AN ACTIVE FILTER FOR INDUSTRIAL MAINS

S.N. Kalaschnikow, Ph. D.
VA TECH ELIN EBG Elektronik GmbH
Ruthnergasse 1, A-1210 Vienna Austria
E-mail: s.kalashnikow@eel.elinebg.at

Abstract - **This paper presents a new structure and control scheme for a parallel active filter. System intended for harmonic compensation of large non-linear mains loads, such as speed controlled electrical derives, up to 5MVA. The filter has relatively small rating; it is about 15% of non-linear load power rating. The control scheme is based on the DHC-method (Dircct harmonic Control method).**

I. INTRODUCTION

Non-linear loads such as diode or thyristor Converters contribute to the degradation of the supply quality. Non-sinusoidal currents of the non-linear loads result in the distortion of the supply voltage wave form at the point of common coupling due to the finite supply impedance.

In industrial mains, the passive filters have traditionally been used to absorb harmonics generated by the load, primarily due to their low cost and high efficiency. This is a good approach when power factor correction is needed too. However, they have the following drawbacks:

- the mains impedance strongly influences the compensation characteristics of the filter;
- they result in new resonances and therefore magnify the levels of the other harmonics;
- they can not be rated only for the loads being compensated. They are affected by harmonic currents from other non-linear loads or by harmonics from the power System.

Compared with the passive filter, the active filters can be used to reduce harmonics in the industrial mains without worrying about all the problems associated with applying passive filters [l]. Additionally they can not be overloaded by harmonics from the power system. Due

to the fact that active filters use the same IGBT-inverter technology that is used in adjustable speed drives, their cost is not high.
Moreover, the active filter can be easily adjusted to specific industrial applications by simply modifying the software or control parameters.

Usually, the control circuit of the filter detects the nonlinear load harmonics and controls the active filter to inject the compensating harmonic in the opposite phase. There are a number of methods for determining the harmonic contents of a non-linear load current to control the active filter. All these methods make it possible to compensate all harmonics at once, without control of the individual harmonic amplitudes. It means the output power of the active filter must not be lower than the distortion power of the non-linear load. However, for practical applications, the International Standard IEC gives limits for individual harmonic orders and the total harmonic distortion coefficient of the current for industrial networks. The limits are related to the ratio of the short-circuit power of the source to the fundamental apparent power of the load. To satisfy these values it is not necessary to compensate all harmonics completely, and as a result, the power rating of the active filter can be decreased.
In this paper, the direct harmonic control (DHC) method [2,3] is used to control the active filter. This method makes it possible to control the individual harmonics of the supply current, so this method makes it possible to reduce the rating of active filters.
The power unit of the active filter is implemented by two parallel-connected voltage source inverters. Owing to the fact that the parallel connection and appropriate control of the inverters reduce the high-frequency switching-ripple of the filter current, this all make the proposed active filter more attractive.

II. GENERAL STRUCTURE

Fig. l shows the block diagram of the active filter for the industrial (l0 kV) mains with a non-linear load. There are two three-phase voltage source inverters, which are linked through a common voltage dc rail and they are connected in parallel by a coupling circuit to the mains. This connection of the voltage source inverters makes it possible not only to increase the power rating of the filter, but also to reduce the high-frequency switching-ripple current in the mains. The

last one is reached by using a special control of both these voltage source inverters.
The mains coupling has two main functions: - firstly, the interface filter function; secondly, to adjust the nominal value of the ac inverter voltage to the mains voltage (step-down function).

III. CONTROL OF THE ACTIVE FILTER

Fig.2 shows a block diagram of the active filter control unit. The control scheme is based on a cascade control with a current control in the inner loop. The current Controller sets the Output voltage of the voltage source inverters for cach sampling period of the control system so that the line current has a reference value. The voltage controller allows the dc voltage to have an almost constant value. The output signal of the dc-link voltage controller determines the value of the active current of the mains non-linear load.

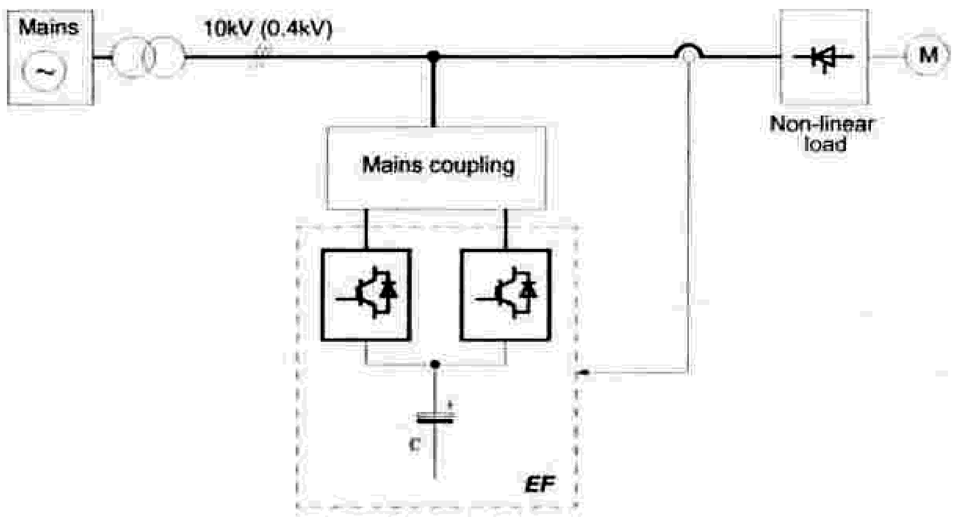

Fig.1. Block diagram of the extended Filter

A. Current control

The control value of the current control loop is the supply current. This current is a result of the sum of the measured non-linear load current (see Fig. 1) and the ac current of both voltage source inverters. These two three-phase System currents are summed and then are transformed to a signal of the two-phase quantities $i_{S\alpha,\beta}$ (see Fig.2 $i_{S\alpha}, i_{S\beta}$).

The reference value for the current Controller $i_{d,q}^{ref}$ (*d* and *q* components) is transformed to the stationary reference frame a - *ß*. The $e^{ja_1 t}$ transformation of the vector $i_{d,q}^{ref}$ to the $i_{1\alpha,\beta}$ vector is executedby, derived from a phase-locked loop PLL (see Fig.2).

The selection of the switching sequence for every switch of the both voltage source inverters is realised through the use of a sliding mode controller. The select of the switching sequence for every switch through the use of the sliding mode control is discussed extensively in [4,5]. This makes it possible to control the active filter without mains voltage sensors [6]. It simplifies the hardware configuration of the active filter very much, especially for 10 kV mains applications. The Output Signals of two P-controllers $u_{W\alpha}, u_{W\beta}$ with Saturation represent two components of the mains voltage vector , $u_{W\alpha\beta}$ which are used to detect the position of the voltage vector by PLL (see Fig.2). For more information see [6].

To reduce the high-frequency switching-ripple of the line filter current, the out-of-phase switching of the IGBT-transistors of the active filter is used.

The direct harmonic control method is used to control the individual harmonic amplitudes of the supply current.

B. Direct harmonic control. Principle of control.

Let us define

$$x = i^{ref} - i_S \tag{l}$$

is a state variable, as it is shown in Fig.3, where the complex vector of the i^{ref} reference current is given by

$$i^{ref} = I_1^{ref} e^{j(wt-\varphi_1^{ref})} + \sum_m I_m^{ref} e^{j(max-\varphi_m^{ref})} \tag{2}$$

with *m=1±6k,k=l,2,3....*

From Fig.3 with (l) the line current of an active filter is written as

$$i_F = i^{ref} - i_L - x \tag{3}$$

The line current of the non-linear load (for example, of the diode rectifier) can be defined as:

$$i_L = I_{L1}e^{j(wt-\varphi_{L1})} + \sum_m I_m^{ref} e^{j(\max -\varphi_{Lm})} \quad (4)$$

with $m=1\pm 6k, k=1,2,3....$
Suppose, (hat the system is maintained on the sliding surface [7,8], so that

$$x=0. \quad (5)$$

In this case, from (3) you can see, if

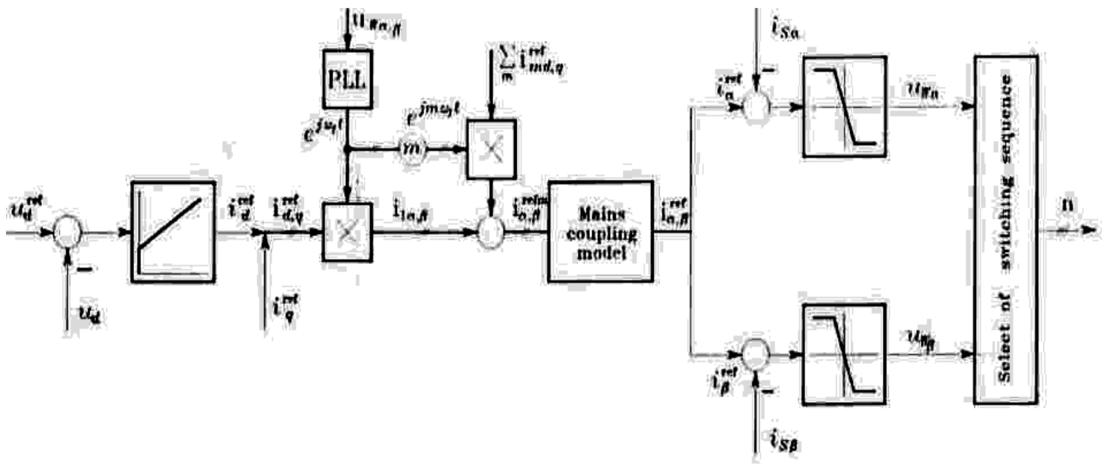

Fig.2: Block diagram of the control unit

(6)

then

$$i_F = -\sum_m I_{Lm} e^{j(\max -\varphi_{Lm})} \quad (7)$$

i.e. the supply current i_S has only a fundamental hannonic.

$$i_S = I_{L1} e^{j(wt-\varphi_{L1})} \quad (8)$$

In this way, all harmonics of the non-linear load are compensated by the active filter. If the reference signal has not only the main harmonic but also, for another harmonics as well.

$$i^{ref} = I_{L1} e^{j(wt-\varphi_{L1})} + \sum_m I_m^{ref} e^{j(\max-\varphi_{Lm})} \quad (9)$$

Then the supply current has the fundamental harmonic and other harmonics too. The amplitudes of the harmonics of the supply current correspond with their reference values. But the amplitudes of the harmonics of the active filter current are defined äs the difference between the reference values and the load current harmonics, or

$$i_F = -\sum_m (I_{Lm} - I_m^{ref}) e^{j(\max-\varphi_{Lm})} \quad (10)$$

In this case, the power rating of the active filter can be reduced by corresponding choice of the harmonic reference values.

In Fig. 2 to control the individual harmonic (amplitudes) of the supply current, the reference values for individual $\sum_m i_{md\ ,q}^{ref}$ harmonics are added to $i_{1\alpha,\beta}$

C. Mains coupling model

In medium high voltage applications a step-down transformer is used to adjust the nominal value of the ac inverter voltage to the mains voltage. Because the time-domain transfer function of the transformer does not equal a function of the proportional gain, and what is more, the magnetic field of the transformer has saturation properties, the mains coupling model is used. This model is intended to compensate the non-linear characteristic of the transformer and to achieve that the forward-path transfer function of the control loop has only an integral term.

D. DC voltage control

With non-sinusoidal current of the active filter, the dc-link voltage contains not only a ripple of the frequent switching of transistors, but also a low frequency voltage ripple. This low frequency voltage ripple must be filtered in the control loop by feeding back the dc voltage. Otherwise this voltage would be increased by the proportional part of the voltage controller and it would be passed on to the line current control loop.

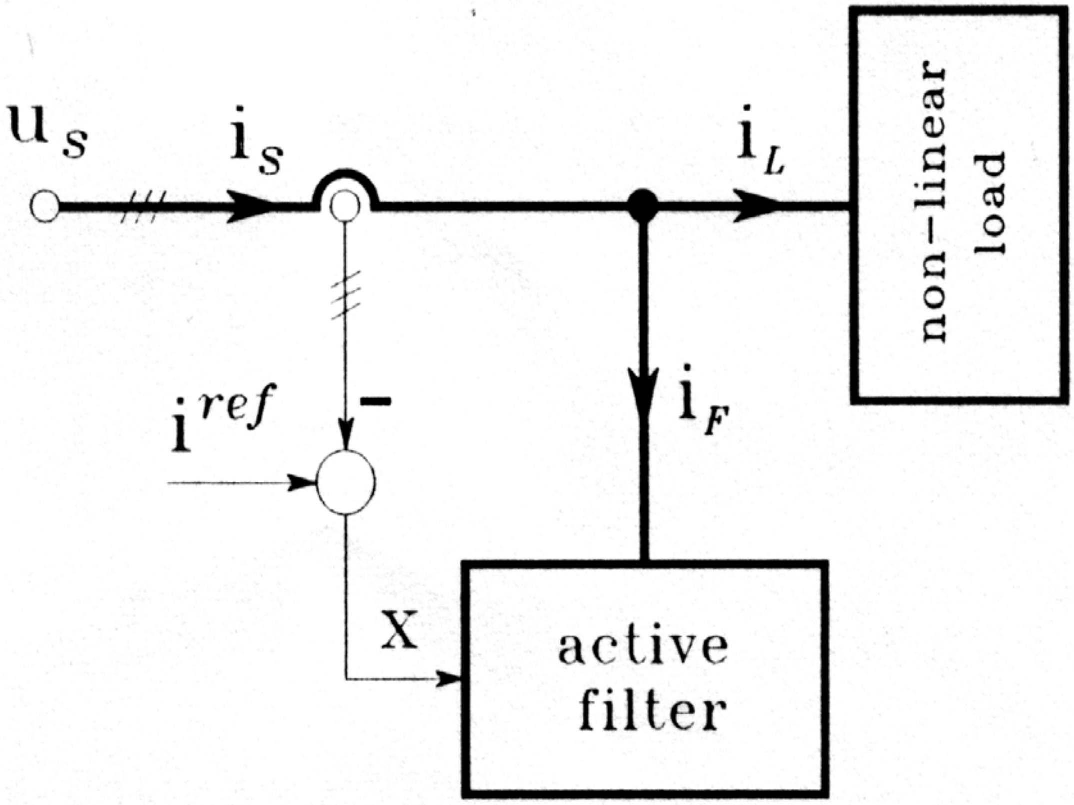

Fig.3. Active filter with a non-linear load

Therefore, the line currents would be distorted [9].
The cut-off frequency of the feedback low-pass filter must be f_0 =50-75Hz. The low cut-off frequency of the feedback filter causes the large delay time in the dc-voltage measurement and therefore the dc-link voltage control has a low dynamic performance.
To improve the time response of the dc-link voltage control, we use an adaptive control System, whose parameter values of the feedback filter and PI Controller are changcd in accordance with the value of the dc-voltage error [9].

IV. IMPLEMENTATION ISSUES AND TEST RESULTS

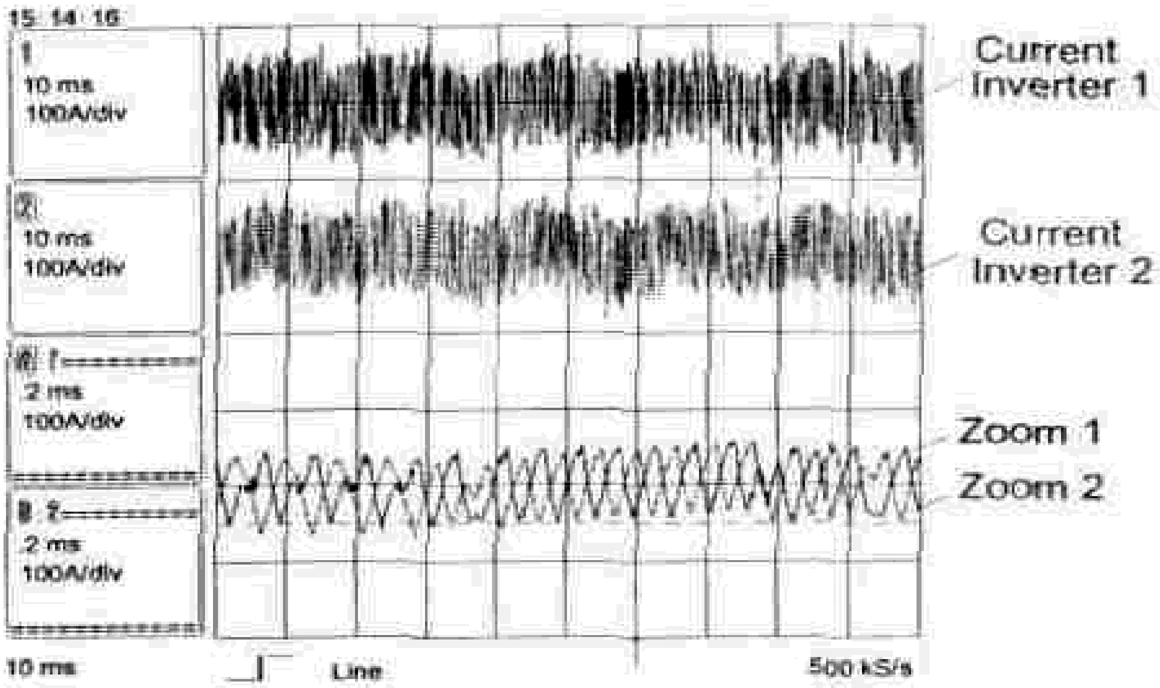

Fig.4. Measured line currents of the active filter (100A/div)

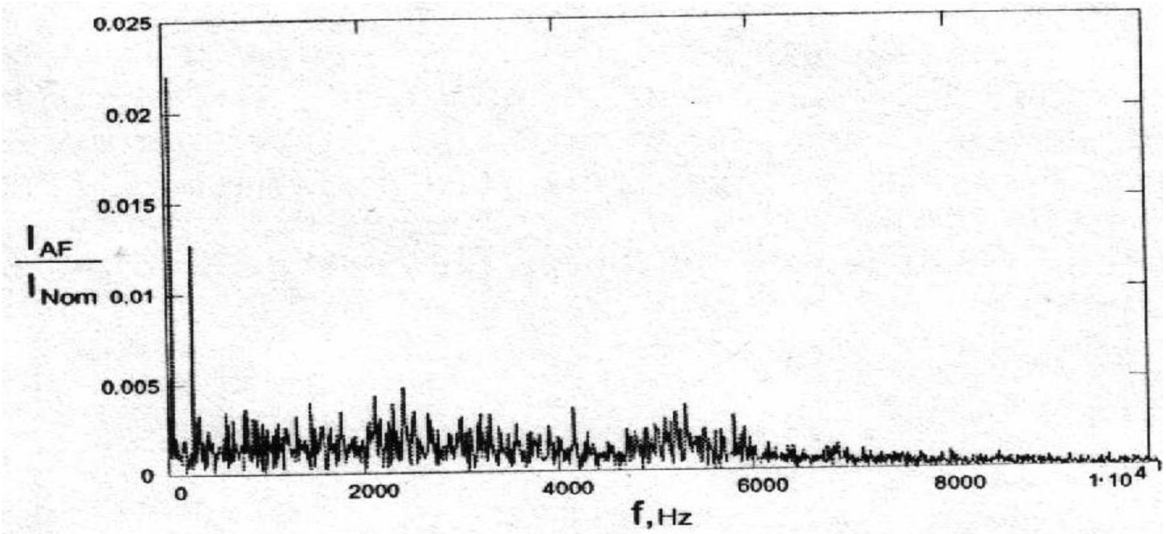

Fig.5. Spectra of the line current of the active filter without load IAF – filter current, INQM -nominal current

In this section, experimental wave forms are presented, which have been created by testing the active filter with the reactive power nominal value Q_N = 800 kVAr on an industrial plant. The active filter was connected to 10kV mains by two 10/0.4A-F 500 *kVA* step-down transformers.

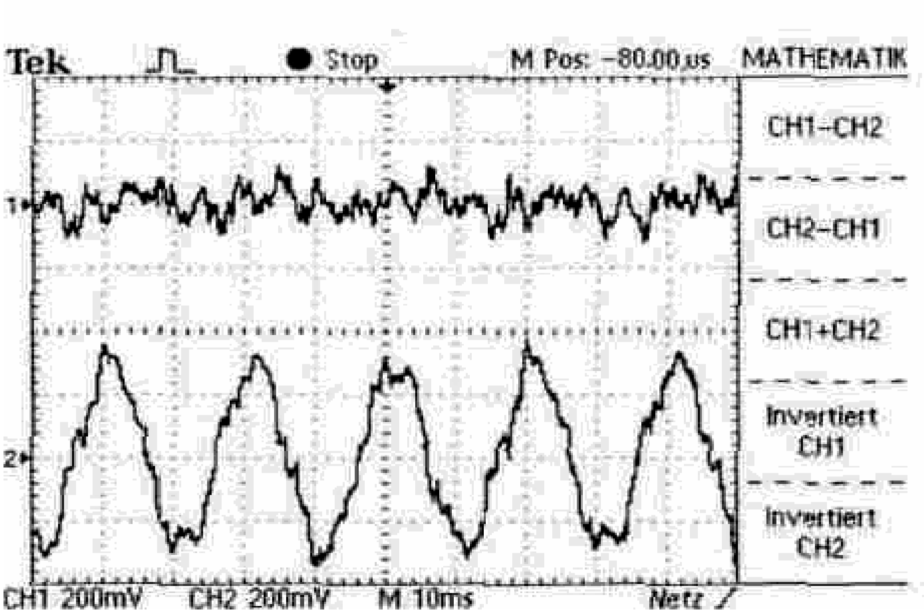

Fig.6. The wave forms of the active filter current and the ac drive current (10 kV mains, 20A/div)

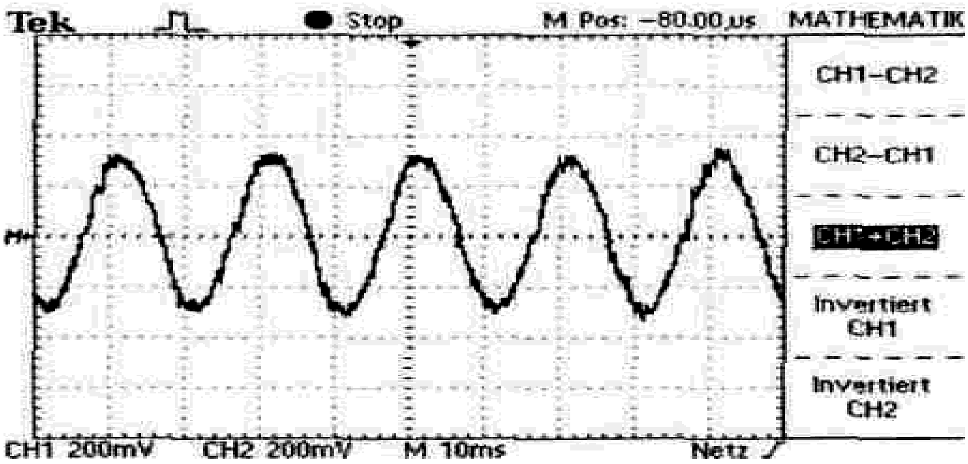

Fig.7. The currents sum of the measured non-linear load current and of the filter current (20A/div).

It was estimated that the active filter would adequately compensate five ac drives supplied by a 12-pulse current source inverter rated up to 1000 *kW.* The control part of the active filter was implemented by using the digital signal processors TMS320C30.

Fig. 4 shows the measured line currents of the active filter on the low voltage side of the transformer. The wave forms 1 and *2* are the one-phase (phase R) line currents of two voltage inverters accordingly. The wave forms ***A* and *B*** represent the wave forms 1 and *2* in a zoom mode.

Frorn Fig.4, it is clearly seen that the line filter currents are out-of-phase. The maximum of the line current of the first inverter takes place if the current of the second inverter has the minimum. As a result, the high-frequency switching-ripple of the sum current is very low as you can see in Fig.5

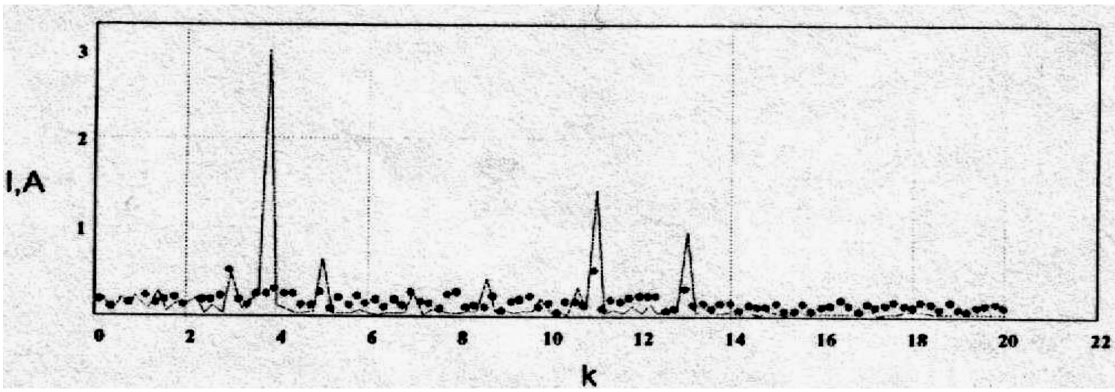

Fig.8. Spectra of the ac drive current (lines) and the sum current (dots); the fundamental harmonic is not shown.

Fig.6 shows the wave forms of the line current (one phase) of the ac drive and the phase current (the same phase) of the active filter. These currents was measured on the l0 kV side of the transfonner.

The sum current is presented in Fig.7. Because it was not possible to measure the sum current, it is not the measured current. It is the sum current witch is calculated by the oscilloscope from the measured currents from Fig.6.From Fig.7 it is seen that the sum current has practically sinusoidal and periodical wave form. The harmonics of the ac drive current are practically eliminated as you can see from the spectra of the ac drive current and spectra of sum current (see Fig.8).

V. CONCLUSION

The proposed structure and control scheme for a parallel active filter for non-linear loads makes the application of the active filter in the industry more real. The control without mains voltage sensors simplifies the hardware configuration of the active filter very much, especially for 10 kV mains applications. The experimental results show that the proposed control structure makes it possible to achieve quite good compensating performance of the filter in both stationary and transient states of the non-linear load.

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