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# Sampled Method of Active Power Filter Control (Part II)

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***Summary*: The aim of the paper is to demonstrate how to use sampled method of control of a shunt active power filter to maintain invariable power of a supplying voltage source, even though the supplied load varies randomly. The definition by S. Fryze of load current components is used as a basis for the construction of a family of shunt active power filters. The distinctive property of these filters is maintaining non-deformed source current in every one individually considered period *T*.**

**The main features of the family of filters are described in the first part of the paper, which is devoted to *DC* circuit. In the second part, the results are implemented to a single- and a three-phase circuit. Additionally, some new features, which may be applied only for *AC* circuit, are discussed in the second part. All the presented waveforms are obtained using computer simulation tools.**

**Keywords**:
*shunt active power filter*
*power factor*
*power quality*

## 3. ACTIVE FILTER FOR SINGLE-PHASE CIRCUIT

Almost the same structure of the active filter and the same method of obtaining the equivalent conductance $G_{T(n)}$ (Expression 7, Part I) can be used as well in a *DC* as in an *AC* circuit. The difference is, that in an *AC* system the source voltage run is of sinusoidal shape, so there are very convenient moments for synchronizing the filter: at the very end of each period *T* of the source cycle. As in the case of a *DC* circuit, the filter can also balance energy flowing from the source to the load [3]. Additionally, in an *AC* circuit the filter can perform extra functions [2, 3, 4]. Some of these functions are presented in this section.

Figure 19 illustrates, as an introduction, how the active filter “cleans” the source current from the non-active component.

Within the first period $T_1$ of the source cycle, during the time interval $t \in$ (0–20ms), the active filter — operating during the period as source of energy — feeds the load. Beginning from the second cycle of source voltage (period $T_2$), the filter compensates the non-active component in the source, individually in each period $T_n$. The filter “injects” the compensating current into the source branch (waveform 2 in Fig. 20). As for the *DC* circuit, the transfer of energy from the source to the load is delayed for one period *T* (for one cycle of the source run here).

For the example shown in Figure 20 the load current is the same as in Figure 19. The Figure presents the filter capacitor voltage, and then the current which is forced by the active filter through the source. The filter current may be named the “cleaning current.”

The voltage across the capacitor of the active filter follows the power of the load. The impact of the energy stored in the filter’s reactor on the calculation of equivalent conductance $G_{Tn}$ may be neglected as well in *DC* as in *AC* system.

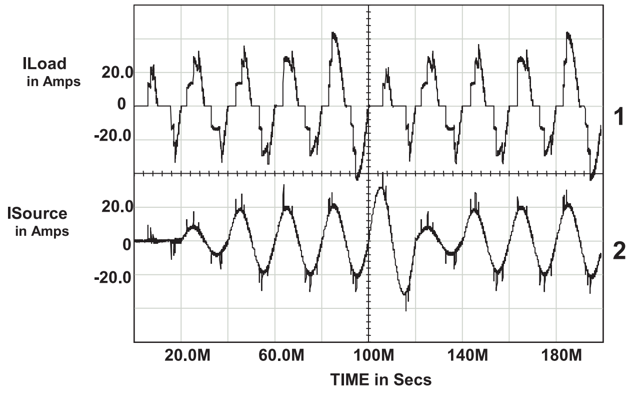

Fig. 19. RMS of load current (waveform 1) for $t \in$ (0–100ms) is 17.7A. *RMS* of source current (waveform 2) for $t \in$ (20ms–120ms) is 15.3A

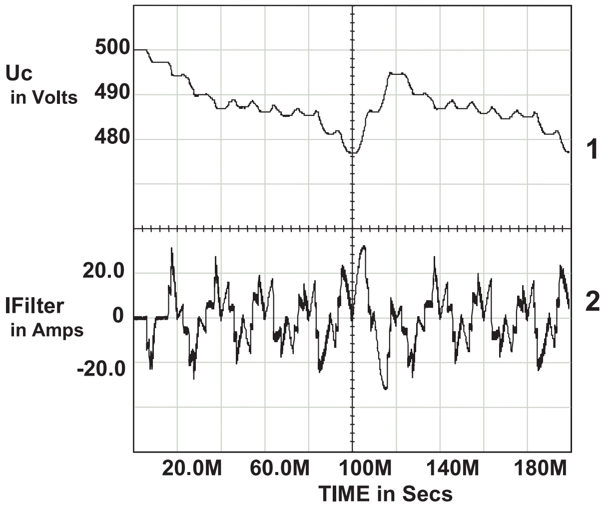

Fig. 20. Filter capacitor voltage (waveform 1), and active filter current (waveform 2, *RMS* in $t \in$ (20ms–120ms) is 12.6A)

### 3.1. Diminishing the coefficient $K_u$

The diminishing the coefficient $K_u$ may be used for reducing of the source apparent power and averaging its changes as well in *DC* (see section 2.1, Part I) as in *AC* system. As a matter of fact, the diminishing of the coefficient $K_u$ inserts some kind of inertia in the active filter acting. This inertial-type response of the filter does not create an inductive-type component in the source current, for the inertia impacts not the source current directly, but rather indirectly modifying the equivalent conductance $G_{T(n)}$ — which is applied only once a synchronization period $T$ (see Expression 7, and Figure 7, Part I).

Figure 21 shows the impact of diminishing the coefficient $K_u$ on current of the source, filter's capacitor voltage, and the equivalent conductance $G_{T(n)}$. *RMS* of the load current (the current is the same as in Figure 19 but in $t \in (0.500\text{ms})$) is 17.5A. When the nominal magnitude of $K_u$ is applied, the *RMS* of the source current decreases to 15.2A, and for $K_u$ reduced by half—even to 14A (Figure 21, waveform 1). The active filter acts with much lower voltage of the capacitor (see Figure 20 waveform 1, and Figure 21 waveform 2).

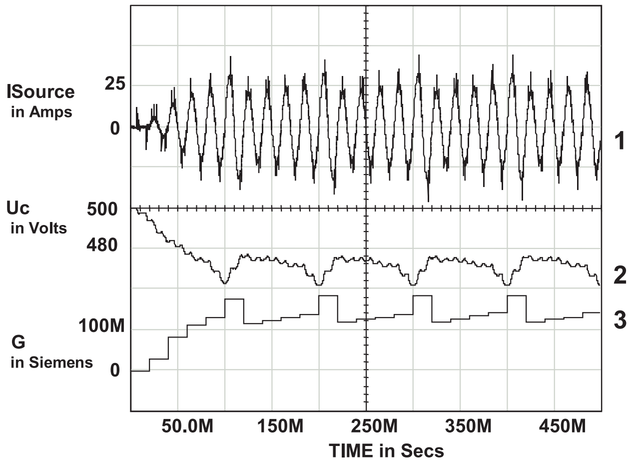

Fig. 21. Source current for $K_u$ reduced by half (waveform 1). Its *RMS* is 14.1A for $t \in (20\text{ms–}500\text{ms})$. Filter capacitor voltage (waveform 2). Load equivalent conductance $G_{T(n)}$ (waveform 3, $t \in (100\text{ms–}500\text{ms})$): average 140mS, standard deviation 22mS. Load current *RMS* is 17.5A

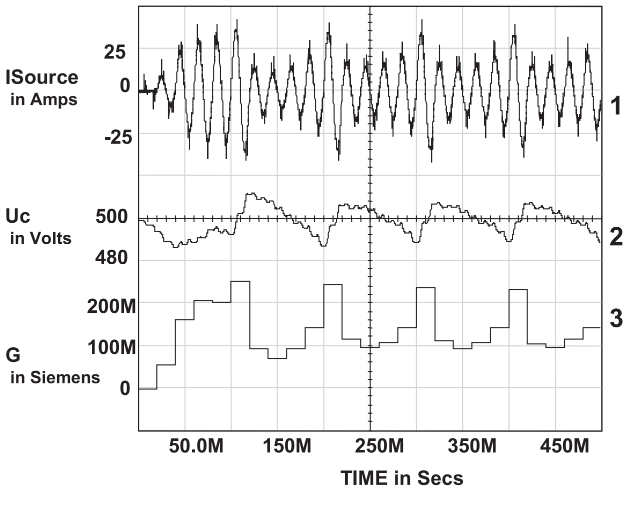

Fig. 22. Source current when $K_u$ is reduced by half and filter capacitor voltage is supplemented, *RMS* is 15.7A (waveform 1, 20ms–500ms); filter capacitor voltage (waveform 2), and then load equivalent conductance $G_{T(n)}$: average 131mS, standard deviation 50mS (120ms–500ms, waveform 3). Load current *RMS* is 17.5A

### 3.2. Supplementing the filter capacitor voltage

The procedure of supplementing voltage across filter's capacitor may be also used for the active filter working in *AC* system. Unfortunately, if applying this procedure, the *RMS* of the source current may increase due to a forced by the active filter additional source current component, which maintains the capacitor voltage near its initial value $U_{C0}$. During the work of the active filter, the capacitor voltage may go higher then the initial magnitude $U_{C0}$. The capacitor must be uncharged by an extra current flowing through the capacitor and the source, and the *RMS* of source current increases for this reason. The related effect is shown in Figure 22. Compare waveforms from this Figure to those shown in Figure 21. Load current is the same as for examples shown in Figure 19.

In an *AC* system supplementing of the capacitor voltage may be more useful then in a *DC* system. The active filter may not only compensate non-active current of load, but may be also used as a rectifier for an extra *DC* load. The *DC* load may be connected in parallel to the filter's capacitor *C* [2, 4]. The way of controlling the source current is the same for the "pure" active filter and for the active filter/rectifier. So, the additional source current component, which carries energy from the source through the active filter/rectifier to the extra *DC* load, is still of sinusoidal shape and in-phase with the source voltage (not shown in figure). Such type of rectifier can act with high power factor.

### 3.3. Lengthening of synchronization period

This is another method considered for improving the source work (see Section 2.3, Part I). The method may average changes of the source current when load power varies. Figure 23 shows the equivalent conductance $G_{T(n)}$ obtained by the active filter for various lengths of synchronization period $T$.

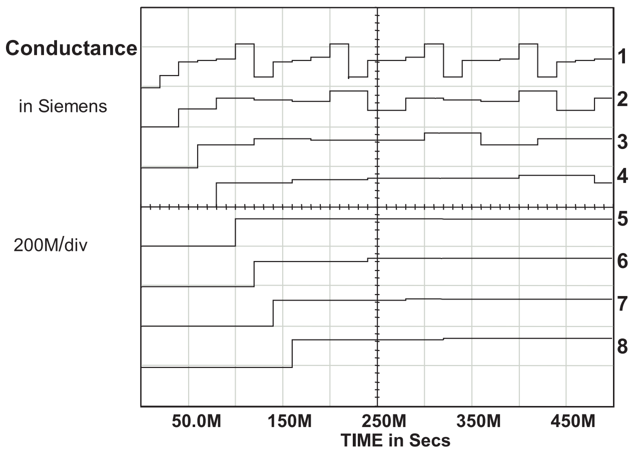

Fig. 23. Load equivalent conductance $G_{T(n)}$ from $T = 20\text{ms}$ (waveform 1) till $T = 160\text{ms}$ with step 20ms

For example, when period $T$ equals 20ms the average value of the conductance (waveform 1) is 134mS and its standard deviation is 51mS, then for $T = 40$ms (waveform 2) the conductance is 134mS and its standard deviation is 32mS, for $T = 60$ms (waveform 3): 136mS and 19mS, respectively.

Supplementing of the filter's capacitor voltage may increase *RMS* of the source current in the similar way as is described in the example shown in Figure 22.

### 3.4. Frequency characteristic of load and source current

Spectrum of load and source currents, related to the foregoing examples, is shown in the next figure (Fig. 24).

The first waveform shows the characteristic of load current and is related to the waveform 1 in Figure 19. The second waveform is obtained when basic arrangement of the active filter (without modifying $K_u$ and $T$, and without supplementing the capacitor voltage) is used, and is associated with the waveform 2 in Figure 19. Waveform 3 is related to waveform 1 in Figure 21, when the active filter acts with the coefficient Ku reduced by half. Waveform 4 is obtained when period $T$ equals 80ms and is associated with waveform 4 in Figure 23.

Waveforms 2–4 in Figure 24 show, that methods described in this section, may be useful for "cleaning" the source current from non-active current components.

### 3.5. Forcing predefined power factor

Since this mode of operation of the active filter may be applied only to an *AC* system, it was not considered in the section devoted to *DC* circuit.

In *AC* circuit a sinusoidal non-active current component of fundamental frequency, usually of inductive type, is very often included in the total source current. Its complete compensation is often dispensable, because in many cases some magnitude of this current component is tolerated under permission of electric utility companies. In this situation the power factor of the compensated load can be controlled or kept constant a little less then the ideal power factor, which should be as near unity as possible. Such action is beneficial, because the active filter current can be lowered, so power of the active filter and its energy losses can be diminished [2, 4].

Incomplete compensation of non-active current component of fundamental frequency may be described using the tangent function as:

$$tg\,(\varphi) = \frac{I_q}{I_p} = const \tag{17}$$

The reference run for the inductive component to be left in the source current within $T_n$ period of source cycle may be expressed like:

$$i_{qref,T(n)} = \mathbf{1}_L \sqrt{2} G_{T(n-1)} U_s \, tg\,(\varphi) \tag{18}$$

where:

$\mathbf{1}_L$ — is sinusoidal inductive current component with the unitary amplitude.

This inductive current component reference should be added to the active current reference, and then treated by the filter as the new total reference run. The example-effect, when the Expression (18) is put to use, is shown in Figures 25 and 26. The $tg(\varphi)$ factor is set to magnitude 0.3.

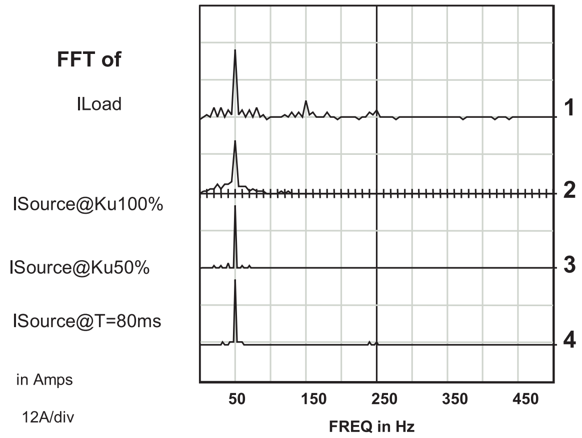

Fig. 24. Spectrum of load current (waveform 1), source current when basic arrangement of active filter is used (waveform 2), source current when $K_u$ is reduced by half (waveform 3) and source current when period $T$ is lengthened to 80ms (waveform 4)

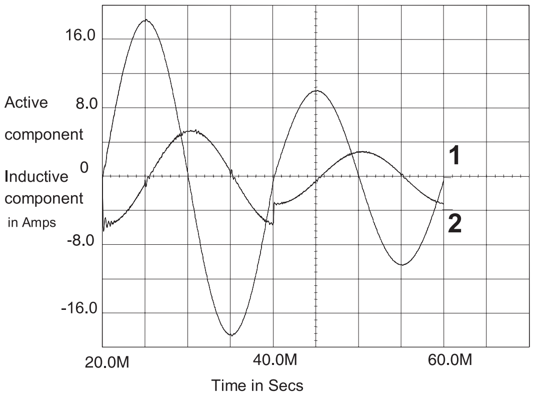

Fig. 25. Two current reference waveforms: load active component (waveform 1) and then inductive component (waveform 2) to be left in source current at $tg(\varphi) = 0.3$

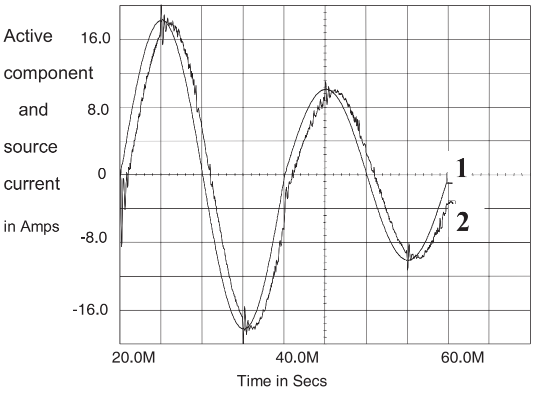

Fig. 26. Load active current (waveform 1), and source current (waveform 2) with inductive component. Waveform 2 is realized by active filter as sum of waveforms shown in Fig. 25

The active filter can also be controlled to generate a non-active current component (either of inductive or capacitive type) with constant (as in Expression 17) or variable $I_q/I_p$ ratio.

### 3.6. Work of active filter switches

When the active filter acts, both of the source parameters: current vector $\underline{I}_s$ and voltage vector $\underline{U}_s$ have the same direction. If there is no *AC* load but *DC* load is present, fed from the active filter capacitor, source current is equal to filter current: $i_s = i_F$. The active filter acts as a rectifier drawing input current of sinusoidal shape and in phase with source voltage. If $i_{Ls} \neq 0$ (*AC* load is present) then $i_F \neq i_s$, and direction of source current can be different from direction of filter current. In this case the active filter compensates non-active current, and simultaneously acts as a rectifier. The following cases can be specified:

a) $u_s \geq 0$ and *PA-NB* pair is in state *ON*;
b) $u_s \geq 0$ and *NA-PB* pair is in state *ON*;
c) $u_s < 0$ and *PA-NB* pair is in state *ON*;
d) $u_s < 0$ and *NA-PB* pair is in state *ON*.

Let's look carefully the cases.

**The case a).**

The formula (8, Part I) can be rewritten ($\sigma$ is equal to –1) as:

$$\frac{di_s}{dt} = \frac{u_s + (-1)u_c}{L} + \frac{di_{Ls}}{dt}$$

Taking into account that $u_{c\,min} > \sqrt{2}U_s$ we have:

$$\frac{u_s - u_c}{L} < 0$$

The following three cases are possible now:

$$\alpha) \qquad \left|\frac{u_s - u_c}{L}\right| > \left|\frac{di_{Ls}}{dt}\right|$$

$$\beta) \qquad \left|\frac{u_s - u_c}{L}\right| < \left|\frac{di_{Ls}}{dt}\right|$$

$$\gamma) \qquad \left|\frac{u_s - u_c}{L}\right| = \left|\frac{di_{Ls}}{dt}\right|$$

**The case $\alpha$).**

The derivative $\frac{di_s}{dt}$ is negative, what results from the filter decision: source current $i_s$ should be decreased.

**The case $\beta$).**

The filter's control circuit requires negative value of the derivative $\frac{di_s}{dt}$, however this demand will not become realised if derivative $\frac{di_{Ls}}{dt}$ will be positive. Just the opposite of waited fall, source current increases. The filter counteracts enlarging the source current, keeping in state *ON* the pair of switches which cause negative value of the derivative of source current: the *PA-NB* pair in this situation.

After a "saturation" of *AC* load current $i_{Ls}$, the active filter diminishes source current until of moment, when the difference between the load active current reference and source current meets the point, at which the second pair of switches is turned on. The described occurrence is visible as a short duration increase of source current, and fall of filter current $i_F$ (see Figs 27 and 28 shown below).

**The case $\gamma$).**

The filter activity in this case results from description in points $\alpha$) and $\beta$).

**The case b).**

The formula (8, Part I) can be rewritten ($\sigma$ is equal to +1) as:

$$\frac{di_s}{dt} = \frac{u_s + 1 \cdot u_c}{L} + \frac{di_{Ls}}{dt}$$

It should be noticed that:

$$\frac{u_s + u_c}{L} > 0$$

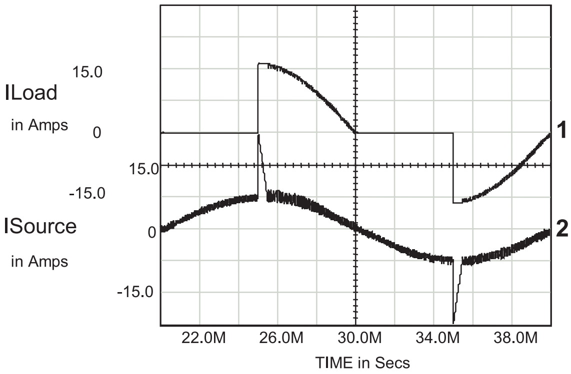

Fig. 27. Example of *AC*-side load current $i_{Ls}$ (waveform 1) and source current is (waveform 2). The active filter is acting

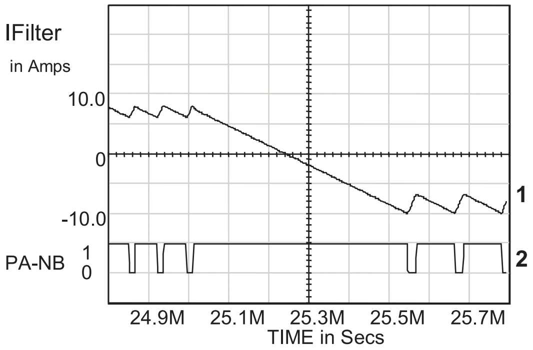

Fig. 28. Filter current $i_F$ (waveform 1) and control signal of *PA-NB* pair of switches (2)

The control circuit demands positive source current, that means source current should increase. Taking under attention sign and value of the derivative $\frac{di_{Ls}}{dt}$, the analogous reasoning as in points a), b), g) can be passed.

**The case c).**

In this situation $u_s < 0$, and the pair *NA-PB* is in state *ON*. The formula (8, Part I) looks as follows:

$$\frac{di_s}{dt} = \frac{-u_s + (-1)u_c}{L} + \frac{di_{Ls}}{dt}$$

From figure of the formula we can infer that the control circuit undertakes a decision to enlarge absolute value of source current. The meaning of component $\frac{di_{Ls}}{dt}$ is as above.

**The case d).**

Source voltage is negative $u_s < 0$, the *NA-PB* pair of switches is in state *ON*. The figure of formula (8, Part I) is as follows:

$$\frac{di_s}{dt} = \frac{-u_s + u_c}{L} + \frac{di_{Ls}}{dt}$$

Remembering that $u_{c\,min} > \sqrt{2}U_s$ we ascertain that the control circuit aims to diminish absolute value of source current.

As a conclusion it should be noticed, see points a) and b), that if source voltage is positive (or equal to zero) turning the pair *PA-NB* in state *ON* causing that the filter current $i_F$ is diminished, and, if the component $\frac{di_{Ls}}{dt}$ can be skipped, the source current is also decreased. Switching on the pair *NA-PB* causes increasing the filter current, and, possibly, the source current. If the source voltage is negative, then — see points c) and d) — turning the pair *PA-NB* on causes that the filter current (and perhaps the source current) increase (in absolute value); and turning on the pair *NA-PB* instead causes that the filter current (and possibly source current) fall down. So we can see that the function of the pairs of switches depends on sign of source voltage.

One can prove that a pair of switches is in *ON* state during (approximately) the time $t_s$:

$$t_s \approx \left| \frac{2\Delta IL}{u_s - \sigma u_c} \right| \tag{19}$$

where $\Delta I$ is a tolerance band around the reference current. The shortest $t_s$ periods are expected when:

a) $u_s = u_{s\max}$, $\sigma = -1$,

b) $u_s = -u_{s\max}$, $\sigma = +1$.

Besides, the case when:

c) $u_s = 0$, and: $\sigma = +1$ or $\sigma = -1$

should be taken under attention.

**Ad a).**

This means, that source voltage is positive (and even has the maximum value), and the pair *PA-NB* is turned on.

$$t_{s\,min,PA-NB} \approx \frac{2\Delta IL}{u_{s\,max} + u_c} \tag{20}$$

and the time period when the pair *NA-PB* is turned on is approximately equal to:

$$t_{s,NA-PB} \approx \left| \frac{2\Delta IL}{u_{s\,max} - u_c} \right| \tag{21}$$

It can be noticed, that:

— $t_{s\min,PA-NB} < t_{s,NA-PB}$,

— the sign of the total voltage in the denominator of the (20) formula is of the same sign as the source voltage sign;

— the sign of the total voltage in the denominator of the (21) formula has the opposite sign compare with the source voltage sign.

**Ad b).**

In this case the source voltage is negative (reaches its minimum value), and the pair *NA-PB* is in state *ON:*

$$t_{s\,min,NA-PB} \approx \left| \frac{2\Delta IL}{-u_{s\,max} - u_c} \right| \tag{22}$$

The time period when the opposite pair of switches (*PA-NB*) is turned on is nearly equal to:

$$t_{s,PA-NB} \approx \frac{2\Delta IL}{-u_{s\,max} + u_c} \tag{23}$$

It is visible, that:

— $t_{s\min,NA-PB} < t_{s,PA-NB}$,

— the sign of the total voltage in the denominator of the (22) formula is of the same sign as the source voltage sign;

— the sign of the total voltage in the denominator of the (23) formula has the opposite sign compare with the source voltage sign.

**Ad c).**

In this case:

$$t_{s,PA-NB} \approx \frac{2\Delta IL}{u_c}, \qquad t_{s,NA-PB} \approx \left| \frac{2\Delta IL}{-u_c} \right|$$

It should be noticed, that:

— $t_{s,NA-PB} = t_{s,\ PA-NB}$

— the sum of ts the time periods: ($t_{s,PA-NB} + t_{s,NA-PB}$) is the shortest here, so the switching frequency is here the greatest.

From passed above discussion results, that in some cases - namely, when in the denominator of the formula (19) the sign of the total voltage is of the same sign as the source

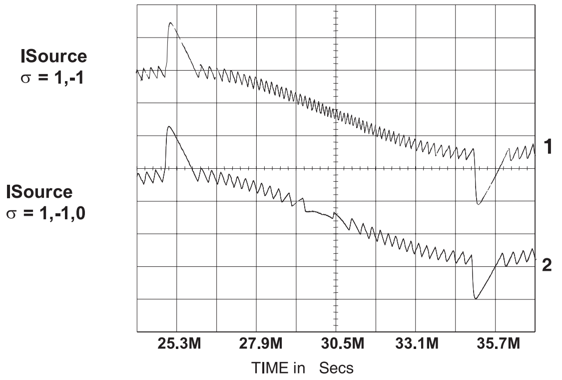

Fig. 29. Source current before and after introducing the additional $\sigma = 0$ state of switches work

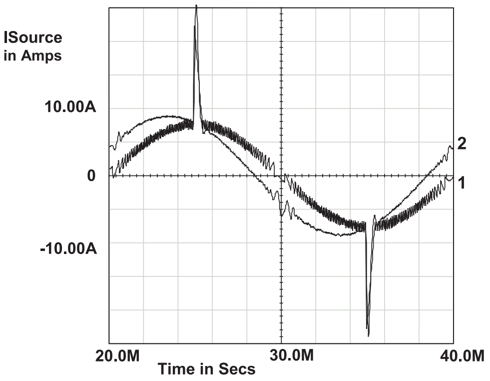

Fig. 31. Source current waveform before passive filtration, and with the passive filter. Three-state control method with the $\sigma = 0$ state is used

voltage—exist the possibilities of extension of the time period in which the given pair of switches is in state *ON*. It can be done by substituting the sum of voltages ($u_{s\max} + u_c$ ) only by the voltage $u_{s\max}$. Using above awareness it is possible to diminish the switching frequency in the area, for which the frequency has the greatest magnitude: when source voltage is nearly zero. To execute this idea the pair *NA-NB* (or the pair *PA-PB* that leads to the same effect) should be turned on in required period of time. Result obtained in this way is shown in Figure 29.

Using the three-state control by introducing the new state of the filter switches work, namely $\sigma = 0$ — see the (8, Part I) and (9, Part I) formulae — when either the pair *NA-NB* or *PA-PB* is turned on, is profitable due to reduction of frequency of the filter switches work. In the most critical area before, when the source voltage is nearly zero, the pairs *NA-PB* and *PA-NB* are almost not switched. Losses of energy across the active filter switches may be reduced in this way.

### 3.7. Reduction of current distortions in source branch

The amplitude of high frequency current component, appearing in the source current during the operation of the active filter, can be reduced.

This may be effected using two principal methods: filtration of current and/or reducing the tolerance band around the reference current. The circuit shown in Figure 30 outlines the idea of the filtration method.

The shown passive filter consists of the capacitor *CF*, the in parallel resistor *RR* and the damping in series resistor *RF*. The passive filter, connected in parallel to the active filter, reduces the “from active filter” high frequency current component in the source branch. It may be based on a capacitor instead of the tuned *LC* circuit because of the range of frequency rather then the single frequency of the operation of switches in an active filter.

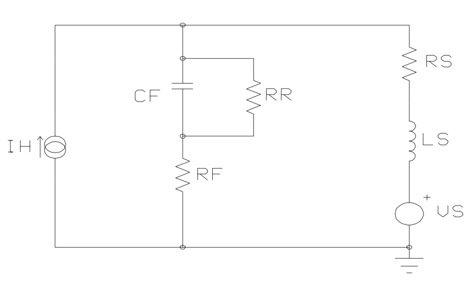

Fig. 30. Schematic of shunt passive filter and its location within the circuit.

The result of the passive filtration is illustrated in Figure 31. The “thick” waveform (with the tag 1) shows the source current without, and the “thin” waveform (with the tag 2) with the passive filter. As one can see, the amplitude of high frequency component has been considerably reduced, but in the source current appears a new component of the capacitive type.

As mentioned earlier, the active filter is able to operate with a predefined power factor, so it can compensate current of the passive filter. This active and passive filter co-operation is illustrated by the first waveform in Figure 32.

Equation (8, Part I) implies that the lower input inductance of the filter is used (or the higher voltage is applied across the active filter capacitor), the more dynamically can the active filter shape the current in its own and in the source branch. Unfortunately, it increases the commutation frequency of the filter switches, and more power is consumed by the active filter.

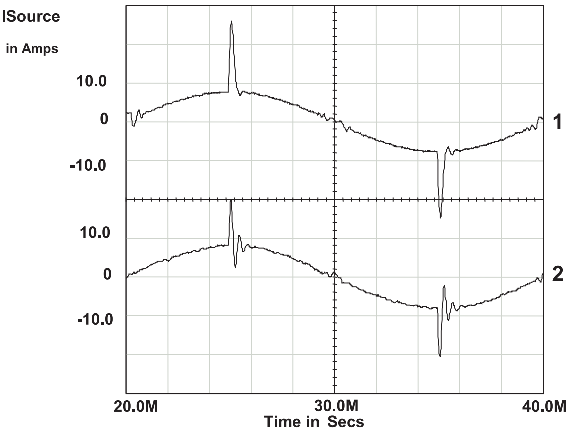

Fig. 32. Source current waveform when the passive filter is present, the capacitive current component is compensated, the three-state control is used; and then (the second waveform) lower reactor of the active filter is applied ($L$ = 2mH instead of $L$ = 5mH)

However, using the three-state control method (with $\sigma = 0$ state) the active filter input inductance $L$ can be lowered without increasing the switching frequency. It gives an opportunity to reduce the amplitude of the current pulses at the moments when the load rapidly changes. The effect achieved on this way is shown in Figure 32: see the difference of current transients between the both waveforms. This effect may be considerably improved if the compensated load can be connected to the source through a reactor. The active filter has a little more time available to reduce the current transient in this case.

The other way of reducing the current distortions, using an additional input reactor together with an additional switching leg in the active filter, is described in section 2.5 (Part I).

## 4. ACTIVE FILTER FOR THREE-PHASE SYSTEM

### 4.1. Introduction to three-phase shunt compensation

The nature of the non-active current components is more complex in a three-phase circuit than in a single-phase circuit. This is due to a possible asymmetry of the load or source. The active power $P$ of a three-phase load is:

$$P=\sum_{k=1}^{k=3}P_k=\frac{1}{T}\sum_{k=1}^{k=3}\int_{T}^{\tau+T}u_k i_k\,dt \qquad (24)$$

According to definition of S. Fryze, an active component flowing through the $k$-th phase of a three-phase circuit is:

$$i_{pk}=\frac{P}{\sum\limits_{k=1}^{k=3}U_k^2}u_k=G_T u_k \qquad (25)$$

and the total current of the phase $k$ is:

$$i_k=i_{pk}+i_{qk} \qquad (26)$$

where $i_{qk}$ is non-active component in the phase $k$.
From (24) and (26) we obtain:

$$P=\frac{1}{T}\sum_{k=1}^{k=3}\int_{\tau}^{\tau+T}u_k(i_{pk}+i_{qk})dt=P+\frac{1}{T}\sum_{k=1}^{k=3}\int_{\tau}^{\tau+T}u_k i_{qk}\,dt \qquad (27)$$

One can see, that:

$$\frac{1}{T}\sum_{k=1}^{k=3}\int_{\tau}^{\tau+T}u_k i_{qk}\,dt=0 \qquad (28)$$

The sum (28) is equal to zero when each addend equals zero or when they compensate each other. A phase current component need not to be orthogonal to its source phase voltage to be non-active current component (see filter currents in phase 1 and 2 in Figure 34, since these currents compensate non-active components, they are reversed non-active current components of the load). This is the reason that a combination of single-phase filters cannot eliminate this type of non-active current components. Therefore, given the three-phase utility grid, three-phase filters are very useful or even indispensable.

A three-phase shunt active filter can distribute active power evenly among each phase of the load (Expr. 25) and corrects asymmetry of the load. Figures 33, 34 and 35 illustrate a case of highly asymmetrical load. The load is pure resistive ($R_1 = 5\Omega$, $R_2 = 20\Omega$ and $R_3 = 1\mathrm{Meg}\Omega$), and is of the star connection. Figure 33 shows that asymmetrical, even resistive-type load, forces non-active current component through the source, which looks like capacitive (waveform 4) or inductive (waveform 5) type.

Figure 34 shows currents in each of the three phases of he active filter belonging to the presented family of synchronized filters. During the first period T of the source cycle in phase 1 the filter feeds the load. Starting from the beginning of the second period (in respect to phase 1) the filter makes the non-symmetric load to be seen by the source as the symmetric one. In particular, the filter forces active current in the phase 3, which is, practically, opened (see waveforms shown with the same tag 6 in Figures 33, 34, 35.

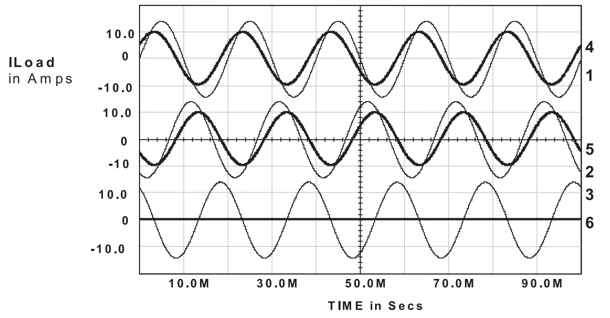

Fig. 33. Source voltages (waveforms 1, 2, 3) and load currents (waveforms 4, 5, 6)

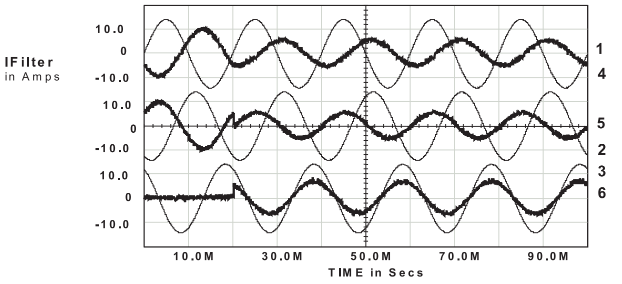

Fig. 34. Source voltages (waveforms 1, 2, 3) and active filter currents (waveforms 4, 5, 6)

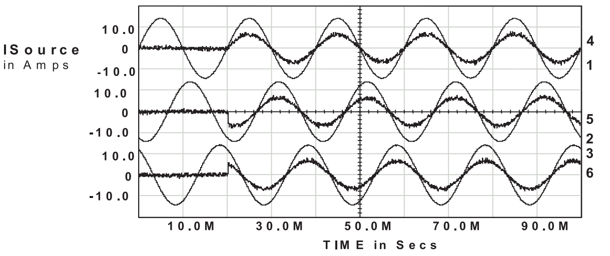

Fig. 35. Source voltages (waveforms 1, 2, 3) and source currents (waveforms 4, 5, 6)

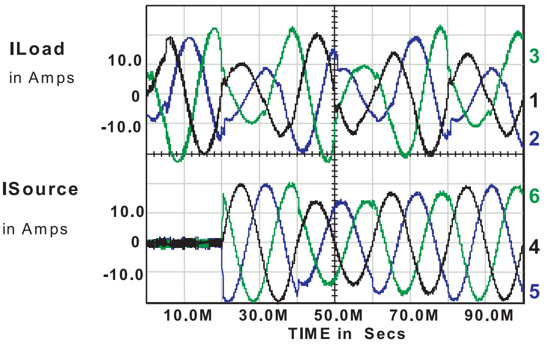

Fig. 36. Load currents and source currents

The voltage of the capacitor of the active filter contains information on the active power of load. The equivalent conductance of load is obtained in the same way as for a *DC* and for an *AC* single-phase circuit. Voltage across the capacitor of the filter is sampled once a synchronization period, and then the voltage is used for calculating the equivalent conductance $G_{T(n)}$. The equivalent conductance relates to all three phase and is valid, for basic arrangement of the filter, only within a single synchronization period *T*.

Figure 36 shows an example of non-linear load. The filter betters shape of source's currents, but can maintain non-deformed current only in one source's phase. This fault is clearly visible first of all at $t \approx$ 20ms, and also at $t \approx$ 40ms and $t \approx$ 80ms (waveforms 4, 5, and 6).

### 4.2. Shaping source current

There is a difficulty related to the synchronization of the three-phase active filter, because there is no really suitable point to apply the equivalent conductance: each phase k of the source starts its cycle at a different moment. Choosing one phase as the source of synchronization we agree, that the process of synchronization may deform currents in two of the source's phases if there is a difference between two "neighbour" equivalent conductances: $G_{T(n)} \neq G_{T(n+1)}$. This case is illustrated in Figure 37, which corresponds to Figure 36. The filter is synchronized by voltage of phase 1 at $t = 40$ms.

The synchronization fault can be alleviated by application the introduced for *AC* circuit some kind of inertia to the active filter action, for example by diminishing the coefficient $K_u$. The diminishing of the coefficient $K_u$ has been described in sections 2.1 and 3.1 (Part I). The inertia spreads in time the response of the active filter on sudden changes of power of load. Figure 38 shows, that if the diminishing method is applied, the synchronization point of the filter may be almost invisible in waveforms of currents of source.

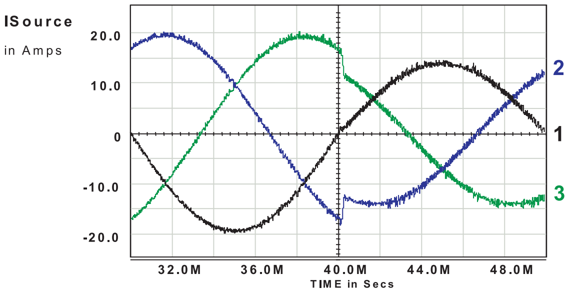

Fig. 37. Source currents, $G_{T(n)} \neq G_{T(n+1)}$. Coefficient $K_u$ is nominal

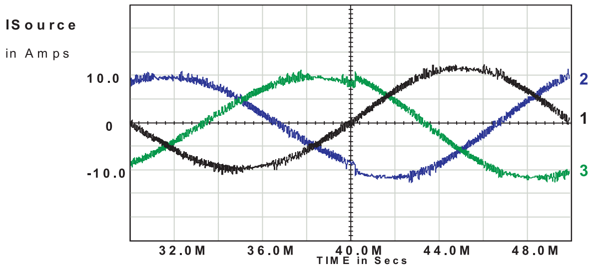

Fig. 38. Source currents, $G_{T(n)} \neq G_{T(n+1)}$. Coefficient Ku is diminished

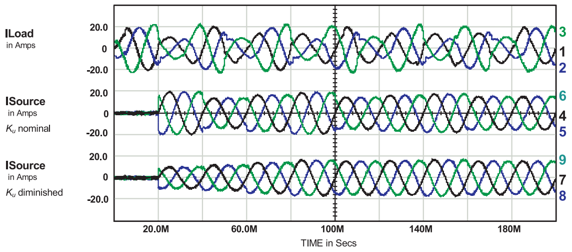

Fig. 39. Stabilizing source currents. Load currents (1, 2, 3); source currents if nominal value of coefficient *K* is applied (4, 5, 6); and currents of source (7, 8, 9) after diminishing of the coefficient $K_u$ by half

Diminishing the coefficient $K_u$ implies more regular run of source currents, as is shown below.

Waveforms marked 4, 5, 6 are without the inertial response of the filter, and waveforms 7, 8, 9 are with the inertial response. Waveforms 1, 2 and 3 illustrate currents of the load. Looking at the waveforms 4, 5, 6 and 7, 8, 9 we can see, that when the coefficient $K_u$ is diminished, source's currents start having lower amplitudes (see also Figures 37 and 38), and then they have more regular shape.

The following set of data also describes the example shown in Figure 39. The waveforms tagged as (1), (4), and (7) are connected with phase 1, the waveforms (2), (5), and (8) with phase 2, and the waveforms (3), (6), and (9) with phase 3.

*Base frequency characteristics for voltage and current in phase 1:*

*Source voltage Phase: –2.0deg*

| | |
|---|---|
| *Load current* | |
| *THD:* | *17%,* |
| *RMS:* | *10.7A,* |
| *DC comp.:* | *1A,* |
| *50Hz comp.:* | *15.7A,* |
| *Phase* | *– 8deg* |
| *Source current* | |
| *THD:* | *1%,* |
| *RMS:* | *9.8A,* |
| *DC comp.:* | *0A,* |
| *50Hz comp.:* | *15.4A,* |
| *Phase* | *–2deg* |

*Base frequency characteristics for voltage and current in phase 2:*
*Source voltage Phase: –125 deg*
*Load current*
*THD: 34%,*
*RMS: 9.7A,*
*DC comp.: –0.5A,*
*50Hz comp.: 13.9A,*
*Phase: –121deg*
*Source current*
*THD: 1%,*
*RMS: 9.7A,*
*DC comp.: 0A,*
*50Hz comp.: 15.5A,*
*Phase: –122 deg*

*Base frequency characteristics for voltage and current in phase 3:*
*Source voltage Phase: 118.0 deg*
*Load current*
*THD: 36%,*
*RMS: 12.1A,*
*DC comp.: –1A,*
*50Hz comp.: 16.6A,*
*Phase: 121deg*
*Source current*
*THD: 2%,*
*RMS: 9.7A,*
*DC comp.: 0A,*
*50Hz comp.: 15.4A,*
*Phase: 118 deg*

The active filter may work using a self-regulation algorithm (see section 2.2, Part I). When the coefficient $K_u$ is lowered, the source acts stabile even if power of the load varies. Note, that even then the coefficient $K_u$ varies continuously, it affects the source currents not continuously, but only at the moments of synchronization of the active filter.

From the other hand, if work of the load does not vary in some neighbour periods, the inertia in the filter's response should be diminished. The parameter $\lambda$ should increase, and thus the higher coefficient $K_{uvar}$ should be calculated and applied.

The effect of this way of control of the filter is illustrated in Figure 40. The power of the compensated load changes periodically in each phase of the load, as is shown by waveform tagged (1), (2) and (3). The waveform tagged (4) shows the equivalent conductance $G_{T(n)}$ when the constant coefficient $K_u$ is replaced by the load-dependent coefficient $K_{uvar}$. Changes of the equivalent conductance are diminished.

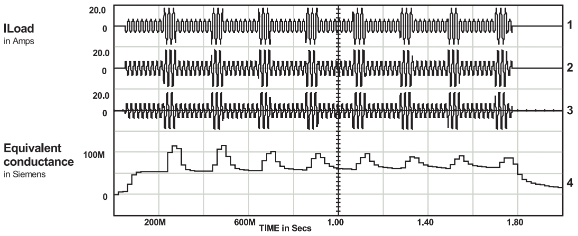

Fig. 40. Load currents and equivalent conductance $G_T$ of compensated load

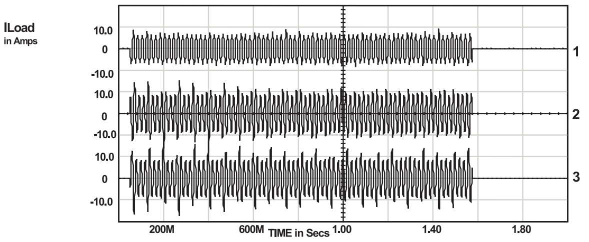

Fig. 41. Load currents

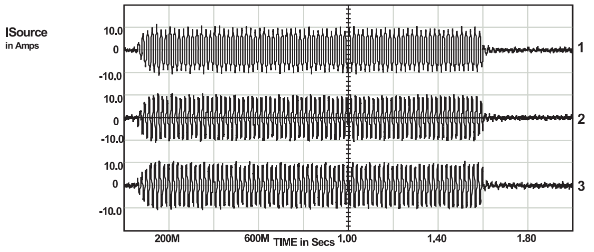

Fig. 42. Source currents

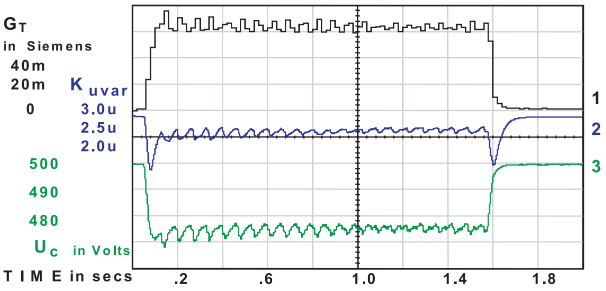

Fig. 43. Equivalent conductance $G_T$ (waveform1), coefficient $K_{var}$ (waveform 2), voltage of capacitor of filter (waveform 3)

The next three figures present an example of complete cycle (start-work-end) of work of the circuit consists of source, active filter and compensated load. The active filter acts with the load dependent coefficient $K_{uvar}$. The load is both asymmetrical and non-linear, and power of the load changes randomly. Figure 41 shows currents of the load. Currents of the source, in each phase respectively to the Figure 41, are illustrated in Figure 42.

The next Figure, tagged 43, relates to Figure 4 and Figure 42. The equivalent conductance of the load (waveform 1), the coefficient $K_{uvar}$ (waveform 2), and voltage of the filter's capacitor (waveform 3) are illustrated in this Figure. All the mentioned profitable trends, that means averaging of the equivalent conductance, and both rising and averaging of voltage of the active filter's capacitor, are presented in this example.

### 4.3 Stabilizing source power

Figure 44 presents power of load in a case of the resistive-type and asymmetrical load, with one phase, tagged 3, off (see also Figures 33, 34, and 35).

In Figure 45, which corresponds to Figure 44, we can see the power in source's phases (waveforms 3, 2, and 1) and the total power of the three-phase source (waveform 0) when the active filter is acting. From the source's point of view the

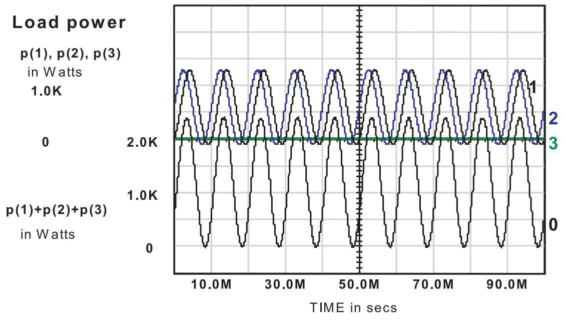

Fig. 44. Load power in phases 1, 2, and 3 (waveform1, 2,and 3), and then total power $p_{\text{tot}} = p(1) + p(2) + p(3)$ (waveform 0)

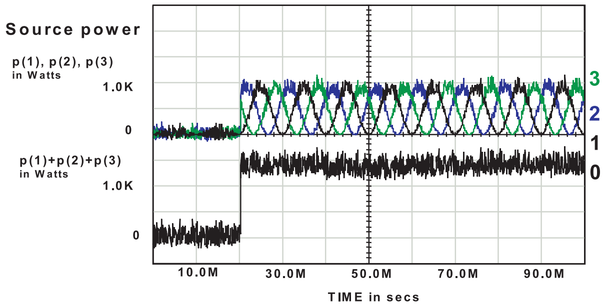

Fig. 45. In-phases (waveforms 1, 2, and 3) and total power of source (waveform 0)

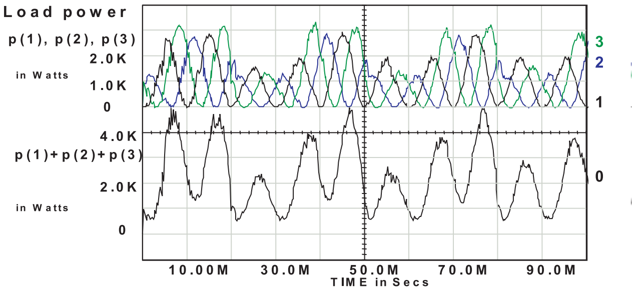

Fig. 46. Load power in each phase: $p(1)$, $p(2)$, $p(3)$, and total power of load $p_{tot} = p(1) + p(2) + p(3)$

active filter symmetrizes the load. It acts as an energy buffer and eliminates the pulsating component from the source's power run. The conversion of energy from its primary form (from a mechanical, or chemical, or any other form), into the electrical form (such conversion in fact does any source of electric power), goes on homogeneously, alike in case of a *DC* source feeding invariable load. The supply of the primary form of energy processes with constant rate, what may be very profitable.

The effect of stabilizing of the total power of source may be observed of course in case of a non-liner load. Figures 46 and 47 illustrate such a case. Figure 46 shows power in each phase of load (waveforms 3, 2, and waveform 1), and then the total power $p(1) + p(2) + p(3)$ of load (waveform 0).

Figure 47 presents source power in each phase individually (waveforms 7, 6, and 5), and then the total power of source (waveform 0). The coefficient $K_u$ is nominal here, so the total power of source contains relatively large oscillating component.

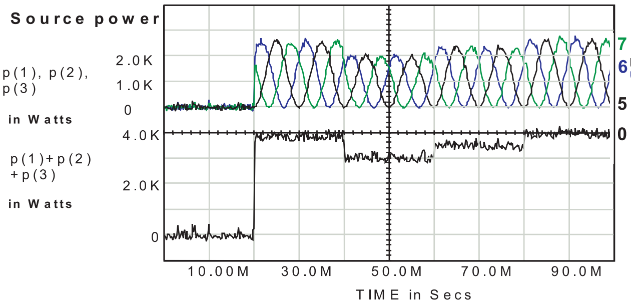

Fig. 47. Source power in each phase: $p(1)$, $p(2)$, $p(3)$, and then total power of source $p_{tot} = p(1) + p(2) + p(3)$

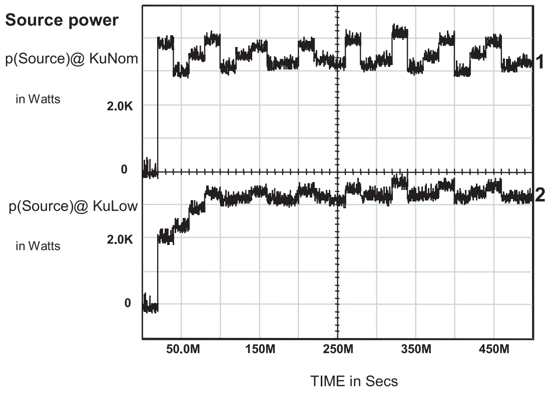

Fig. 48. Source total power: $p_{tot} = p(1) + p(2) + p(3)$ at nominal coefficient $K_u$ (waveform 1), and then at $K_u$ reduced by half (waveform 2)

Figure 48 makes possible comparing the total power of source when the active filter acts without the inertial response (the coefficient $K_u$ is set to the nominal level in this case, waveform 1), and then with the inertial response ($K_u$ reduced by half, waveform 2).

When the coefficient $K_u$ is set to the nominal level, the average level of the total power of source equals 3.47kW. The standard deviation of the source power reaches 350W. These two parameters, the total power and its standard deviation, are measured within time period $t \in$ (100ms, 500ms), for the active filter acting with the reduced coefficient reaches the steady state beginning from the moment about 100ms. But the total power of source can be much more stabile if the coefficient $K_u$ is reduced. For the same time period $t \in$ (100ms, 500ms) the average power is 3.33kW, but its standard deviation decreases to about 190W. This feature may gain the efficiency of the whole supply system.

## 5. CONCLUSION

A distinctive and important property of active filters belonging to the filter family discussed is that they not only handle non-active current components, but also play positive significant part in transferring the active energy from the source to the load. These filters stabilize the flow of this energy, and can lower losses of transport of energy from the source to the load.

As a matter of fact the electric source is an energy converter, which transfers the energy from a primary form to the electric form. The use of the considered active filter allows reaching the primary side of the energy conversion. A steady stream of primary form of energy can be kept in the supply system, just alike for *DC* system, which feeds a constant load.

The first step on this way was introducing the synchronization as a tool, which makes possible attaining non-deformed run of source current within a single synchronization cycle. The next step was decreasing the differences of source power between neighbour synchronization cycles. Two possibilities of achieving this decreasing were considered: introducing some kind of inertia into the filter's action, and forcing the filter's action around a mean level of load power.

The presented active filter can act as a rectifier simultaneously. Such possibility is very convenient, because both of the functions can be performed by the "two-in-one" active filter/rectifier device. Additionally, the "rectifier-part" of the device acts with sinusoidal input current. The active filter working with supplementing the filter's capacitor voltage was also considered. This type of working may be profitable for improving the dynamics of the filter. It may be double-profitable when the filter acts simultaneously as a rectifier. However, the supplementing of the capacitor's voltage worsen the source-and-load co-operation. The filter cannot stabilize the flow of energy. To supplement the voltage or not, a decision is needed.

There were also considered some possibilities of increasing of functionality and usefulness of the active filter. It turned out, that the examined active filter is very susceptible to developing.

A little facetious digression at the end: There is a common regularity in our world, that flowing of any form of energy, or information, or finance, or any kind of goods, should have a suitable rhythm. Sources and receivers should be open to each other by means of mutual adjustment. If they are not, some amount of resources goes to waste. From this there are so many buffer-systems like banks, stores, libraries, hard disks and the camel's hump. From this point of view improving of an active filter, as a device for adjusting a source to a receiver, is even philosophically substantiated.

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