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Power electronics parallel active filter with controlled dynamics and improved EM immunity

***Abstract**. Present tendencies of evaluation current distortion compensation methods aim to work out such compensator (parallel active filter) which would be able to realize real time compensation of current distortions. Unfortunately dynamics of every real power electronics current source, being essential part of such filter, is limited. Proposed idea of increasing dynamics of active filter depends on temporarily changing inductance of coil at the output of the current source. For improving EM immunity of that, the low-pass filter has been utilized. The paper presents idea of such parallel active filter as well as selected investigation results of simulation model. (**Energoelektroniczny równoległy filtr aktywny o sterowanej dynamice I polepszonej odporności na oddziaływania elektromagnetyczne**).*

***Streszczenie.** Obecne tendencje rozwojowe metod aktywnej kompensacji odkształceń prądu sieci zmierzają do opracowania takiego kompensatora (równoległego filtru aktywnego), który realizowałby kompensację w czasie rzeczywistym. Niestety dynamika rzeczywistego źródła prądu, będącego istotną częścią równoległego filtru aktywnego, jest ograniczona. Odpowiada za to skończona wartość indukcyjności cewki znajdującej się na wyjściu przekształtnika. Proponowana idea zwiększenia dynamiki źródła prądu polega na sterowaniu wartością tej indukcyjności. W celu polepszenia parametrów związanych z kompatybilnością elektromagnetyczną układu na wyjściu przekształtnika zastosowano dolnoprzepustowy filtr LC. W artykule przedstawiono ideę takiego filtru oraz wybrane wyniki badań modelu symulacyjnego.*

Keywords: power electronics active filter, converter control, passive filter, Pulse Width Modulation (PWM), signal processing.
Słowa kluczowe: energoelektroniczny filtr aktywny, sterowanie przekształtnikami, filtry pasywne, modulacja szerokości impulsów, cyfrowe przetwarzanie sygnałów.

Introduction

The present tendencies of evaluation current distortion compensation methods, aim to work out such compensator (active filter), which would be able to: realize real time compensation of distortion, be more resistant to interferences caused by power network (and receivers) and fulfills EMC requirements. These include also optimization of power grid work conditions. According to Fryze`s suggestion and its further progress [1], it is necessary to eliminate differential current of power source to achieve such compensation. It is always possible with usage of current source which generates such current in opposite phase. In practice, obtaining such source is difficult and needs utilization of active systems with wide-band power electronics controlled current sources.

The assumed aim of filter work is dynamic compensation of differential current, which is the difference between load current and reference current. The differential current is generated by power electronics controlled current source, being part of active filter [2,3,6]. The reference current is the optimal active current calculated with the appropriate method. Due to sinusoidal shape of voltage waveform in power grid, optimization process should lead to minimize RMS value of source current (current at the input of active filter) and its deformations – toward sinusoidal waveform. It results also in minimization of power loses while transmission of energy from source to receiver. Unfortunately dynamics of every real power electronics current source is limited. That is result of several reasons: limited value of inverter DC link voltage, finite value of coil inductance (at the output of inverter) and necessity of obtaining stability of filter circuit (working in closed feedback loop), so regulator gain has to be limited also.

Proposed idea of increasing dynamics of active filter, what lead directly to limitation THD value of source current, depends on temporarily changing inductance of coil at the output of current source. The inductance value follows slew rate (dynamics) needed by current source. The active filter is also further modified toward minimization of parasitic PWM components within source (power grid) current.

The paper presents investigation results of simulation model of such active filter. Some practical solutions are proposed as well.

Structure of active filter

The assumed aim of filter work is dynamic compensation of differential current, which is the difference of load current $i_L(t)$ and reference current $i_{REF}(t)$. The reference current is the optimal active current calculated with the method proposed in [1,2,6]. On Fig. 1 the block diagram of the active filter is shown.

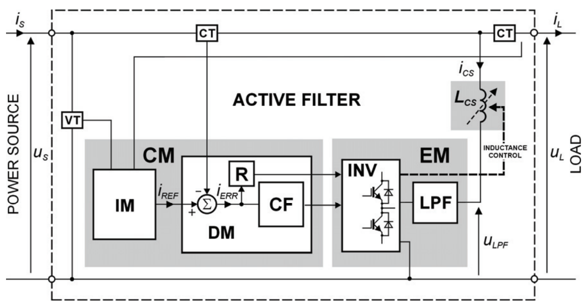

Fig. 1. The block diagram of 1-phase parallel active filter with controlled dynamics of current source

The active filter consists of several blocs, grouped within control module (CM) and execution module (EM):

- identification module (IM) – responsible for generation proper reference signal $i_{REF}(t)$;
- correction filter (CF) – responsible for shaping desired transfer function of filter circuit;
- regulator (R) – responsible for controlling inductance value of coil (L_{CS}) at the output of inverter;
- power electronic inverter (INV) – working in PWM mode;
- output passive low-pass filter (LPF) – responsible for limitation of slew rate value of $u_{LPF}(t)$ voltage at inductor (L_{CS});
- wideband voltage (VT) and current (CT) transducers.

The current source control algorithm should shape current of current source $i_{CS}(t)$ according to equation:

(1) $$i_{CS}(t)=i_L(t)-i_{REF}(t)$$

The general aim of optimization is minimization RMS value of filter input current $i_S(t)$ and its deformations toward sinusoidal waveform. It results also in minimization of power loses while energy transmission from source to receiver occurs. To determine current, having such properties, variational method has been applied [1]. As result, an expression describing optimal reference current has been obtained in following form:

(2) $$i_{REF}(t)=i_a(t)=k_e(t)G_e(t)e(t)=A_{REF}(t)e(t)$$

where: $e(t)$ – power grid voltage, $G_e(t)$ – equivalent power source conductance in form: $G_e(t)=P_a(t)/E^2(t)$, where: $P_a(t)$, $E(t)$ – instantaneous values of active power and RMS of voltage source of power grid.

Phases of reference signal $i_{REF}(t)$ and fundamental harmonics of voltage source should be the same [1,2,6].

In case of widely used today parallel power electronics active filters, inductance value of coil in current source (L_{CS}) is fixed. Main role of that part depends on obtaining such output impedance of current source which minimizes enough current ripples being results of utilized there pulse (PWM) modulation. Thanks implementation at the output of inverter low-pass filter (LPF), slew rate value of $u_{LPF}(t)$ is, in comparison to standard solutions, much decreased.

Unfortunately, due to finite value of L_{CS} and presence of LPF, dynamics of output current $i_{CS}(t)$ is limited to value given following equation:

(3) $$i_{CS}(t)=\frac{1}{L_{CS}}\int\left[u_{LPF}(t)-u_S(t)\right]dt \, .$$

Effect of that limitation are "current spikes" within source current $i_S(t)$ – in cases when slew rate of load current $i_L(t)$ is greater then maximum slew rate value of source current $i_{CS}(t)$ – Fig. 2.

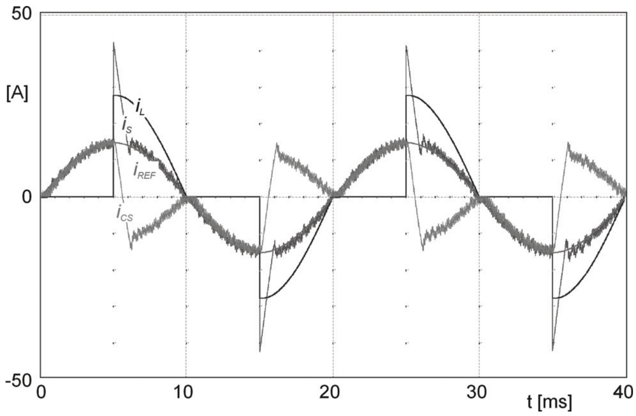

Fig. 2. Waveforms of currents in active filter with fixed value of coil inductance while slew rate value of load current is extremely high

As result, bandwidth of current source is limited also. Thus effectiveness of active filter acting within higher frequencies range can be poor.

Due to limitation of filter dynamics results mainly from limited (non-zero) value of L_{CS} (assuming DC link voltage is kept at constant level), only way to increase this is utilizing inductor with variable inductance. That idea lets achieve higher slew rate values of current source $i_S(t)$ when necessary and, for normal conditions of filter work, keeping current ripples at acceptable level.

Coil with controlled inductance

A few possible solutions lead to increasing dynamics of current source. One of them depends of utilization an additional inductor, connected in parallel with main one, powered by additional half-bridge inverter [4]. Serious disadvantage of such solution is high cost, particularly in multi phase filters. Alternative solution depends on utilization of coupled coils with arbitrary chosen magnetic coupling coefficient k , which should be much less then 1.0 [5]. The k coefficient is given by equation:

(4) $$k=\frac{M}{\sqrt{L_{CS-1}L_{CS-2}}}$$

where: L_{CS-1}, L_{CS-2} – self-inductances of coils, M – mutual inductance.

This results in existing some, strictly specific, leakage inductance of each of coupled coils. When slew rate value of load current is low, secondary winding is opened. When high slew rate of this current is necessary, secondary winding is short circuited, resulting in decreasing of equivalent inductance of coupled coils, so dynamics of current source can be much increased. The role of power switch, short-circuiting the secondary winding, fulfills additional single IGBT and rectifier with pulse diodes – Fig. 3.

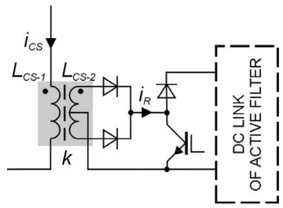

Fig. 3. Realization details of coil with controlled equivalent inductance

Additional advantage of such solution is returning of coil magnetic field energy (proportional to value of coupled coils second side currents), in passing states (when IGBT switch is turned off) directly to DC link.

Active filter simulation model

For checking theoretical assumptions OrCAD/PSPICE simulation model of 1-phase parallel active filter with controlled inductance and low-pass filter at the output has been widely investigated.

Main parameters of simulation model have been as follows:

- external power grid parameters: 230V/ 50 Hz;
- power range of receiver: 1.0 – 3.5 kVA;
- PWM carrier frequency: 10 kHz;
- sampling frequency in control circuit: 20 kHz;
- parameters of coils: L_{CS-1} = L_{CS-2} =10 mH, k =0,85;
- low-pass filter parameters: second order, with cutoff frequency about 3,2 kHz.

Selected investigation results in form of filter input current $i_S(t)$ and load current $i_L(t)$ waveforms are shown on Fig. 4 and 5. The receiver, in that case voltage regulator with 90 el. degree turning on angle loaded by resistor, has generated distorted current with extremely high dynamics (slew rate value) – Fig. 4.

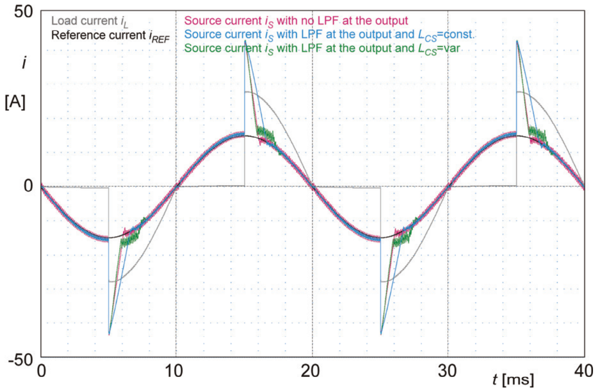

Fig. 4. Waveforms of characteristic currents of active filter for either, fixed and variable inductance of coil in current source

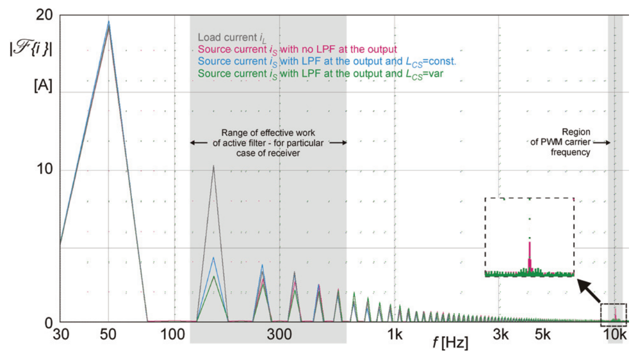

Fig. 5. Spectrum of characteristic currents of active filter for either, fixed and variable inductance of coil in current source

As can be observed on Fig. 5, for variable inductor solution "current spikes" are much narrower then for fixed one. This results in decreasing amplitudes of higher harmonics, about orders from 3 to 11. Some disadvantage of variable inductor solution depends on temporarily increasing of source current $i_S(t)$ ripples, caused by pulse modulation, when inductance value is lowered. This undesirable effect is also limited by utilized at the output of inverter low-pass filter (LPF).

Overall THD value of filter input current $i_S(t)$, measured within 1.5 kHz band, is decreased about approximately 40% for filter with variable inductance – in comparison to solution with fixed one.

In case of low-pass filter implementation, amplitudes of parasitic PWM components are decreased approximately 3 times – in comparison to solution with inductor only at the output of inverter.

Coils with Controlled Inductance in 3-Phase Version

In case of 3-phase parallel active filter, utilization of similar solution is possible. Moreover, control circuit dedicated each of coils can utilize only one common IGBT switch. The common IGBT switch solution cause, like before, temporarily increasing of current ripples in every phase but overall THD values of filter input currents are much smaller [5].

Role of power switch, short-circuiting the secondary windings, can fulfill additional IGBT called "breaking IGBT". Most of standard IPMs are equipped with such additional IGBT, together with pulse diode in collector circuit so cost of implementation of proposed solution seems relatively low.

The 3-phase version of filter needs separate low-pass filter at the output of each sub-inverter – realized as full- or half-bridge solution.

Conclusions

It is possible to increase bandwidth of power electronics active filter and minimize value of energy of "current spikes" and current ripples within filter input current. First feature can be achieved by temporarily decreasing value of leakage inductance of coupled coils at the output of current source. Thanks of that, the active filter is able more effective shape the input current (power grid current) what results in essential minimization of THD value. The "breaking switch", together with accompanied pulse diode, which controls the inductance, is a part of most popular IPMs. Thus, cost of such modification of active filter structure seems relatively low.

Overall EM characteristics of active filter can be significantly increased and current ripples can be decreased thanks implementation at the output of inverter passive low-pass filter.

Practical implementation of presented solution in laboratory model of 1-phase active filter for evaluation purposes is expected soon.

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