ACTIVE COMPENSATION OF HARMONICS IN INDUSTRIAL APPLICATIONS

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ABSTRACT

In industrial low and medium voltage mains, passive filters and PFC capacitors have traditionally been used to improve the supply quality. However, they cannot 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 [1]. Compared with passive element compensators, an active harmonic compensator (AHC) can be used to improve the supply quality without worrying about all the problems associated with applying passive elements.

I. INTRODUCTION

The increased use of non-linear loads in general and of electrical drives in particular, typically connected to the mains with a diode or SCR rectifier, and loads such as arc furnaces with rapid fluctuations of reactive and active power consumption contribute to the degradation of power supply quality. Non-sinusoidal currents of the non-linear loads and fluctuations of the power consumption result in the distortion of the supply voltage wave form and cause voltage fluctuations (flicker) at the point of common coupling due to the finite supply impedance.

These issues is recognized widely throughout the industry and in industrial mains passive filters are traditionally used to absorb harmonics generated by the non-linear load and PFC capacitor banks to compensate reactive currents, primarily due to their low cost. However, they have a number of significant drawbacks:

- the mains impedance strongly influences the compensation characteristics;
- they result in new resonances and therefore magnify the levels of the other harmonics;
- they cannot 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.

The use of active mains compensation holds a number of advantages compared to the passive. The AHC:

- Is easy to size to the application as the design is independent of line impedance
- Does not generate resonance
- Actively controls both harmonic and reactive currents.

Despite the advantages, AHC's have a limited market share mainly due to high cost. However, a number of trends and factors indicate that this is about to change.

- New developments enable the use of mass produced hardware in the active filter, which significantly will reduce the cost.
- Due to the large amount of cobber and steel used in passive filter, the increase of material cost has a higher impact on passive solutions than on active solutions

The AHC described in this paper was developed for industrial mains with non-linear loads and consumers with rapid fluctuations of reactive and active power consumption to improve the supply quality of other loads supplied from the same mains. As the AHC unit uses the same IGBT-inverter platform that is used for variable speed drives, thus the cost is limited compared to traditional AHCs.

The goal of this paper is twofold: *firstly*, to present a general structure of the AHC, and *secondly*, to give some examples of industrial applications to improve the voltage quality of industrial networks with non-linear loads and consumers with rapid fluctuations of reactive and active power consumption.

II. GENERAL STRUCTURE

Fig.1 shows the block diagram of the AHC. The three-phase voltage source inverters is connected to (see Fig.1) the industrial network.

An industrial plant may include different types of electrical loads, divided into linear loads (regenerative power units, resistive loads, ac-machines) and non-linear loads (Adjustable Speed Drives, arcing devices, etc.)

The Active Harmonic Compensator has to detect the current harmonics and generate a compensation current that cancels the harmonic component, leaving mainly the fundamental current to be drawn from the power supply. The control of the AHC consists of a closed loop control for regulation of the inverter current and dc-voltage, and the detection and generation of compensation current reference. Thus, depending on applications, the AHC may include harmonic compensation, reactive current or flicker mitigation.

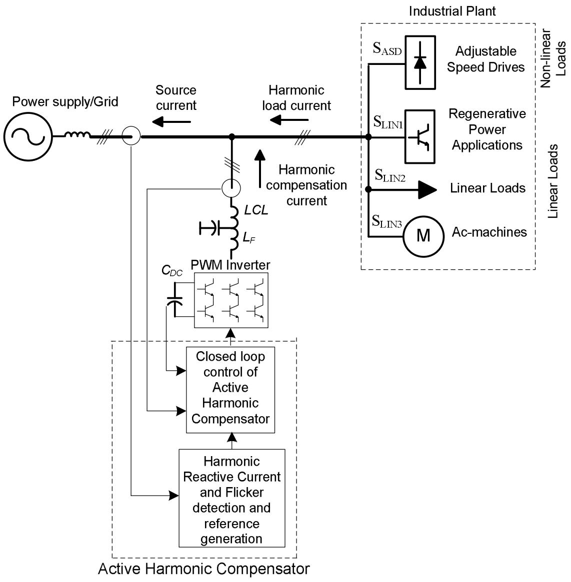

Fig. 1: Electrical diagram of the Active Harmonic Compensator connected to industrial plant.

A. Control system

Fig.2 shows a block diagram of the control unit of the AHC. The control scheme is based on a cascade control with a current control in the inner loop without mains voltage sensors. The current controller sets the output voltage of the voltage source inverters for each 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 load and losses of the power unit of the restoring system [2,3]. The reactive current is calculated by the reactive power and flicker estimation module of the control unit (see Fig.2). To reduce the high-frequency switching-ripple of the AHC line current, a high frequency LCL filter is connected in between the mains and the AHC.

B. 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 load current (see Fig.1) and the ac current of voltage inverter. These two three-phase system currents are added together and then are transformed to a signal of the two-phase quantities $\mathbf{i}_{S\alpha,\beta}$. In Fig.2 this current is represented as $\mathbf{i}_{S\alpha}$ and $\mathbf{i}_{S\beta}$.

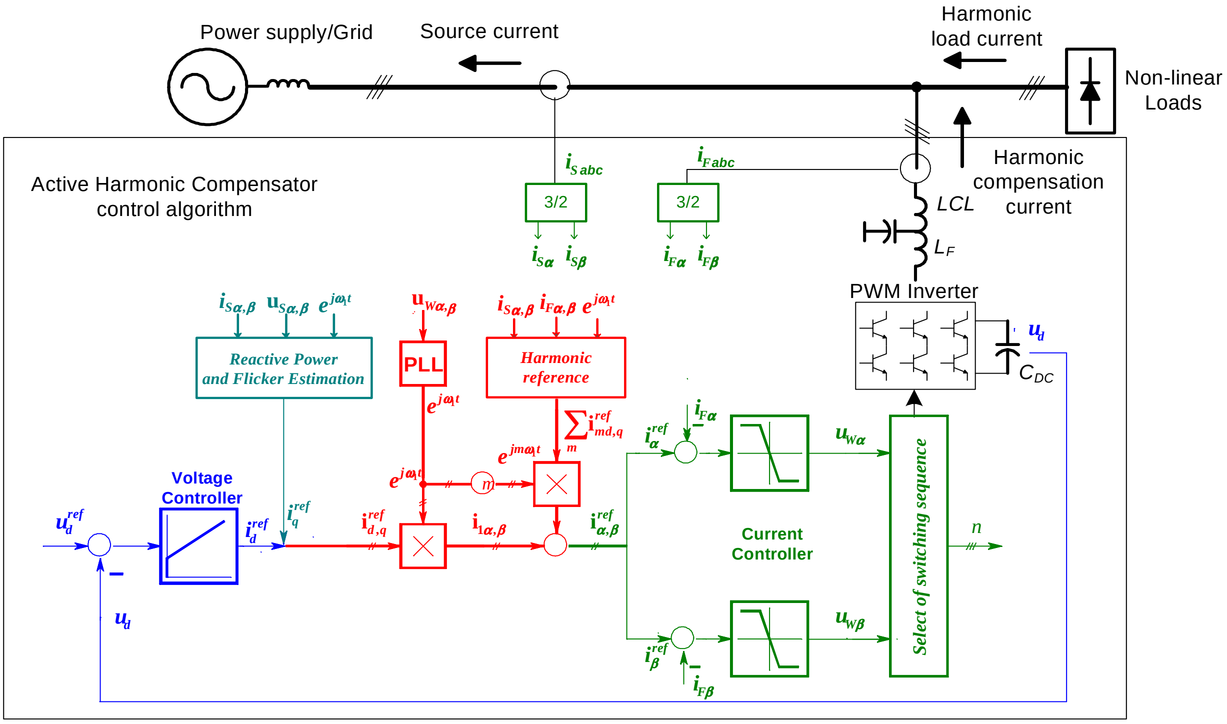

Fig.2: Block diagram of the control unit

The reference value for the current controller $\mathbf{i}_{d,q}^{ref}$ (*d* and *q* components) is transformed to the stationary reference frame $\alpha-\beta$. The transformation of the vector $\mathbf{i}_{d,q}^{ref}$ to the vector $\mathbf{i}_{1\alpha,\beta}$ is executed by $e^{j\omega_1 t}$, derived from a phase-locked loop PLL (see Fig.2).

The selection of the switching sequence for every switching operation of the both voltage source inverters is achieved through the use of a sliding mode controller. The selection of the switching sequence for every switching operation through the use of the sliding mode control is discussed in detail in [4-6]. This makes it possible to control the active filter without mains voltage sensors [7]. It significantly simplifies the hardware configuration of the active mains compensator, especially for medium and high voltage applications. The output signals of two P-controllers with saturation represent two components of the mains voltage vector $\mathbf{u}_{W\alpha}$, $\mathbf{u}_{W\beta}$ which are used to detect the position of the voltage vector by PLL.

To control harmonic amplitudes in the network, the harmonic calculator is used. The principle of the operation is based on the direct harmonic control method. This method is briefly described in [2,3].

C. DC-link Control

With non-sinusoidal mains current of the voltage inverter, the dc-link voltage contains not only a ripple from transistor switching operations, but also a low frequency voltage ripple like the dc voltage at the dc-link of the diode rectifier with capacitor. This low frequency voltage ripple must be filtered in the control loop by feeding back the dc voltage otherwise this voltage ripple would be increased by the proportional part of the voltage controller and it would be passed on to the line current control loop. Therefore the line currents would be distorted [8].

To decrease the influence of the dc-link voltage ripple on the current control loop, 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, an adaptive control system is used, whose parameter values of the feedback filter and PI controller are changed in accordance with the value of the dc-voltage error [8].

III. SIMULATION RESULTS

The simulation of AHC control shows very high dynamics. This is justified first by the high dynamic of the current controller, which is characteristic to the sliding mode control. Second, due to the implemented adaptive dc-voltage controller the AHC can overcome much faster the transient during the connection/ disconnection of the AHC or the harmonic load change.

A simulation result is available in Fig. 3 (only a single phase is shown).

The harmonic current is generated by a typical three phase diode rectifier Adjustable Speed Drive. Since the displacement power factor is close to unity there is no requirement of reactive power compensation in this case, but only harmonic current mitigation. At time 0.16 the AHC is connected to the power system and starts mitigating the harmonic currents from the ASD. The transient takes almost one fundamental period, until the source current resembles sinusoid waveform.

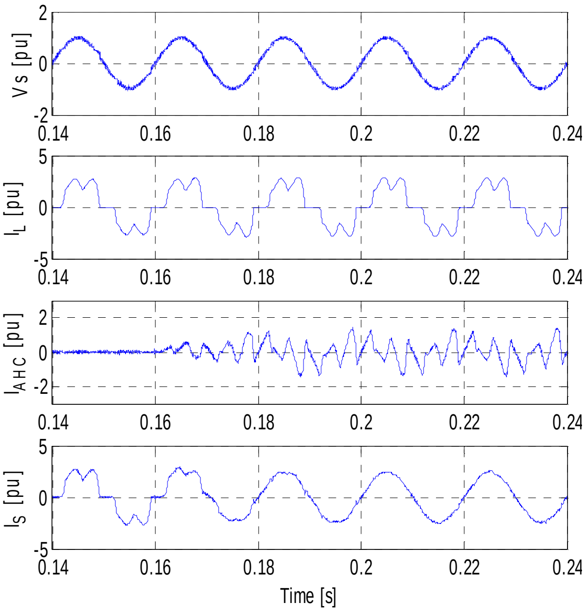

Fig.3. Simulation results of AHC start-up.

Due to its high dynamics the AHC is able to compensate the harmonic currents within one fundamental period.

The current distortion of the non-linear load has a THD of 34 % while the source current reaches a THD of 4 %.

IV. APPLICATION EXAMPLES

The AHC operates as a highly dynamically controlled reactive current source and, thanks to special control algorithms, the compensating reactive current is delivered at exactly the right moment. Thereby the load of the mains is decreased and the mains voltage changes and distortions are reduced to a safe value.

A. Mitigation of Harmonics

In industrial mains, passive filters are traditionally used to absorb harmonics generated by non-linear loads, primarily due to their low cost. This is a good approach when power factor correction is needed too. As they have a lot of drawbacks, the industrial application of passive filters is limited. Compared with a passive filter, an active filter can be used to reduce harmonics in industrial mains without worrying about all the problems associated with applying passive filters [1].

The AHC unit enables a controlled compensation of harmonics and reactive currents like active filters, independent of the mains- and current load configuration and without risk of compensator overload. The AHC unit can also be sized for the compensating load requirement only, leading to a reduction of the installation costs of the compensation unit.

The following experimental wave forms show the high efficiency of the AHC system for mitigation of harmonics. These wave forms have been created by testing the AHC unit with the power rating 800 kVAr on an industrial plant. The AHC unit was connected to 10 kV network by the 10/0.4 kV step-down transformer. It was estimated that the active filter would adequately compensate five ac drives supplied by a 12-pulse current source inverter rated up to 1.0 M*W*.

Fig. 4 shows the wave forms of the line current (one phase) of the ac drive (only one drive) and the phase current (the same phase) of the AHC. These currents were measured on the 10kV side of the transformer.

The network current is presented in Fig.5. It is the sum current which is calculated by the oscilloscope from the measured currents from Fig. 4.

From Fig. 5 it is seen that the sum network 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 network current (see Fig.6).

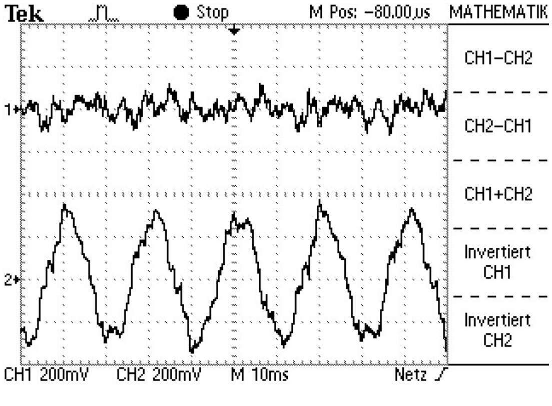

Fig.4: The wave forms of the AHC current and the ac drive current (10kV mains, 20A/div)

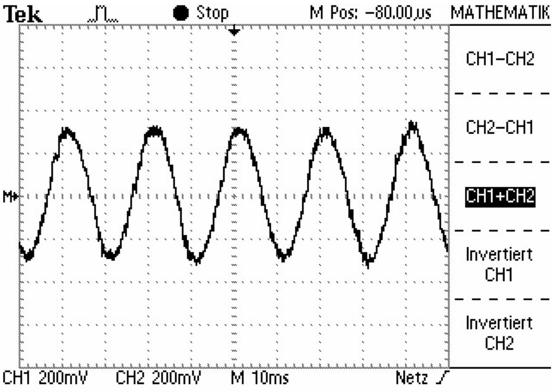

Fig.5: The currents sum of the measured non-linear load current and of the AHC current (20A/div).

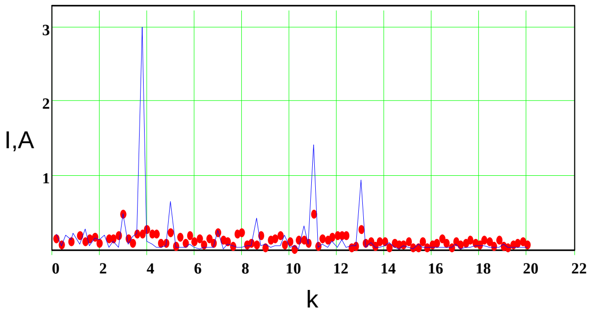

Fig.6: Spectra of the ac drive current (lines) and the sum current (dots); the amplitude of the fundamental harmonic is not shown. K represents the number of harmonics.

B. Flicker Mitigation

Flicker, caused by large fluctuating loads, is one of the power quality problems that include interruption, voltage sags and dips. SCR controlled Static Var Compensators (SVC) are usually used to compensate reactive currents and to reduce the flicker. As it operates

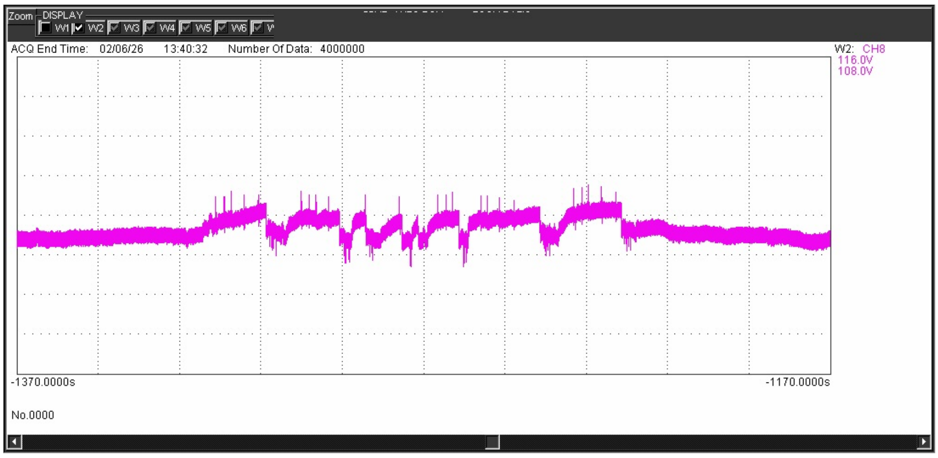

Fig.7: Voltage changes at a 11kV- mains network without AHC (1V/div)

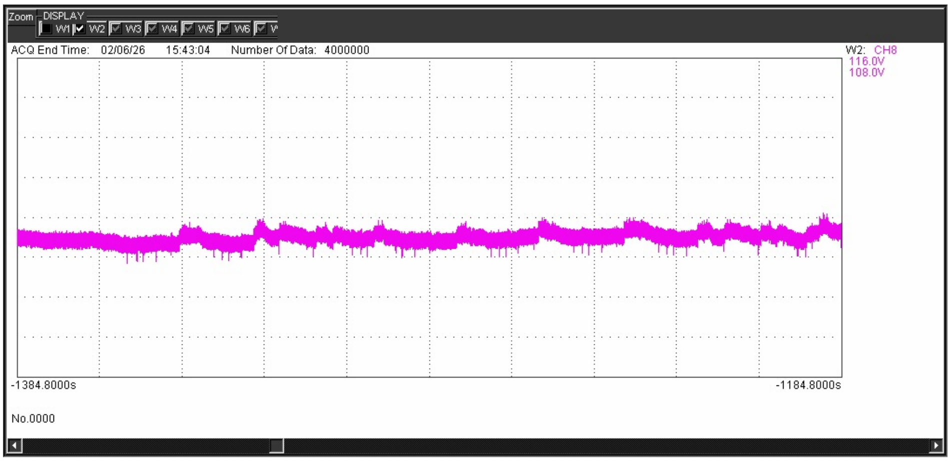

Fig.8: Voltage changes at a 11kV- mains network with AHC (1V/div)

at the fundamental frequency, the capability of the SVC is limited [9]. Thanks to a delay time of only 2ms the AHC is highly suitable for the flicker compensation.

Fig.7 shows the measured voltage changes at the 11kV-network during a test of an engine without a compensation unit. The maximum mains voltage change was approximately 1.2%, a number which, for this frequency, is already over the standard limit value for the flicker. The measured value of the short-time flicker P_{st} equals 1.5.

In Fig.8 the measured voltage changes is shown at the same test of the motor but this time using the AHC. The mains voltage change is approximately 0.3% and lies clearly under the standard limit value. The measured value of the short-time flicker $P_{st} = 0.5$.

C. Compensation unbalanced current from a welding machine

Welding machines are well known to draw a high non sinusoidal current in short periods. Even unbalanced line current, where only 2 phases are loaded are common. An example hereof is shown in Fig. 9, where only phase ‘t’ and ‘s’ are loaded with a peak current of 1200A, while phase ‘r’ remains unloaded.. Note also the non sinusoidal shape of the current. The AHC will compensate the harmonic distortion as well as the unbalance between the phases as shown in Fig 10. As a result of that load is shared by all three phases, the peak current is significant lower, which also improves voltage quality. The peak current of above 1200A in phase s’ is reduced to 400 A in all three phases.

V CONCLUSION

The proposed active harmonic compensation AHC for industrial networks can be successfully used with non-linear loads and consumers with rapid fluctuations of reactive and active power consumption to improve the supply quality of other loads supplied from the same mains. Clear reduction of the voltage wave form distortion and the voltage changes (flicker effects) as well as the stabilisation of the mains voltage are the main advantages of the proposed AHC. These all make the application of the power electronics to improve the supply voltage quality in industrial networks more effective in comparison to passive filters and PFC capacitors.

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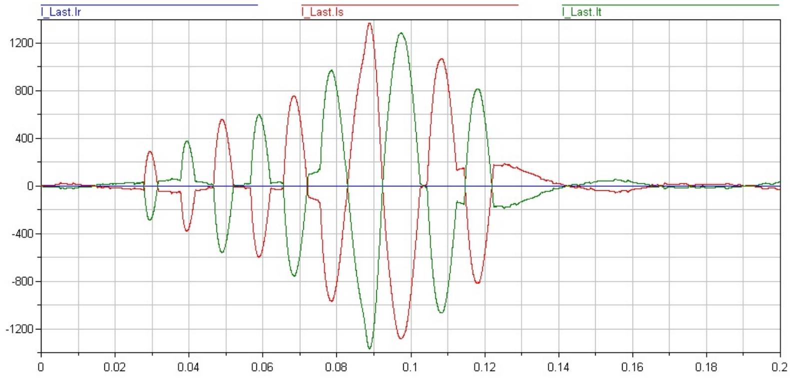

Fig.9: The wave forms of the welding machine line currents without AHC

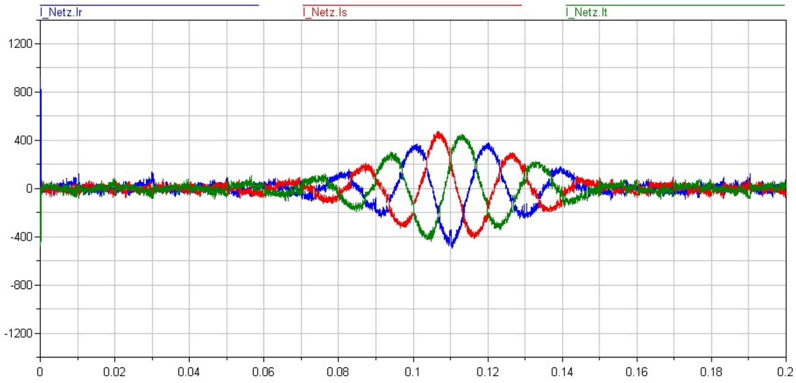

Fig.10: The wave forms of the welding machine line currents with AHC