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# NOVEL CONTROLLER FOR SOFTWARE-BASED BALANCING OF CURRENT DISTRIBUTION IN MULTI-CHANNEL CONVERTERS

**ABSTRACT** *The parallelism is a well known technique for increasing the power capacity of converters because it helps to overcome the current limitations of semiconductor devices. Multi-channel (interleaved) converters use a kind of parallelism that, thanks to their own particular features, makes it possible to map more accurately the converter output signal in a reference one. However, multi-channel converters present several disadvantageous. The most important problem consists in the fact that the output current may not be distributed equally in converter channels what requires additional components supporting this mechanism. In contrast to the generally used methods software only solution of the controller for balancing of current distribution is proposed in this paper. The controller constitutes part of a control system of wide-band power electronics current and voltage source. The paper presents an idea and principles of work of such controller. Also, results of converter simulation model experiments are presented.*

**Keywords:** *converter control, current distribution, interleaved converters*
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## 1. INTRODUCTION

The parallelism (a parallel connection) is a commonly used technique for increasing the power capacity of converters because it helps to overcome the current limitations in the semiconductor devices. High power converters can be built by using lower rating power components, what makes them more competitive. Also, the parallelism enables the modular construction of the converter what leads to a lower cost of its maintenance. Also, other connection types of a number of inverters are used – it concerns, e.g., of multilevel converters [10].

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Multi-channel (interleaved) converters, e.g., [9, 13], use a kind of parallelism whose characteristics include, apart from the ones mentioned above, the following:

- the possibility of reducing the size of the passive elements or the reduction of the switching frequency without increasing the current or output voltage ripples so, e.g. cost of the converter can be reduced,
- the possibility of increasing the regulator gain in a control system having a very advantageous impact on the performance of an converter – a control algorithm allows to match more accurately the output signal in the reference one, in comparison to a standard converter,
- due to parallel connection of two converters the equivalent output impedance of such system is lowered, and its pass-band is extended,
- the effective PWM carrier frequency components in the output signal is shifted towards higher frequencies, so the amplitude of current ripples in the output quantity, caused by modulation, is reduced as well – despite the decrease of converter output impedance.

Next to these advantages the mechanism of action of multi-channel converters causes several problems; the most important ones include:

- the converter total output current may not be distributed equally between the converter channels,
- channel cross-currents are generated increasing a converter power loss.

The present article is focused mainly on the control of the current distribution in converter channels without paying special attention to other problems. In contrast to the generally used methods, the control of the current distribution is done exclusively by software solution.

The following text is divided into five sections. The first one deals with the commonly used solutions for balancing of a current distribution. The second one shows the basic description of the multi-channel converter as an execution part of a wide-band power electronics controlled current or voltage source. The third one describes the method proposed by the author for converter control – focused on balancing of current distribution. The fourth part shows the results of simulation for the controlled current and voltage sources. The last part is dedicated to the conclusions.

## 2. COMMONLY USED METHODS FOR BALANCING OF CURRENT DISTRIBUTION

Most of existing solutions proposed to overcome the unbalanced distribution of the current are based on the use of circuits with a magnetic coupling [3, 7]. E.g., [2, 3, 12] replaces the separated channel inductors with one inductor with a center derivation which is connected to the output of the interleaved converter while the other terminals are connected to the outputs of each converter connected in parallel. Owing to that, currents in channels are balanced naturally. If the current in one of the channels is greater than in the other one, it will generate an electromagnetic field in the other channels resulting in an additional impedance compensating an imbalance.

The interesting solution with resonant filters is proposed in [18]. They are connected in series to the DC bus tuned at the multiples of $f_c$ lower than $Mf_c$, where $M$ is the number of converter channels. This technique is based on the fact that when the current is distributed in a balanced way the current supplied by the DC bus has harmonic components only in frequencies higher than $Mf_c$. So, if the imbalanced current distribution arises, the voltage drop on the resonant filters will increase. As a consequence, the effective DC voltage on the channel with higher current will be lower than that on the channel with the lower current. This ensures a natural balance in the total current distribution.

Another possibility of controlling the current distribution is by feedback control with additional current sensors [17]. The main problem is that the modulating signals will not be identical to each other as the current of each channel will be controlled independently. Nevertheless, if the differences between the legs are not too big, the feedback control can be used without affecting strongly the characteristics of interleaving. Also, many other combined hardware and software methods of current distribution control can be found, e.g., [16]. A common disadvantage of all of them is more or less complexity in hardware. Most solutions need components based on magnetically coupled circuits or (and) extra components, e.g., for current (voltage) measurement. It results in higher dimension, weight and cost of a converter.

# 3. POWER ELECTRONICS CONTROLLED CURRENT AND VOLTAGE SOURCES BASED ON A MULTI-CHANNEL CONVERTER TOPOLOGY

In spite of that presented concept of the controller can be implemented in any kind of multi-channel converter, including the widely used interleaved DC/DC converters, e.g., [6, 13], further consideration will be related to wide-band power electronics controlled current and voltage sources only. This class of converters is particularly focused on precision matching an output quantity (current or voltage) within a reference signal and has a wide range of applications in advanced power electronics converters [4, 5, 11, 14].

In Figure 1, the general structure of a voltage controlled current source (VCCS) and voltage controlled voltage source (VCVS) is shown. Both of them are based on a concept of multi-channel converter, where the total output current $i_{REC}$ is proportional to a sum of individual channel currents $i_{L,i}$: $i = 0, 1,\ldots, M-1$. Thus, in the case of "ideal" balancing of output current distribution:

$$i_{L,i} = a\frac{i_{REC}}{M} : i = 0,\ 1,\ldots, M-1 \tag{1}$$

where $a$ = const. In the case of VCCS, $a = 1$, while for a VCVS $a < 1$.

The controlled current and voltage sources are systems which operate in a closed, voltage type, negative feedback loop. Converters in an execution block are

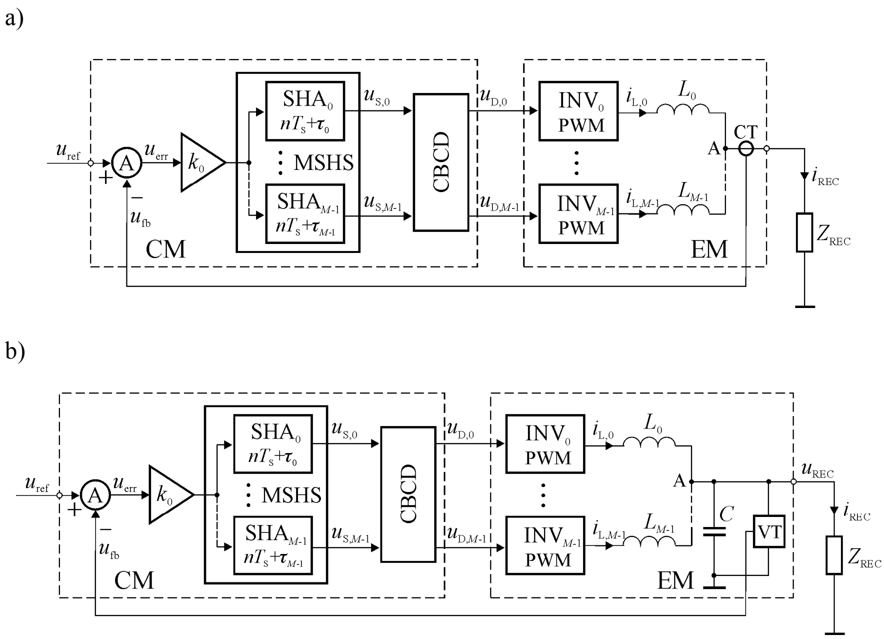


**Fig. 1. General scheme of a VCCS (a) and a VCVS (b) with a controller for balancing of a current distribution**

controlled in PWM mode with the constant value of a carrier frequency, e.g., [9]. One of the fundamental blocks of the controlled source is a passive low-pass filter at the output of converter(-s). It minimizes the amplitude of PWM carrier components in the output (receiver) current and enables the converter to meet the requirements of EMC.

The general structure of VCCS and VCVS consists of two main internal modules, the control module (CM) and the execution module (EM). The control module includes the following internal blocks:

– adder (A), calculating the error signal $u_{err}$ as $u_{err} = u_{ref} - u_{fb}$,
– regulator of the output signal with the gain factor of $k_0$,
– $M$-order multi-dimensional sampling-and-hold system (MSHS) consisting of $M$ connected in parallel Sample-and-Hold Amplifiers,
– controller for balancing of current distribution (CBCD).

The execution module includes the following:

– $M$ connected in parallel half-bridge type converters controlled in PWM mode with $f_c$ of a carrier frequency,
– passive output filter (L or LC type),

– current (CT) or voltage (VT) transducer measuring the feedback voltage $u_{fb}$ being proportional to the output current $i_{REC}$ or to the output voltage $u_{REC}$ of the converter, respectively.

The converter is loaded by the receiver expressed as $Z_{REC}$ impedance and controlled by a reference voltage $u_{ref}$ at the input of the CM.

Sampling instants in individual channels of the MSHS block are shifted relative to each other by the $T_s/M$ time, where $T_s$ is a master sampling period. Also, PWM carrier signals in individual channels of the EM are shifted by the same period of time. The general principles of operation of the MSHS are derivative of the Generalized Sampling Expansion (GSE) proposed by Papoulis [1] as an extension of Whittaker-Kotelnikov-Shannon sampling theory. The theory of operation of the multidimensional sampling-and-hold system and its role in the control system of a multi-channel converter has been the subject of other studies by the author [8, 9].

## 4. OPERATION PRINCIPLE OF THE CONTROLLER FOR BALANCING OF CURRENT DISTRIBUTION

Investigations of the multi-channel converters point at a spectrum of the error signal $u_{S,i}$ aliasing phenomenon [15] as the main reason for the loss of information about this one. This, together with different sampling instants of the error signal $u_{err}$ in individual MSHS channels, can make signals $u_{S,i}$ different as well. The MSHS signal sampling process, involving the small-signal model of this module, is shown in details in Figure 2.

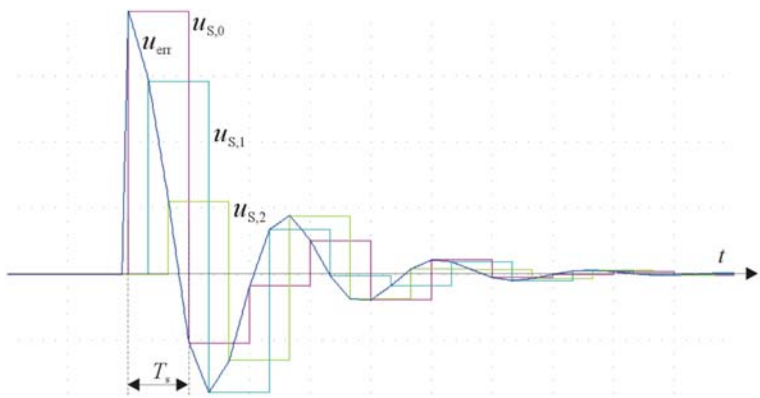


**Fig. 2. Example of the error signal $u_{err}$ and its sampled images $u_{S,i}$ in individual channels of MSHS for the case of $M$ = 3**

Waveforms $u_{S,i}$ of the sampled error signal $u_{err}$ are different in the individual MSHS channels. As result, the individual converter channel currents are also different. This phenomenon is illustrated in Figure 3 where the work of the VCCS small-signal model is analyzed for two cases of the reference signal shape.

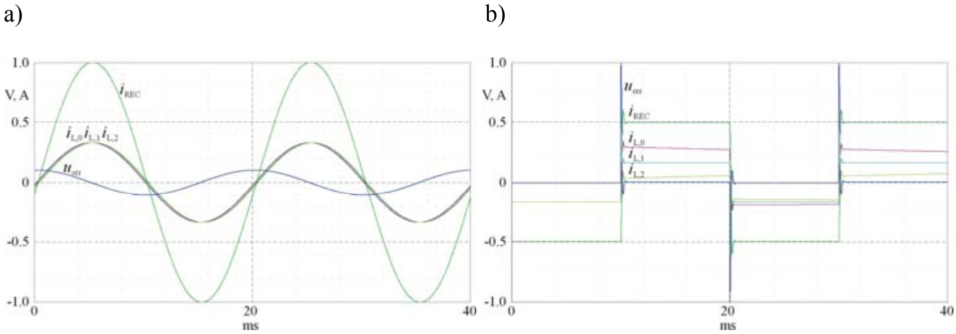


**Fig. 3. Waveforms of the error signal, receiver current and channel currents in the VCCS small-signal model for the case of *M* = 3 and:** a) sinusoidal shape of the reference signal; b) rectangular shape of the reference signal

The first case concerns the sinusoidal reference signal, thus, the band of error signal is limited. The second one refers to the rectangular one resulting in the spectrum of error signal beyond the Nyquist band. Because the assumed receiver impedance $Z_{REC} = 0$, the receiver current is just the sum of channel currents allowing for a reliable evaluation of the system properties.

In the case of the limited band of error signal spectrum the channel currents are distributed properly (Fig. 3a). In the opposite case (Fig. 3b) channel currents are different in amplitude significantly.

The proposed idea of the system independence, software only solution of a controller for balancing of the current distribution, focuses on two aspects of CM operation:

– increasing the effective sampling frequency of the error signal in individual channels of CM,
– obtaining the same shape of control signals in each of CM channels.

Meeting these objectives results in the extension of the Nyquist band of CM and comparable properties of $u_{D,j} : j = 0,1,\ldots,M-1$ signals at the input of the execution module (i.e. input of pulse modulators). This effect can be obtained with the aid of the signals interleaving process (SIP) which is the basis of the CBCD module work. This process allows for a suitable shape of the individual output signal $u_{D,j}$ of the CBCD which comprises an in-time sequence of CBCD input signals. The every next CBCD output signal sequence consists of rotated by one position – in relation to the CBCD input channel number – the same input signal sequence. The signal sequence rotation time interval is, in other words, the SIP work interval $\boldsymbol{T}_{SIP} : \boldsymbol{T}_{SIP} \Rightarrow \langle nT_S, (n+1)T_S \rangle : n \in C$.

The CBCD module works on the $M \times M$ dimensional array consisting of a set of signals $u_{j,k} : j,k = 0,\ 1,...,M-1$, where $j$ is the CBCD output channel number and $k$ is the number of time slot in the $\boldsymbol{T}_{\mathrm{SIP}}$ interval. An individual cell of the array contains a $u_{\mathrm{S},i} : i = 0,\ 1,...,M-1$ signal sample. The structure of the array is shown in Figure 4.

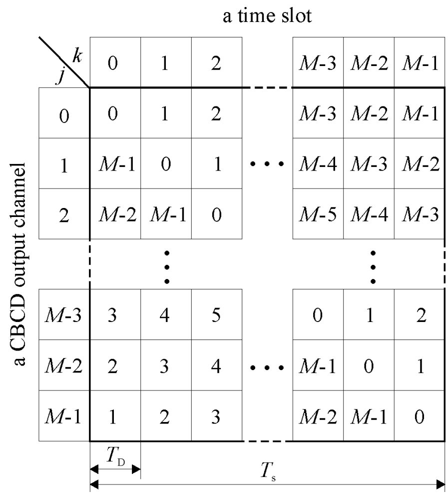


**Fig. 4. Structure of the signal processing array in the CBCD module**

Formally, the rule of the CBCD module work is defined by the following equation in a time domain:

$$u_{\mathrm{D},j}(t) = \begin{cases} \displaystyle\sum_{i=0}^{M-j-1} u_{\mathrm{S},i}\left[t-(n+j+i)\frac{T_{\mathrm{S}}}{M}\right]\mathrm{rect}\left(\frac{t-(n+j+i)\frac{T_{\mathrm{S}}}{M}}{\frac{T_{\mathrm{S}}}{M}}\right) : j = 0, n \in C \\ \displaystyle\sum_{i=0}^{M-j-1} u_{\mathrm{S},i}\left[t-(n+j+i)\frac{T_{\mathrm{S}}}{M}\right]\mathrm{rect}\left(\frac{t-(n+j+i)\frac{T_{\mathrm{S}}}{M}}{\frac{T_{\mathrm{S}}}{M}}\right) + \\ \displaystyle + \sum_{i=M-j}^{M-1} u_{\mathrm{S},i}\left[t-(n+j+i-M)\frac{T_{\mathrm{S}}}{M}\right]\mathrm{rect}\left(\frac{t-(n+j+i-M)\frac{T_{\mathrm{S}}}{M}}{\frac{T_{\mathrm{S}}}{M}}\right) \\ : j = 1,2,...,M-1, n \in C \end{cases} \tag{2}$$

and the rect() function is defined as $\mathrm{rect}\left(\frac{t}{\Delta t}\right) = \mathbf{1}(t) - \mathbf{1}(t-\Delta t) = \begin{cases} 1 : \mathrm{t} \in \langle 0, \Delta t) \\ 0 : \mathrm{t} \notin \langle 0, \Delta t) \end{cases}$.

The equation above respects both, a signal sampling and a signal holding processes realized by the CBCD module. The sampling period $T_D$ of a $u_{D,j}$ signal is $M$-times decreased, comparing to the period of the input signal $u_{S,i}$ and, therefore, is equal to $T_s/M$. Thus, the Nyquist band of the output signal is now $M$- times extended.

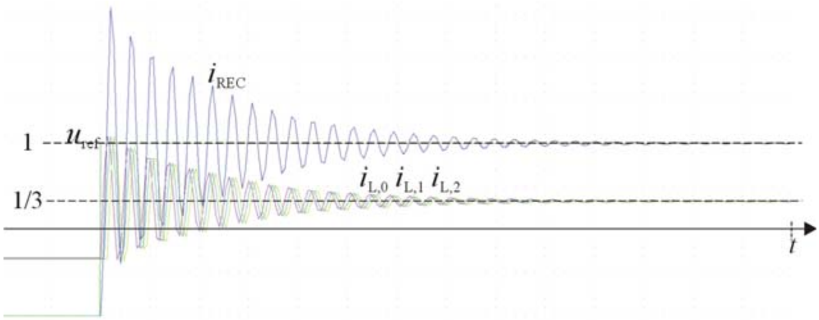


**Fig. 5. The step response of the VCCS small-signal model with the CBCD module**

The selected simulation result of the VCCS small-signal model is shown in Figure 5. It concerns model parameters as follows: $M = 3$, $L_i = 2.5$ mH, and $Z_{REC} = 0$.

The model has worked closely to a system stability border, hence, the duration of the transition state is relatively long. However, in the steady state, the value of the component current $i_{L,i}$ is equal to 1/3 of the total output current $i_{REC}$ with the error below of ±1.5%. This confirms high effectiveness of the current balancing algorithm.

## 5. SIMULATION EXPERIMENTS

The complex studies of the VCCS and VCVS simulation model with the controller for balancing of current distribution have been done in OrCAD/Pspice environment. They make it possible to evaluate not only effectiveness of the controller operation but also the impact of the CBCD on matching of the output quantity waveform in the reference signal. Basic simulation model parameters have been as follows: converter DC link voltage $U_{DC} = 60 \div 120$ V, $M = 2, 3$, $T_s = 100$ µs, $f_c = 10$ kHz, kind of PWM – two-sided, $L_i = 2.5$ mH, $C = 1$ µF, the receiver resistance in the VCCS model $R_{REC} = 0.01 \div 1$ Ω while in the VCVS model $R_{REC} = 2 \div 20$ Ω, and the nominal amplitude of the output current $I_{REC,n} = 12$ A. Ready to use models of power electronics devices that are implemented in OrCAD/PSpice have been modified towards real devices utilized in LABINVERTER evaluation system [19].

Some results of the studies, representative for real operation conditions of the VCCS and the VCVS, are presented in Figures 6 and 7. These assume $M = 3$. The upper figure shows waveforms in the simulation model with the CBCD module being turned off while the lower ones for the CBCD being turned on. The presented waveforms refer to the case of the rectangular shape of the reference signal which is the most demanding in the performance of the controlled source work. Used in the following text the formulation "CBCD is turned off" means that $u_{D,i} = u_{S,i}$: $i = 0, 1, 2$. In other words, individual inverters are controlled by $u_{S,i}$: $i = 0, 1, 2$ signals directly.

a) b)

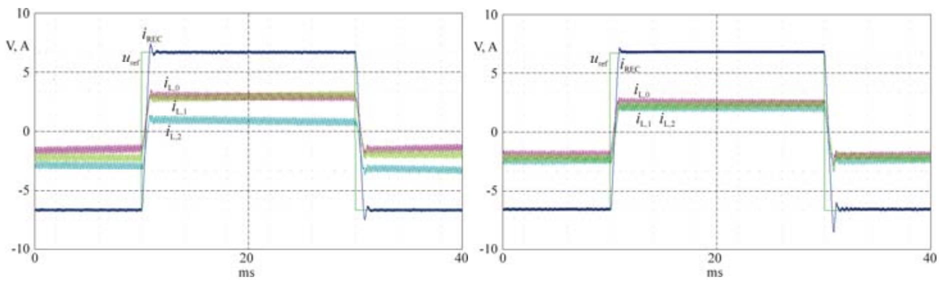


**Fig. 6. Waveforms of the reference signal, receiver current and channel currents in the VCCS simulation model for the case of rectangular shape of reference signal while:** a) CBCD is turned off; b) CBCD is turned on

a) b)

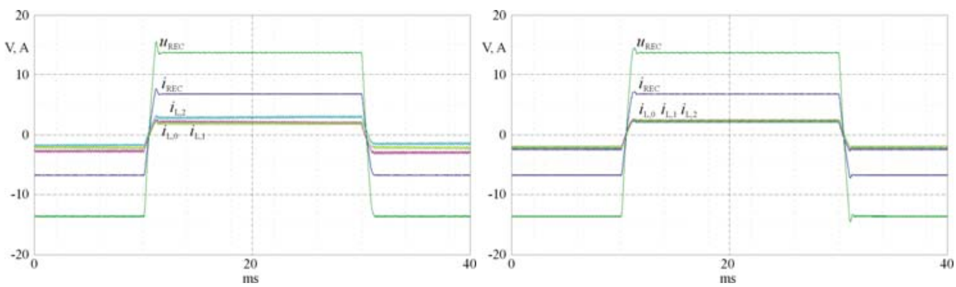


**Fig. 7. Waveforms of the receiver voltage, receiver current and channel currents in the VCVS simulation model for the case of rectangular shape of reference signal while:** a) CBCD is turned off; b) CBCD is turned on

Results of investigations indicate that, while the CBCD module is turned off, the distribution of the output current is strongly imbalanced. Also, these results confirm the assumed efficiency of work of the proposed solution of the controller. In the case of the VCCS the maximal registered spread of the average value of channel currents has not excided ±3% of the nominal value of output current (divided by $M$, i.e., by 3). For the VCVS this error has been even lower due to the output filter limits band of the $u_{fb}$ signal. Because the CBCD does not include any additional delay in the system signal path, it does not affect the stability of the system. In consequence, it has a negligible impact on the converter output signal parameters.

# 6. CONCLUSIONS

The proposed digital controller for balancing of current distribution fulfills the assumed task with small only spread of current values in individual channels of the converter. Its effectiveness has been confirmed by the research on small-signal and simulation models of wide-band controlled current or voltage sources with this controller in their control block. Moreover, the proposed approach to the control system retains the basic characteristics of its original small-signal model. Owing to that impact of the controller on the quality of the converter output current or voltage is negligible. Thus, the proposed solution seems to be an economically attractive alternative to the commonly used methods of current distribution control.

Researches of the laboratory model of a power electronics active filter based on the VCCS with CBCD will be the next step which is planning to take.

**LITERATURE**


1. Papoulis A.: Generalized Sampling Expansion, IEEE Transactions on Circuits and Systems, Vol. 24, Issue 11: 652 – 654, 1977.
2. Matsui K., Murai Y., Watanabe M., Kaneko M., and Ueda F.: A pulsewidth-modulated converter with parallel connected transistors using current-sharing reactors, IEEE Transactions on Power Electronics, Vol. 8, No. 2: 186-191, 1993.
3. Ueda F., Matsui K., Asao M. and Tsuboi K.: Parallel-connections of pulsewidth modulated converters using current sharing reactors, IEEE Transactions on Power Electronics, Vol. 10, No. 6: 673-679, 1995.
4. Gwóźdź M., and Porada R.: Compensate for Loading Effects on Power Lines with a DSP-Controlled Active Shunt Filter, Analog Dialogue, Analog Devices Inc., Vol. 33, No 9, 1999, http://www.analog.com/library/analogDialogue/archives/33-09/filter/index.html.
5. Gwóźdź M., Porada R. and Frąckowiak L.: Active compensation system of influence of nonlinear receivers on power network, Proc. of COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 20, No. 4: 905-913, 2001.
6. Huang X.: Parasitic ringing and design issues of digitally controlled high power interleaved boost converters, IEEE Transactions on Power Electronics, Vol. 19 , Issue 5: 1341-1352, 2004.
7. Jiang Y. and Pan J.: Single phase full bridge converter with coupled filter inductors and voltage doubler for PV module integrated converter system, BULLETIN OF THE POLISH ACADEMY OF SCIENCES TECHNICAL SCIENCES, Vol. 57, No. 4: 355-361, 2009.
8. Gwóźdź M.: Stability of Discrete Time Systems on Base Generalized Sampling Expansion, Elektryka, Politechnika Śląska, Vol. 1 (217): 29-40, 2011.

9. Gwóźdź M.: Power electronics wideband controlled voltage and current sources on base of interleaved converters, (in Polish), Przegląd Elektrotechniczny, Nr 10A: 132-134, 2012.
10. Iwaszkiewicz J., Bogusławski P., Krahel A., and Łowiec E.: Three-phase voltage outages compensator with cascaded multilevel converter, Archives of Electrical Engineering, Vol. 61(3): 325-336, 2012.
11. Gwóźdź M.: Power Electronics Active Shunt Filter with Controlled Dynamics, Proc. of COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 32, No. 4: 1337-1344, 2013.
12. Matsui K., Asao M., Ueda F., Tsuboi K. and Iwata K.: A technique of parallel-connections of pulsewidth modulated NPC converters by and using current sharing reactors, Proceedings of the IECON'93, International Conference on Industrial Electronics, Control, and Instrumentation, Vol. 2: 1246-1251, 1993.
13. Huth S.: DC/DC converters in Parallel Operation with digital load distribution control, Proceedings of the IEEE International Symposium on Industrial Electronics ISIE '96, Vol. 2: 808-813, 1996.
14. Seliga R., and Koczara W.: High Quality Sinusoidal Voltage Converter for Variable Speed AC Drive Systems, Proc. of EPE-PEMC2002 10th International Power Electronics and Motion Control Conference, Cavtat & Dubrovnik, Topic 11, 2002.
15. Gwóźdź M.: Impact of Aliasing Effect on Work of Wide Band Power Electronics Current Source, Proc. of XIX Symposium Electromagnetic Phenomena in Nonlinear Circuits, Maribor, Słowenia: 147-148, 2006.
16. Le Bolloch M., Cousineau M. and Meynard T.: New Masterless Current-Sharing Modular Approach for DC/DC Parallel Converters, Proc. of EPE-PEMC 2010 14th International Power Electronics and Motion Control Conference, Ohrid, Macedonia, Topic T3: 73-80, 2010.
17. Díaz S., Cortizo P., Santos R. and Severo M.: Analysis of digital controllers for equilibrated current distribution in an interleaved converter, Proc. of IECON 2010 – 36th Annual Conference on IEEE Industrial Electronics Society, Glendale, USA: 83-90, 2010.
18. Devancens P.: “Etude de l’équilibrage Naturel des Courants dans les Convertisseurs Multicellulaires Paralléle. Validation Expérimentale sur une Structure à MCT”, Tese de doutorado, L’Institut National Polytechnique de Toulouse, 1997.
19. http://analog.alfine.pl, accessed: March 2015


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# CYFROWY KONTROLER ROZPŁYWU PRĄDÓW W PRZEKSZTAŁTNIKU WIELOKANAŁOWYM

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**STRESZCZENIE** *Łączenie równoległe przekształtników jest przyjętym sposobem zwiększenia mocy dysponowanej dla zasilania odbiorników energii elektrycznej. W przypadku przekształtników wielokanałowych (ang. „intereleaved") możliwe jest również uzyskanie lepszej wierności odwzorowania energetycznego sygnału wyjściowego w sygnale referencyjnym (odniesienia). Przekształtniki te mają jednak, co najmniej jedną niekorzystną cechę związaną z tym, że prąd wyjściowy może nie rozpływać się równomiernie w poszczególnych kanałach. Wymaga ona stosowania dodatkowych rozwiązań sprzętowych, wspomagających mechanizm równoważenia rozpływu prądów. W przeciwieństwie do powszechnie używanych metod, w pracy przedstawiono propozycję kontrolera rozpływu prądów rozwiązanego wyłącznie programowo. Możliwe jest przez to ograniczenie kosztów, stopnia złożoności oraz gabarytów przekształtnika. W pracy przedstawiono zasadę pracy takiego kontrolera w sterowanym energoelektronicznym źródle napięcia i prądu. Zamieszczono w niej również wybrane wyniki badań modelu symulacyjnego układu.*

**Słowa kluczowe:** *przekształtniki wielokanałowe, równoważenie rozpływu prądów, sterowanie przekształtnikami*

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