A SHUNT ACTIVE FILTER FOR LOW VOLTAGE APPLICATIONS

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ABSTRACT

This paper discusses the harmonic filtering performance that may be obtained under practical conditions with a modern, commercially available active filter. The requirements of a practically viable low voltage active filter are discussed and the characteristics of the filter considered in this paper are presented. It is shown that the filter functions well in the presence of ripple control systems and may be installed next to capacitor banks and passive filters. Also, the filtering performance when compensating rapid fluctuating loads is shown. A variety of data recorded on site are presented to illustrate the excellent filtering performance that may be obtained.

INTRODUCTION

In an industrial environment, a variety of loads may be encountered. An increasing percentage of these loads introduces harmonic distortion by injecting harmonic current components in the supply system. At present, power electronics based equipment (e.g. drives) is the main source of the harmonic pollution in the low voltage network, although other loads may also be sources of some distortion (e.g. lighting systems, iron cores in saturation, arc furnaces).

Harmonic pollution causes a number of problems. Some possible problems are the overheating of transformers, cables, power capacitors and electrical motors. This results in a premature ageing of the whole electrical installation. In addition, harmonic pollution may cause fuses to blow unexpectedly and breakers to trip. Other effects include wrong firing pulses being applied to thyristors and control circuits that malfunction.

The harmonic pollution may affect equipment in the polluting plant only 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 Commision (IEC) has issued the technical report IEC 1000-3-7 [3] which outlines an assessment procedure to determine whether large distorting loads may be connected to the medium or high voltage public power system.

A variety of solutions exist to limit the problems due to harmonics. One approach is to connect sensitive loads to a clean part of the network. While this solution is easy to apply at the design stage of a plant, it may be impossible to implement for existing plants. 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.

When the harmonic levels are too high, a harmonic filter solution is needed. Traditionally, passive filters have been used but recently active filters have become commercially available. The modern active filters consist of a PWM-inverter, supplied by a DC storage capacitor, which amplifies the signal generated by a controller. The majority of the active filter systems are IGBT-based and as these components continue to improve, it is likely that they will remain present in most of the active filters in the next years. Preferably, a digital signal processing (DSP) system is used as the controller platform, because it offers the processing capability necessary to handle the amount of real time calculations involved.

This paper discusses the harmonic filtering performance that may be obtained with a modern commercially available active filter aimed at low voltage applications. Consideration is given to the requirements to be fulfilled by a practically viable active filter. Then, the characteristics of the filter considered are summarised. A variety of data recorded on site are presented to illustrate the filtering performance that may be obtained.

ACTIVE FILTER REQUIREMENTS

Fig. 1 shows a schematic diagram of a plant having linear and non-linear loads.

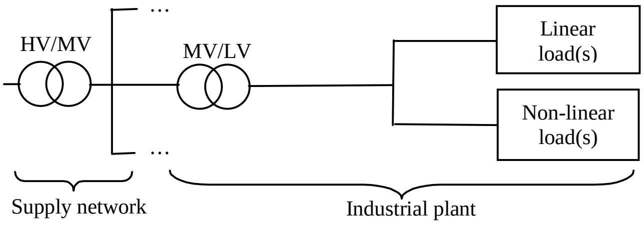


Fig. 1. Schematic diagram of an industrial plant having linear and non-linear loads.

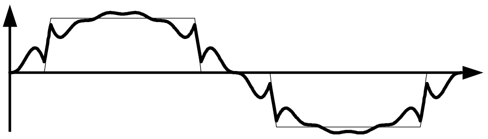
As an example, the non-linear loads could be drive-motor combinations while the linear loads could include motors directly connected to the supply. In many applications, due to the presence of capacitor banks the impedance at the connection point of the non-linear loads is resonant in the same frequency range as the frequency range in which harmonic currents are injected. Harmonic currents produced by non-linear loads at parallel resonant frequencies may result in high voltage distortion. This phenomenon makes it more difficult to meet the standards.

On the supply voltage to the plant, a mains signalling voltage ('ripple control system') may be superimposed. This voltage is used by the public supplier for the transmission of signals. Its magnitude can be up to 10 % of the fundamental rms voltage [4].

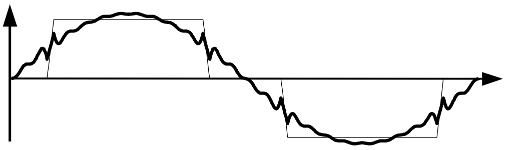
Furthermore, the supply voltage may be unbalanced.

The main requirement of an active filter installed in an industrial plant is to attenuate the harmonics produced by the non-linear loads of the plant. The quality of filtration should be satisfactory regardless of the impedance characteristic at the filter connection point and the filter should not interfere with any ripple control systems that may be present. An additional benefit would be that the customer can select the frequencies of the distortion components to be attenuated. In this way, the active filter can be installed next to an already existing passive filter without interfering with the passive filter operation.

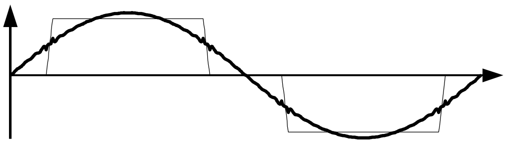
While most standards only give harmonic limits up to about the 25th harmonic component, the total harmonic voltage distortion at the point of common coupling (PCC) is often calculated up to the 40th [4] or the 50th [1] harmonic. Furthermore, the total number of harmonics that can be filtered determines directly the quality of the resulting current. This is illustrated in Fig. 2 which shows the unfiltered and filtered waveforms obtained for a number of cases.



(a) Filtering up to the 13th harmonic.



(b) Filtering up to the 25th harmonic.



(c) Filtering up to the 50th harmonic.

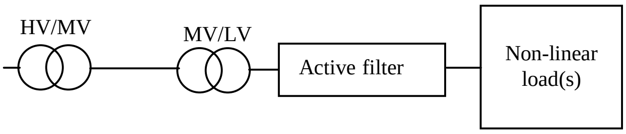
Fig. 2. Waveforms obtained by eliminating the harmonic components of a quasi-rectangular periodic signal up to the (a) 13th harmonic, (b) the 25th harmonic and (c) the 50th harmonic.

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

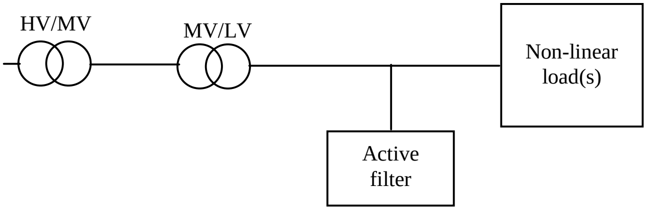
It may be useful if the active filter allows for the manual selection of the filtration level. In this way the amount of current allowed to remain in the supply current can be specified for each harmonic. This feature is interesting if the purpose of the active filter is to meet the limits set by a standard. It results in a better use of the available compensation power. With a passive filter the filtration level cannot be predefined nor controlled.

Other requirements of an active filter may include reactive power compensation and the balancing of the load current [5].

Active filters exist in series and shunt topologies ([6], [7]). The first type is connected in series with the supply to the plant while the second type is connected in parallel with the loads to be compensated. Fig. 3 shows these basic arrangements.



(a) Series active filter topology.



(b) Parallel active filter topology.

Fig. 3. Basic active filter arrangements.

From the user's point of view, the parallel filter topology is more desired since the filter connection can be made with high flexibility. In addition, it has less losses. Furthermore, an active filter using this topology can easily be upgraded and cannot be overloaded. When the active filter limits are reached, e.g. after installing additional loads, the filter continues to operate at its maximum capacity without danger for overload. This is not the case for the series active filter or the passive filter which will be disconnected or damaged in case of overload.

ACTIVE FILTER CHARACTERISTICS

The operating principle of the filter evaluated is shown in Fig. 4. It constantly monitors the supply current and injects compensation current into the supply system. The compensation current is added to the load current. As a result, the selected harmonic components are cancelled.

The active filter employs a closed loop measurement approach (current measured at point A in Fig. 4). This approach is more reliable than an open loop measurement approach (current measured at point B in Fig. 4). Only standard current transformers are required to make the closed loop active filter control system work. Furthermore, there is no risk that the active filter increases the distortion injected into the supply due to measurement errors.

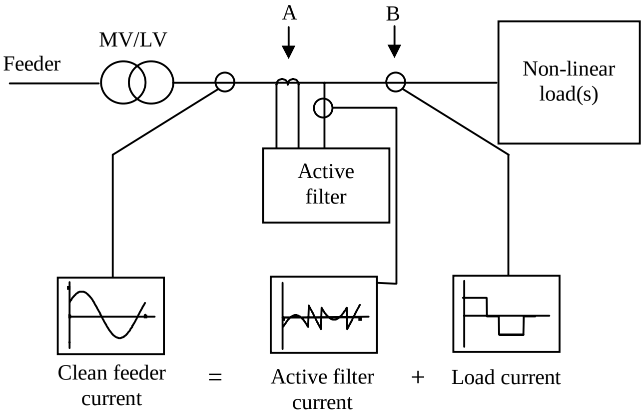


Fig. 4. Operating principle of the shunt active filter evaluated.

The filter considered has a modular structure. One digital control module can control up to eight power modules. A typical power module is rated at 150 kVA. With the total compensation power potentially exceeding 1 MVA this filter can be used for the compensation of individual loads as well as entire plants. Two power modules can be placed in a cubicle with dimensions WxDxH = 800 mm x 600 mm x 2100 mm. This is a very small size for the compensation power available. It makes this active filter interesting for applications in which not much physical space is available or when unforeseen harmonic problems arise.

All characteristic harmonics in a frequency range up to the 50th harmonic can be filtered simultaneously. The harmonics to be filtered and the corresponding filtration levels can be freely selected. In addition, the filter can act as a reactive power compensator and works well under unbalanced conditions. Priority levels can be set to define the importance of the reactive power compensation with respect to the filtering of harmonic components in case of full load operation. Installation and operation next to passive filters and reactive power compensation units can be done without any problems. Also, the filter does not affect ripple control signals.

PERFORMANCE DATA

The active filter considered has been installed at a number of industrial sites. This section presents typical performance data that has been obtained for some applications.

A first set of data has been recorded in a cable-car application. The active filter was required to eliminate the harmonic currents produced by two 230 kW 6 pulse DC drive-motor combinations. In addition, the reactive power had to be compensated in order to obtain a power factor equal to at least 0.93. The local utility was extensively using remote control signals for switching generators and loads. Two ripple control frequencies were used, one being 1050 Hz and the other one 1600 Hz. An active filter with one power module was installed in parallel with the loads. Fig. 5 shows a one-line diagram of the installation.

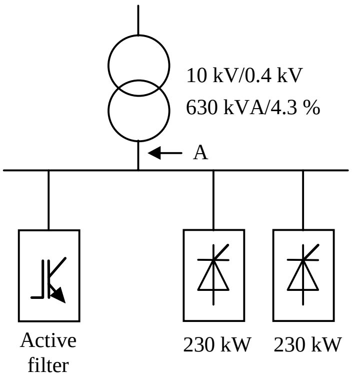


Fig. 5. One-line diagram of the cable-car application.

The supply current measured at point A (Fig. 5) was used as the input for the active filter controller. Fig. 6 (a) shows the supply current and the corresponding harmonic analysis when the active filter is not operating. Fig. 6 (b) shows the same quantity when the active filter is operating.

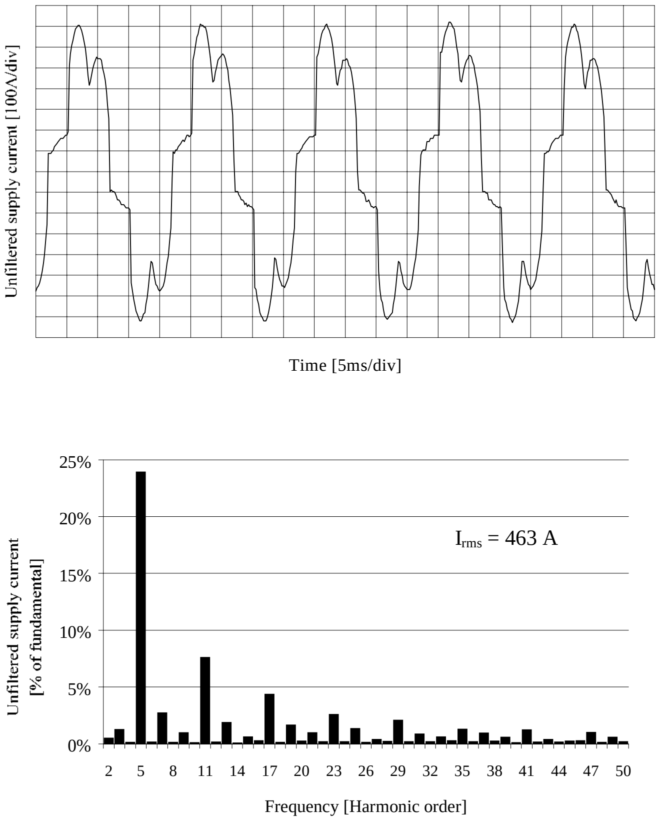


Fig. 6 (a). Supply current at point A of Fig. 5 when the active filter is not running.

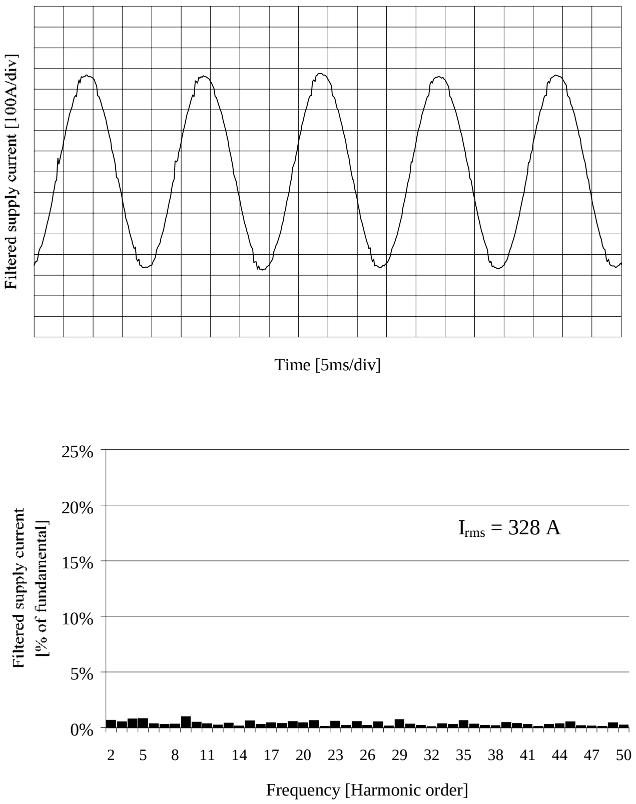


Fig. 6 (b). Supply current at point A of Fig. 5 when the active filter is running.

Based on a visual inspection of the waveforms and the spectra shown in Fig. 6 (a) and Fig. 6 (b), it may be concluded that the filter is reducing the harmonic current components up to the 50th harmonic. Table 1 summarises the characteristic parameters of the current when the filter is operating and when the filter is not operating.

Table 1: Summary of the characteristic parameters of the cable-car application supply current with and without active filter.

	Filter ON	**Filter OFF**
RMS	328 A	463 A
Harmonics	10 A	117 A
THD(I)	3 %	26 %

The RMS current is reduced by a factor approaching 30%. Consequently, the losses are drastically reduced. The reduction in RMS current is partially caused by the reactive power compensation and partially by the cancellation of harmonics. The total harmonic current distortion THD(I) drops from 26 % to 3 %.

Figs. 7 (a) and (b) show the effect of the active filter on the supply voltage, also measured at point A of Fig. 5. Fig. 7 (a) shows the supply voltage waveform when the filter is not operating and Fig. 7 (b) shows the supply voltage when the filter is operating.

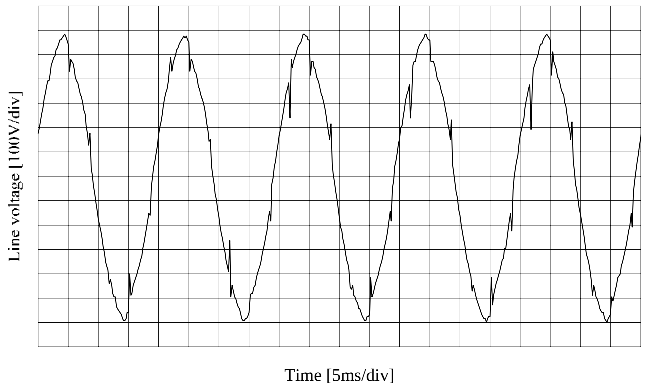


Fig. 7 (a). Supply voltage waveform at point A of Fig.5 when the active filter is not running.

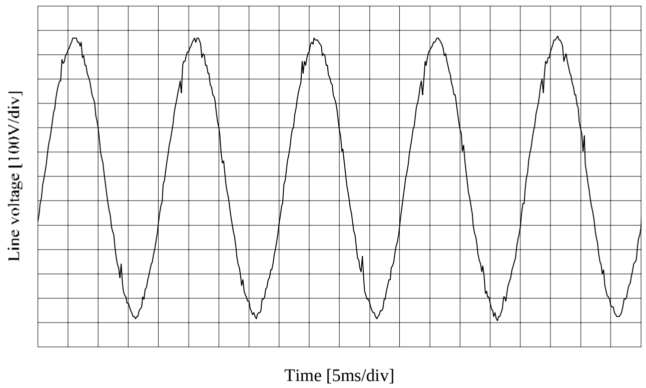


Fig. 7 (b). Supply voltage waveform at point A of Fig. 5 when the active filter is running.

Figs. 7 (a) and (b) illustrate that the filter not only reduces the low frequency voltage distortion but that it is also capable of reducing the high frequency notches introduced due to commutation effects of the DC drives.

A second set of performance data has been recorded in a plant in which the electrical load consists mainly of electrolysis equipment. The front-end of each electrolysis device is a 600 kVA 6-pulse converter. All the converters operate simultaneously. Fig. 8 shows a single line diagram of the installation.

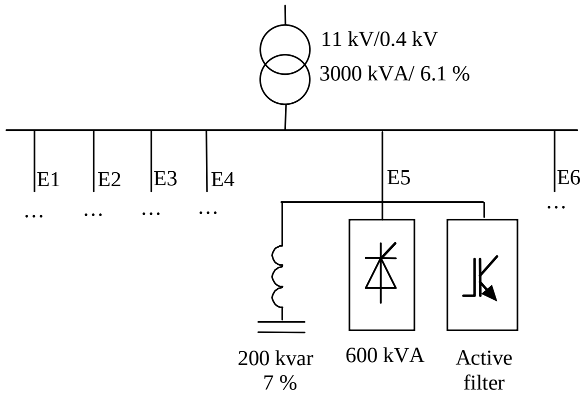


Fig. 8. Single line diagram of the plant with electrolysis equipment.

At each point E1..E6 in Fig. 8 a 600 kVA converter and a 200 kvar/7 % automatic capacitor bank is connected.

The active filter is connected in parallel with the load at point E5. The current measured at point E5 was used as the filter-controller input. Fig. 9 (a) shows the supply current measured in one phase at point E5 when the filter is not operating and Fig. 9 (b) shows the same current when the filter is operating.

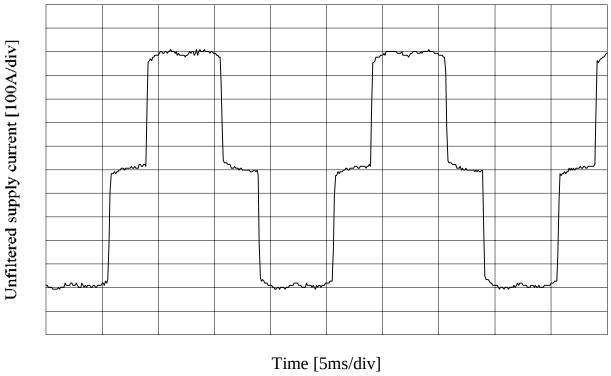


Fig. 9 (a). Supply current waveform measured at point E5 of Fig. 8 when the active filter is not running.

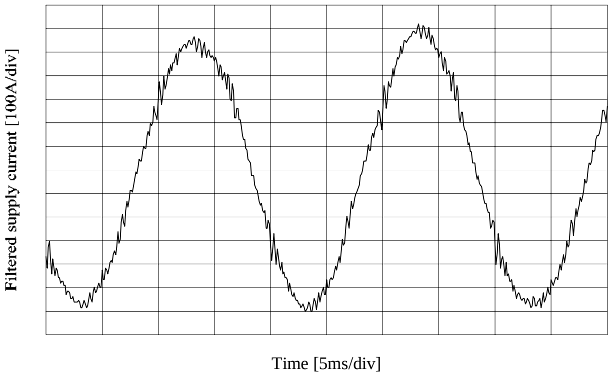


Fig. 9 (b). Supply current waveform at point E5 of Fig. 8 when the active filter is running.

Based on the results presented in Figs. 9 (a) and (b), the following conclusions can be drawn: the active filter is not overloaded despite the presence of the five other converters which were also operating. A passive filter solution would be heavily overloaded if used in the same conditions or would have to be dimensioned taking into account all the converters. Furthermore, the switching action of the capacitor bank does not affect the filter performance. The high frequency ripple present on the current waveform is caused by the voltage distortion introduced by the other converters connected to the main bus bar.

Fig. 10 (a) shows the supply voltage at point E5 (Cf. Fig. 8) when the filter is not operating and Fig. 10 (b) shows this voltage when the filter is operating. In Fig. 10 (b), it is seen that the filter reduces the distortion of the supply voltage but it cannot eliminate this distortion completely since it only reduces the contribution of one drive.

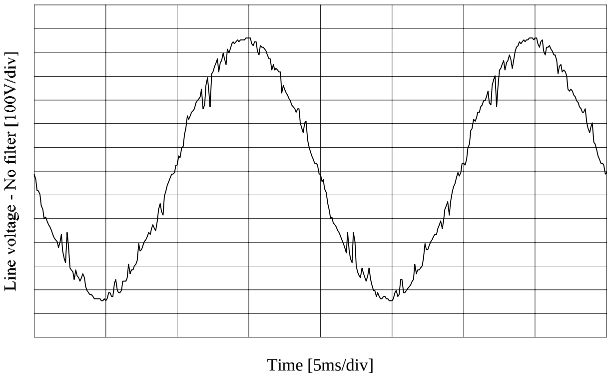


Fig. 10 (a). Supply voltage waveform measured at point E5 of Fig. 8 when the filter is not running.

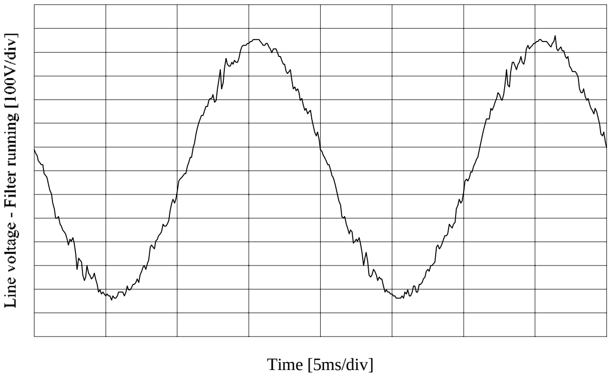


Fig. 10 (b). Supply voltage waveform measured at point E5 of Fig. 8 when the filter is running.

A perfect performance would be obtained if the filter would be sized for the complete installation and use the supply current at the secondary of the main transformer as the input for the active filter controller.

A third application for which the active filter was used is the compensation of a division of a car manufacturing plant. In this division a considerable number (> 1000) of single phase welders are used to assemble the individual car panels into one body. The welders are connected phase to phase. Fig. 11 shows a schematic diagram of the installation.

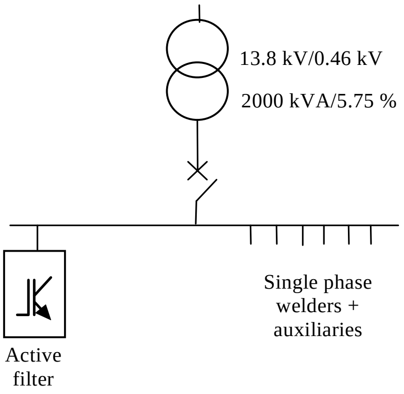


Fig. 11. Schematic diagram of the active filter set-up in a division of a car manufacturing plant.

Due to the welder's operation, the load current is fluctuating considerably and is unbalanced. Fig. 12 shows typical load current fluctuations and Fig. 13 shows the corresponding total harmonic current distortion THD(I) measured upstream (i.e. the supply side) and downstream (i.e. the load side) of the active filter.

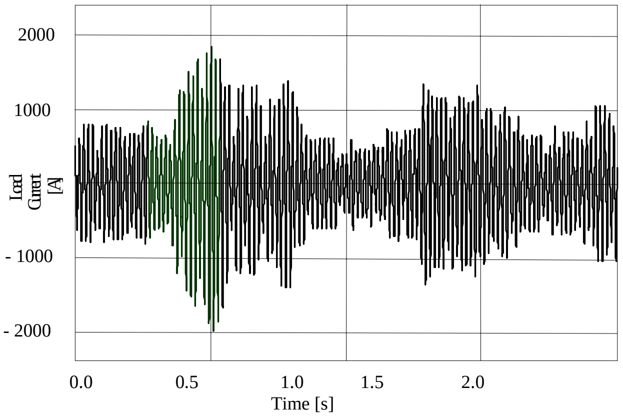


Fig. 12. Typical load current waveform obtained from the welder installation.

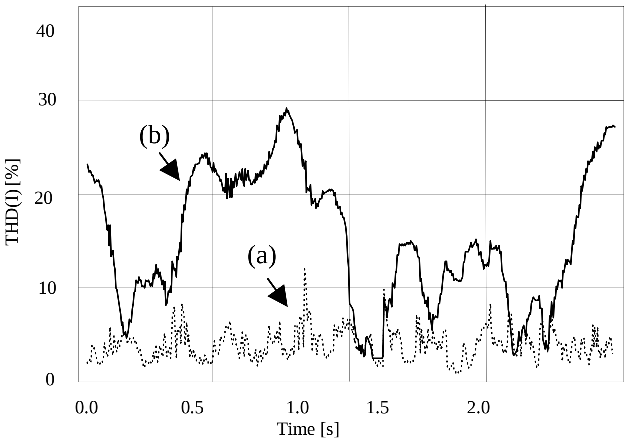


Fig. 13. Total harmonic distortion THD(I) of the supply current to the welders measured (a) upstream and (b) downstream of the active filter.

From Fig. 13 it may be concluded that with the active filter the THD(I) is about 5 % whereas it reaches 20 % to 30 % without the active filter. This shows that a properly designed active filter can be used to filter the harmonic pollution produced by a large number of fast varying loads which operate in an unbalanced fashion.

The last example considers the harmonic compensation of a paper mill installation that consists of three AC drive-motor combinations, one of which is used for regenerative braking. During the acceleration phase of the motors the harmonic injection was so high that the THD(V) rose to an unacceptably high level (above 6 % - Cf. Fig. 16). Fig. 14 shows a single line diagram of the installation considered and Fig. 15 shows the time domain waveforms of the supply voltage with and without active filter. A considerable improvement of the voltage shape may be observed when the active filter considered is operating.

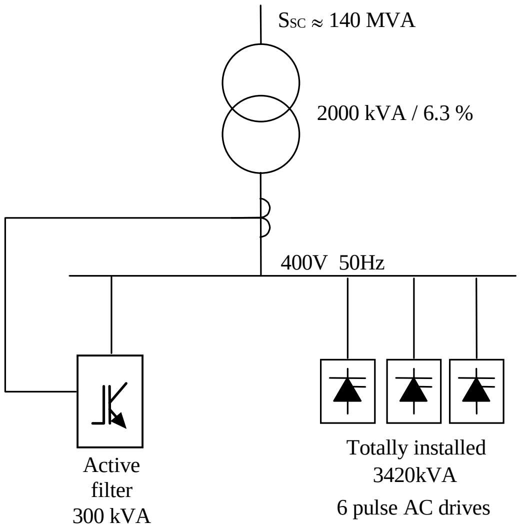


Fig. 14. Single line diagram of the paper mill installation with an active filter.

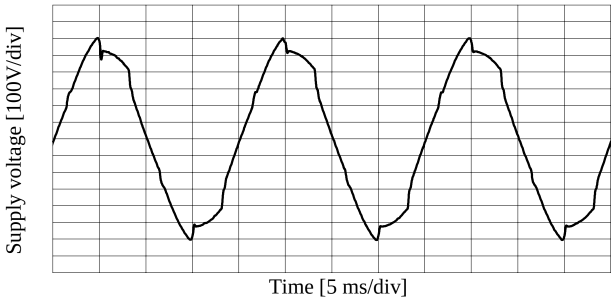


Fig. 15.a. Time domain waveform of the supply voltage without active filter.

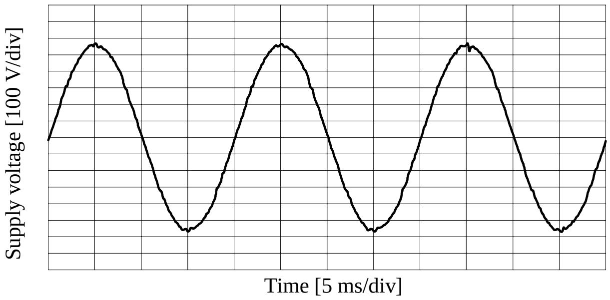


Fig. 15.b. Time domain waveform of the supply voltage when the active filter is running.

Fig. 16 presents the THD(V) corresponding to the time domain voltage waveforms of Fig. 15.

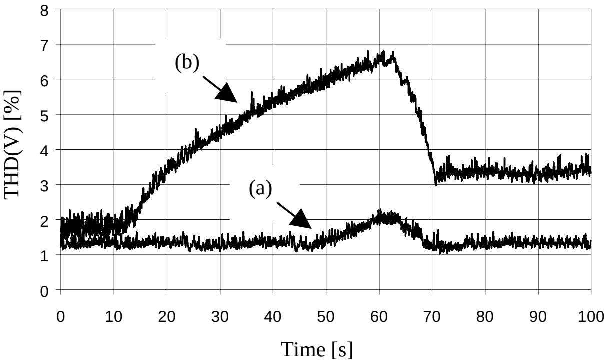


Fig. 16. Total harmonic voltage distortion at the secondary of the main transformer (a) with and (b) without the active filter.

Fig. 16 shows clearly the voltage distortion reduction that is obtained by installing the active filter. The average THD(V) when the active filter is operating is about 1.5 %. A small increase in THD(V) up to 2 % may be observed around 60 s. This is due to the filter reaching its compensation limits for a short time. It should be noted that this result was obtained with an active filter rated at about 10 % of the loads to be compensated (Cf. Fig. 14).

Fig. 17 shows the power factor of the paper mill installation with and without the active filter running.

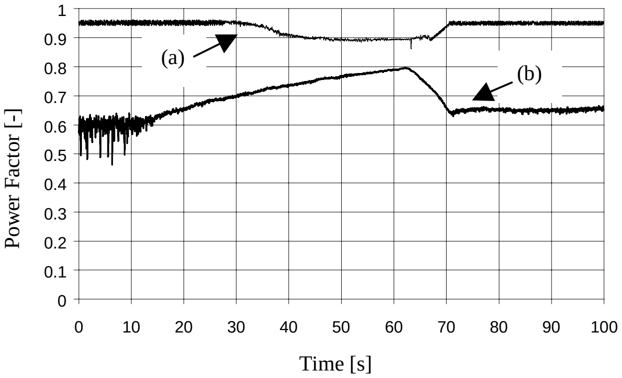


Fig. 17: Power factor of the paper mill installation (a) with and (b) without the active filter running.

When the active filter is not running, the power factor varies between 0.6 and 0.8, although the drives considered are of the AC-type (diode bridge at the supply side). The low power factor is mainly caused by the high amount of harmonics present in the current drawn from the supply. When the active filter is running, the power factor improves significantly and varies between 0.9 and 0.95. At around 30 s, the active filter reached a first limit (Cf. Fig. 17) and as a result switched off the reactive power compensation feature in order to maximise the resources available for active filtering. This explains the drop in the power factor to 0.9 during this period. Fig. 17 also illustrates that the power factor of an installation may be improved by simply filtering the harmonics.

CONCLUSION

This paper discusses the harmonic filtering performance that may be obtained under realistic conditions with a modern, commercially available active filter. First, the requirements of a practically viable low voltage active filter are discussed and the characteristics of the filter evaluated described. Then, a variety of on-site results are presented which illustrate the filtering performance that may be obtained with the filter considered. It is shown that the filter can reduce harmonics up to the 50th order. It does not interfere with ripple control systems and can be put in parallel with capacitor banks and passive filters already present in the installation. Furthermore, it is illustrated that the active filter evaluated can be installed at locations where it is not possible to use a conventional passive filter due to the danger for overload. Moreover, the active filter can compensate the harmonic pollution produced by a large number of fast varying loads, possibly operating in an unbalanced fashion. It is also demonstrated that it performs well in applications in which regenerative braking occurs. Finally, it is illustrated that the active filter may be used to increase the power factor of the installation.

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