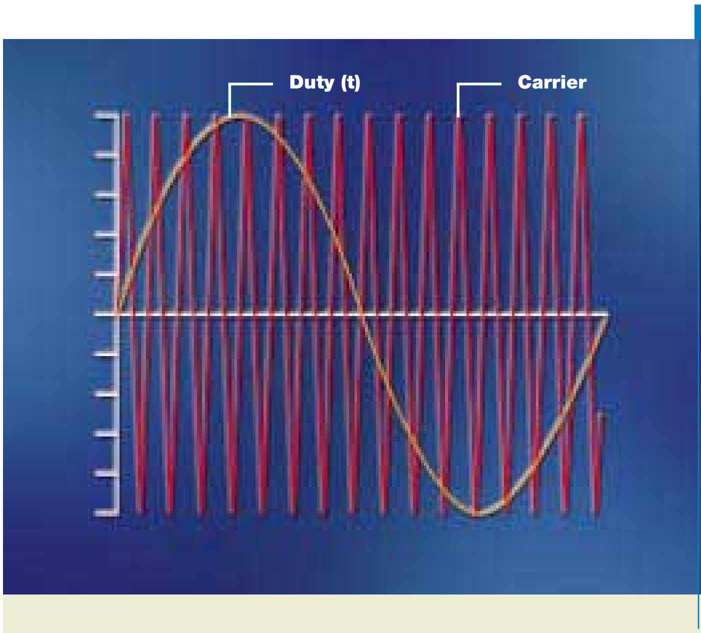
Step 3

Step 1 and 2 have demonstrated how it is possible to control the DC voltage. However, in case of the active filter, an AC voltage needs to be created and controlled from a DC voltage source. This can be achieved with a time varying duty cycle as is indicated in figure II.12. Any duty cycle may be used providing that its frequency is strictly inferior to half the value of the carrier frequency.

- **If $\delta(t) = \sin(2\pi f t)$**
  $\Longrightarrow U_{out}(t) = U \sin(2\pi f t)$
  – Valid if $f < \frac{f_{carrier}}{2}$ (Nyquist)
- **Any $\delta(t)$ with max frequency $< \frac{fc}{2}$**

Figure II.12 *Time varying duty cycle*

Figures II.13 and 14 show a sine wave duty cycle, the triangular carrier and the resulting control voltage. The system is called pulse width modulation since the AC output voltage, which has the same shape as the duty cycle, is generated by controlling the width of the voltage pulses.



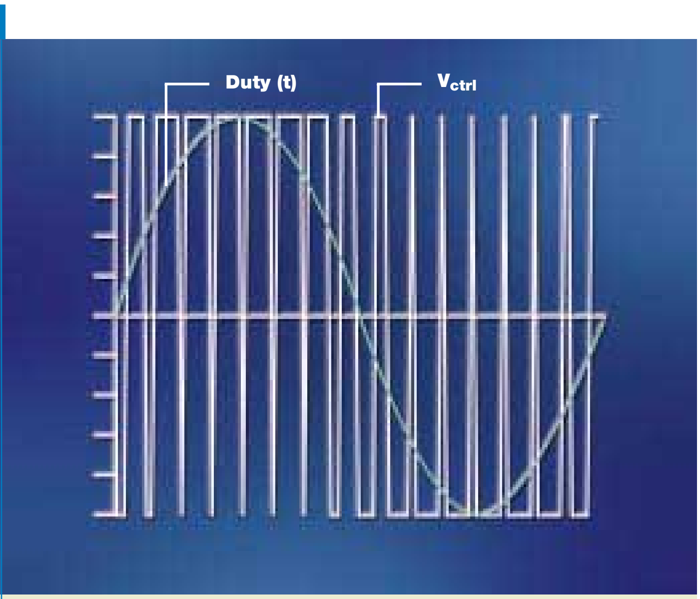


Figure II.13 *Pulse Width Modulation : sine wave duty cycle* **Figure II.14**

2.3.Control electronics

Control approach: closed loop vs. open loop control

To control the active filter the choice stands between open loop and closed loop current control. Figure II.15 shows open loop current control. The harmonics currents are measured on the load side of the active filter that computes the required compensating current and injects it into the network.

Closed loop current control as performed by the PQF is shown in figure II.16 In this topology the resulting current to the network is measured and the active filter operates by injecting a compensating current minimising this resulting current. In this configuration, the filter directly controls its effect on the filtration.

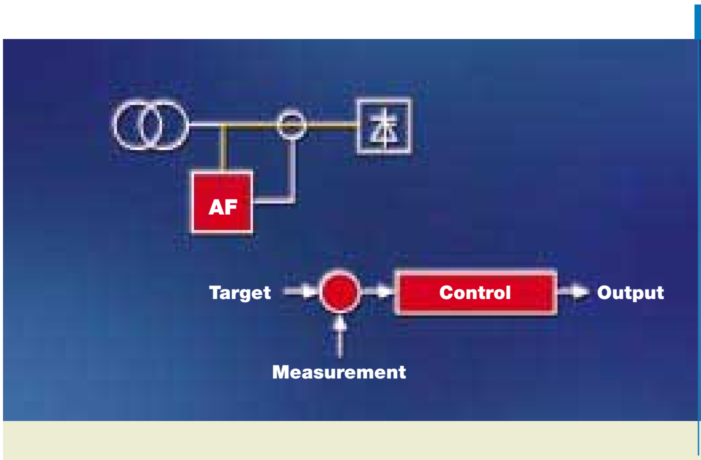


Figure II.15 *Open loop control*

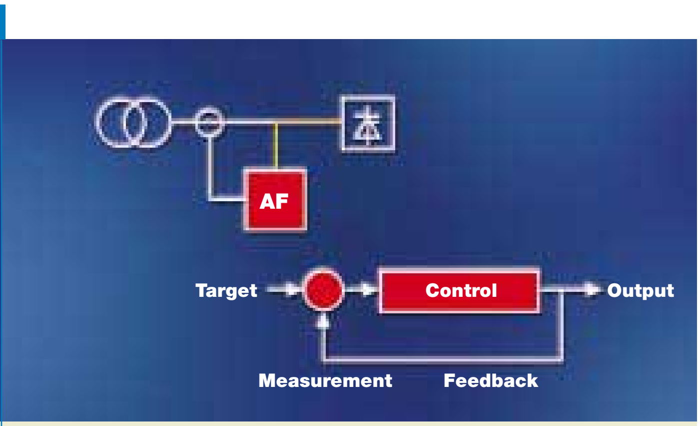


Figure II.16 *Closed loop control*

The open loop control system requires higher-class current sensors and increases the risk of inefficiency and inaccuracy. In addition to being more precise, the closed loop control system also allows for a direct control of the degree of filtering. Furthermore, the closed loop control system ensures that measurement errors do not result in a higher distortion.

DSP based control

To fully exploit the potential of an active filter we need a digital measurement and control system that is fast enough to operate in true real time. We need to be able to track the individual harmonics and control the compensating current according to the requirements of the plant and this with full control at every instant in time. To achieve this, we need advanced Digital Signal Processors, DSP's.

Among the physical signals needed by the PQF, the three line currents have to be measured. Standard CTs with 5A secondary are usually sufficient. Those analogue signals must first be acquired, levelled and antialias-filtered before digitalisation. Fast and high precision analogue-to-digital converters are used to create a digital representation of the analogue signals. The digitised signals are then sent to the powerful DSP that controls all measurements and calculations in real time, and builds the PWM references for the inverter. It is another processor, a microcontroller, which handles all digital input/output (including the command of the PWM inverter). More dedicated to control than to calculations, this microcontroller ensures for instance the closing of the relays and contactors. One control is needed per PQF system and can handle more than one power module simultaneously.

Ripple control signals

It may happen that a mains signalling voltage ('ripple control system') is superposed on the supply voltage of the plant. This voltage is used by the public supplier for the transmission of signals and can be situated at virtually any frequency. Its magnitude can be up to 10 % of the fundamental rms voltage. The active filter must obviously work without interfering with any ripple control systems that may be present. If no special precaution is taken, the filter will act as a short-circuit for these signals, stopping them from being further transmitted. Consequently, the PQF has been designed to leave this signal clean and undisturbed.

3. The PQF: performances.

3.1. Filtering

The ideal filter

The main requirement for an active filter installed in an industrial plant is to attenuate the harmonics produced by the non-linear loads of the plant.

The ideal active filter should allow the user to choose freely which harmonic components to filter and should offer an adjustable degree of filtering.

It is also worth noting that while most standards only give harmonics limitations up to the 25th harmonic component, the total harmonic voltage distortion at the point of common coupling (PCC) is often calculated up to the 40th [1] or the 50th [2] harmonic. Furthermore, the total number of harmonics that can be filtered determines directly the quality of the resulting current.

This is illustrated in figure II.17 which shows the filtered waveforms obtained by filtering up to different harmonic orders.

Figure II.17 *Waveforms obtained by eliminating the harmonic components of a rectangular periodic signal up to the (a) 13th harmonic, (b) the 25th harmonic and (c) the 50th harmonic*

Filtering up to the 13th harmonic.

Filtering up to the 25th harmonic.

Filtering up to the 50th harmonic.

This figure highlights the need for an active filter that can operate up to sufficiently high harmonic frequencies.

The PQF can filter simultaneously 20 independent harmonics up to the 50th for 50 Hz based networks. On 60 Hz based networks, 15 independent harmonics may be filtered up to the 50th. The number of harmonics to be filtered as well as their frequencies is completely programmable by the user.
Figure II.18 shows typical harmonics generated by common six-pulse semi-conductor loads. There are 16 up to the 50th order. The PQF is able to filter all those harmonics simultaneously. The resulting power quality level is very high.

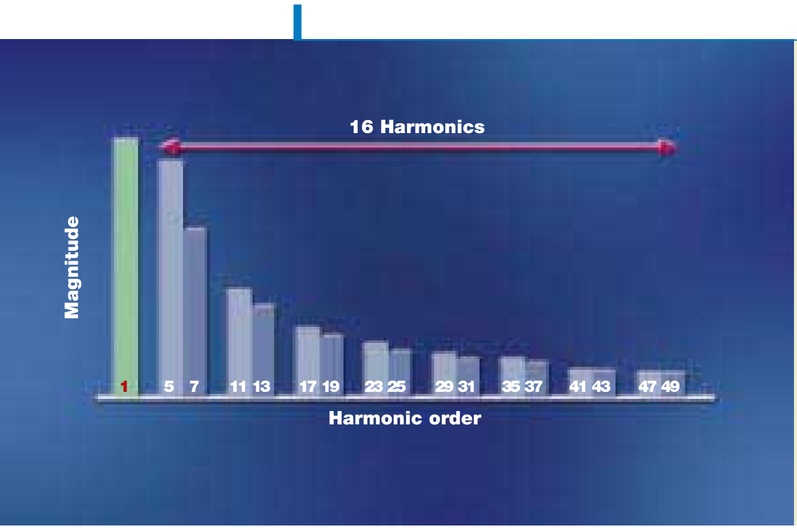


Figure II.18 *Typical harmonics generated by common six-pulse semi-conductor loads*

Besides the harmonic selection functionality, the user also has the possibility to specify a filtration level for each selected harmonic. The PQF will filter the selected harmonics until the current is reduced to the residual level permitted by the user. This residual level is programmable by the user and may be different for each selected harmonic. This functionality, which is illustrated in figure II.19, is especially useful when the objective is to fulfil the requirements of a standard and results in a better use of the available compensation power. As already explained, this is a major advantage against passive filters for which the filtration level cannot be predefined nor controlled. It also allows the installation of active filters on networks already fitted with a fixed passive filter.

We can see that we are very close to the ideal filter: the choice of which harmonic components to filter is free and the degree of filtering is adjustable according to the wishes of the user.
Moreover, all typical harmonics generated by three-phase non-linear loads may be filtered simultaneously.

RMS current rating

The ratings of the PQF range are presented in Part III. However, it is important to already note that the rating of a PQF is expressed by its RMS current capability.
The RMS current value of a given harmonic spectrum is obtained by the geometric combination of the individual components magnitudes.
For instance, the following spectrum:

H5: 150A
H7: 66A
H11: 47A
H13: 31A

gives a total RMS current of: $\sqrt{(150)^2 + (66)^2 + (47)^2 + (31)^2} = 173$ Arms

Current capability and higher frequencies

For a given RMS current rating, the current capability decreases with the injected frequency. Indeed, when the frequency increases the impedance of the PWM reactors also increases and according to Ohm's law, the injected current decreases.

However, this natural effect (it is a consequence of Ohm's law) is not a restrictive limitation since typical harmonics spectrum of non-linear loads have the same shape than the current injection pattern of the PQF.

3rd harmonic filtering

We have seen that the PQF may filter harmonics up to the 50th order, which includes the 3rd harmonic. However, the PQF has no neutral connection and does not filter zero-sequence harmonics (e.g. the 3rd harmonic generated phase to neutral). It is important to stress that it is only the case for loads connected phase to neutral: triplen harmonics generated between phases will be removed by the PQF. An example of third harmonic current generated by single-phase welders connected between phases is shown in Part IV. It will be seen that the filter's effect on the third harmonic is impressive.

3.2. Reactive power

Besides the filtering functionality, reactive power compensation is also possible with the active filter. Compared to traditional capacitor banks, the reactive compensation of the PQF is continuous ("stepless"), fast and smooth (no transients at switching). The compensation can be either capacitive or inductive, depending on the load type.

Two types of compensation are available: automatic compensation where a target power factor has to be set, and fixed compensation based on a predefined amount of kvar.

The user is free to select and program reactive power compensation independently of harmonics filtering. The only limit is the active filter rating.

However, it is important to note that reactive power consumes current capability of the filter and it is not its main priority. This remark on filter priorities is further detailed in point 3.3.

3.3. Priorities / Filter mode

The filter can basically perform three different tasks:

- Filter the selected harmonics until their magnitudes are close to zero ("maximum filtering")
- Filter the selected harmonics until their magnitudes reach the prescribed level ("filtering to curve")
- Compensate reactive power

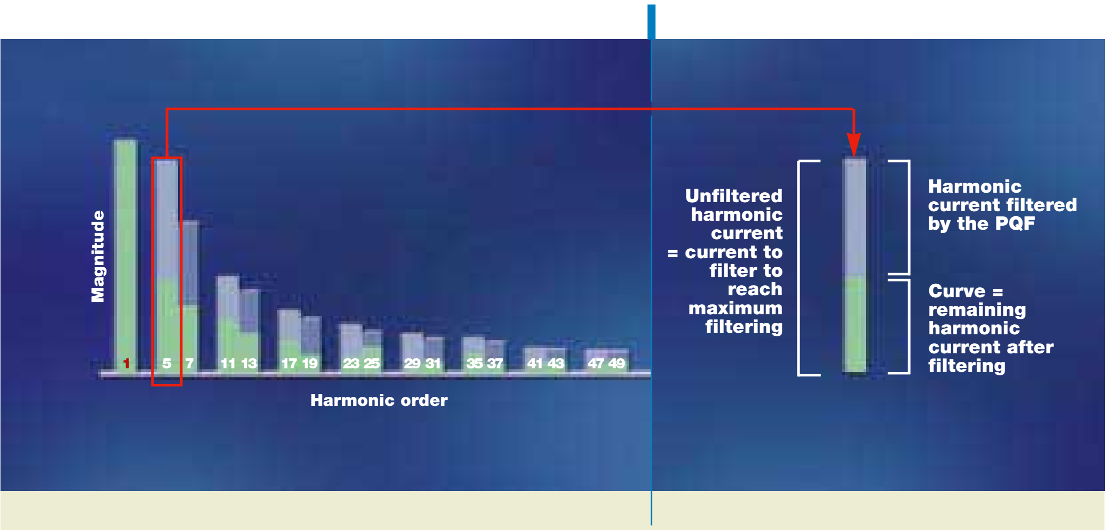


Figure II.19 *Meaning of filtering to curve*

Filtering to curve means that the PQF will filter the harmonics until the current is reduced to the residual level permitted by the user.

This residual level called the curve, is programmable in Amps or as a percentage of the fundamental or total RMS current and may be different for each selected harmonics.

Figure II.19 graphically explains this functionality.

In order to offer a maximum of flexibility to the user, three modes of operation have been defined. Each mode allocates different priority levels to the actions detailed above. Those three modes are as indicated in table II.2.

Table II.2 *Filter modes*

	HIGHEST → 1ST PRIORITY	2ND PRIORITY	LOWEST 3RD PRIORITY
MODE 1	FILTERING TO CURVE	MAXIMUM FILTERING	REACTIVE COMPENSATION
MODE 2	FILTERING TO CURVE	REACTIVE COMPENSATION	MAXIMUM FILTERING
MODE 3	FILTERING TO CURVE	REACTIVE COMPENSATION	

It can been seen that the action “filtering to curve” has always the first priority whatever the mode.
To illustrate this concept of priority and the filtering strategy, suppose that we have initially an ideal situation: the PQF is performing maximum filtering and reactive power compensation.
If the PQF reaches one of its limits, it will automatically release the action having the lowest priority level: reactive power if in Mode 1 or maximum filtering if in Mode 2. The objective of the PQF is now to perform maximum filtering if in Mode 1 or filtering to curve and reactive compensation if in Mode 2.
If the PQF still hits one of its limits, it will concentrate its resources on the first priority action only: filtering to curve.
If the level of harmonics is still too high for the PQF to achieve the required filtering to curve, it will filter to its hardware limit preventing it from being overloaded.
Once the load current contains less harmonics again, the PQF automatically adapts its working pattern according to the programmed mode of operation.
Modifications of the working pattern happen in a smooth fashion.

4. Protections and alarm.

4.1. Protections

The PQF is fitted with two types of protection:

- Slow protection
- Fast protection

The role of the slow protection is to change on-line the way the filter is working according to the filter stress and programmed parameters as illustrated in 3.3. This ensures that the filter is never overloaded and always has an optimal filtering effect.

The fast protection is only activated in case of abnormal working conditions and ensures the integrity of the filter.
The fast protection means include:

- The main incoming circuit breaker with undervoltage release (PQFA) or fuses (PQFL).
- Blocking system of the IGBT bridge in case of:
  - AC overvoltage on the mains
  - DC overvoltage on the DC bus
  - Filter over current
  - IGBT over current
  - IGBT over temperature

  If an error persists, the main breaker or contactors will also intervene.
- Short-circuit or overcurrent (peak & thermal) protection inside the IGBTs drivers.

4.2. Alarm

The PQF is fitted with a normally open alarm contact (voltage free contact) allowing remote supervision of the unit. It is activated (open) when the filter is in error condition, off or if it is working properly but not able to filter to the pre-defined level (hardware limitation). When it is closed the filter is working properly and all filtering requirements are fulfilled.

References

[1] IEEE Standard 519-1992, "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", IEEE, New York, NY, USA, 1993.

[2] Recommendation G5/3, "Limits for Harmonics in the UK Electricity Supply System", The Electricity Council Chief Engineers Conference, United Kingdom.

PQFB

Part III: Choosing and installing a PQF

1. PQF range and ratings

According to the level of harmonics to be filtered, the frequency and the voltage of the network, ABB provide a wide range of PQF solutions.

For voltages up to 600V (50 or 60Hz), two solutions are available: the PQFL and the PQFA. Based on the same principle, the PQFL and the PQFA mainly differ in their current capability, the PQFL being the smallest unit.

Above 600V and up to 1000V, the solution provided by ABB is the PQFB. The PQFB consists in a PQFA connected to the network through coupling capacitors.

All ABB Power Quality Filters offer the following advantages:

- **Systems for 50Hz may filter up to 20 harmonics simultaneously up to the 50th harmonic. Systems for 60 Hz may filter up to 15 harmonics simultaneously up to the 50th harmonic.**
- **The filtering strategy and the harmonics to be filtered are totally programmable by the user. Individual harmonics may be chosen for filtering either to zero or to a level defined in absolute or relative terms.**
- **Closed loop control for best accuracy.**
- **Not overloadable.**
- **Filtering does not generate or absorb any reactive power (except for the PQFB). However, remaining resources after filtering to the desired level may be used for reactive power compensation. This feature is totally programmable (except for the PQFB).**

1.1. PQF systems up to 600V

PQFA

Physical mounting

A PQFA system consists of one controller and up to 8 power modules mounted in cubicles together with auxiliary apparatus and wiring to form a factory assembled and tested system.

Each cubicle may contain one controller and one or two power modules.

As illustrated in figure III.1, a PQFA cubicle may exist under one of the following configurations:
- configuration A: one controller and one power module
- configuration B: one controller and two power modules
- configuration C: no controller and one power module
- configuration D: no controller and two power modules

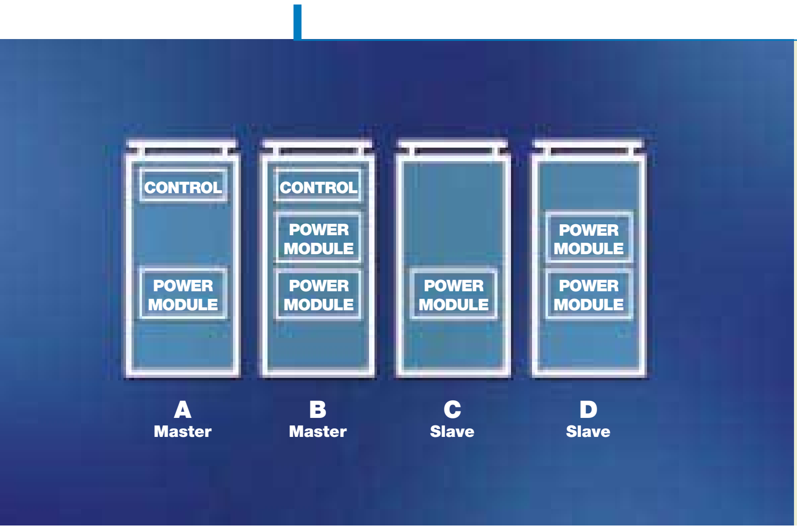


Figure III.1 *PQFA configurations*

Configurations C and D are slave units without controller. They can only be used if connected to a "master unit" fitted with a controller (configuration A or B).

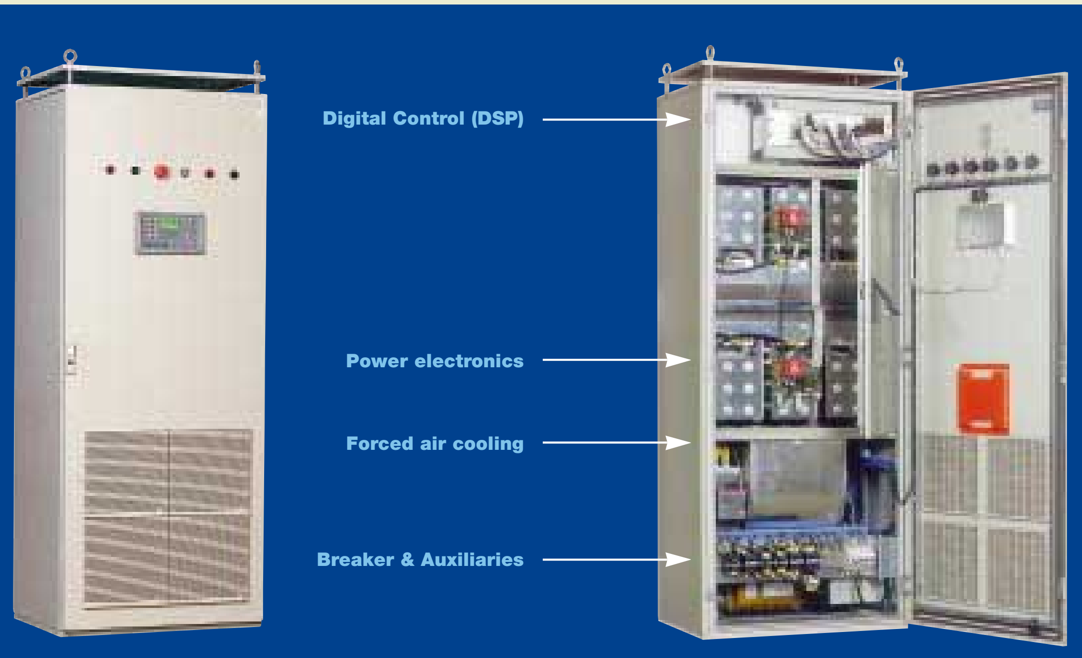
The cubicle sections have standard dimensions of 800 x 600 x 2150 mm (width x depth x height). Systems made of several cubicles are usually mounted on a base for a total height of 2250 mm. Each cubicle is fitted with its own bottom cable entry and circuit breaker.
The following PQFA systems are available (Table III.1):

Table III.1 *PQFA systems*

CONFIGURATION	NUMBER OF MODULES	NUMBER OF CUBICLES
PQFA-A	1	1
PQFA-B	2	1
PQFA-B+C	3	2
PQFA-B+D	4	2
PQFA-B+D+C	5	3
PQFA-B+D+D	6	3
PQFA-B+D+D+C	7	4
PQFA-B+D+D+D	8	4

Picture III.1 shows a PQFA-B (2 power modules). It can be seen that the power modules are located in a pressurised cabinet where air is blown by a fan assuring the cooling of the power electronics. The breaker and auxiliaries are located at the bottom of the cubicle. The control is at the top.

Picture III.1 *PQFA-B*



Current capability
Power modules for the PQFA are available with voltage ratings up to 600V for 50 or 60Hz. The thermal rating for one module is maximum 225 Arms.
The power module ratings at 50 and 60 Hz are represented in figures III.2 and III.3 hereafter.

When several modules are used in the same system, a derating of 5% must be applied to the power module current. The apparent power (kVA) of the module is given by ($\sqrt{3}$ x voltage rating x current rating).

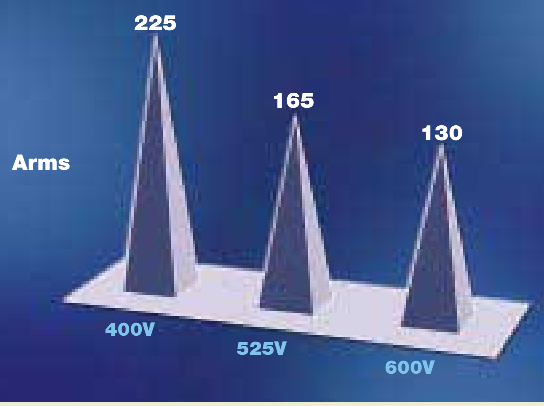


Figure III.2 *Power modules ratings – 50Hz (up to 8 power modules may be connected to one controller)*

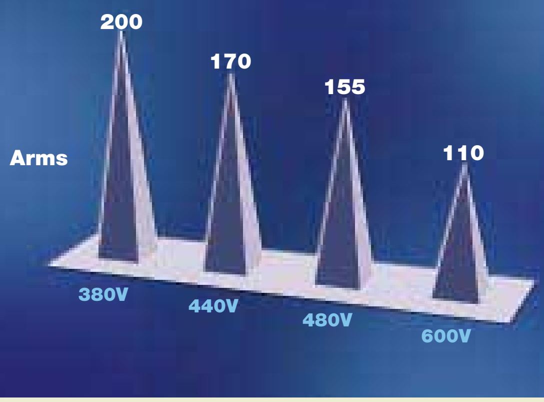


Figure III.3 *Power modules ratings – 60Hz (up to 8 power modules may be connected to one controller)*

Physical mounting

A PQFL system consists of one controller and up to four power sections.
Two executions are available: cubicle or plate execution (IP00).

The plate execution is intended to be installed in the customer's own cubicle at site. It is equipped with a terminal for the connection of the wires to the cubicle front door. All the accessories to be installed on the front door are also supplied. The standard dimensions of the mounting plate are 498 x 400 x 1896 mm (width x depth x height).

The cubicle execution is factory assembled with auxiliary apparatus and wiring.
Each cubicle may contain one controller and one power section.

As illustrated in figure III.4, a PQFL cubicle may exist under one of the following configurations:

- configuration M: one controller and one power section
- configuration S: no controller and one power section.

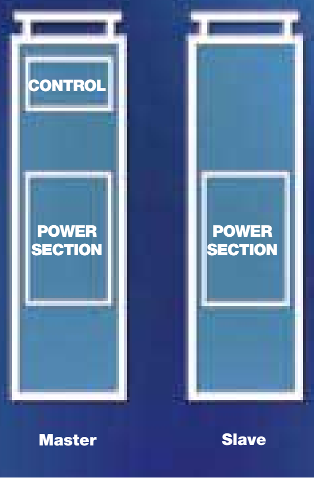


Figure III.4 *PQFL configurations*

Configuration S has no controller and is named "slave unit". It can only be used if connected to a "master unit" fitted with a controller (configuration M). Only power sections of the same rating may be connected to a common controller.

The standard dimensions of the cubicle are 600 x 600 x 2150 mm (width x depth x height).

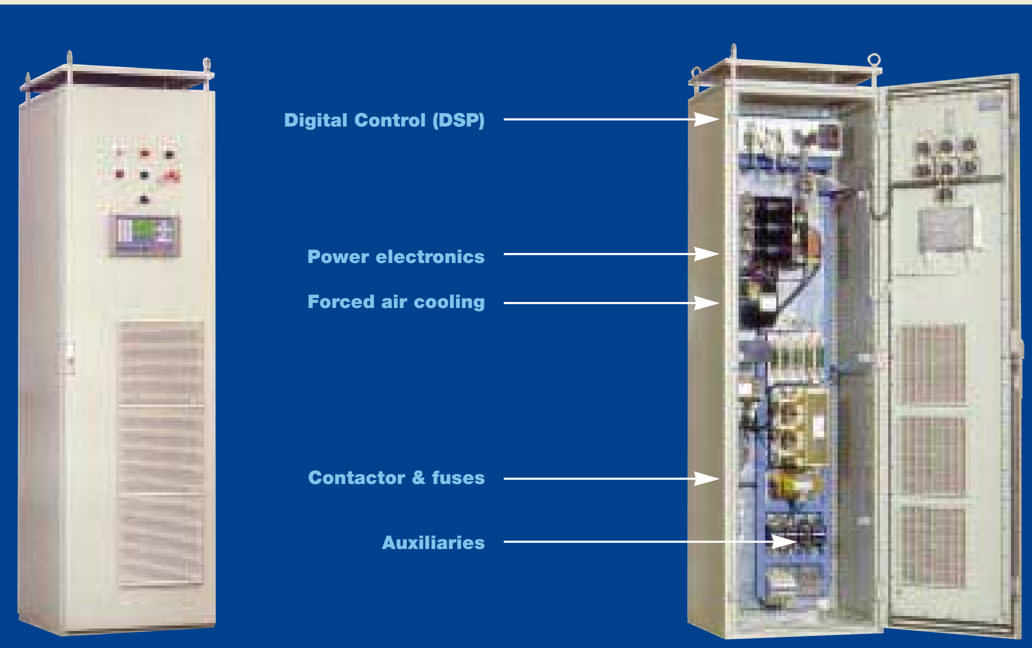
The following PQFL systems are then available:

Table III.2 *PQFL systems*

CONFIGURATION	NUMBER OF POWER SECTIONS	NUMBER OF CUBICLES
M	1	1
M + S	2	2
M + S + S	3	3
M + S + S + S	4	4

Picture III.2 shows a PQFL. The fuses and auxiliaries are located at the bottom of the cubicle. The control is at the top.

Picture III.2 *PQFL*



Current capability

The PQFL is rated for 400V (415V) – 50Hz or up to 480V at 60Hz. The thermal rating for one power section is maximum 130Arms.
The power section ratings at 50 and 60Hz are represented in figures III.5 and III.6 hereafter.

When several modules are used in the same system, a derating of 5% must be applied to the power module current. The apparent power (kVA) of the module is given by ($\sqrt{3}$ x voltage rating x current rating).

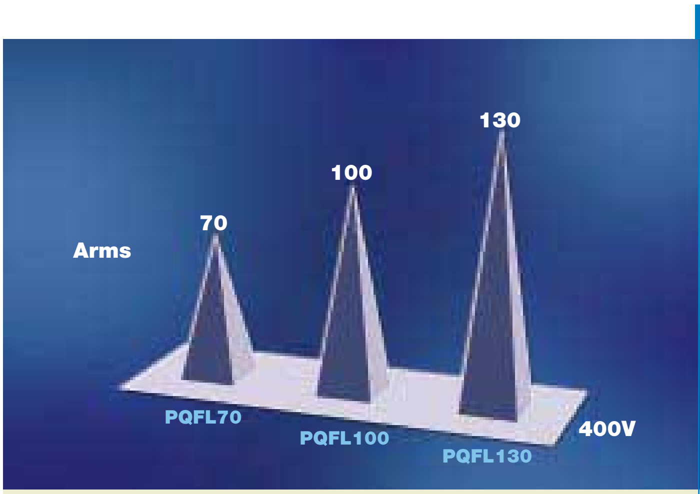


Figure III.5 *PQFL range - 400V - 50 Hz*

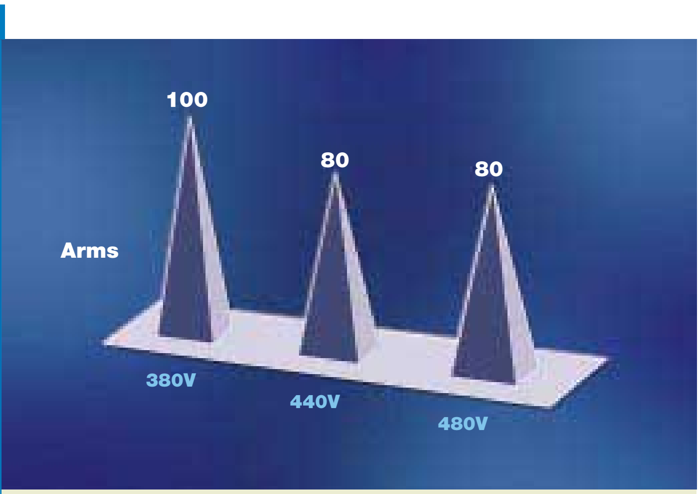


Figure III.6 *PQFL range - 60 Hz*
(up to 4 power sections of the same rating may be connected to one controller).

Technical specifications

Active filter for connection between the three phases of a three-phase network with or without neutral for filtering of non zero-sequence harmonics and optional reactive power compensation.

		PQFL	PQFA
RMS current per module			
	50 Hz - 400V (415V)	70A, 100A or 130A / power section	225A / power module
	- 525V	-	165A / power module
	- 600V	-	130A / power module
	60 Hz - 380V	100A	200A / power module
	- 440V	80A	170A / power module
	- 480V	80A	155A / power module
	- 600V	-	110A / power module
		Other voltages and ratings on request	Other voltages and ratings on request
Modularity(*)		Up to 4 power sections / system	Up to 8 power modules / system
Physical mounting		1 power section / cubicle	Up to 2 power modules / cubicle
Voltage tolerance		+/- 10%	+/- 10%
Harmonics to filter	50 Hz:	Up to 20, programmable up to the 50th harmonic	Up to 20, programmable up to the 50th harmonic
	60 Hz:	Up to 15, programmable up to the 50th harmonic	Up to 15, programmable up to the 50th harmonic
Degree of filtering		Individually programmable per harmonic in relative or absolute terms	Individually programmable per harmonic in relative or absolute terms
Typical filtering efficiency		Better than 97%	Better than 97%
Reactive power		Power factor programmable from 0.6 inductive to 0.6 capacitive	Power factor programmable from 0.6 inductive to 0.6 capacitive
Communication		RS232 port	RS232 port
Programming	Alt 1)	Using PC (not provided) and software supplied with the equipment	Using PC (not provided) and software supplied with the equipment
	Alt 2)	Using optional PQF-Manager	Using optional PQF-Manager
	Alt 3)	Using PC (not provided) and optional PQF-Link software	Using PC (not provided) and optional PQF-Link software
Response time		40 ms	40 ms
Active power		Less than 3 kW per section at full load	Less than 7 kW per module at full load
Protection		IP23 (IP20 open door) - Plate execution IP00	IP23 (IP20 open door)
Cubicle dimensions		600 x 600 x 2150 mm (W x D x H)	800 x 600 x 2150 mm (W x D x H)
Plate dimensions		498 x 400 x 1896 mm (W x D x H)	-
Weight		Appr. 250 kg (IP00 : appr. 200 kg) - unpacked	Appr. 600 kg (with two power modules) - unpacked
Colour		RAL 7032 (Beige)	RAL 7032 (Beige)

Installation	PQFA & PQFL IP23: Floor fixation. Lifting lugs provided. Cable entry from the bottom PQFL IP00: plate to be mounted in cubicle (not provided)
Environment	Indoor installation in clean environment up to 1000m altitude
Ambient temperature	-10°C/+40°C
Humidity	Maximum 95% RH; non-condensing
Options	Socle (200 mm) Current transformers (ratings and dimensions to specify) PQF-Manager PQF-Link

(*) A derating of 5% should be considered for systems with more than one power module / section.

1.2. PQF systems up to 1000V: PQFB

For voltages above 600V and up to 1000V, the PQFA is connected to the network through coupling capacitors. This system is the PQFB.
The aim of these capacitors is to increase the voltage capability of the PQFA.
All the characteristics of the PQFA apply to the PQFB except the reactive power control. Indeed, a fixed reactive power is generated and cannot be controlled. However, this reactive power is small compared to a passive filter.
Regarding the dimensions, the system is made of PQFA cubicles as described previously and of cubicles containing the coupling capacitors and cable entry.
Power modules are rated at 200Arms including the fundamental.
This solution is tailor made. Please contact your local ABB agent.

Picture III.3 shows a three-module PQFB for a chemical plant (570A - 630V - 60Hz system).

Picture III.3 *Three-module PQFB - 570A - 630V - 60Hz*

2. Programming the active filter

Each PQF is provided with programming software: the PQF-Prog.

More advanced programming and monitoring accessories are also available as an option: the PQF-Manager and the PQF-Link.

2.1. PQF- Prog

The PQF-Prog, included in the standard PQF package, allows for the complete programming of the filter.

The software runs on Windows NT 4.0 Service Pack 3 minimum.

One free RS232 port of the PC (not provided) has to be connected to the corresponding port located on the control rack of the PQF.

The programming procedure of the active filter is very simple and is as follows:
1) Select the filter mode
2) Specify the harmonics to filter
3) Specify the reactive power if any
4) Switch the filter on

• Filter Mode selection

The filter can have three types of effect on the network:

- Filter the selected harmonics until their magnitudes are close to zero (maximum filtering);
- Filter the selected harmonics until their magnitudes reach the prescribed level (filtering to curve);
- Compensate reactive power (not available for PQFB)

Three pre-programmed modes allocating different priority levels to the three above-described tasks are available. The following table shows the three available modes:

Table III.3 *Filter modes*

	HIGHEST	→	LOWEST
	1ST PRIORITY	2ND PRIORITY	3RD PRIORITY
MODE 1	FILTERING TO CURVE	MAXIMUM FILTERING	REACTIVE COMPENSATION
MODE 2	FILTERING TO CURVE	REACTIVE COMPENSATION	MAXIMUM FILTERING
MODE 3	FILTERING TO CURVE	REACTIVE COMPENSATION	-

• Harmonics

The main task of the PQF is to filter harmonics. Frequencies that have to be filtered and the permitted residual level for each selected frequency may be freely specified.
The curve (the remaining level after filtering) may be expressed in Amps (A), in % of fundamental current (%Ifund) or in % of RMS current (%Irms).

- **Reactive Power (not available for the PQFB)**

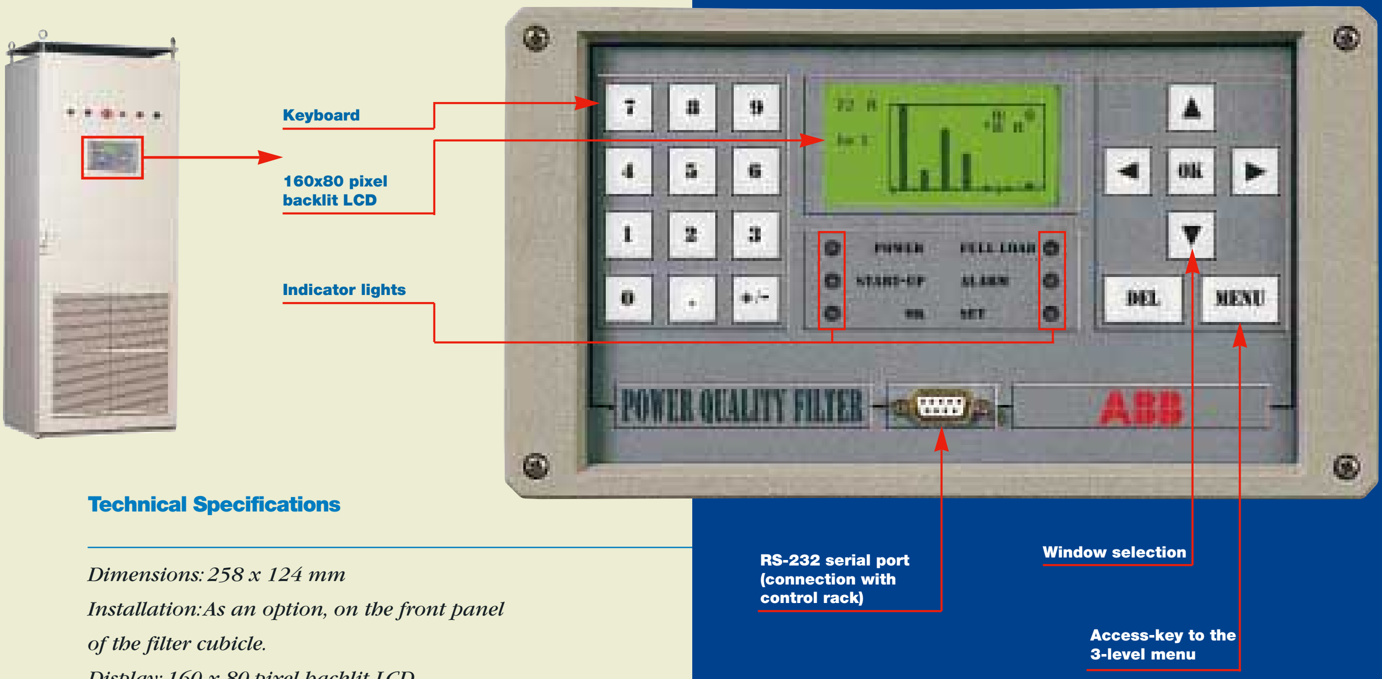
This window allows selecting power compensation if needed and specifying the type of required compensation: fixed reactive power (capacitive or inductive) or automatic compensation (target power factor to be fixed).

The filter can be switched on or off from the PC.

1.2. PQF- Manager (optional)

If you want to control, program and monitor your active filter PQF directly from the front panel without having to use a PC, the optional PQF-Manager will satisfy your needs.
This graphical user interface provides detailed information on the filter and on the network and gives also access to all the programming features.
The PQF-Manager is made of a 180 x 60 – pixel backlit LCD, an alphanumerical key pad and selection keys.

Picture III.4 *The PQF-Manager*



Technical Specifications

Dimensions: 258 x 124 mm
Installation: As an option, on the front panel of the filter cubicle.
Display: 160 x 80-pixel backlit LCD

The PQF-Manager is basically organised in three main menus:

- Consulting level (default level)
- Filter operation
- Hardware set-up

The consulting level informs about the filter and network status and can also perform a detailed harmonic analysis.
The filter operation level allows for the complete programming of the filter.
The hardware set-up level is intended for commissioning purposes.

Consulting level

The PQF-Manager displays information on the filter status: it indicates the load level of the filter as a percentage of capability used as well as error messages if the filter is in error condition.

The network status section indicates the values of the lines voltages and currents as well as the voltage and current Total Harmonic Distortion. The PQF-Manager also displays the waveforms of the line voltages, the line currents and the filter currents.

Beside the Total Harmonic Distortion, the detailed harmonic analysis performed by the PQF-Manager allows the display of the harmonic spectrum up to the 50th order of the line voltages, line currents and filter currents. The spectrum includes a graphical representation (bar graph) and the volts or amps value of each harmonic component.

Filter operation

Programming your PQF consists in setting the filtering mode, specifying the harmonics to be filtered and their level of filtration. Reactive power is also controllable for the PQFA and PQFL.

- **Mode**
  The basic operation is to filter to a prescribed level. The function Mode allows using the additional capabilities of the filter for maximum filtering (harmonics close to zero) or for generation of reactive power.
- **Harmonics**
  The frequency components to actively filter may be freely selectable. The degree of filtering may be specified per component in Amps or as a percentage of the fundamental or total RMS current.
- **Reactive Power**
  Reactive power compensation functionality may be selected. If fixed compensation is chosen, then the output power needs to be set. If dynamic compensation is chosen, then the desired target power factor needs to be set.

Hardware set-up

This level gives access to hardware configuration parameters: network characteristics and filter sensors.

Filter operation and hardware set-up are password protected. In order to increase safety, the displayed menu automatically goes down to the consulting level after one minute of non-use of the PQF-Manager.

1.3. PQF- Link (optional)

With the PQF-Link software, the active filter may be completely programmed, monitored and controlled from a PC through the RS-232 serial port.

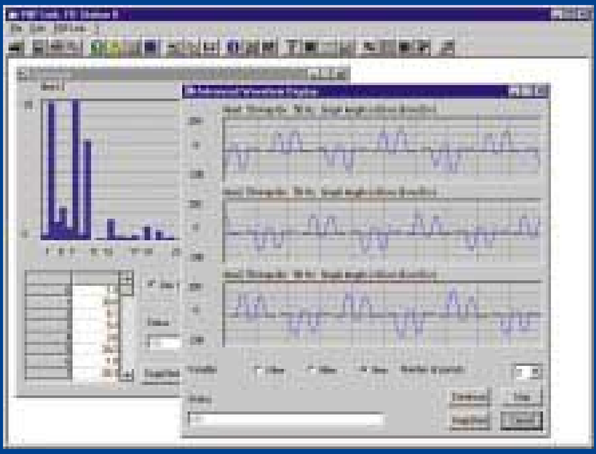
The software runs on Windows NT 4.0 Service Pack 3 minimum.

The RS232 port of the PC (not provided) will be connected to the corresponding port located on the control rack of the PQF (it is not necessary to have a PQF-Manager to connect the PC to the active filter).

Particular features include:

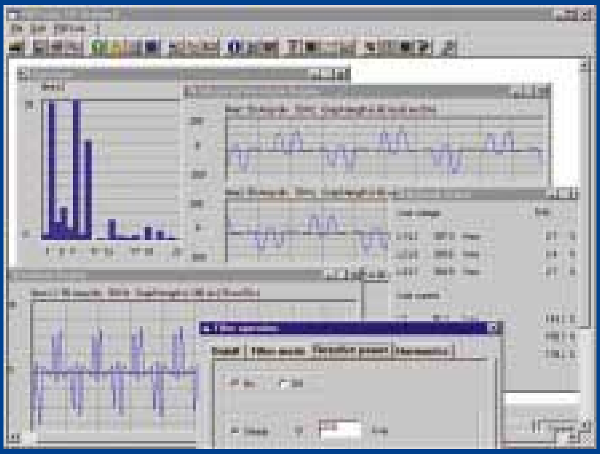
- Detailed information on filter status:
  - % of filter capability used
  - error history
- Advanced spectrum display: bar graph and table of values in the same window:
  - line voltages
  - line currents
  - filter currents
- Display of the filter and network waveforms with a customised time base:
  - line voltages
  - line currents
  - filter currents
- Simultaneous waveform display for the 3 phases
- Continuous updating of displayed information or snapshot display
- Remote control and programming of the PQF
  - On/off
  - Mode selection
  - Harmonics and reactive power specifications
- Remote hardware set-up
  - Network characteristics
  - Filter sensors
  - Filter hardware
- Display of several windows simultaneously
- Add/remove users and define their access level

The log-in procedure proposes three different access levels that are password protected.



Picture III.5

Line current spectrum and waveform (3 phases) displayed simultaneously



Picture III.6

Simultaneous display of several windows

3. Choosing a PQF: selection guide

The following section will help you selecting the most adequate active filter for your particular application. Three selection methods are proposed in our selection guide: one is based on the voltage harmonic distortion and the other two on the current harmonic distortion.
Please note that these selection methods are only applicable for PQFA and PQFL systems. It should be used for indication only and does not give any performance guarantee. For any specific inquiry, please consult your local ABB agent.

Method 1

The objective of this method is to size the PQF to install in a central position (on the transformer) in order to reach a pre-set target voltage THD on the LV side, the contribution of the MV side not being taken into account.
This situation is represented in figure III.7.

The following data is needed for this method:

- Total power of the non-linear loads (the harmonics sources of the plant creating the voltage distortion). The power to be considered is either the nominal value or the working power if different.
- Voltage THD on the LV side. This value may be obtained either by measurement at the point at which the active filter CT's will be connected or by simulation.
- Target voltage THD at the point of connection of the active filter CT's. If no regulation is applicable, ABB recommend keeping the voltage THD on the LV side below 5%.

Method 2

The objective of this method is to size the PQF to install on the basis of the current THD.
The following data is required for this method:

- Identification of the point at which the harmonic distortion has to be reduced.
- Current THD at the identified point. This value may be obtained by measurement at this point or by simulation.
- Total fundamental current at the same identified point. Please note that in this case it is indeed the total fundamental current that has to be considered (not only non-linear loads).
- Target current THD at the same identified point.

As already mentioned, there is a major difference between methods 1 and 2. In the case of the voltage-based method, the voltage reference is a nominal and constant value for the whole system. We then only need the characteristics of the harmonics sources (the non-linear loads) to select a PQF for a given objective.
As far as the current-based method is concerned, the current reference is the total fundamental current and is load dependent. It is also important to note that the current THD is only meaningful in relation to the fundamental current.

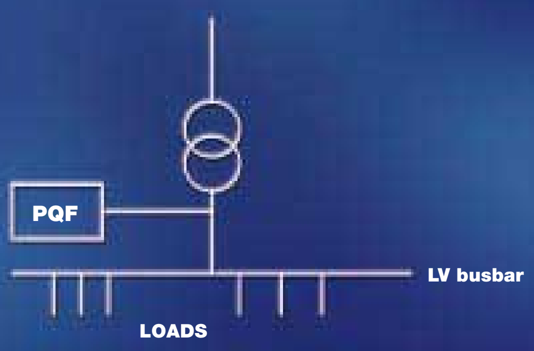


Figure III.7 *Method 1: location of the PQF*

Method 3

The objective of this method is to size the PQF to install in central position on the basis of the power of the transformer and the current THD. It is equivalent to the application of method 2 with the assumption that the fundamental current equals 0.75 the nominal current of the transformer and the target is 10% current THD.

Figure III.8 illustrates the three methods and their respective input data.

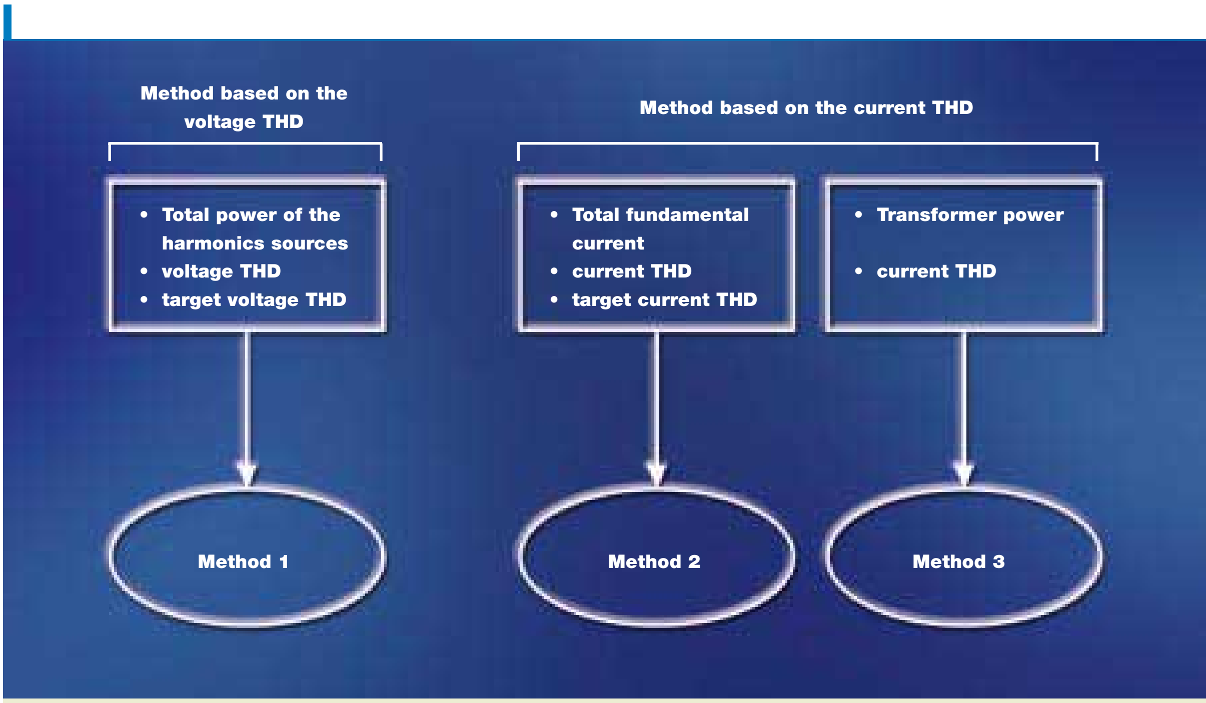


Figure III.8 *Choosing a PQF: method 1, 2 and 3*

Remark concerning capacitors.

If plain capacitors are installed on a system with a high level of harmonics, the first action to take is to replace those capacitors with a detuned capacitor bank (capacitors and reactors).

The first effect of the reactors is to suppress the risk of resonance with the harmonics generated by the loads and in turn to protect the capacitors. Not suppressing the resonance would lead to an oversizing of the active filter.

Secondly, although the detuned bank is not a passive filter, it will have some filtering effect and the harmonic distortion will be lower than if no capacitor was installed.

Before taking any measurement and selecting an active filter, please ensure that all capacitors banks are fitted with reactors. Contact ABB for an optimal solution.

Instructions for measurements

Before taking any measurements, analyse carefully the considered industrial process. You have to make sure that your measurements will be representative of the worst conditions. The harmonic distortion may indeed vary in time according to the working cycle of the loads. Please also make sure to follow all the instructions accompanying your measurement equipment, including all the safety rules and disconnect all capacitors from the network during your measurements.

3.1. PQF selection guide: method 1 based on voltage THD

Step 1

Identify the nominal three-phase voltage V_N and the nominal frequency.

Step 2

Calculate the total DC drives apparent power in kVA : S_{DC}
If only the active power (P_{kW}) is available, then $S_{DC} = 1.5 \times P_{kW}$

Step 3

Calculate the DC drives harmonic coefficient $C_{DC} = 0.173 \times \frac{S_{DC}}{V_N}$

Step 4

Calculate the total AC drives apparent power in kVA : S_{AC}
If only the active power (P_{kW}) is available, then $S_{AC} = 1.1 \times P_{kW}$

Step 5

Calculate the AC drives harmonic coefficient $C_{AC} = 0.289 \times \frac{S_{AC}}{V_N}$

Step 6

Calculate the total drives harmonic coefficient $C = C_{DC} + C_{AC}$

Step 7

Determine the initial voltage THD on the LV side. This value can be obtained by measurements or by simulation. Please consult your local ABB agent.

Step 8

Identify the active filter coefficient k from table III.4 below.
This table indicates the coefficient k to choose according to the initial voltage THD on the LV side (in %) and to the target voltage THD on the LV side (in %). The initial THD to be considered is the one directly superior to the measured or calculated value. Distortions created by the MV side cannot be reduced by the PQF.

Table III.4 *Active filter coefficient*

THD TARGET (%)	1	2	3	4	5
THD INITIAL (%)					
1	0	-	-	-	-
2	0.65	0	-	-	-
3	0.87	0.43	0	-	-
4	0.98	0.65	0.33	0	-
5	1.04	0.78	0.52	0.26	0
6	1.08	0.87	0.65	0.43	0.22
7	1.11	0.93	0.74	0.56	0.37
8	1.14	0.98	0.81	0.65	0.49
9	1.16	1.01	0.87	0.72	0.58
10	1.17	1.04	0.91	0.78	0.65
11	1.18	1.06	0.95	0.83	0.71
12	1.19	1.08	0.98	0.87	0.76
13	1.20	1.10	1.00	0.90	0.80
14	1.21	1.11	1.02	0.93	0.84
15	1.21	1.13	1.04	0.95	0.87

Step 9

Calculate the minimum RMS current of the active filter to install I_{RMS} (A) = k x C x 1000

Step 10

From the table with the appropriate voltage and frequency, choose the active filter with the RMS current directly superior to the minimum I_{RMS} calculated at step 9.

		PQF TYPE	NUMBER OF POWER MODULES	TOTAL RMS CURRENT (A)
Table III.5	V_N = 400V (415V) – 50Hz	PQFL - 70	1	70
		PQFL - 100	1	100
		PQFL - 130	1	130
		PQFA - A	1	225
		PQFA - B	2	427
		PQFA – B + C	3	641
		PQFA – B + D	4	855
Table III.6	V_N = 525V – 50Hz	PQFA - A	1	165
		PQFA - B	2	313
		PQFA – B + C	3	470
		PQFA – B + D	4	627
Table III.7	V_N = 600V – 50Hz	PQFA - A	1	130
		PQFA - B	2	247
		PQFA – B + C	3	370
		PQFA – B + D	4	494
Table III.8	V_N = 380V – 60Hz	PQFL	1	100
		PQFA - A	1	200
		PQFA - B	2	380
		PQFA – B + C	3	570
		PQFA – B + D	4	760
Table III.9	V_N = 440V – 60Hz	PQFL	1	80
		PQFA - A	1	170
		PQFA - B	2	323
		PQFA – B + C	3	484
		PQFA – B + D	4	646
Table III.10	V_N = 480V – 60Hz	PQFL	1	80
		PQFA - A	1	155
		PQFA - B	2	294
		PQFA – B + C	3	441
		PQFA – B + D	4	589

Please note that this selection method is only applicable for PQFA and PQFL systems. It should be used for indication only and does not give any performance guarantee.
For further inquiries, please consult your local ABB agent.

3.2. PQF selection guide: method 2 based on current THD

Step 1

Identify the nominal three-phase voltage V_N and the nominal frequency.

Step 2

Compute or measure the total fundamental current I1. If the value is computed, it has to be based on the total nominal or working apparent power, resulting of the geometric combination of the active and reactive power consumed. If capacitor banks are installed, their reactive power has to be deducted from the reactive power consumption of the loads (the effect of those capacitors is to reduce the total fundamental current).

Step 3

Compute or measure the current THD. This value may be calculated on the basis of the magnitudes of the harmonic components and of the fundamental by the following formula:

$$(THD_I)_0 = \frac{\sqrt{\sum_n I_n^2}}{I_1}$$

where $(THD_I)_0$ is the initial current THD (to be expressed in %)
I_n is the current magnitude of harmonic n

Please contact your local ABB agent for support.

Step 4

Set the target current THD at the considered point: $(THD_I)_F$ in %

Step 5

Calculate the minimum RMS current of the active filter to install
I_{RMS} (A) = 0.013 x $((THD_I)_0 - (THD_I)_F)$ x I1

Step 6

From the table with the appropriate voltage and frequency, choose the active filter with the RMS current directly superior to the minimum I_{RMS} calculated at step 5.

Table III.5 V_N = 400V (415V) – 50Hz

PQF TYPE	NUMBER OF POWER MODULES	TOTAL RMS CURRENT (A)
PQFL - 70	1	70
PQFL - 100	1	100
PQFL - 130	1	130
PQFA - A	1	225
PQFA - B	2	427
PQFA – B + C	3	641
PQFA – B + D	4	855

Table III.6 V_N = 525V – 50Hz

PQFA - A	1	165
PQFA - B	2	313
PQFA – B + C	3	470
PQFA – B + D	4	627

Table III.7 V_N = 600V – 50Hz

PQFA - A	1	130
PQFA - B	2	247
PQFA – B + C	3	370
PQFA – B + D	4	494

Table III.8 V_N = 380V – 60Hz

PQFL	1	100
PQFA - A	1	200
PQFA - B	2	380
PQFA – B + C	3	570
PQFA – B + D	4	760

Table III.9 V_N = 440V – 60Hz

PQFL	1	80
PQFA - A	1	170
PQFA - B	2	323
PQFA – B + C	3	484
PQFA – B + D	4	646

Table III.10 V_N = 480V – 60Hz

PQFL	1	80
PQFA - A	1	155
PQFA - B	2	294
PQFA – B + C	3	441
PQFA – B + D	4	589

Please note that this selection method is only applicable for PQFA and PQFL systems. It should be used for indication only and does not give any performance guarantee.
For further inquiries, please consult your local ABB agent.

3.3. PQF selection guide: method 3

Step 1

Identify the nominal three-phase voltage V_N, the nominal frequency, the nominal power of the transformer and the current THD.

Step 2

From the table with the appropriate voltage and frequency, choose the active filter according to the power of the transformer and the current THD. It is assumed that the fundamental current equals 0.75 the nominal current of the transformer and the target is 10% current THD.

		$(\mathrm{THD})_I \leq 20\%$		$20\% < (\mathrm{THD})_I \leq 30\%$		$30\% < (\mathrm{THD})_I \leq 40\%$	
		TRANSFORMER POWER (kVA)	ACTIVE FILTER	TRANSFORMER POWER (kVA)	ACTIVE FILTER	TRANSFORMER POWER (kVA)	ACTIVE FILTER
Table III.11	V_N = 400V (415V) – 50Hz	500 – 900	PQFL – 130	500 – 800	PQFA – A	500 – 1000	PQFA – B
		900 – 1600	PQFA – A	800 – 1500	PQFA – B	1000 – 1500	PQFA – B + C
		1600 – 2500	PQFA – B	1500 – 2200	PQFA – B + C	1500 – 2000	PQFA – B + D
				2200 – 2500	PQFA – B + D	2000 – 2500	PQFA – B + D + C
Table III.12	V_N = 525V – 50Hz	500 – 1500	PQFA – A	500 – 700	PQFA – A	500 – 900	PQFA – B
		1500 – 2500	PQFA – B	700 – 1400	PQFA – B	900 – 1400	PQFA – B + C
				1400 – 2200	PQFA – B + C	1400 – 1900	PQFA – B + D
				2200 – 2500	PQFA – B + D	1900 – 2400	PQFA – B + D + C
Table III.13	V_N = 600V – 50Hz	500 – 1400	PQFA – A	500 – 700	PQFA – A	500 – 800	PQFA – B
		1400 – 2500	PQFA – B	700 – 1300	PQFA – B	800 – 1300	PQFA – B + C
				1400 – 1900	PQFA – B + C	1300 – 1700	PQFA – B + D
				1900 – 2500	PQFA – B + D	1700 – 2200	PQFA – B + D + C
						2200 – 2500	PQFA – B + D + D
Table III.14	V_N = 380V – 60Hz	500 – 1300	PQFA – A	500 – 600	PQFA – A	500 – 800	PQFA – B
		1300 – 2500	PQFA – B	600 – 1200	PQFA – B	800 – 1200	PQFA – B + C
				1200 – 1900	PQFA – B + C	1200 – 1700	PQFA – B + D
				1900 – 2500	PQFA – B + D	1700 – 2100	PQFA – B + D + C
						2100 – 2500	PQFA – B + D + D
Table III.15	V_N = 440V – 60Hz	500 – 600	PQFL	500 – 600	PQFA – A	500 – 800	PQFA – B
		600 – 1300	PQFA – A	600 – 1200	PQFA – B	800 – 1200	PQFA – B + C
		1300 – 2500	PQFA – B	1200 – 1900	PQFA – B + C	1200 – 1600	PQFA – B + D
				1800 – 2500	PQFA – B + D	1600 – 2100	PQFA – B + D + C
						2100 – 2500	PQFA – B + D + D
Table III.16	V_N = 480V – 60Hz	500 – 700	PQFL	500 – 600	PQFA – A	500 – 800	PQFA – B
		700 – 1300	PQFA – A	600 – 1200	PQFA – B	800 – 1200	PQFA – B + C
		1300 – 2500	PQFA – B	1200 – 1800	PQFA – B + C	1200 – 1600	PQFA – B + D
				1800 – 2500	PQFA – B + D	1600 – 2000	PQFA – B + D + C
						2000 – 2500	PQFA – B + D + D

Please note that this selection method is only applicable for PQFA and PQFL systems. It should be used for indication only and does not give any performance guarantee.
For further inquiries, please consult your local ABB agent.

4. Installing a PQF

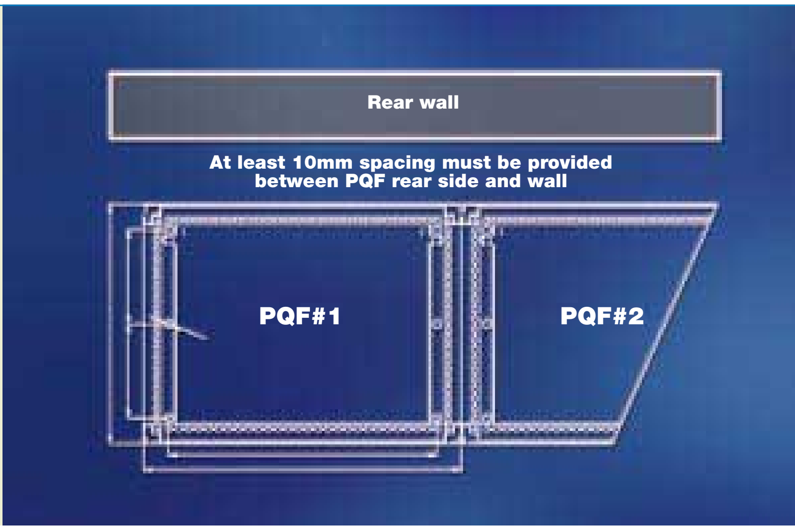
4.1. Location

The PQF is suitable for indoor installation, on firm foundations, in a well-ventilated area without dust and excessive aggressive gases where the ambient parameters do not exceed the following values:

- 40°C max;
- 30°C (average temperature) over 24 hours;
- Minimum temperature: +5°C
- Humidity less than 95% RH non-condensing

For units with nominal voltage above 415V, the rear side of the cubicles must be located at least at 100mm from the wall as represented in figure III.9 hereunder.

Figure III.9 *Cubicles location*



4.2. Overvoltage

The PQF is able to withstand continuously an overvoltage (inclusive of harmonics but not transients) of up to 110 % of the rated voltage. Higher voltages than the rated one would imply an operation at limited power of the filter. Since operation at the upper limits of voltage and temperature may reduce its life expectancy, the PQF should not be connected to systems for which it is known that the overvoltage will be sustained indefinitely.

4.3. Connection

The PQF is to be connected between the 3 phases of a three-phase network with or without neutral.

Cabling of the equipment requires:

- three power connections per cubicle
- ground/PE
- six control wires from the current transformers.

Note that there is no neutral connection to the PQF.

Power connection
When selecting the appropriate cable size due consideration should be given to possible future extension of the equipment. Cables and isolating switchgears should be rated at 1.5 times the nominal filter current of the total PQF and should always be co-ordinated with the current rating of the back up fuses. If single core cables are used an alloy gland plate is recommended.

Control wiring
Twin 2.5 mm^2 control cable is usually suitable for this application.

Current transformers
C.T.'s of Class 1 accuracy and appropriate burden with secondary current 5A will normally be used. 15 VA transformers are sufficient (including 30 meters of cable) if no other load is connected to the CT. Primary rating must be at least equal to the maximum load current.

Typical connections
The PQF will be connected as represented in figure III.10.

The current transformer must be located in a position to monitor the load current together with the PQF current (closed loop).

Power circuits are protected against overcurrent by the power circuit breaker (PQFA) or fuses (PQFL). An auxiliary circuit breaker protects the filter controller.

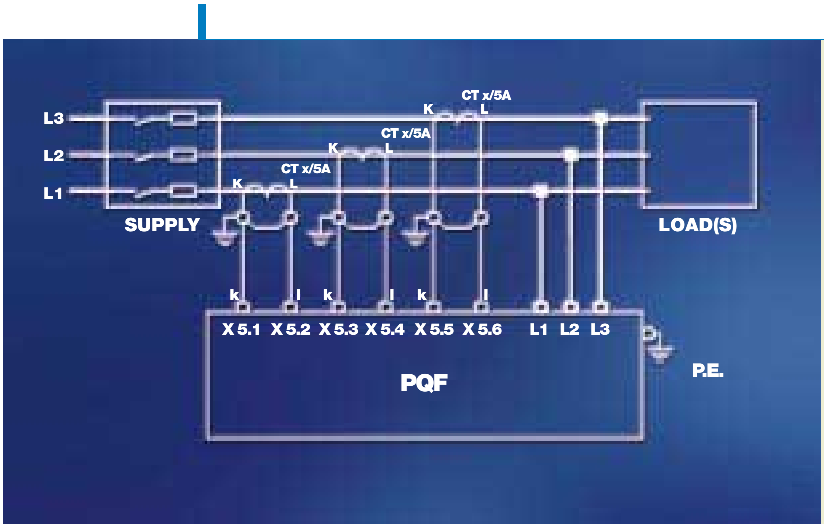


Figure III.10 *PQF connection diagram*

4.4. Operation

The front panel of the cubicle includes several indicators and push buttons:

- Push buttons :
  - RUN: starts the PQF
  - RESET: stops switching of the IGBT's and opens the power circuit breaker (PQFA) or contactors (PQFL).

- Indicators :
  - White on: the PQF controller is connected to the supply
  - Green on: the power circuit breaker (PQFA) or contactors (PQFL) are opened.
  - Red on: the power circuit breaker (PQFA) or contactors (PQFL) are closed.

- Switch : remote or local control of the filter. If remote is on, the push buttons are not operational.

The programming of the filter may be changed at any time with the PQF-Prog software supplied with the equipment, the optional PQF-Manager or the optional PQF-Link software.

4.5. Maintenance

The maintenance procedure of the PQF is rather simple and should include the following:

- Remove dust deposits from the enclosure, filters and power module(s) (heatsinks, fan), clean all parts and paint metalwork as required;

- Check breaker & fuse condition;

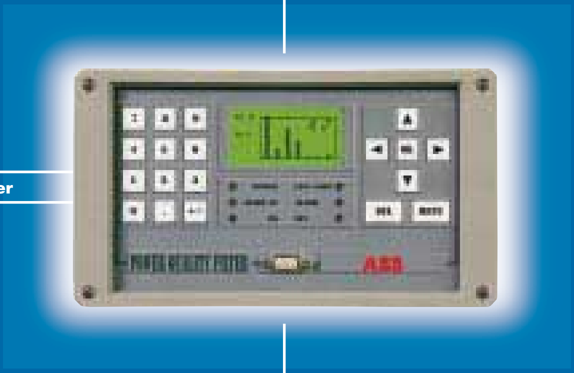
- Check tightness of all electrical connections;

- Check condition of discharge resistors on power module(s);

- Check isolator connections and operation;

- Check ambient temperature and equipment ventilation.

Depending on the dirtiness of the air filters, this procedure should be repeated at least every six months.



PQF Manager

Part IV: PQF applications and practical examples

Any industrial application involving DC or AC drives might show a potential need for active filters. Obviously, the range of applications is very wide, with among others:

- pulp & paper
- printing presses
- chemical plants
- water industry
- off-shore drilling
- tubes manufacturing
- steel plants
- car industry
- cement factories
- sky lifts

This short list is of course not exhaustive.

Banks, insurance companies, telecommunication centres and hotels also show an increasing interest in active filter due to the large number of computers and UPS systems used.

ABB PQF active filters have been installed all around the world in a wide range of industrial and non-industrial applications. Some practical examples illustrating the effects of the PQF are presented hereafter.

1. Electrolysis equipment

In this example a relatively small filter was for experimental purposes installed in a big installation. A 3 MVA transformer feeds six similar groups with mainly 6-pulse controlled rectifier loads. In each group is since previously installed a 7% de-tuned capacitor bank of 200 kvar. One active filter of type PQFA was installed in one of these groups.

Figure IV.1 shows the installation and figure IV.2 the measured currents taken before and after commissioning of the filter. Measurements were taken at point A. The remaining small current distortion is caused by the other large unfiltered loads.

This example shows how a really much too small filter installation is able to efficiently reduce harmonics in a network up to its capacity and function correctly in a distorted environment. It also demonstrates the co-existence with a capacitor bank.

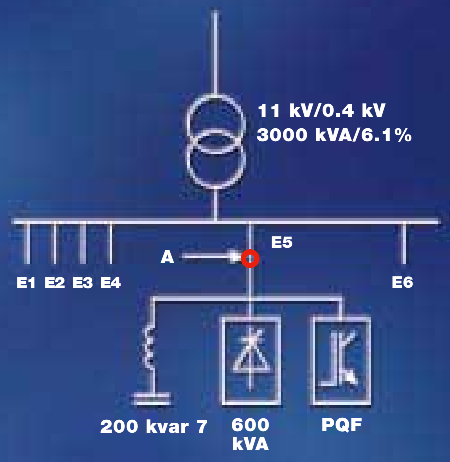


Figure IV.1 *Active filter in an electrolysis plant*

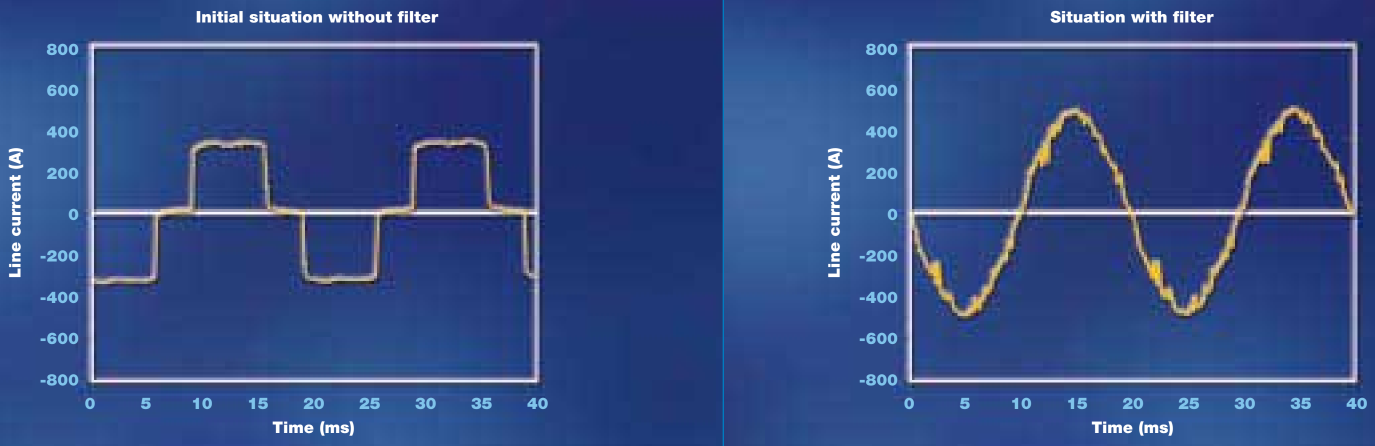


Figure IV.2 *Electrolysis plant: initial and filtered line current*

2. Induction heating

In this second example one PQFA-B was installed to compensate the harmonic distortion caused by a set of 6-pulse drives with a total installed power of 945kVA for induction heating. Figure IV.3 represents the sketch of the installation.

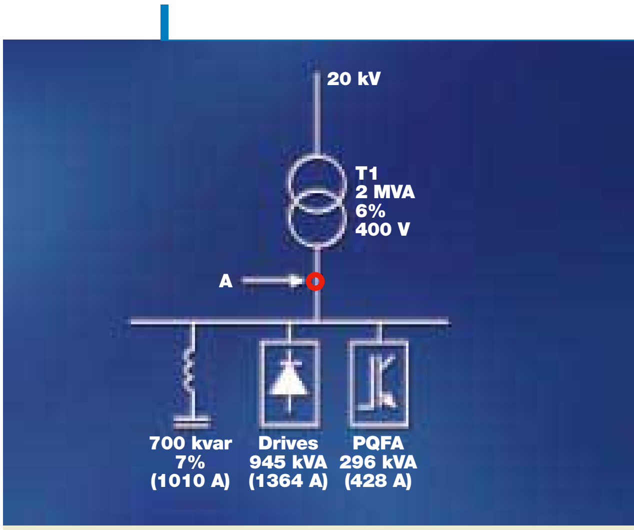


Figure IV.3 *Induction heating case: single line diagram of the installation*

The initial and filtered line currents as measured at point A are shown in figure IV.4. If we analyse the harmonic content of this figure, it appears that the ability of the active filter to filter currents up to the 50th harmonic has been crucial to achieve this impressive level of performance.

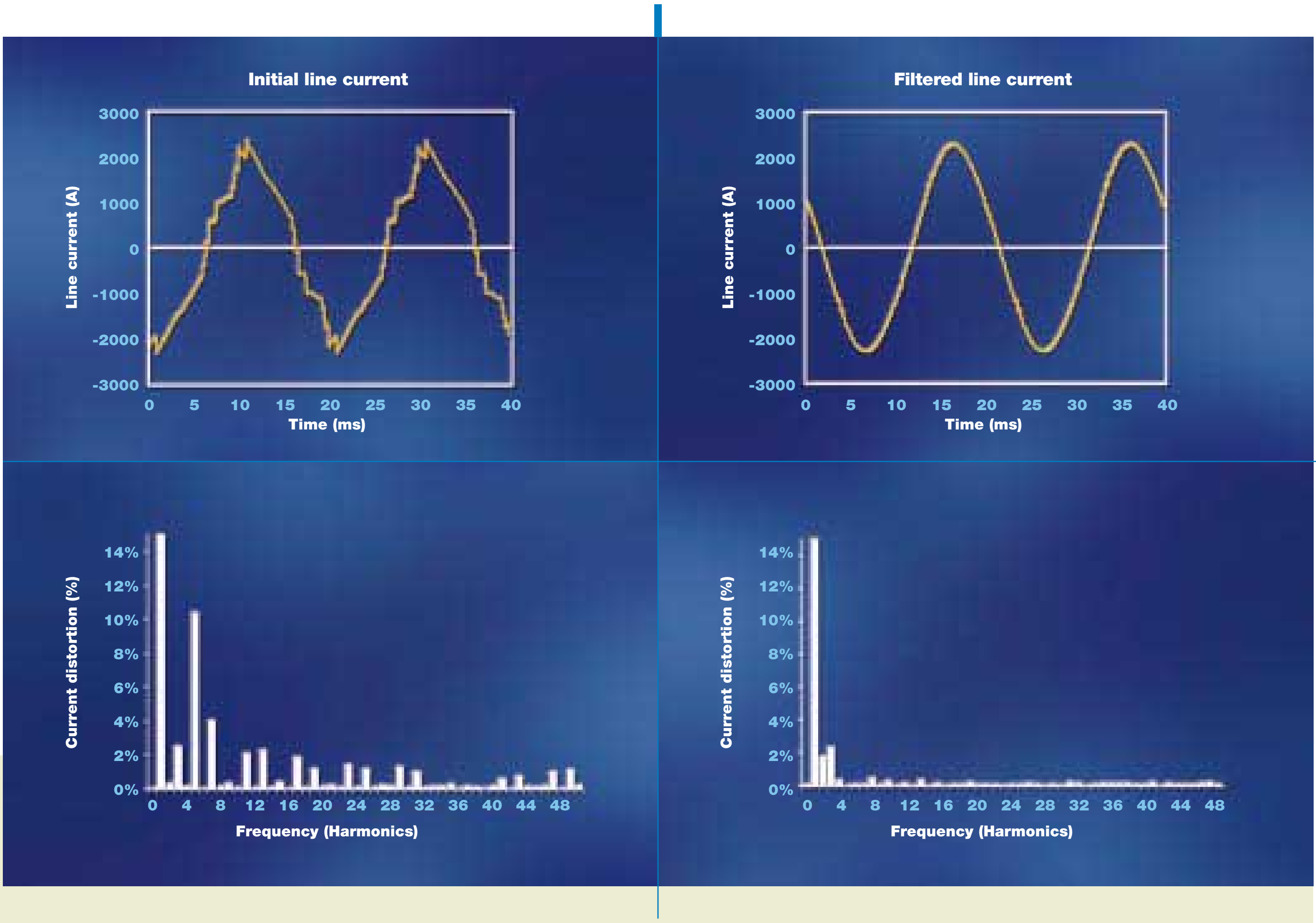


Figure IV.4 *Induction heating: initial and filtered line current*

3. Cable car

In the third example a filter for 400V, 50 Hz with a filtering capacity of 225A was installed for a cable car. The load consisted of two 230 kW 6-pulse drives. High requirements on harmonic distortion were specified up to 2500 Hz and the power factor should remain above 0.93. Line carrier tone-frequency communication was present at 1050 and 1600 Hz.

A sketch of the installation together with current measurements before and after the commissioning of the filter are shown in figures IV.5 and IV.6. The current measurement to the filter and the other measurement data were taken at the point A.

The example shows the very high degree of filtering obtained by the active filter in this rather weak network and also that the filter is able to work without disturbing the line carrier communication. The simultaneous reactive power compensation is also demonstrated.

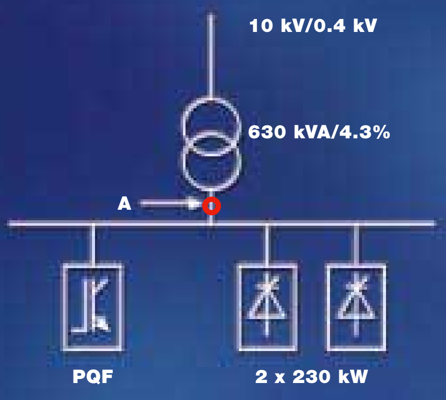


Figure IV.5 *Active filter for a cable car*

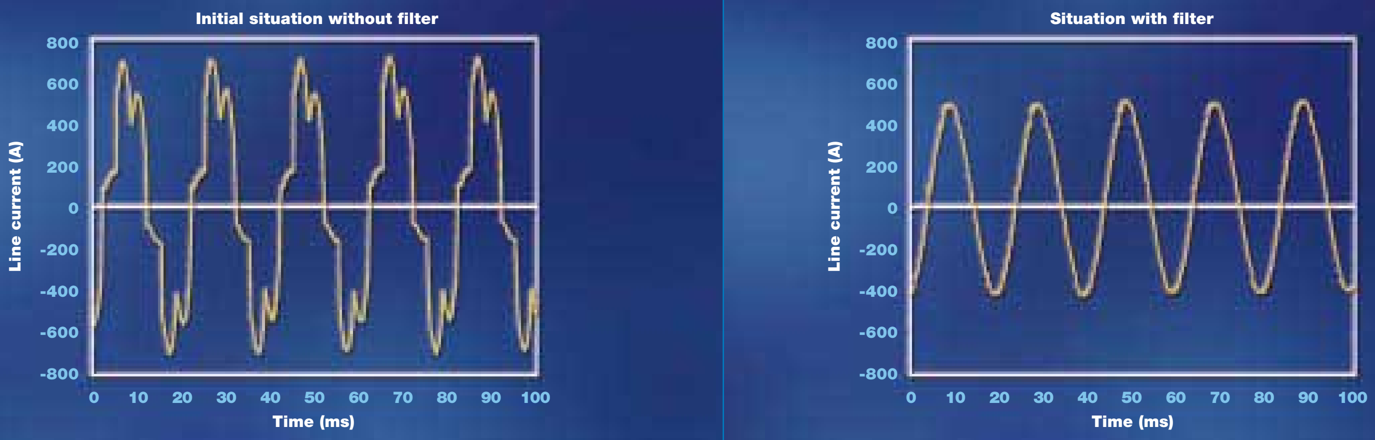
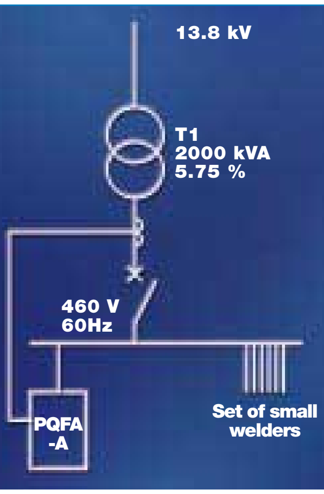


Figure IV.6 *Cable car: initial and filtered line current*

4. Welders

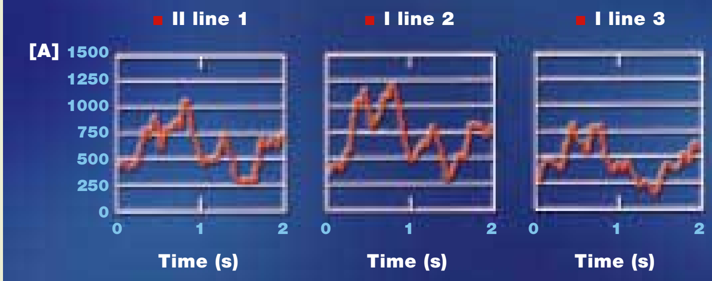
In this last example an active filter PQFA-A has been installed to reduce the distortion created by a set of small single-phase welders of a car manufacturer. These welders are all connected between phases and work randomly.
The sketch of the installation is shown in figure IV.7.

Figure IV.7 *Set of welders: sketch of the installation*



This system is characterized by a high level of third harmonic generated between phases and the filter has to work under very severe unbalanced and dynamic conditions.
Figure IV.8 illustrates this unbalanced situation by showing the three line currents.

Figure IV.8 *Welders: three line currents*



The level of 3rd harmonic before and after filtering as shown in figure IV.9 clearly indicates the ability of the filter to suppress 3rd harmonics currents when generated between phases. We can also see that the reaction time of the PQF is very short indeed.

Moreover, since the filter monitors each phase independently a similar result is obtained in each line.

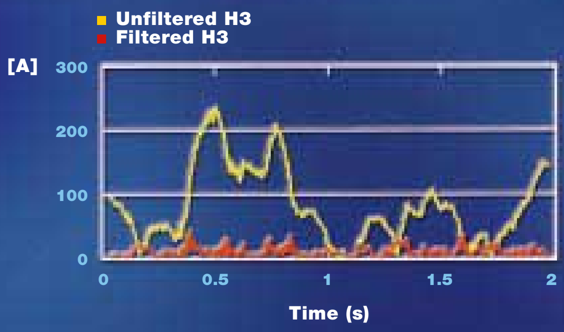


Figure IV.9 *Welders: third harmonic before and after filtering*

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