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Effectiveness of the Work of an Active Power Filter Based on a Multi-channel Converter

***Abstract**. The subject of the paper is the active power shunt filter based on a multi-channel converter topology. Thanks to the property of the filter its frequency response is extended. In the result the filter input current (power grid current) is better mapped in the reference signal, compared to a conventional filter solution. Also, the amplitudes of pulse modulation components in the input current are minimized. The paper shows the layout of such the 1-phase shunt active filter. Selected aspects of the control algorithm and research results of the simulation model of the active filter are also presented.*

***Streszczenie.** Przedmiotem artykułu jest energoelektroniczny równoległy filtr aktywny wykorzystujący topologię przekształtników wielokanałowych. Dzięki temu rozwiązaniu filtr posiada rozszerzone pasmo przenoszenia. W rezultacie jego prąd wejściowy (prąd sieci) jest lepiej odwzorowany w sygnale referencyjnym – w stosunku do rozwiązań konwencjonalnych. Również składowe tego prądu, związane z sygnałem nośnym modulacji impulsowej, są zminimalizowane. W artykule przedstawiono możliwe rozwiązanie filtru aktywnego tego typu. Zaprezentowano również wybrane aspekty pracy układu sterowania oraz wyniki badań modelu symulacyjnego układu. (**Energoelektroniczny filtr aktywny oparty na przekształtnikach wielokanałowych**).*

Keywords: controlled current source, multi-channel converter, power electronics active filter, PWM.
Słowa kluczowe: energoelektroniczny filtr aktywny, MSI, przekształtnik wielokanałowy, sterowane źródło prądu.

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Introduction

Present tendencies of the evaluation of current distortion compensation methods aim to work out such an active filter which would be able to realize real time compensation, be more resistant to interferences caused by power network (and receivers), and fulfils EMI requirements. These methods include also optimization of power grid work conditions. The assumed aim of the shunt filter work is the dynamic compensation of the differential current, which is the difference of load current and a reference current. The differential current is generated by the power electronics controlled current source which is the fundamental block of the shunt active filter - regardless of a filter configuration e.g. [2-5,12,14].

A reference signal is an optimal active current calculated by means of an appropriate method. It results in minimization of a power loss while transmission of an energy from a source to a receiver occurs.

Unfortunately a dynamics (a frequency response) of every real power electronics current source is limited. This is the result of several reasons, mainly:

– limited value of an inverter DC link voltage,
– presence of an inductor at an output of a current source,
– limited, due to the need to ensure a filter stability (as a closed loop electrical system), current regulator gain.

The proposed idea of the active filter layout depends on using in the controlled current source a multi-channel converter concept. Such the converter lets increase significantly the frequency response of the active filter.

The paper explains the general concept of such the 1-phase active shunt filter. Also, selected investigation results of the active filter simulation model in the OrCAD/PSpice environment are presented.

Structure of the Active Filter

In the Fig. 1 the block diagram of the 1-phase active filter is presented. The assumed aim of the filter work is dynamic compensation of the differential current being the difference of the load current and the reference current. It means that in so called the "ideal case" of the active filter work occurs $i_S(t) = \frac{1}{r_{CT}} u_{REF}(t) = i_{REF}(t)$ dependency, where r_{CT} =const. The reference current is an optimal active current calculated by means of the method proposed in [1].

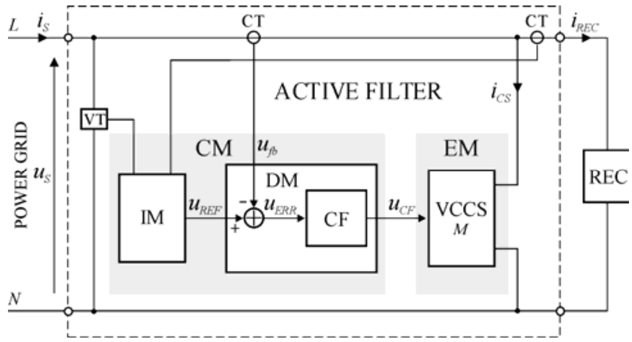


Fig.1. Block diagram of the 1-phase active shunt filter

The active filter consists of following blocs, grouped in the control module (CM) and the execution module (EM):

– identification module (IM), which is responsible for generating a proper reference signal u_{REF} ,
– correction filter (CF), in the decision module (DM), which is responsible for shaping the desired "transfer function" of the active filter,
– EM, consisting, among other items, of the voltage controlled current source (VCCS),
– voltage (VT) and current (CT) transducers.

The active filter is loaded by a non-linear receiver represented by the REC block.

The block diagram of the execution module is shown in the Fig. 2. The EM bases on a multi-channel converter topology e.g. [5,10,11,13] and consists of set of M connected in parallel half-bridge type inverters. In the result, the total converter output current i_{CS} is the sum of currents in individual converter channels.

From the point of view of the filter quality work, the better solution is use two sets of inverters, being connected each other in the fully differential manner so the unipolar pulse modulation can be achieved. However, the cost of such the solution is essentially higher.

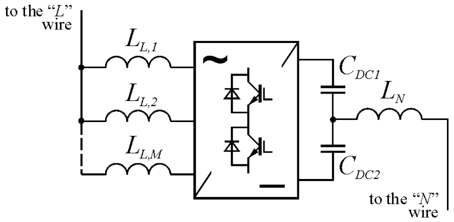


Fig.2. Block diagram of the EM based on a multi-channel converter

It is assumed that values of all inductances at the individual inverters outputs are the same: $L_{L,1} = L_{L,2} = ... = L_{L,M}$ and $L_N << L_{L,i} : i = 1,2,...,M$.

In the Fig. 3 the small-signal (linear) model of the VCCS is shown. This model has been used for the VCCS stability analysis. This one has been based on the Nyquist criterion [9].

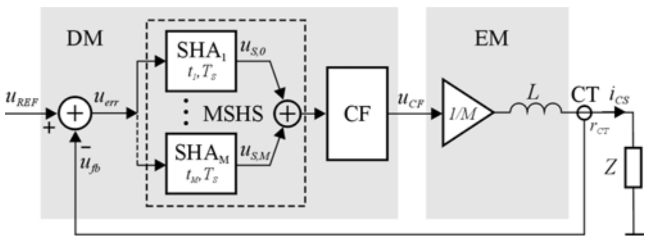


Fig.3. Small-signal model of the VCCS

The transfer function of the model is given by the formula:

$$(1) \qquad G_{VCCS}(j\omega) = \frac{I_{CS}(j\omega)}{U_{REF}(j\omega)} = \frac{K(j\omega)}{1 + r_{CT}K(j\omega)} ,$$

where

$$(2) \qquad K(j\omega) = \frac{K_{MHS}(j\omega)K_{CF}(j\omega)}{j\omega L + Z} .$$

The MSHS block is the Multi-dimensional Sampling-And-Hold System and $K_{MHS}(j\omega)$ is the static (time-invariant) part [8,9] of its transfer function. The $K_{CF}(j\omega)$ factor is the transfer function of the correction filter while, mentioned earlier, the r_{CT} factor is the CT block gain. The correction filter is responsible for the system stability and introduces the *lead-lag* correction of the system transfer function.

Both, sampling moments in the MSHS block and PWM carrier signals in individual converter channels are shifted each other by $\frac{T_S}{M}$ time, where T_S is the signal sampling period in the control module. In consequence, a small signal transfer function of the system is suitable modified and risk of the system un-stable work is minimized [9,10]. Thanks to that the regulator (i.e. CF) gain can be increased by approx. 2-times [9], what has a very advantageous impact on the performance of the active filter. In other words the control algorithm lets more accurately map the filter input (power grid) current i_{CS} in the reference signal u_{REF} , compared to a standard filter solution. Next, due to the equivalent output inductance of the VCCS is now about M -times lowered ($L = \frac{L_{L,i}}{M} + L_N : i = 1,...,M$) the frequency response of the VCCS is M -times increased, compared to the one channel converter. Owing to shifting by time $\frac{T_S}{M}$ of carrier signals in individual VCCS channels, the effective PWM carrier frequency components in the i_{CS} current is shifted now M -times towards higher frequencies. By this, amplitude of current ripples, caused by PWM, in the VCCS output current is significantly reduced as well – despite a decrease of the VCCS output impedance.

The disadvantage of multi-channel inverters is the known problem of imbalance of the total output current distribution in individual channels of the converter. Most of solutions of this problem are complex hardware designs, e.g. [6,7]. Instead, the author has proposed the only software solution for currents equalization. However, this one is not the subject of this paper.

Reference Signal

The general aim of the optimization of the active filter work is minimizing of the RMS value of the filter input current i_{CS} and its deformations – towards the sinusoidal waveform. It also results in the minimization of power loss while transmission of energy from a source (i.e. power network) to a receiver occurs. Thus, the filter control algorithm should obtain shaping of the VCCS output current i_{CS} in relation to the following equation:

$$(3) \qquad i_{CS}(t) = \frac{1}{r_{CT}} u_{REF}(t) - i_{REC}(t) .$$

To determine the reference signal having such properties the variational method [1] has been used. As result, the expression describing of both, the optimal source (power grid) current and the reference signal are obtained in the following form:

$$(4) \qquad u_{REF}(t) = r_{CT} k_e(t) G_e(t) e(t) = r_{CT} A_{REF}(t) e(t)$$

where $e(t)$ is a source voltage of a power network, $G_e(t)$ is an equivalent power network conductance – expressed as $G_e(t) = P_{a,REC}(t) / E^2(t)$ where: $P_{a,REC}(t)$ and $E(t)$ are instantaneous values of a receiver active power and a RMS value of a source voltage in power network, $k_e(t)$ is a coefficient referred to parameters of an equivalent diagram of a power source [1]. A phase value of the $u_{REF}(t)$ signal should be equal to a phase of fundamental harmonic of the $u_S(t)$ voltage.

Active Filter Simulation Model

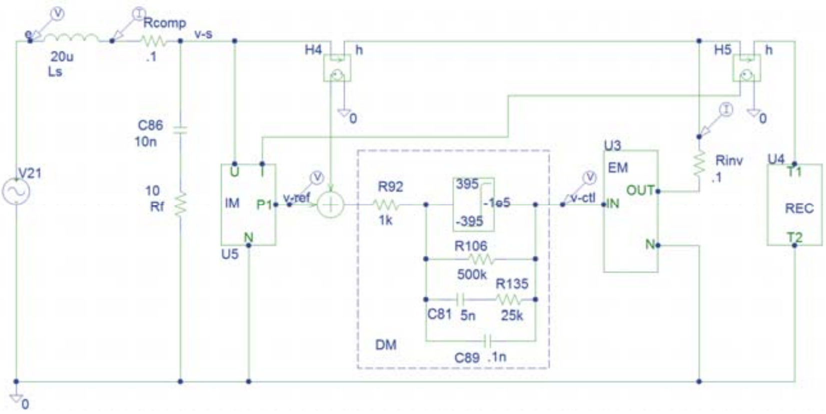
For checking theoretical assumptions the simulation model of the 1-phase shunt active filter with use of the OrCAD/PSpice tool has been investigated. The model is shown in the Fig. 4. It consists of the main block (Fig. 4 a) and the execution module (Fig. 4 b).

Generally, a name of each block of the simulation model corresponds to the active filter diagram shown in the Fig. 1. The CBCD module is a controller for current distribution equalization in individual channels of the inverter.

The parameters of the filter simulation model are as follows:

- number of converter channels: M =1, 2 and 3,
- power network parameters: 230V / 50 Hz,
- nominal value of the receiver power: 5 kVA,
- PWM carrier frequency: f_C =10 kHz,

a)



b)

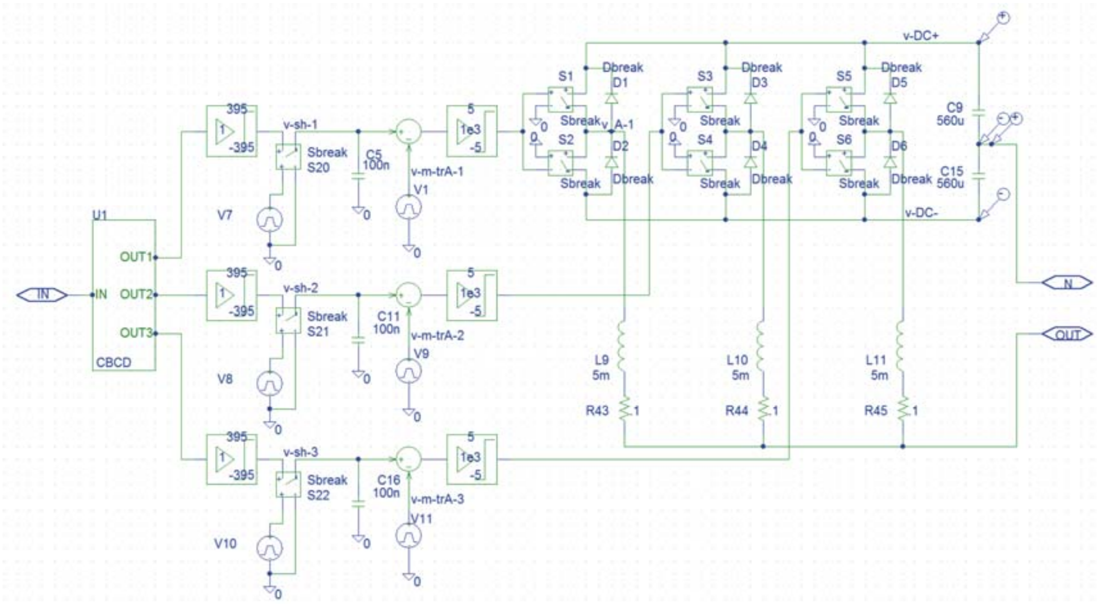


Fig.4. Block diagram of the active filter simulation model (fig. a) and details of the execution module (fig. b)

– maximal value of the filter input current: $A_{S,\max}$ =50 A,
– master sampling frequency in the control module: f_S =20 kHz,
– output inductance of an individual channel of the inverter: $L_{L,i}$ =5 mH $: i = 1,2,3$.

It is assumed in further considerations that the receiver is the thyristor voltage regulator with 90 el. deg. of firing angle, loaded by a resistor. This type of receiver generates the distorted current with an extremely high slew rate value, thus being very rich in higher harmonics. This case of the receiver allows impartially evaluate the quality of the active filter work.

Table 1. Selected parameters of the filter input current as the function of the VCCS channels number M

M	THD of i_S [%]	Parameters of the first PWM carrier component in i_S	
		Freq. [kHz]	Amp. [A]
1	23.7	10	1.74
2	15.5	20	0.66
3	12.2	30	0.31

In the Table 1 selected parameters of the filter input current are presented. E.g. while M =3 the THD value is lowered twice, compared to the standard (i.e. one-channel) filter solution. Also, amplitude of the first PWM carrier component in the input current is decreased significantly (approx. 6-times) in this case, compared to the case of M =1.

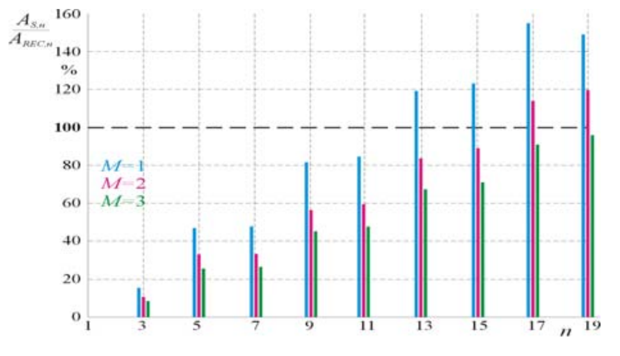


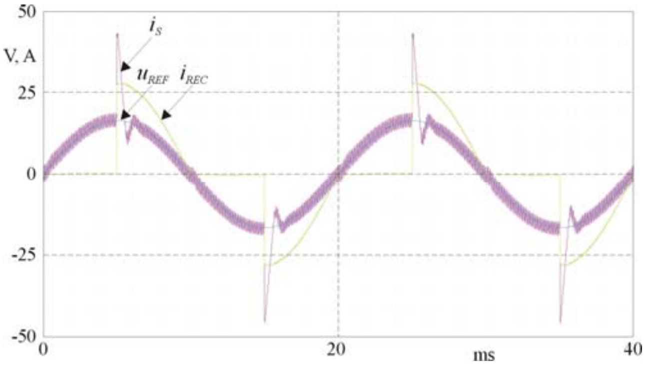
Fig.5. Amplitudes of i_S higher harmonics related to i_{REC} harmonics as function of the VCCS channels number M

In the Fig. 5 relationship of higher harmonics amplitudes of the filter input current and the receiver current as the function of M is shown. The number of analyzed harmonics is equal to 18 (3÷19). Wherein smaller function value indicates that the filter better works, thus if the function value is above 100 % it means that filter works at least inefficiently.

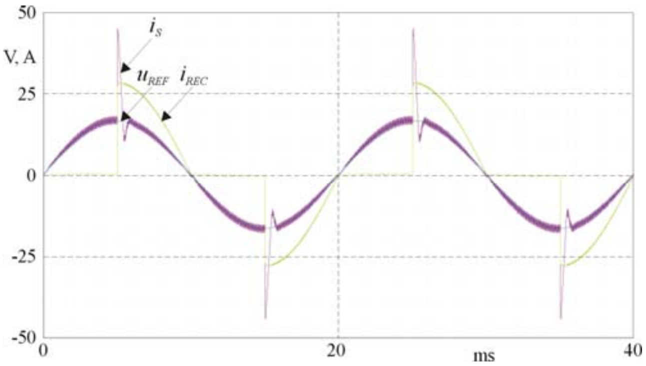
As the study shows, only 3-channel version of the VCCS allows a reduction of amplitudes of all analyzed harmonics of the filter input current.

In the Fig. 6 characteristic signal waveforms in the simulation model are shown. They concern mentioned earlier the example of receiver. The receiver power is equal to approx. 55% of the nominal one.

a)



b)



c)

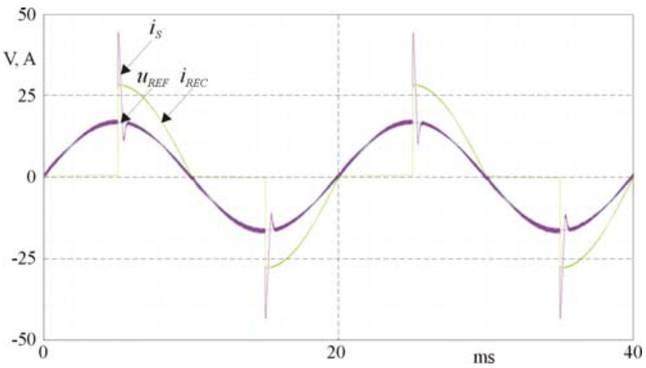


Fig.6. Characteristic signal waveforms in the active filter simulation model while a number of channels: a) M =1, b) M =2, and c) M =3

As can be observed while M value increases the width of “current spikes” in the filter input current decreases. This is due to the filter frequency response is extended. It results in lower amplitudes of higher harmonics of i_S .

As expected, while number of the converter channels increases the overall quality of the filter work is better.

Conclusions

It is possible to increase a quality of an active filter input current, even in a case of very distorted a receiver current. However, it needs complex hardware solutions of an active filter and an advanced control algorithm. Good choice is utilization in a filter execution block of a multi-channel converter.

Due to essentially higher cost of such system, it is reasonable to apply this kind of technology for a group of non-linear receivers rather than a single one. Moreover, taking into account commercially available IPM/IGBT modules [15] it is economically justified to use the filter in 3-channel configuration (i.e. M =3). The approximate estimation of the cost of power part of the converter can be obtained by means of the installed power.

In the control module a digital signal processor equipped with a pulse width modulator could be used. The good example seams the Analog Devices Inc. 3rd- or 4th-gen. SHARC® DSP family [16].

In the next step tests of an active filter laboratory model are provided.

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