

# Conductance-controlled global-compensation-type shunt active power filter<sup>\*</sup>

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**Abstract:** This paper presents a load equivalent conductance based control method for a shunt active power filter. The principle of energy balance in the circuit, which means between supplying source – active filter – load, is used to obtain the control formula. The natural inertia of the active filter action is exploited, so no *PI* regulators are needed. The active filter can compensate for non-active current and, additionally, can stabilise the supplying source active power. In a case of generating loads energy harvesting is possible. The presented method is useful as well for voltage-source as current-source inverter based active filters, and for *DC* system as well as for *AC* single- or three-phase one.

**Key words:** shunt active power filter, active current, indirect control method, instantaneous compensation, load equivalent conductance, energy flow control

## 1. Introduction

Numbers of control techniques for shunt active power filters have been considered and employed. Performance of an active filter is highly sensitive on its reference current obtaining method. Many of them are reported in [2]. In general, each control technique may be referred to as the selective or global one.

The selective compensation is considered as delivering only selected non-active current/power components to the load. It is obvious that all non-active current components have to be continuously determining before they are synthesizing by the active filter. Selected components to be compensated may be altered in time by means of introducing changes to the compensation strategy. From this point of view the selected-type compensation is flexible. As a result the actual active filter capacity may be regulated, what seems to be profitable. But it is obvious, that if the selected compensation is used then some amount of non-active current components remain in the source current. However, such omitted components can be removed

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from the source current using passive filtration. Optimization strategy for sizing of active power filters is considered in [6].

On the other hand the global compensation is aimed to maintain the source current to provide only the active component of the load current/power. It is considered as a “stiff” method because there is no compromise about components to be compensated: all of them should vanish (however, a selective approach can also be found in the literature, [5, 9]).

In general, two techniques of realizing the global compensation can be implemented. The first one consist in detecting all undesirable components of the load current/power and, concurrently, synthesizing the active filter current to be the sum of currents which compensate undesirable components. Such approach needs large computational effort. On the contrary the second technique consists in detecting only the active power of the load. Knowing this power the reference for the supplying source current, the active current, can be obtained in proportion to the source voltage waveform. The proportionality factor is the load equivalent conductance  $g$ , which is a function of the load active power. Finally, the active filter – in fact a controlled current source – drives the supplying source current to be equal to the active current component of the load.

The compensation reference signal is often indicated using the asterisk as the superscript. Using this notation the symbol  $i_S^*$  denotes the reference signal for the current to be synthesized in the source branch. It can be obtained using two factors: a signal  $g$  that is associated with the equivalent conductance of the load, and the signal  $u_S$  of the source voltage, Equation (1):

$$i_S^* = gu_S. \quad (1)$$

## 2. Load equivalent conductance signal

### 2.1. Basic configuration of shunt active filter

In general shunt active filter consists of two main blocks: the controlling block and the converter. The controlling block produces the reference signal, which is then executed by the converter, Figure 1. The diagram shown in Figure 1 is made in a single-phase system conventionality. In the figure thin lines are assigned to voltage or current signals.

Dependently of chosen control technique – the direct or indirect one – the conductance signal  $g$  is being calculated on the base of various signals:

1) *The direct control technique*: the load current  $i_L$ , the source voltage  $u_S$  and the active filter’s capacitor voltage  $u_C$  are monitored and processed. Signals  $i_L$  and  $u_S$  are employed to produce the load equivalent conductance signal. The capacitor voltage signal  $u_C$  is utilized to calculate an additional component of the conductance signal that is connected with energy loss in the filter’s converter block. The signal  $i_F$  of the filter current is employed as an element of the current control loop. The source current  $i_S$  is neither sensed nor utilized in the direct control technique.

2) *The indirect control technique*: the capacitor voltage  $u_C$ , the source voltage  $u_S$  and – optionally – the filter current  $i_F$  are monitored and processed. The signal  $u_C$  of the capacitor voltage is employed to produce the entire conductance signal  $g$ . In other words this signal contains as well information on the load active power as information on energy loss in the filter's converter block. Optionally, the signal  $i_F$  of the filter current can be also used in order to track the load and the converter powers more precisely. The signal  $i_S$  of the source current is employed as an element of the current control loop. The load current  $i_L$  is neither sensed nor utilized in the indirect control technique.

The mentioned above two techniques of obtaining the conductance signal  $g$  are essential, therefore they are detailed in next sections. Firstly, the direct control technique is considered in Sections 2.2, 2.3 and 2.4. Then the indirect one is discussed.

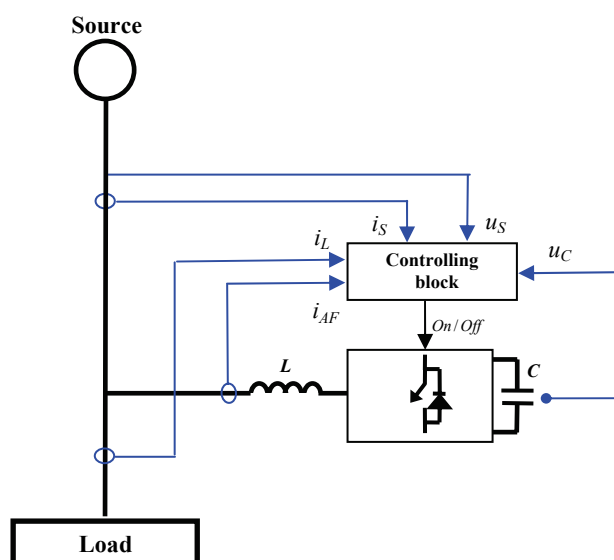


Fig. 1. Basic configuration of a shunt active power filter. Single-phase system conventionality is used

## 2.2. Load equivalent conductance signal based on FBD theory

The signal  $g$  of the load equivalent conductance can be based on load instantaneous voltages and currents. According to the Fryze–Buchholz–Depenbrock (*FBD*) theory, [4], the signal  $g$  is determined as:

$$g_D = \frac{\sum_k u_k i_k}{\sum_k u_k^2}, \quad (2)$$

where  $k$  is phase index,  $u_k$  is instantaneous phase voltage and  $i_k$  is instantaneous load phase current.

Then the Depenbrock's *power currents* are introduced as follows:

$$\dot{i}_{p,k} = g_D u_k. \quad (3)$$

In turn Depenbrock's *instantaneous powerless currents* are defined:

$$i_{n,k} = i_k - \dot{i}_{p,k}. \quad (4)$$

The powerless currents do not contribute to the load active power. Therefore, these currents can be compensated in the source branch. Compensating these currents reduces energy loss in the supply line and diminishes voltage drop on the line.

The currents defined in (3) or in (4) can be used as the reference signal for the source current (5) or for the active filter current (6), respectively:

$$i_{S,k}^* = g_D u_k, \quad (5)$$

$$i_{C,k}^* = i_k - \dot{i}_{p,k}. \quad (6)$$

While forming source currents in accordance with (5) the active filter generates the compensating currents (4) "automatically", on the base of the Kirchhoff's Current Law. The compensating currents (currents of the active filter) are not to be computed explicitly.

While performing compensation according to (5) then the objective of compensation – the current of the source – is controlled actually. Contrarily, if apply (6) then the active filter current looks like to be the objective of the compensation and the source current is not monitored.

For the balanced system with sinusoidal voltages and currents the signal  $g_D$  is constant. Therefore, the reference currents (5) are sinusoidal and in-phase with the corresponding phase voltages. After compensation the source currents are optimal and carry pure active power.

Unfortunately, the source current-to-voltage linearity no longer exists under unbalanced and/or non-sinusoidal and/or transient conditions, when as well the numerator as the denominator of the Equation (2) may vary. Consequently, the reference (5) may be distorted even if source phase voltages are sinusoidal and the load is pure resistive.

The example shown below, Figure 2, presents a three-phase circuit seen from the perspective of the *FBD* theory. The source is sinusoidal and balanced. Each phase voltage *RMS* is 100 V. The load is unbalanced and consists of three resistors in Y configuration, where  $R_A = R_B = 10 \Omega$  and  $R_C = 100 \Omega$ . Load phase currents are sinusoidal with *RMS* equal 8.7 A, 8.7 A and 1.4 A for phases *A*, *B* and *C*, respectively. The Buchholz's norm of the load current equals 12.4 A. Figure 2 shows the conductance signal  $g_D$ , in compliance with Equation (2), and then Depenbrock's phase power currents, in compliance with Equation (3).

The conductance signal  $g_D$  can be decomposed into a constant and an oscillating component. Parameters describing these two components are: 57.1 mS (mean) and 85.7 mS (peak-to-peak).

The shown in Figure 2 power currents can be used as references for source currents. Indeed, power currents' *RMS* are: 7.4 A, 7.4 A and 4.2 A for phases *A*, *B* and *C*, respectively, and the Buchholz's norm of these currents equals 11.3 A. It is visible that if take the Depenbrock's power currents as references for the source currents and perform compensation then

the source currents could be diminished. Buchholz's norm of reference currents is lower than that of actual phase currents. Unfortunately, the large oscillating component causes distortion of power currents. Large third-order harmonic components appear in reference currents and source currents remain unbalanced. It is visible that there is still large space to improve the quality of the compensation.

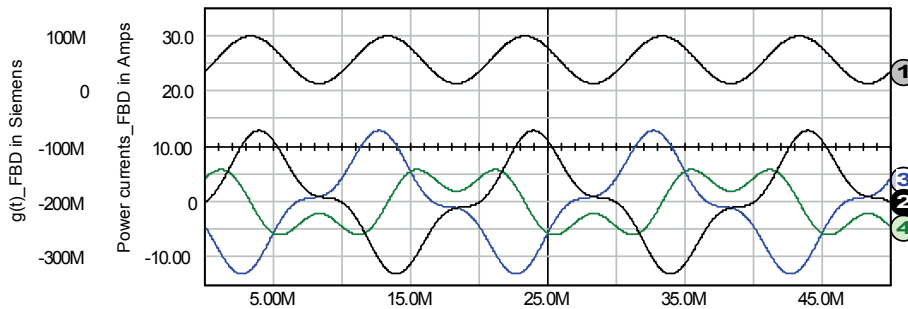


Fig. 2. FBD theory approach. Conductance  $g_D$  signal, waveform nr. 1, and Depenbrock's phase power currents, waveforms 2, 3 and 4 in phase A, B and C, respectively

The signal of the load equivalent conductance (2) can vary in time due to changes of energy stored in the active filter and source voltage distortion. Applying inertia to the active filter's action can reduce fluctuations of the conductance signal and improve compensation for non-active currents. In next sections such possibility is discussed.

### 2.3. Load equivalent conductance signal based on Fryze's theory

The unity power factor can be reached if eliminate the oscillating component from the conductance  $g_D$  signal. This leads to Fryze's active currents that are defined as:

$$i_{a,k} = \frac{P_L}{U_\Sigma^2} u_k = G_F u_k, \quad (7)$$

where:

$$P_L = \sum_k P_k, \quad P_k = \frac{1}{T} \int_\tau^{\tau+T} u_k i_k dt, \quad k \text{ is phase index,}$$

$$\text{and } U_\Sigma^2 = \sum_k U_k^2, \quad U_k^2 = \frac{1}{T} \int_\tau^{\tau+T} u_k^2 dt.$$

The time period  $T$  (one period of source cycle) is indispensable to obtain active powers and RMS of phase voltages. For that reason Equation (7) cannot be implemented directly as the active current reference. This problem can be solved by delaying realization of the reference current for one  $T$  period, [10, 13-15]:

$$i_{k,nT}^* = \frac{P_{L,(n-1)T}}{U_{\Sigma,(n-1)T}^2} u_{k,nT} = G_{F,(n-1)T} u_{k,nT}, \quad (8)$$

where  $n$  is index of ongoing  $T$  period.

In this case the initial conductance  $G_{F,(0)}$  is set to be zero, hence during the initial period  $T$  the load is supplied from the active filter's capacitor.

Alternatively, the load equivalent conductance signal can be computed according to Equation (9):

$$G_{alt} = \bar{g}_D = \frac{1}{T} \int_{\tau}^{\tau+T} \frac{\sum_k u_k i_k}{\sum_k u_k^2} dt. \quad (9)$$

In comparison with the method based on Equation (7) the method based on Equation (9) can reduce the computational effort.

#### 2.4. Controlling the active filter capacitor voltage

If use conductance signal defined in (2), (7) or (8) the converter's power loss is ignored (the source active power covers only the load active power). As the result the active filter capacitor discharges. In order to maintain the capacitor mean voltage at the same level an extra conductance-like component, related to converter's power loss, has to be added to the conductance signal.

#### 2.5. Direct and indirect control technique

As was mentioned in Section 2.1 the compensation strategy may be realised using the direct or indirect control technique. If the direct one is implemented then the active current reference signal is being computed on the base of signals of the load voltage and current [3], [5, 17]. On the other hand the conductance signal can be obtained with no use of the load current. In particular this can be done on the base of monitoring changes of energy stored in reactance elements of the compensator [8, 10, 12-16] – that means using the indirect control technique.

From a circuit diagram point of view, the difference between these two control techniques consists in measuring the active filter capacitor instantaneous voltage instead of load phase instantaneous currents. In practice employing the indirect technique instead of the direct one leads to some benefits:

- 1) Only one voltage is to be measured and processed instead of  $k$  currents.
- 2) Measuring of the active filter capacitor voltage instead of load currents is easier because it is of significant lower dynamics than load currents dynamics.
- 3) The capacitor voltage has to be measured as well if utilize the direct as the indirect technique.

If use the formula (2), that means if use the “pure” direct control technique, then a kind of low-pass filtration may be necessary to diminish the oscillating component of the  $g_D$  signal – see the example shown in Figure 2.

A noteworthy fact is that the indirect technique can be implemented without any additional filtration devices used in order to eliminate the oscillating component of the conductance signal. The followed sections consider this possibility.

### 3. New formula of equivalent conductance signal

#### 3.1. Equivalent conductance formula

In order to obtain new formula for the load equivalent conductance signal the analysis of energy changes for the source – active filter – load circuit was performed. The following assumptions about the conductance signal were made:

- 1) Each change of magnitude of the load active power is transformed into the adequate change of magnitude of the load equivalent conductance signal.
- 2) After each change of the load active power the source current, the active current and the signal of the load equivalent conductance aims the steady state exponentially with a time constant  $\tau$ .
- 3) A time parameter  $T_{st}$  of achieving the steady state is introduced. This parameter may be selected longer or shorter dependently on the load power dynamics. The parameter  $T_{st}$  is associated with the time constant  $\tau$  using a coefficient  $N_\tau$ :  $T_{st} = \tau N_\tau$ .

A zero-to- $P_L$  step-change of the load active power is used to obtain the conductance signal. Let the load is turn on at time  $t = 0$ . Then, currents of the source, the active filter and the load fulfil following constraints:

source phase currents:

$$i_{S,k}(t = 0) = 0. \quad (10)$$

$$i_{S,k}(0 < t \leq T_{st}) = \frac{P_L + P_{AF}}{U_\Sigma^2} u_k \left( 1 - e^{-\frac{tN_\tau}{T_{st}}} \right),$$

and

$$i_{S,k}(t > T_{st}) = \frac{P_L + P_{AF}}{U_\Sigma^2} u_k,$$

active filter phase currents:

$$i_{AF,k}(t = 0) = \frac{P_L + P_{AF}}{U_\Sigma^2} u_k, \quad (11)$$

$$i_{AF,k}(0 < t \leq T_{st}) = \frac{P_L + P_{AF}}{U_\Sigma^2} u_k e^{-\frac{tN_\tau}{T_{st}}}$$

and

$$i_{AF,k}(t > T_{st}) = 0,$$

load phase currents:

$$i_{L,k} = i_{S,k} + i_{AF,k} = \frac{P_L + P_{AF}}{U_\Sigma^2} u_k, \quad (12)$$

where:  $i_{S,k}$ ,  $i_{AF,k}$  and  $i_{L,k}$  are instantaneous source, active filter and load phase currents, respectively;  $P_{AF}$  is power dissipated (loss) in the active filter;  $N_\tau$  is number of time constants  $\tau$  needed to achieve the steady state:  $N_\tau = T_{st}/\tau$

According to these assumptions and constraints the general equation describing energy relations between the load, the active filter and the source can be formulated:

$$(P_L + P_{AF})t = (W_{AF0} - w_{AF}(t)) + \sum_k \int_0^t u_k i_{S,k} d\tau, \quad (13)$$

where:  $W_{AF0}$  is the initial energy stored in the active filter's reactance elements;  $w_{AF}(t)$  is energy stored in these elements at instant  $t$ .

The Equation (13) describes the idea that each change of the load active power is balanced by the active filter and buffered before the load active power is supplied fully from the source. In order to describe the energy relation in the circuit using only energy stored in the active filter a parameter  $N_{SF}$  is defined:

$$N_{SF} = \frac{W_S[0, T_{st}]}{\Delta W_{AF}[0, T_{st}]} = \frac{\sum_k \int_0^{T_{st}} u_k i_{S,k} d\tau}{W_{AF0} - w_{AF}(T_{st})}. \quad (14)$$

Taking into account that after change of the load active power the source current and the active filter current rise/falls exponentially, the parameter  $N_{SF}$  can be written using the coefficient  $N_\tau$  as follows:

$$N_{SF} = \frac{N_\tau}{1 - e^{-N_\tau}} - 1. \quad (15)$$

Once the parameter  $N_{SF}$  is introduced the equation (13) can be expressed as a function of active filter's energy:

$$T_{st}(P_L + P_{AF}) = \Delta W_{AF} + W_S = \Delta W_{AF} + \Delta W_{AF} N_{SF} = \Delta W_{AF} (N_{SF} + 1) \quad (16)$$

Finally, the following active filter's energy based formula for the conductance signal can be established:

$$g_E(t) = \frac{(W_{AF0} - w_{AF}(t))(N_{SF} + 1)}{T_{st} U_\Sigma^2}, \quad (17)$$

where:  $g_E(t)$  is the load equivalent conductance signal;  $W_{AF0}$  is the initial energy stored in the active filter's reactance elements;  $w_{AF}(t)$  is energy stored in these elements at instant  $t$ ;  $N_{SF}$  is the ratio of source-to-active filter energy delivered to the load after a step-change of the load



active power;  $T_{st}$  is a selectable time parameter approximating the time needed to reach steady state after the step-change of the load active power;

$$U_{\Sigma}^2 = \sum_k U_k^2,$$

see also (7).

Noteworthy fact is that this formula can be applied to (1) in order to control active filters for *DC* or *AC* in a single- or polyphase circuits, and for voltage- and current-converter based active filters. Then, depends on the electric system considered the source voltage signal in (1) may be the voltage signal of a *DC* source or an *AC* source or a phase voltage signal of a poly-phase source.

### 3.2. Energy flow controlling

The formula (17) enables the active filter not only compensating for non active currents but also to act concurrently as an energy flow controller. This can be done by proper setting of the  $T_{st}$  parameter in (17). The higher this parameter the higher the active filter's inertia and the higher energy flow buffering. Additionally, if block negative value of the conductance signal in a case of consuming-and-generating loads the active filter can accumulate, or harvest, such "reverse" energy in its reactance elements.

The active filter/buffer can work in the following modes of operation:

- Standard mode: compensation for load non-active current components of any type, including reactive component, harmonics, interharmonics and subharmonics, negative sequence components. The standard mode may be used regardless of energy flow direction: from the source to the load or vice versa. Depending on the  $T_{st}$  parameter changes of the load active power can be averaged (positive or negative active power as well).
- Storing mode: standard compensation and, concurrently, the active filter/buffer can store energy for future use. In particular the filter can store energy from the load when the load becomes an energy generator. When the load becomes an energy consumer again, then the stored energy may be given back to the load. Note, the active filter can compensate for non-active current of one or more loads. In the storing mode the filter can capture energy from generating loads and redistribute it among consuming ones.

## 4. Verifications

### 4.1. General verification of the conductance signal formula

Figures 3. and 4. verify Equation (17) by illustrating energy changes after a step-changes of load power. The three-phase circuit is considered. The source is symmetrical and the load is linear, purely resistive and balanced, consists of three  $8 \Omega$  resistors arranged in Y-connection. The load is switched on at  $t = 4$  ms and switched off at  $t = 114$  ms.

Three-phase voltage source converter based active filter is considered. Energy  $W_{AF}$  of the active filter is stored in its *DC*-side capacitor  $C = 4$  mF. The initial capacitor voltage  $U_{C0}$  is

500 V. The initial energy  $W_{AF0}$  stored in the active filter is 500 J. Some amount of energy exists in AC-side phase reactors  $L_n$ , but this energy is small and usually can be ignored.

For the voltage source converter based active filter the Equation (17) has to be rewritten to the form exposing energy stored in the DC-side capacitor  $C$  and AC-side phase reactors  $L_n$ :

$$g(t) = K_U (U_{C0}^2 - u_C^2(t)) + \sum_{n=1}^3 K_{L,n} (i_{AF0,n}^2 - i_{AF,n}^2(t)), \quad (18)$$

where:

$$K_U = \frac{C(N_{SK} + 1)}{2T_{st}U_{\Sigma}^2}, \quad K_{L,n} = \frac{L_n(N_{SK} + 1)}{2T_{st}U_{\Sigma}^2}$$

and  $n$  is phase index.

Other parameters for Equation (17) are:  $L_n = 2$  mH,  $i_{AF0,n} = 0$ ,  $N_{SF} = 5.5$ ,  $T_{st} = 140$  ms and  $U_{\Sigma} = 100$  V.

Figure 3 details behaviour of the circuit, in particular in the phase  $A$ , around the load turn-on time instant. There is only a small active filter's active power associated with power dissipation within the converter before the load is switched on. Just after this moment the conductance signal is still low, so the load is fully supplied using energy stored in the active filter capacitor: load current and active filter current are the same, waveforms nr. 1 and 2. Of course active filter capacitor voltage diminishes: waveform nr. 4. Then, according with (17) the conductance signal rises, the waveform nr. 5, and, consequently, the load power is taken gradually by the source: the waveform nr. 3 displaying the source current. This process is continued until the steady state, that means until the load is supplied by the source exclusively.

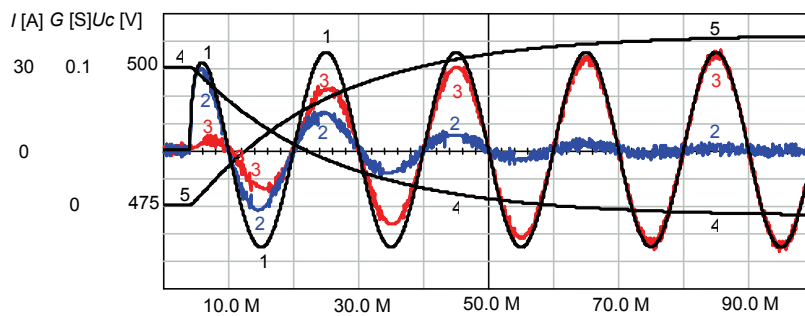


Fig. 3. Load turn-on process. Currents of phase  $A$  are presented: load current (waveform 1), active filter current (waveform 2), source current (waveform 3). Then active filter capacitor voltage (waveform 4) and conductance  $g$  signal (waveform 5) are depicted. The exact description is above the figure

Signals shown in Figure 3. are continued in Figure 4. The source fully supplies the load before the load is turned-off at  $t = 114$  ms. Due to inertial control of the active filter the conductance signal remains still high for a while after the load turned-off moment. Therefore the source current still flows charging the active filter's capacitor. Consequently, according to (17) the

conductance signal decreases, so the source current gradually diminishes. This process is continued until the steady state, when the source supplies only power dissipation within the converter.

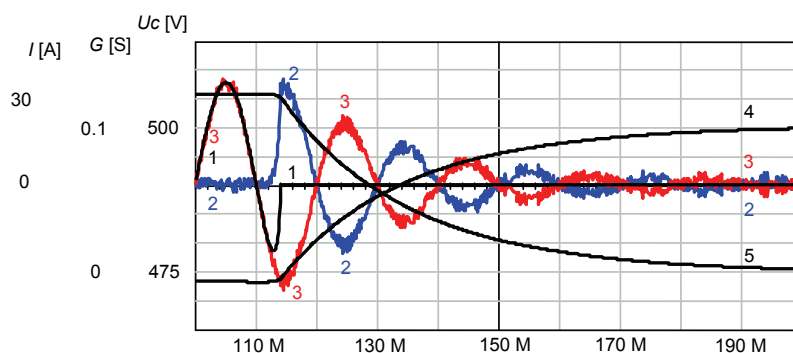


Fig. 4. Load turn-off process. Currents of phase *A* are presented: load current (waveform 1), active filter's current (waveform 2), source current (waveform 2). Then active filter capacitor voltage (waveform 4) and conductance *g* signal (waveform 5) are depicted. The exact description is above the figure

Figures 3 and 4 together present the whole cycle of active filter activity. Because of linear resistive and balanced load there were no non-active currents to be compensated. Nevertheless the active filter's dynamics were clearly presented. The waveforms shown confirm the Equation (17) validity.

#### 4.2. Compensation for non-active currents in three-phase circuit

The example-circuit presented earlier in Figure 2 is considered once again in Figure 5, but this time the Equation (17) instead of the Equation (2) is used to calculate the conductance signal. The load is switched-on at  $t = 14$  ms and switched-off at  $t = 128$  ms. Signals parameters reported below are measured for 108-128 ms time period, where the circuit is practically in the steady state.

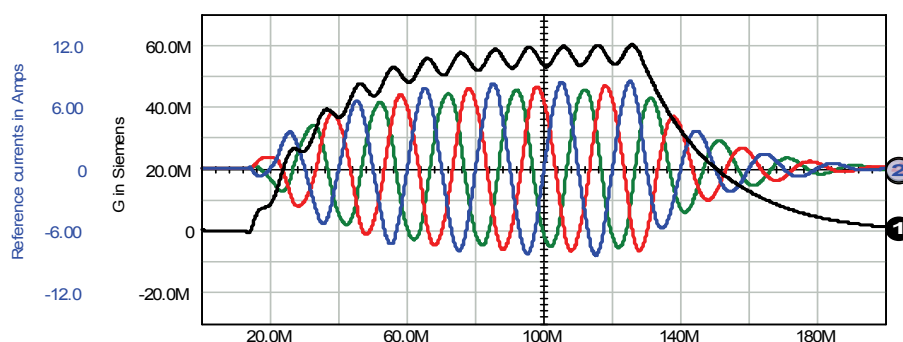


Fig. 5. Three-phase unbalanced, resistive load. Conductance  $g_E$  signal, waveform 1, and phase *A*, *B* and *C* reference currents

The conductance signal  $g_E$  can be decomposed into a constant and an oscillating components. Appropriate parameters describing these two components are: 56.75 mS (mean) and 6.34 mS (peak-to-peak). The shown in Figure 5 currents  $RMS$  are: 5.8 A, 5.5 A and 5.6 A for phases  $A$ ,  $B$  and  $C$ , respectively; and the Buchholz's norm of these currents equals 9.8 A. It is clearly visible that using the Equation (17) instead of the Equation (2) significantly improves effectiveness of the compensation.

Figures 6, 7 and 8 illustrate compensation in a case of an unbalanced, variable and highly distorted load. Its phase currents are of different  $RMS$  and frequencies – they are:  $I_{La} = 22.9$  A and  $f_a = 60$  Hz;  $I_{Lb} = 20.3$  A and  $f_b = 55$  Hz;  $I_{Lc} = 22.6$  A and  $f_c = 60$  Hz. Such load seems to be unrealistic, but it is a hard challenge for the active filter. Fortunately, the exam is passed very well. The compensation results in source current balancing and reducing its  $RMS$  to 6.4 A for each phase. Noteworthy, there is the same current frequency of 50 Hz in each phase of the source.

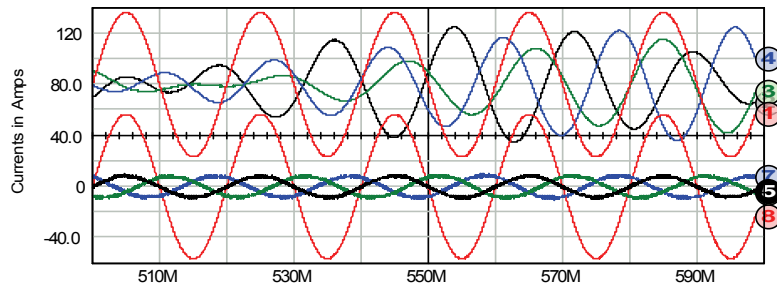


Fig. 6. Case of a three-phase highly variable load, load and source currents. Phase  $A$  source voltage, waveforms nr. 1 and 8; load phase  $A$ ,  $B$  and  $C$  currents: waveforms 2, 3 and 4. Source phase  $A$ ,  $B$  and  $C$  currents, waveforms 5, 6 and 7. The same scale for all current runs is used.

The compensation result demonstrated in Figure 6 may be also reported using load and then source instantaneous powers, Figures 7 and 8. This allows showing usefulness of the energy buffering function of the active filter. Figure 7 presents instantaneous powers of the load. From the power waveforms presented clearly results that the load considered acts not only passively, but can also generate electric energy.

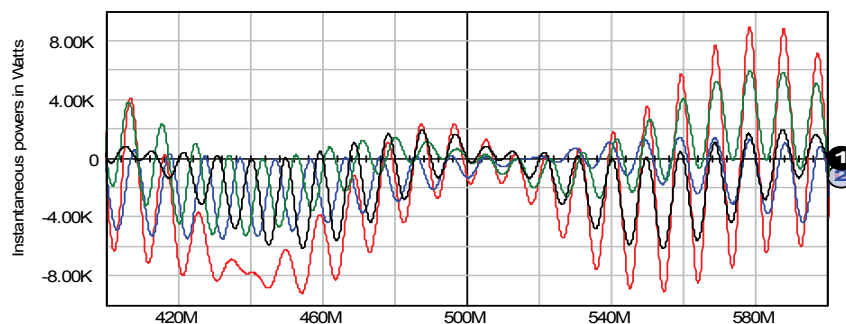


Fig. 7. Case of a three-phase highly variable load - continued from Fig. 6. Load phase  $A$ ,  $B$  and  $C$  powers individually and then the sum of load phase powers (waveform with the largest variation)

The compensating-and-buffering process results in “converting” the load into pure resistive, or consuming, one, which is practically balanced and seen by the source as slowly variable. The effect of such “conversion” of the load is presented using source instantaneous powers in Fig. 8.

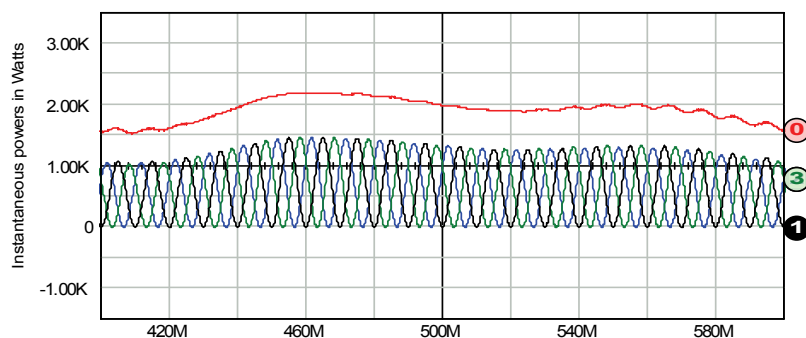


Fig. 8. Case of a three-phase highly variable load – continued from Fig. 7. Source phase *A*, *B* and *C* powers individually (waveform 1, 2 and 3, tag of waveform 2 is covered by tag of waveform 3) and then the sum of source phase powers (waveform 0)

#### 4.3. Compensation and energy buffering in single-phase circuit

The Equation (17) can be easily adapted for a single-phase system. This can be done by replacing the collective source voltage  $U_S$  for the source voltage  $U_S$ .

Two modes of filter operation were introduced in Section 3.2. Figures 9, 10 and 11 compare the active filter action in the store mode versus the average mode.

In the store mode the active filter compensates for non-active current and, at the same time, can capture and store energy generated by the load. In order to show clearly such active filter properties the load current is executed using a well-suited current source. It generates a non-active component and, concurrently, generates fluctuating positive/negative active power. The sinusoidal current source of different frequency versus the source voltage frequency, for example 60 Hz vs. 50 Hz, qualifies these requirements.

Figure 9 presents the source voltage, the load current and then the load instantaneous power in the steady state. The *RMS* of the load current is 20 A.

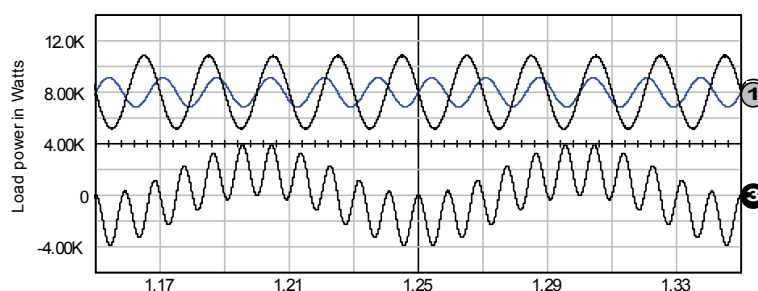


Fig. 9. Case of a single-phase consuming/generating load. Source voltage (the waveform of the larger amplitude of the two at the top), load current (the waveform of the smaller amplitude of the two at the top) and load instantaneous power (waveform 3)

Figure 10 shows the conductance signal determined for the average mode, waveform 1, and then for the store mode of active filter's operation, waveform 3. Then the source current is displayed on the background of the source voltage for the both modes of operation. It is visible that the active filter stabilizes the flow of energy very efficiently. The *RMS* of the source current for the average and the store mode are 5.6 A and 0.6 A, respectively.

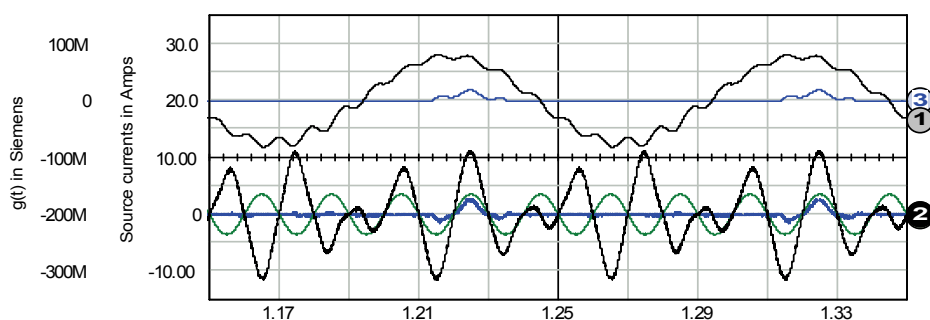


Fig. 10. Case of a single-phase consuming/generating load – continued from Fig. 9. Conductance signal for average mode and store mode (waveform 1 and 3, respectively); then source currents for average mode (waveform with the largest variation of the three at the bottom) and store mode (waveform with the smaller variation of the three at the bottom, corresponding with the waveform 3); and then source voltage (the sinusoidal waveform of the three at the bottom)

Figure 11 demonstrates source instantaneous power for the both modes of operation. From the figure results that the source power is considerably lower comparing with the load power as well when applying the average mode as the store mode. In the average mode the source emits and collects energy alternately. In the store mode the active filter almost fully buffers the load energy consumed/emitted; hence the source only generates a very small amount of energy. If use the *RMS* norm as a measure of the instantaneous power the load and the source powers for the average and store mode are 2000 W, 697 W and 69 W, respectively. One can see that in the case of the store mode the filter/buffer acts almost perfectly: the supply source is practically uncharged.

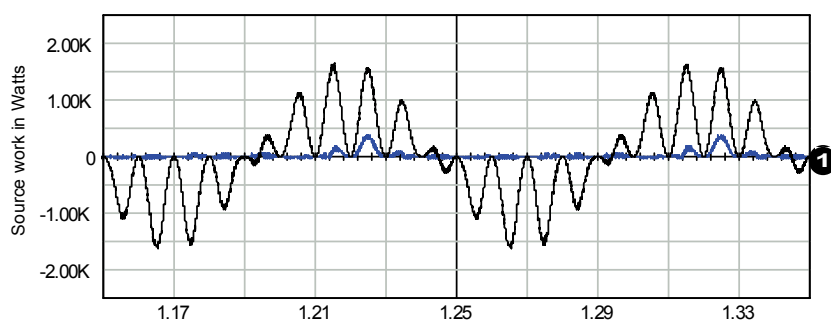


Fig. 11. Case of a single-phase consuming/generating load – continued from Fig. 10. Source instantaneous power in average mode (high variable wave) and in store mode ("flat" wave)

A worrisome question can occur: In the analyzed examples the active energy circulates between the load and the active filter. Is it still the classic active energy? Does the active filter buffer the flow of the active energy or does it compensate for a kind of non-active energy?

#### 4.4. Compensation and energy buffering in DC-supplied circuit

The active current component is useful by means of carrying the active power. The non-active one may appear not only in *AC* systems, but also in a *DC*-supplied circuit and may be regarded as energetically useless. Hence, compensation may be also advantageous in *DC*-systems. In addition, some new benefits may appear if implement energy flow control function to the filter action. For example, the life-time of a *DC*-battery depends on characteristic of battery's current [11]. If use a properly controlled active filter the battery may work more efficiently and the life-time of the battery may be increased.

Equation (17) can be also adapted for a *DC*-supplied system. This can be done by replacing the collective source voltage  $U_S$  for the *DC* source voltage  $U_S$ .

Figure 12 presents compensation for the non-active current and buffering of energy flow in the circuit consists of a *DC* voltage source and a variable consuming/generating load. For such circuit the active component of the current equals the mean of the total current of the load.

In the example load current parameters for the time period 200 ms-450 ms are: *RMS* 7.0 A, st. deviation 6.0 A, peak-to-peak amplitude 26.1 A and mean 3.7 A.

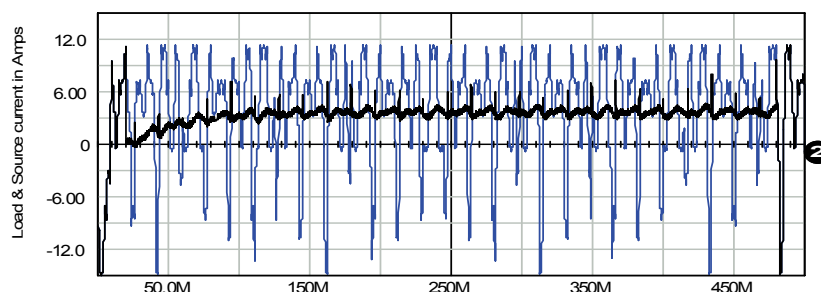


Fig. 12. Case of a variable load powered from a *DC*-voltage source. Load current (high variable waveform) and source current (averaged waveform)

At time  $t = 20$  ms the active filter is turned-on. It is initialized to operate in the average mode. For the considered above time period 200 ms-450 ms the same parameters of the source current are significantly lower. They are: *RMS* 3.8 A, standard deviation 0.5 A, peak-to-peak amplitude 5.3 A (or 1.8 A if ignore spikes, which appear at rapid changes of load power) and mean 3.7 A. Note, while the active filter is acting the source current is unipolar, so the source power can flow unidirectionally. By the use of the active filter the source current is practically cleared from non-active components: it almost equals the load current mean.

## 5. Conclusions

The global compensation strategy in cooperation with the indirect current control technique is considered in this paper. The presented method of compensating for undesirable current components seems to be the simplest among all compensation methods. Despite the method simplicity it allows an active filter to perform two extra functions: stabilizing the supplying source active power and energy harvesting from generating loads. These extras can be added to the conventional active filter duties and can reduce the burden of the supply source.

Important features of the presented method may be outlined: simple and universal control algorithm of the active filter, no need of using *PI* regulators, indirect method of obtaining the active filter's reference signal, no need of harmonic components extraction, control of active energy flow between the source and the load for the both energy flow directions.

Noteworthy the global compensation strategy with the use of the load equivalent conductance notion can be also seen from perspective of the well known *p-q* theory [1]. But, contrarily to the considered in the paper method, the *p-q* theory based approach utilises the direct control technique.

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