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OPERATING CHARACTERISTICS OF SINGLE – PHASE SHUNT ACTIVE POWER FILTER WITH HYSTERESIS – CURRENT CONTROL

PhD,Assoc. Professor Mihail H. Antchev –TU-Sofia
MSc Engineer in Electronics, Assist. Professor Mariya P. Petkova –TU-Sofia
Technical University of Sofia, Department of Power Electronics, 1000 Sofia, Bulgaria, 8 Kl.Ohridski Blvd., Bl. 1, Phone +3592-9652122
E-mails: first author: antchev@tu-sofia.bg; Second author: mariya_petkova@tu-sofia.bg

ABSTRACT

Single–phase shunt active power filter, compensating power factor of nonlinear load – single-phase bridged uncontrolled rectifier with active-capacitive load, is studied in this paper. Hysteresis-current following of reference sinusoid in phase with source voltage is used to control filter devices. There is a possibility to break off the following of reference sinusoidal during an interval into half-period because of the consumed nonlinear load current waveform. This effect is studied in dependence of load characteristics and filter elements through mathematical description and computer simulation. Graphical relationships and experimental oscillogrammes are carried out. Filter control is based on digital signal processor (DSP) TMS320LF2407.

KEYWORDS: Single-phase shunt active power filter, hysteresis-current control, uncontrolled rectifier with active-capacitive type of load, DSP.

1. INTRODUCTION

Active power filters are an effective means for increasing indicators in respect to source network when the device has already been installed. Different schemas of shunt filters are known, such as voltage-feed or current-feed converter, switched-capacitor converter [1]. Bridged and half-bridged schemas are most often used as a single-phase filter [2]. They are studied in operation together with active-inductive load [3], uncontrolled rectifier with active-capacitive type of load [4], uncontrolled rectifier with active-inductive type of load [5], thyristor AC regulator [4]. Also, different control strategies are used – Fourier transformation for determining the current, the filter must generate [6], PWM, genetic algorithms [7], fuzzy-logic, a-b-c transformation [8], hysteresis-current control [4], etc. Filter current [1] or source current [9] is monitoring in the last mentioned method.

Using this method with some nonlinear loads with specific consumed current waveform, for example bridged uncontrolled rectifier with active-capacitive type of load, there is a possibility to break off the following of reference current waveform during particular intervals. The authors' aim is to examine the above-mentioned possibility when the reference sinusoid for source current is generating, based on the equivalent active power, which is the same when the system works with and without the filter plugged in [10].

2. FILTER CONTROL METHOD

Fig.1 shows the schema used to study the operation of single-phase shunt active power filter, implemented with half-bridged power converter with transistors VT1 and VT2. In the basis of the control is so called method of "equivalent active power" [10], materialized by DSP TMS320LF2407. Consumed active power is determined by monitoring waveform of source voltage VTr and consumed load current CTr2. So estimated active power is transformed in reference sinusoid of total source current, which is monitoring through CTr1. Thus, generated sinusoidal waveform from the DSP is passed to hysteresis-current control schema, where the sinusoidal value is compared with the instantaneous source current value. If the source current must increase the transistor VT2 is turned on, and alternatively, when the source current must decrease – VT1 is turned on. In the same time the filter capacitor voltages are monitoring, and using PI regulator the reference sinusoid is changed so these voltages to stay constant. This method is effective implemented not only with one time-changing linear load and nonlinear load, but also with a combination of different loads [4].

The filter operation together with different type of loads may be simulated with the assistance of equivalent model and the software OrCAD 9.2. Fig.2 displays source voltage and source current consumed by system filter – uncontrolled bridged rectifier with active capacitive type of load. Fig.3 and fig.4 display experimental oscillogrammes of the operation of uncontrolled rectifier with active capacitive type of load and the operation of the rectifier together with active power filter, respectively. From these waveforms is seen that during specific time intervals in each half-period, the possibility of the system APF – rectifier to follow the reference sinusoidal is broken off.

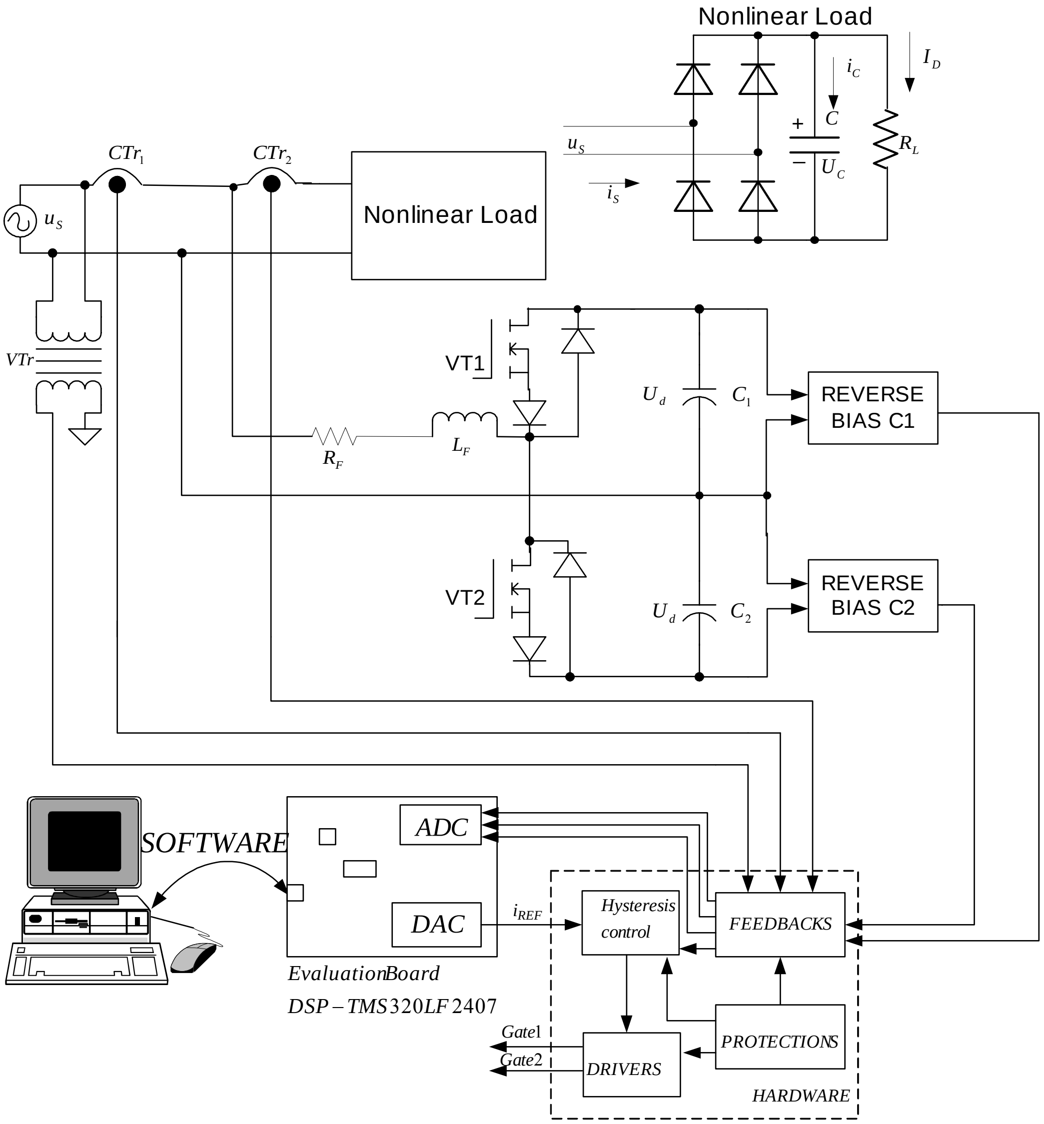

Fig.1.Block schema of the studied system – APF and the rectifier, including control system

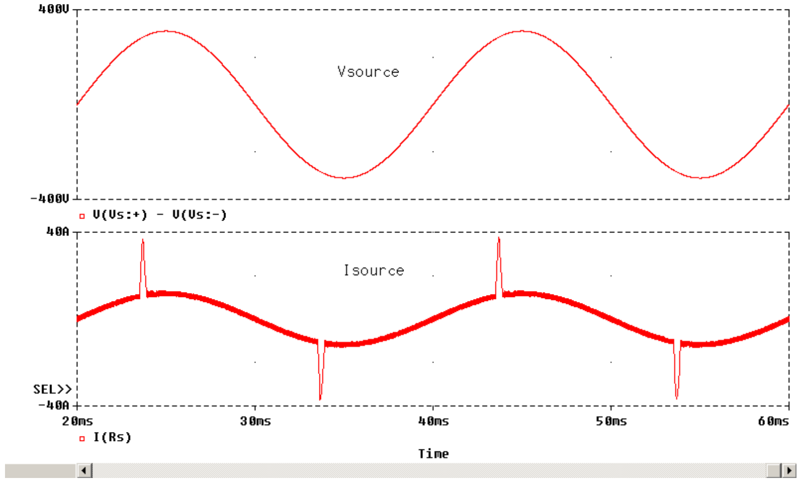

Fig.2 Source voltage and source current consumed by system filter – uncontrolled bridged rectifier with active capacitive type of load

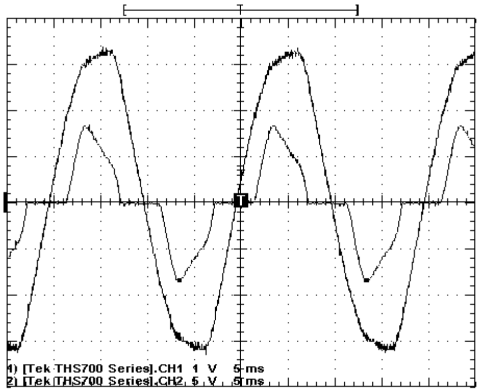

Fig.3 Experimental oscillogrammes of the operation of uncontrolled rectifier with active capacitive type of load – source voltage and source current

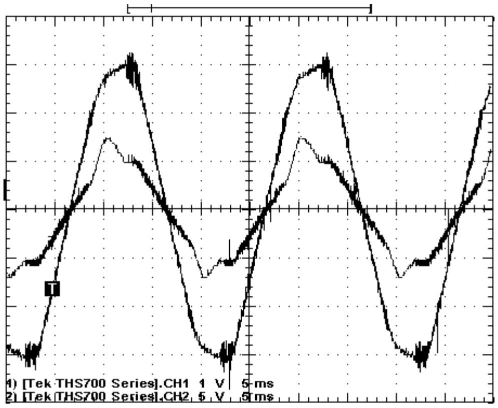

Fig.4.Experimental oscillogrammes of the operation of uncontrolled rectifier with active capacitive type of load together with active power filter - source voltage and source current

3. MATHEMATICAL DESCRIPTION

3.1.UNCONTROLLED RECTIFIER WITH ACTIVE-CAPACITIVE TYPE OF LOAD

Mathematical description of the uncontrolled rectifier operation is made by the assistance of diagrams presented at fig.5. Until $\theta 1$, rectifier diodes do not conduct since the instantaneous source voltage value is smaller than the output voltage value. During the interval ($\theta 1$, $\theta 2$) diodes conduct, and the source current is sum of the output capacitor current and resistive load current.

$$i_S(t) = i_C(t) + i_R(t) = \\ = \frac{u_S(t)}{R_L} + C\frac{du_S}{dt} = \frac{U_{sm}\cdot\sin(\omega\cdot t)}{R_L} + \omega\cdot C\cdot U_{sm}\cdot\cos(\omega\cdot t) \tag{1}$$

During the interval ($\theta 2$, $\theta 3$) the load current is sum of the source current and capacitor current.

$$i_D = i_S + i_C \tag{2}$$

After $\theta 3$ the current, flowing through load resistance is maintained from the capacitor, and the current from source is not consumed. As the interval ($\theta 2 - \theta 3$) is shorter than ($\theta 1 - \theta 2$), the considerations will be made for the interval ($\theta 1 - \theta 2$), in which the breaking off the following of reference sinusoidal is available.

Fig.6 displays source voltage and source current oscillogrammes when the rectifier works without the active power filter. One can see that the front of the current pulse is not as steep as one at fig.5., because of the presence of the source inductance, which is not taken under consideration in above-mentioned mathematical formulas. This is made to study the most unpleasant operation condition of the filter, when in moment $\theta 1$, filter current must change very quick.

Sometimes graphical approximation is made supposed that the capacitor voltage of the rectifier is constant (see fig.7) [2]. The following formula is obtained [2]

$$A = \frac{\pi\cdot r\cdot I_o}{2\cdot U_o} = tg(\theta) - \theta \tag{3}$$

where U_o is the average output voltage value, I_o - average output current, θ - half of the time when diodes are conducted and r is the inner resistance of the rectifier.

The inner rectifier resistance is define as:

$$r = 2\cdot R_{diod} + r_{tr} \approx r_{tr} \tag{4}$$

where r_{tr} is the transformer resistance, and can be estimated from:

$$r_{tr} = k_r \cdot \frac{U_o}{I_o\cdot f\cdot B_m}\cdot\sqrt[4]{\frac{s\cdot f\cdot B_m}{U_o\cdot I_o}} \tag{5}$$

where $k_r = 3.5$, $s = 1$, $B_m = 1T$, $f = 50Hz$.

With the approximation made (see fig.7) the starting time when diodes begin to conduct at fig.5 can be determined or the angle φ may be obtained as:

$$\varphi = \frac{\pi - 2\cdot\theta}{2} \tag{6}$$

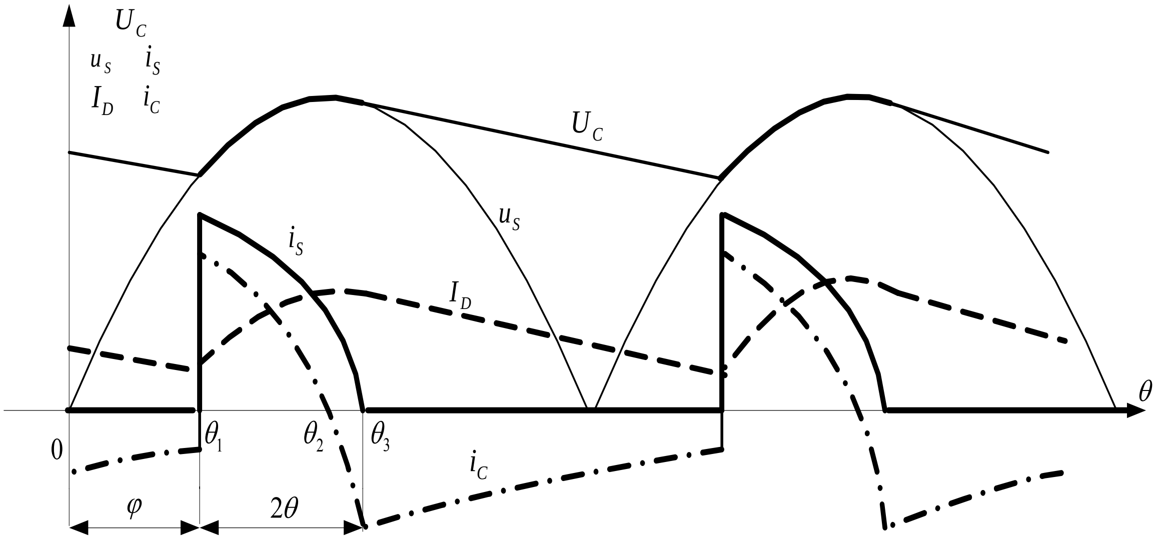

Fig.5. Time variation of source voltage and current, capacitor voltage and current and load current of the uncontrolled rectifier with active capacitive type of load

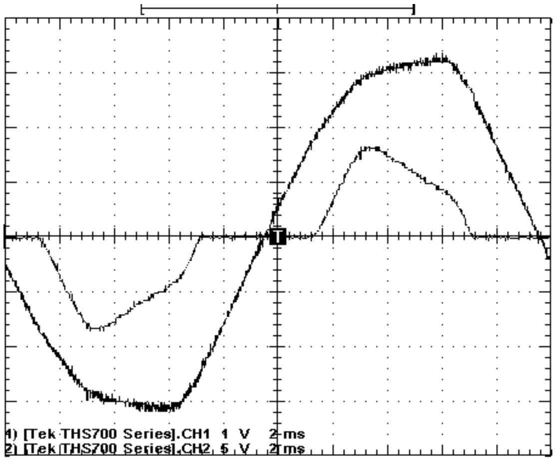

Fig.6. Experimental oscillogrammes of the operation of uncontrolled rectifier with active capacitive type of load - source voltage and source current

3.2. ACTIVE POWER FILTER

From the differential equation, describing the active power filter operation:

$$u_S + R_F . i_F + L_F \frac{di_F}{dt} = \pm U_d \qquad (7)$$

(Sign "+" is corresponding to the time VT1 is switched on, and alternatively sign "–" - when the VT2 is switched on), the equation for filter current value in each moment is obtained:

$$i_F(t) = \frac{U_{sm} \cdot \sin(\omega \cdot t) \pm U_d}{R_F} \left(1 - e^{-t \cdot \frac{R_F}{L_F}} \right) \qquad (8)$$

On the basis of the equivalent active power, consumed from the source when the filter is connected and is not, the following formula for the desired maximum sinusoidal source current corresponding to the operation with the filter plugged in is deducted.

$$I'_m = \frac{2 \cdot P}{U_{sm}} \approx \frac{2 \cdot P_o}{U_{sm}} = \frac{2 \cdot U_o^2}{R_L \cdot U_{sm}} \qquad (9)$$

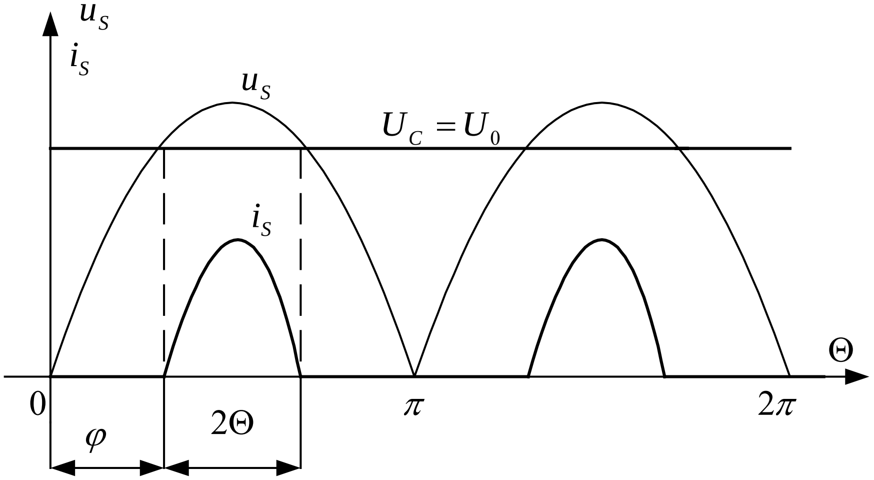

Fig.7. Graphical approximation of the capacitor voltage as a constant voltage

$$L_F(t_s,t)=\frac{-(t_S+t)\cdot R_F}{\ln\left(1-\frac{R_F}{U_{sm}\cdot\sin(\omega\cdot(t_S+t))-U_d}\cdot\left(\frac{2\cdot U_0^2}{R_L\cdot U_{sm}}\cdot\sin(\omega\cdot(t_S+t))-\frac{U_{sm}\cdot\sin(\omega\cdot(t_S+t))}{R_L}-\omega\cdot C\cdot U_{sm}\cdot\cos(\omega\cdot(t_S+t))\right)\right)} \quad (14)$$

So, in real time monitoring the active power P and the effective value of the source voltage, with the assistance of DSP, the reference sinusoid waveform with the above stated maximum value is generated. Consequently, the source current must be changed according to:

$$i_S = I'_m . \sin \omega t \quad (10)$$

As the filter current is the difference between source current and nonlinear load current, then during the interval before $\theta 1$ the filter current will also changed depending on the above-mentioned formula (10) (see fig.7). During the interval ($\theta 1 - \theta 2$), in the beginning of which the possibility to break off the following of the reference sinusoid appeared, the filter current from (10) and (1) must be changed depending on :

$$i_{Fd}(t) = I'_m \cdot \sin(\omega \cdot t) - \frac{U_{sm} \cdot \sin(\omega \cdot t + \varphi)}{R_L} - \\ - \omega \cdot C \cdot U_{sm} \cdot \cos(\omega \cdot t + \varphi) \quad (11)$$

4. GRAPHICAL RELATIONSHIPS

From the moment $\theta 1$, when the time corresponding to the angle φ is passed, the equation between (8) and (11) must be valid, so:

$$i_{Fd}(t) = i_F(t) \quad (12)$$

After determining the angle φ, the corresponding time is defined as:

$$t_S = \frac{\varphi}{\omega} \quad (13)$$

Making equal (8) and (11), the filter inductance can be obtained as (14) (see above).

Using Mathematica 4.1 software, the graphic presented at fig.8 is built. This graphic presented the relationship among the filter inductance, the uncontrolled rectifier parameters and the time during which the reference sinusoidal following can be broken.

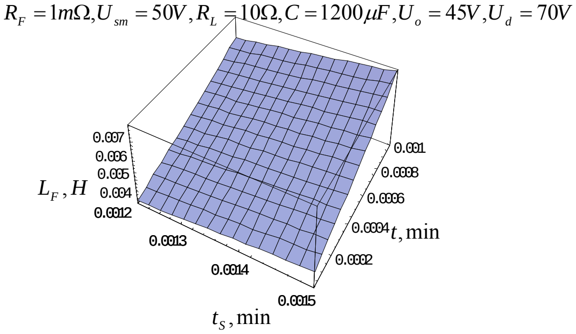

Fig.8 Graphical relationships among the filter inductance, the uncontrolled rectifier parameters and time during the broke of following the reference sinusoid is available

5. SIMULATION AND EXPERIMENTAL RESULTS

The source current, the source voltage and the load current gained after a computer simulation of the filter operation together with the uncontrolled rectifier are displayed at fig.9. The uncontrolled rectifier is performed with 1N4007 diodes, capacitance value is 1200 μ F and the load resistance is $10\,\Omega$. The maximum value of the source voltage is 50V. Its' frequency is 50 Hz.

Experimental results for the source current and the source voltage, gained after the experimental operation of the filter together with uncontrolled rectifier, are showed at fig.10. The rectifier is the same as in already carried out results of its independent work (see fig.6.). Experiments are made in low source voltage, because in this condition the effect of break off the following of the reference sinusoid is more obvious.

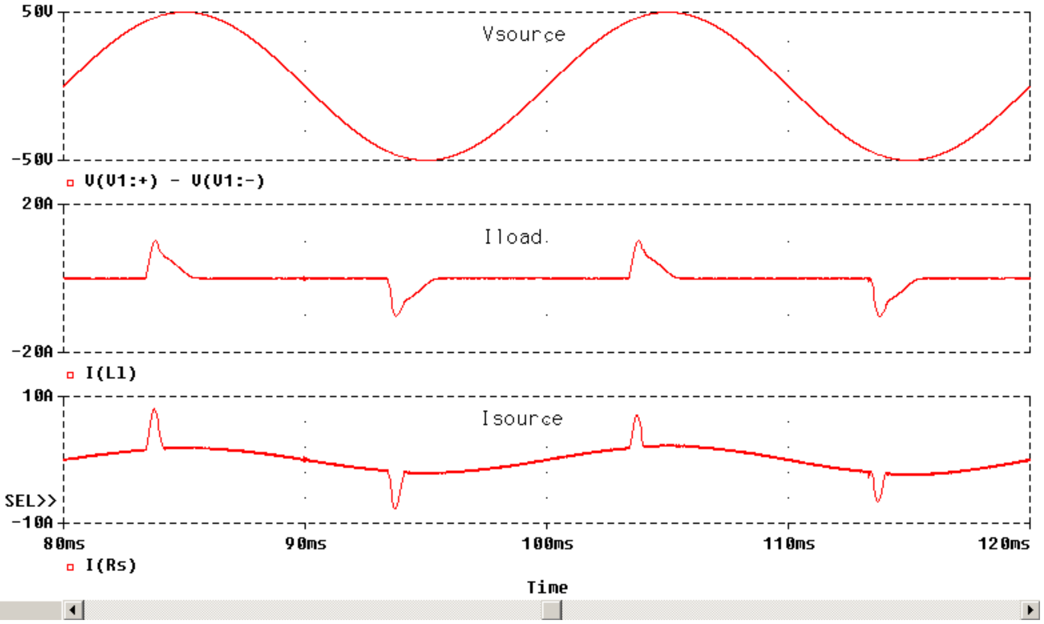

Fig.9 Simulation results for the operation of the uncontrolled rectifier with APF plugged in - the source current, the source voltage and the load current

6. CONCLUSION

The possibility to break off the following of reference sinusoid during particular intervals in half-period, during the operation of shunt active power filter together with uncontrolled bridged rectifier with active-capacitive type of load and hysteresis-current control, has been seen. In agreement with obtained graphical relationships, the choice of the filter inductance must be made in accordance with the desired time to restore the following of the reference sinusoid, after the start of each conducting interval of the rectifier diodes.

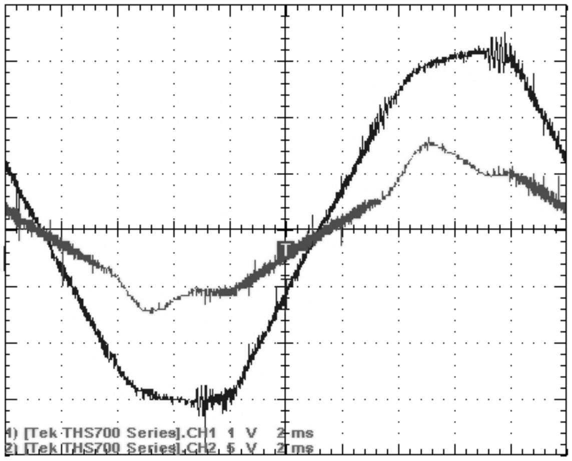

Fig.10. Experimental results of the operation of uncontrolled rectifier with active capacitive type of load together with active power filter - source voltage and source current

7. ACKNOWLEDGEMENTS

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