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METHOD TO DESIGN THE POWER SCHEMA OF A SERIES ACTIVE POWER FILTER

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Abstract: *This paper presents method to design the power schema of a series active power filter. Special features of the design are connected with the operation of the output transformer at non-sinusoidal voltage and current, as well as with the design of the output passive filter. Experimental results for the operation of a single-phase precise stabilizer-filter of AC voltage are included*

Key Words: *series active power filter, design method*

1. INTRODUCTION

With the increase of the number and individual single power of nonlinear electronic converters, the problems, caused by the worsen quality of the consumed electrical energy, become rather significant. Applying series active power filters (SAPFs) is perspective means to improve the quality of the source voltage when a “critical” consumers are fed [1, 4, 5]. Fig.1 displays a block scheme of such SAPF.

The special features of the operation of the transformer **Tr** are describe in [6], while different control methods and control systems – in [2].

The purpose of the paper is to present the results of the elaboration of general method to design the elements of the power scheme of the SAPF – output transformer, elements of the passive LC-filter, parameters required for the inverter transistor choice. Using the method, a single-phase version of a precise stabilizer-filter of AC voltage is implemented. This precise stabilizer-filter is meant for loads which power is up to 3kVA. Experimental results are included at the end of the paper.

2. SPECIAL FEATURES IN OPERATION OF THE PASSIVE OUTPUT FILTER - L_F, C_F

Fig.2 displays the waveforms on which basis the relationships describing the operation of the capacitor C_f and inductance L_f are derived. The survey is limited within a period of a switching of power switches. This period is with a considerably smaller duration of those of the half-period of the AC source **AC**. The symbols in the figure are as follows:

u_{C_f}, u_{L_f} - transitory values of the voltages across the filter capacitor C_f and inductance L_f, respectively;

u_{REF} - transitory value of the reference curve of the voltage of the filter capacitor C_f;

H - the hysteresis value when a hysteresis tracing of the reference curve is applied;

i_{L_f}, i_{C_f}, i_L - transitory values of the currents through the inductance, capacitor and load, respectively;

U_d - the value of the DC voltage feeding the power schema of the inverter.

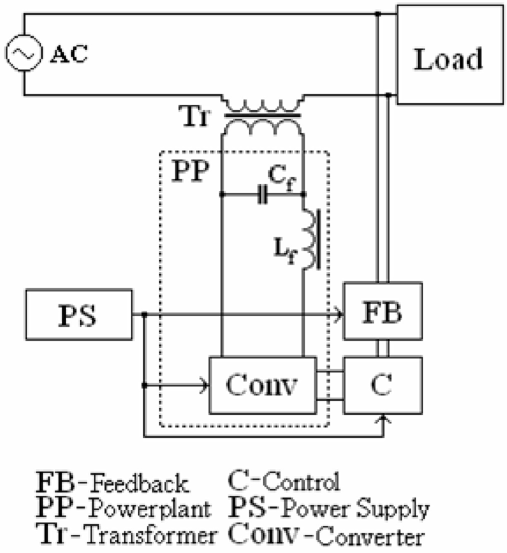

Fig. 1. Blockscheme of SAPF

Single-phase bridge schema is used for inverter implementation. At $\theta=\theta_1$ power devices of this leg of the schema for which the voltage of the passive filter

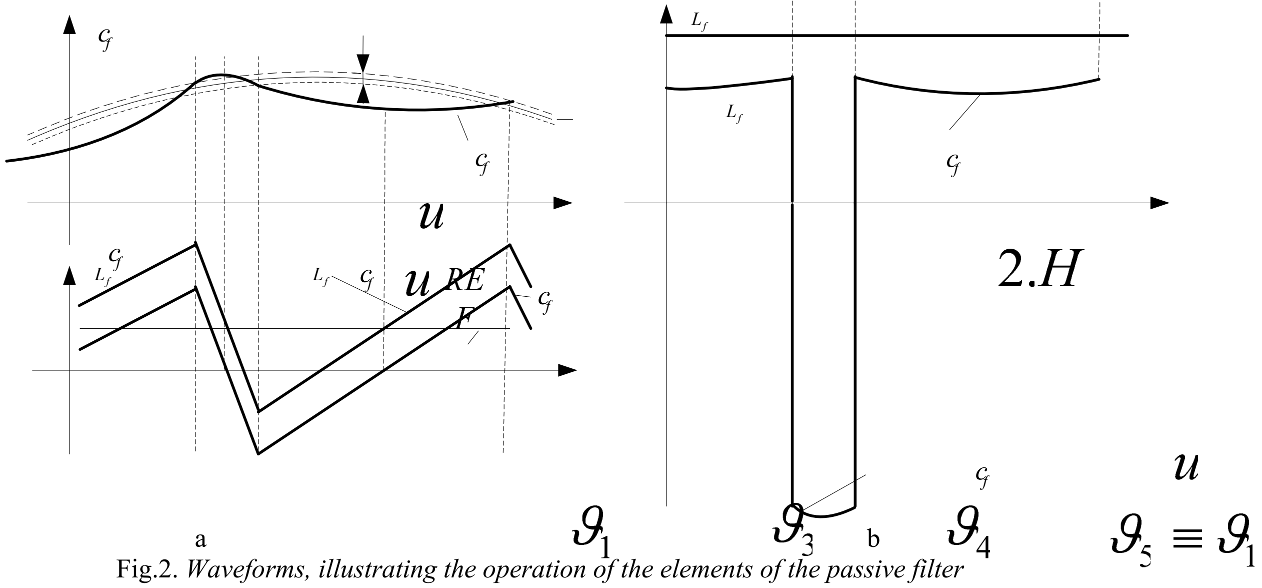

Fig.2. *Waveforms, illustrating the operation of the elements of the passive filter*

capacitor decreases turn on, while at $\theta=\theta_3$ - for which the voltage increase (Fig.2.a – upper diagram). If the ripples of the voltage of the capacitor C_f are neglected, it may be assumed that the current through the inductance L_f (i_{Lf}) changes in both intervals according to the linear law, because DC voltage with approximately constant value is applied across the inductance (Fig.2.b – lower diagram). Owing to the limitation of the time interval, it is very small, the current through the load does not change, i.e. i_L = const. Besides, the relationship among the currents is:

$$i_{C_f} = i_{L_f} - i_L \qquad (1)$$

It is assumed that the control system uses hysteresis control. Furthermore, the relationship between the feeding voltage U_d and the average value of the voltage across the capacitor C_f (u_{Cf}) of the period of switching of the elements of the power part SAPF has to be found. Let $T=\theta_5-\theta_1$ is the period of the switching of the elements of the power schema and let mark with t_{ON} the time corresponding to the interval $\theta_5-\theta_3=t_{ON}$. Because the variations of the current i_{Lf} in the intervals t_{ON} and ($T-t_{ON}$) are equal (see Fig.2.a – lower diagram), therefore:

$$\left(U_d - u_{C_f}\right)\cdot t_{ON} = \left(U_d - u_{C_f}\right)\cdot\left(T - t_{ON}\right) \qquad (2)$$

Furthermore:

$$\frac{u_{C_f}}{U_d} = 2\cdot\delta - 1 \qquad (3)$$

where in

$$\delta = \frac{t_{ON}}{T} \qquad (4)$$

is duty cycle.

From the above-stated equations, the conclusion may be made that if the law of the change of the reference curve of the capacitor voltage C_f - $u_{Cf}(\theta)=u_{REF}(\theta)$ is known then the law of the change of the duty cycle is also known, namely:

$$\delta(\vartheta) = \frac{u_{REF}(\vartheta)}{2.U_d} + \frac{1}{2} \qquad (5)$$

Using equation (5) makes possible to apply and other control method, besides pulse-width modulation (PWM), following a preliminarily set law.

There is a necessity to find the relationship between the peak-to-peak value of the ripples ($|\Delta u_{Cf}|$) of the voltage of the passive filter capacitor and capacitor value. The beginning of the co-ordinate system is moved at the moment θ_2, thus, the following equation is valid:

$$\left|\Delta u_{C_f}{}'\right| = \frac{1}{C_f}\cdot\int_0^{\frac{T-t_{ON}}{2}} \frac{\left|\Delta i_{C_f}\right|}{T-t_{ON}}\cdot t\cdot dt = \frac{1}{8\cdot C_f}\cdot\left|\Delta i_{C_f}\right|\cdot\left(T-t_{ON}\right) \qquad (6)$$

Analogically, if the beginning of the co-ordinate system is moved at the moment θ_4, the following equation is gained:

$$\left|\Delta u_{C_f}{}''\right| = \frac{1}{C_f}\cdot\int_0^{\frac{t_{ON}}{2}} \frac{\left|\Delta i_{C_f}\right|}{T-t_{ON}}\cdot t\cdot dt = \frac{1}{8\cdot C_f}\cdot\left|\Delta i_{C_f}\right|\cdot t_{ON} \qquad (7)$$

Therefore:

$$\left|\Delta u_{C_f}\right| = \left|\Delta u_{C_f}{}'\right| + \left|\Delta u_{C_f}{}''\right| = \frac{1}{8\cdot C_f}\cdot\left|\Delta i_{C_f}\right|\cdot\frac{1}{f} \qquad (8)$$

Or:

$$\left|\frac{\Delta u_{C_f}}{\Delta i_{C_f}}\right| = \frac{1}{8\cdot C_f\cdot f} \qquad (9)$$

Equation (9) may be used to determine the value of the capacitance Cf of the capacitor C_f. If PWM is used, the value of the frequency f is known. If hysteresis-current control is used, the value of the frequency f may be assumed to be equal to an average value for a half-period of the voltage of the AC source. The change of the value of the current through the capacitor, as it is seen in Fig.2, is equal to the change of the current through the inductance. This change may be picked up as a part of the effective value of the load current i_L. Owing to the fact that $|\Delta u_{Cf}|$ is a peak-to-peak value of high frequency AC component put over the output voltage of the filter, $|\Delta u_{Cf}|$ may also be chosen as a part of its effective value. Thus, using (9) the value of the capacitance of the capacitor C_f may be calculated.

3. DESIGN METHOD

The design of the power schema of the SAPF is made using the schema shown in Fig.3.

The following data are assumed as starting data for the design:

- Feeding voltage of the inverter - U_d;
- Load power– S;
- Harmonic coefficient of the AC source voltage – K_H .

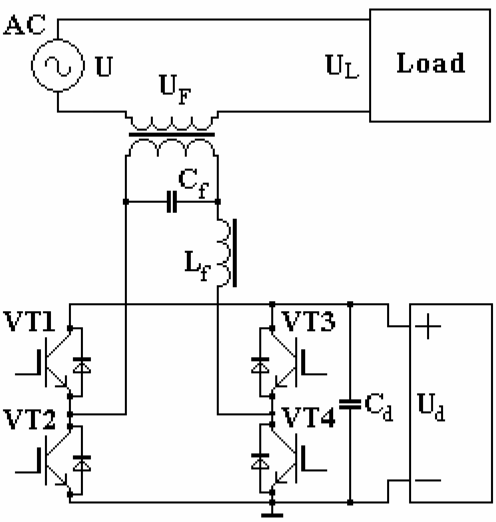

Fig.3. *Schema used to design power part of the SAPF*

The sequence of the design is:

1.Choice of the operational mode of SAPF.

One of the three possible operational modes of SAPF is chosen according to the harmonic coefficient K_H and to the technical conditions of the consumer, as well as to the enforced standards [3].

The most frequently met version is this at which the SAPF eliminates the higher harmonics of the AC source voltage (filtering) as the load is fed with sinusoidal voltage with a frequency equal to the frequency of the fundamental harmonic of the source voltage. Therefore, the primary winding of the output transformer of SAPF will contain only high harmonics. Of course, the last is valid also for the harmonic spectrum of the voltage of the secondary winding. In this case, using [3] the possible decrease in the effective value of the load voltage U_L at the highest value of the coefficient K_H is determined. If a stabilization of the effective value of the voltage of the consumer to a preliminarily set value is required besides the filtering, using [3] the ranges within which the effective value U is changed are determined.

2. Determination of the total power of SPAF (S_F) and of the effective value of the secondary voltage of the transformer (U_F)

When the total power of the load S and the permissible harmonic coefficient are known, the total power of the filter is determined either graphically or analytically [3] corresponding to the chosen operational mode.

The effective value of the load current is known. Therefore, the effective value of the output voltage of the SAPF regarding the AC source (the secondary winding of the output transformer) may be calculated from:

$$I_L = \frac{S}{U};\ U_F = \frac{S_F}{I_L} \tag{10}$$

3. The voltage across the capacitor battery C_d is equal to the set source voltage U_d considering the peak-to-peak value of the ripples ΔU_d.

Usually, the AC source is the network voltage. The effective value of the network is 230V ±10 %. At a peak-to-peak value of the ripples ΔU_d equal to 10% of the value U_d, it is recommended to choose the value of U_d within the range 320÷390V.

This voltage may be obtained using bidirectional transistor converter, using accumulator batteries (through appropriate converters), using photovoltaic cells, etc.

4. The capacity of the capacitor battery C_d is known from the design of the feeding converter ensuring the voltage U_d. Depending on the particular case, the capacity of the capacitor C_d changes within the interval 1000 ÷ 10 000μF.

5. Determination of data required to design the output transformer (Tr) of SAPF

The effective value of the voltage of the transformer secondary side, which is connected in series to the load, is known from (10), but only for the higher harmonics. If stabilization is needed, the effective value of the first harmonic is also calculated. In [6] a trapezoidal approximation of the source voltage is proposed. At this approximation, the value of the angle φ at which the non-parallel side of the trapezium is displaced of the X-axis, for the known harmonic coefficient K_H. The values of the higher harmonics (3, 5, 7,…) are determined for:

$$U_m = U_d \tag{11}$$

According to the standard EN 50160, the values of the higher harmonics have to be calculated to number 25.

Using these data, the effective value of the voltage of the primary winding of the transformer is calculated as:

$$U_{1F} = \sqrt{\sum_{k=2}^{\infty} U_k^2} \tag{12}$$

where in k is the number of the kth harmonic.

The above state is when only filtering is considered. If other operational mode of SAPF is used then the value of the fundamental harmonic has to be added.

Therefore the turn ratio of the transformer is:

$$K_{TR} = \frac{U_F}{U_{1F}}. \tag{13}$$

The effective value of the current through the secondary winding of the transformer is equal to the effective value of the load current.

If the current of the secondary winding and the turn ratio of the transformer are known, the calculation of the current through the primary winding of the transformer is possible.

Up to here, the output data to design the transformer are obtained. After it design, also the total losses of active power has to be calculated, furthermore, an optimization is possible to be made.

6. Design of the low-pass filter C_f, L_f.

Coefficient K_{URMS}, reflecting the influence of the angle φ over the harmonics of the voltage at the chosen trapezoidal approximation, is defined as:

$$K_{URMS} = \frac{2\sqrt{2}}{\pi \cdot \varphi}\sqrt{\sum_{k=2}^{\infty}\frac{1}{(2k-1)^4}\cdot sin^2(2k-1)\cdot \varphi} \quad (14)$$

Fig.4 shows the graphical change of the coefficient.

Used the value of φ obtained through the design method proposed, K_{URMS} is determined either analytically or graphically.

By analogy, coefficient connecting the capacity of the capacitor C_f and the angle φ is defined – equation (15). Fig.5 depicts the graphical presentation of the relationship.

$$K_{Cf} = \frac{2\sqrt{2}\cdot\omega}{\pi\cdot\omega}\sqrt{\sum_{k=2}^{\infty}\frac{1}{(2k-1)^2}\cdot sin^2(2k-1)\cdot\varphi} = \frac{4\sqrt{2}\cdot f}{\varphi}\sqrt{\sum_{k=2}^{\infty}\frac{1}{(2k-1)^2}\cdot sin^2(2k-1)\cdot\varphi} \quad (15)$$

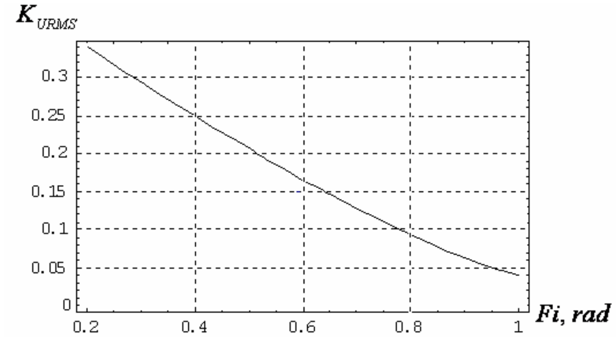

Fig.4. Relationship of the coefficient K_{URMS} from the angle φ

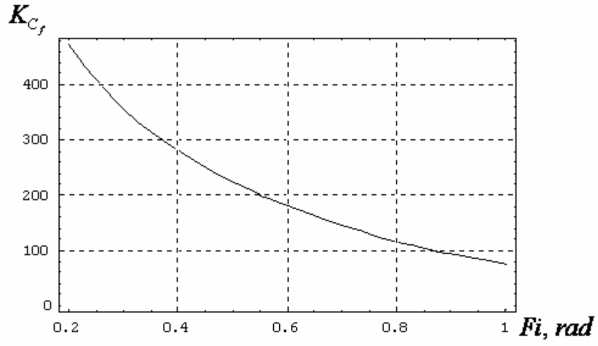

Fig.5. Dependence of K_{Cf} on angle φ regarding (15)

The effective value of the voltage of the AC source (only for the high order harmonics) may be calculated using (14):

$$U_{FRMS} = K_{URMS}\cdot U_m \quad (16)$$

At the assumption that the turn ration of the transformer is equal to 1, i.e. at use only of a decoupling transformer or transformerless connection of SAPF, the maximum value of the kth harmonic of the current trough the capacitor C_f is found as:

$$I_{Cfkm} = U_{Cfkm}\cdot k\cdot\omega\cdot C_f \quad (17)$$

The procedure is analogical when a transformer is included in SAPF.

Thus, the effective value of the high-order harmonics of the current through the capacitor may be calculated as:

$$I_{Cf} = \frac{2\sqrt{2}\cdot U_m\omega C_f}{\pi\varphi}\sqrt{\sum_{k=2}^{\infty}\frac{1}{(2k-1)^2}\cdot\sin^2(2k-1)\cdot\varphi} \quad (18)$$

It is seen from (18) that the variables K_H and I_{Cf} depend on the angle φ. Therefore, at the beginning, at a measured or set harmonic coefficient, this angle has to be calculated as it is shown in [6]. Then, taking in consideration equation (16), after its substitution in (18), it is found:

$$I_{Cf} = K_{Cf}\cdot U_m\cdot C_f \quad (19)$$

Therefore, at a known coefficient K_H, from here also angle φ is known, the coefficient K_{Cf} may be determined. At a known value U_m, the equation (19) gives the relationship between the effective value of the current of the higher harmonics and the capacity value of the filter capacitor C_f. After that the results from the analysis in the chart 2 are used. For this purpose, the value of the switching frequency f is chosen. The ripples ΔU_d has to be chosen within the range 3÷5% of the effective value of the output voltage of SAPF. Thus the peak-to-peak value of the ripples of the current through the capacitor (therefore also of the current through the inductance L_f) is going to be within the range of 5÷10% of the effective value of the load current. Equation (9) is used to calculate the capacity value of the capacitor C_f. The ripples of $|\Delta i_C|$ has to be ensured by calculating the value of the inductance L_f. If the assumption that the operation is without frequency f limitation is made then the maximum value of the frequency will be at the zero crossing point of the network voltage. Then at a chosen $f=f_M$ the value of the inductance may be determined as:

$$L = \frac{U_d}{\Delta i}\cdot\frac{1}{2f_M} \quad (20)$$

The effective value of the current through the transformer is determined taking in consideration that it has three components, namely:

- the first is owing to the higher harmonics to number k = 25, according to the standard EN 50160;
- the second, determined by the ripples with high frequency (see Fig.2.a) and it is equal to $\frac{\Delta i_{C_f}}{2\sqrt{3}}$;
- and the third is taken in consideration only in the cases of stabilization and it is determined by the current with a frequency equal to the frequency of the fundamental harmonic I_{C1}.

The effective value of the first component (I_{Cf}) is calculated from (19). Thus, the effective value of the capacitor current is found as:

$$I_{C_fRMS} = \sqrt{I_{Cf}^2 + I_{C_f1}^2 + \frac{\Delta i_{C_f}^2}{12}} \quad (21)$$

After the values of the filter elements L_f,C_f have been set, the filter resonant frequency is calculated. It has to be within the range of 25th harmonic of the AC source voltage and the switching frequency of the devices.

7. Determination of the output current of the inverter fed by voltage source

This current is the current flowing through the inductance L_f. The equations already found in the point 6 of the design method are used. So:

$$I_{L_fRMS} = I_{C_fRMS} + I_{Tr} \quad (22)$$

where in I_{Tr} is the effective value of the current through the primary winding of the transformer.

To calculate the maximum value of the output current of the converter and the current through the inductance L_f the change of the waveform of the load current I_T regarding the fundamental and high order harmonics of the current I_{Lf} has to be known. Because it is not possible to know this change every time, a method for some of the probable cases to calculate approximately the maximum value of the above stated current.

In all cases one of the components of the maximum value will contain the maximum value of the load current and the half of the ripples:

$$I_{LM}' = I_{LM} + \frac{\Delta i_C}{2} \qquad (23)$$

In case that the SAPF is designed only for filtering, the worst possible version is the coincidence of the maximum value of the load current with the maximum value of the third harmonic. Then, the maximum value of the third harmonic, which may be calculated from (19), is added to the value already calculated from (23). As a result a value $I_{LM}^{''}$ is found. This value may be concerned as the value I_{LM} which is searched for.

If the SAPF is used also for stabilization, the maximum value of the first harmonic of the current through the capacitor (its capacity and the value of the first harmonic of the voltage across it are known up to here) is added to (23). The value found is compared to $I_{LM}^{''}$ and for I_{LM} is taken the highest one. Increase of this value to 10% is recommended to be able to compensate the influence of the transient processes in turning on and also in emergency modes.

After the inductance and the maximum value of the current have been determined, the inductance may be designed. Afterwards, the losses of active power in the inductance are also calculated and an optimization is made.

8. Choice of power devices

The power devices in the schematic of SAPF are chosen according to the following parameters:

- permissible voltage – it has to be higher than U_d. In conformity with the devices offered at the market by the producers, devices with maximum permissible voltage of 600V are appropriate for single-phase SAPF.

- maximum value of the current – calculated in point 7.

- effective value of the current – the power devices conduct in series at every switching over. Thus, it is assumed that each device conducts through time approximately equal to half-period. Therefore, the effective value of the current through a device will be $I_{LfRMS} / \sqrt{2}$, where in I_{LfRMS} is the value of the current calculated in point 7.

- parameters of the power devices concerning their switching – they are chosen in accordance to the maximum switching frequency. This frequency depends on the operational mode chosen.

- power dissipated by the devices – static losses are determined based on the type and the data in the application data of the chosen devices regarding the effective value of the current. Power dynamic losses are calculated based on the average frequency chosen.

- total losses in the SAPF – they are calculated as a sum of the losses in the transformer, in inductance and in the power devices at a maximum load and maximum temperature.

4. EXPERIMENTAL RESULTS

According to the design method proposed, a single-phase precise stabilizer-filter of AC voltage is designed. It is shown in Fig.6 and also it is meant to load with powers to 3kVA. The power of the output transformer is 700VA.

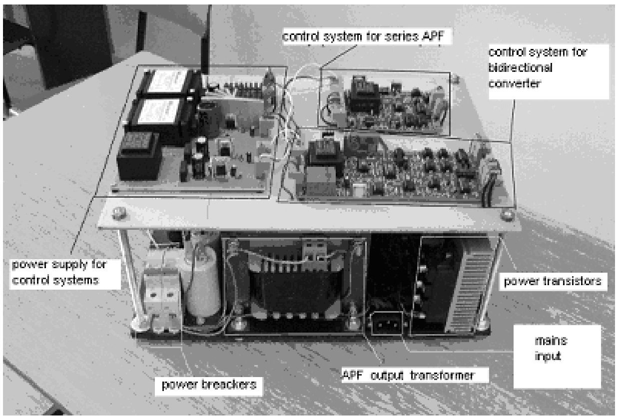

Fig.6. Single-phase precise stabilizer-filter of AC voltage

The inverter is implemented using transistors 2MBI50-060. The value of the capacitor C_f is 5 μF, while the inductance is L_f - 2 mH. The control system is based on hysteresis control.

Fig.7 shows experimental oscilograms at decreased and deformed voltage of the network – left one. Right oscilogram shows the stabilized and filtered voltage that feeds the load.

Fig.8 depicts analogical results at boosted and deformed voltage of the network voltage.

Within the whole range of the change of the network voltage, the value of the voltage feeding the load stays equal to 230 V ± 1.2%. The harmonic coefficient becomes less than 1.7%.

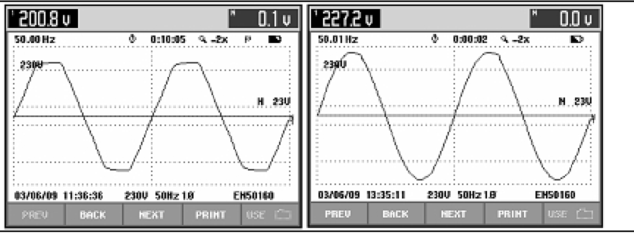

Fig.7. Oscilograms at decreased voltage of the source network

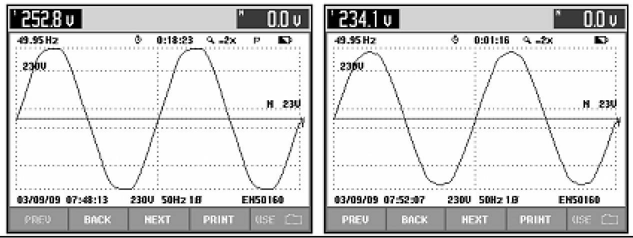

Fig.8. Oscilograms at boosted voltage of the network

5. CONCLUSION

The proposed design method in the paper permits to design the power schematic of SAPF when the total power of the load, effective value of the voltage of AC source and its harmonic coefficient are known. The method is proved by experimental study of single-phase precise stabilizer-filter of AC voltage. The results found may be used also in design of three-phase SAPF.

6. ACKNOWLEGEMENT

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