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# BROADBAND POWER ELECTRONICS CONTROLLED CURRENT SOURCE WITH ANALOGUE CONTROL SECTION AND OUTPUT STAGE BASED ON GaN TRANSISTORS

The paper presents the conception of the power electronics controlled current source based on the sigma–delta modulator (SDM). Due to very high frequency of the SDM output bit stream, in the power stage of inverter the gallium-nitride (GaN) transistors are used. In these circumstances even efficient DSPs are unable, due to limitation of its pass–band of the control path, to obtain right parameters of the output current regulator. So, the regulator is done in the fully analogue manner. As result of these the value of distortions of the inverter output current is much lower, compared to the typical, PWM based, solutions. This benefit is not paid significantly by increase in the system complexity. In work the converter operation basics and results of its simulation model studies are presented.

KEYWORDS: converter control, GaN transistor, interleaved technique, pulse modulation

## 1. INTRODUCTION

A non–linearity of loads, limited frequency response of power electronics converters, and wide–band nature of signal sampling and pulse width modulation processes are reasons of inaccurate mapping a converter's output current in a reference signal. To meet this requirement both advanced solutions of converters in hardware and in control algorithms are necessary.

In this paper the sigma–delta modulator (SDM) [1, 2] is used to direct control of the output stage of the power electronics voltage controlled current source (VCCS). These types of the pulse modulator are used in the Class–D Amplifiers [3, 4], A/D converters [5], and special purpose solutions for electronics systems [6].

The basic premise of the proposed VCCS conception is obtainment of precise mapping of the output current in the input (reference) signal. Besides, the structure of control system is simple, i.e mostly analogue one (no “purely” digital components are used in the SDM nor in the current regulator), and can

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be easily implemented in power electronics equipment where high quality of the output quantity is necessary. Due to very high frequency of the output bit stream (about 1 MHz), in the power stage of inverter the gallium–nitride (GaN) transistors are used. In these circumstances even efficient DSPs are unable, taking into account limitation of the pass–band of the control circuit due to Nyquist law, to obtain right parameters of the output current regulator. So, this one is done in the analogue manner. As result of this the value of distortions of the inverter output current is much lower, compared to the typical, PWM based, solutions [7, 8]. This benefit is not paid significantly by increase in the system complexity.

The following text is divided into three sections. The first one deals with the structure and the rule or work of the current source. The second one shows the simulation model researches for the VCCS. In the last part conclusions are presented.

## 2. BASICS OF CONVERTER'S OPERATION

In Fig. 1a the block diagram of VCCS based on a SDM is shown. The VCCS is an electrical system working in a closed feedback loop. Many factors, e.g. limited frequency response and work of a pulse modulator cause that a load current is often poorly mapped in a reference signal. Particularly it takes place when value of a PWM carrier frequency is low what is enforced by demanding of maximization of a converter's efficiency.

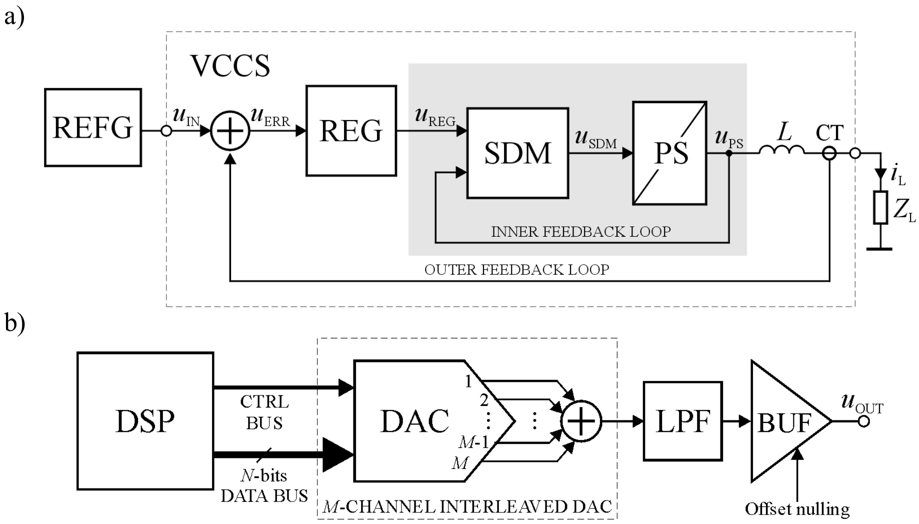


Fig. 1. Block diagrams of VCCS (a) and reference signal generator (REFG) (b)

The VCCS consists of the two main modules: SDM with its inner feedback loop and the power stage at the output and current regulator (REG) with its own (outer) feedback loop. SDM bases on the comparator with the dynamic hysteresis loop, which fundamentals of operation was presented in [9]. REG is a P type regulator based on a single operational amplifier. At the output of the converter the passive low pass filter (inductor $L$) is included. This one minimizes pulse modulation components in the converter's output current ($i_L$). The CT block is the linear, isolated current transducer with $r_{CT}$ the conversion ratio. At the input of VCCS the reference signal generator (REFG) is included. The details of REFG's structure are shown in Fig. 1b. For generating the high quality output signal, in REFG a digital–to–analog interleaved technique [1] was implemented with the interleaving factor equal to $M$. The generator primarily uses the $M$ channel precision digital–to–analog converter (DAC). While each single DAC's channel works at $\frac{1}{T_{DAU}}$ update rate, the effective conversion frequency is $M$ times larger. So, the imaging effects in the output signal, pointed at by the Nyquist law, are significantly minimized. The LPF block is the low–pass filter.

For calculation of boundary values of system parameters – for preventing the system stability – the small–signal model of VCCS was used. This one is shown in Fig. 4. The model bases on works [10,11].

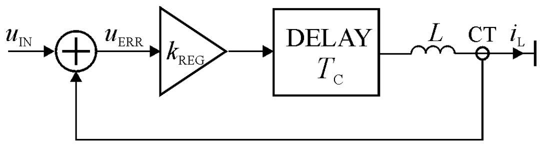


Fig. 2. Diagram of VCCS's linear model used for its stability analysis

The SDM and PS are represented commonly by the DEALY block. The transfer function of the entire VCCS model is given by the following equation:

$$G_{VCCS}(j\omega) = \frac{I_L(j\omega)}{U_{IN}(j\omega)} = \frac{\dfrac{k_{REG}e^{-j\omega T_C}}{j\omega L}}{1 + r_{CT}\dfrac{k_{REG}e^{-j\omega T_C}}{j\omega L}} \tag{1}$$

Taking into account (1), for system stability assurance (on base of the Nyquist criterion), critical value of the regulator gain can be calculated as [10]:

$$k_{REG,cr} = \pi \frac{L}{r_{CT} T_C} \tag{2}$$

where $T_C$ is the period of SDM's output bit stream.

The adequate and reliable criterion of the VCCS output current quality can be the control error $\varepsilon$ defined as:

$$\varepsilon = \sqrt{\frac{\overline{|u_{\mathrm{ERR}}(t)|^2}}{\overline{|u_{\mathrm{IN}}(t)|^2}}} 100\ \% \tag{3}$$

## 3. SIMULATION MODEL STUDIES

For checking theoretical assumptions the simulation model of VCCS with use of the OrCAD/PSpice tool has been investigated. The diagram of the model is shown in Fig. 3. The most valid for the model functionality elements was: AD817 – the fast operational amplifier (Analog Devices), being used in the design of: regulator, integrator, and comparator and GS61008T – the 100 V/ 90 A gallium nitride E–HEMT [12] from GaN Systems, being used in the power stage of the simulation model. In the model ready to use models of GaN E-HEMTs, provided by its manufacturer, were implemented.

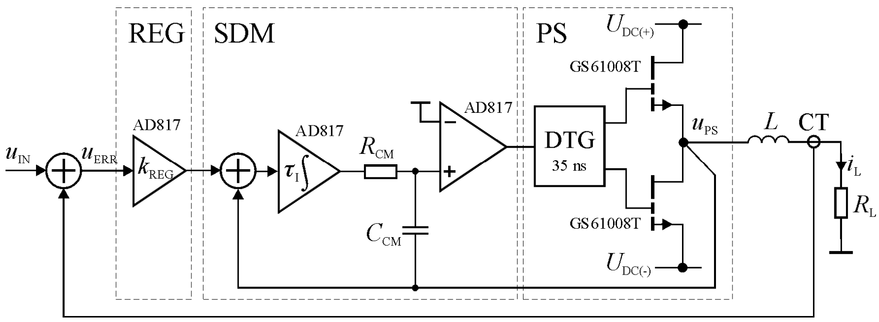


Fig. 3. Block diagram of VCCS's simulation model

The model's parameters were as follows: $\tau_I$ = 500 ns, maximum switching frequency of the SDM – $f_C$ = 1 MHz ($R_{CM}$ = 1 kΩ, $C_{CM}$ = 200 pF), $k_{REG} \cong \frac{1}{2} k_{REG,cr}$ = 157 V/V, dead–time for the half–bridge in the power stage – 35 ns (the dead–time was generated in DTG block), $L$ = 50 μH, $R_L$ = 0.1 Ω, and nominal magnitude of the output current: $I_{L,nom}$ = 20 A. The voltages at inverter's DC rails: $U_{DC}$ =+/– 50 V. REFG section: $M$ = 4, $T_{DAU}$ = 10 μs.

In the following figures exemplary waveforms in the simulation model of the current source are shown. Primarily, they differ in shape, magnitude, and basic frequency of the input signal.

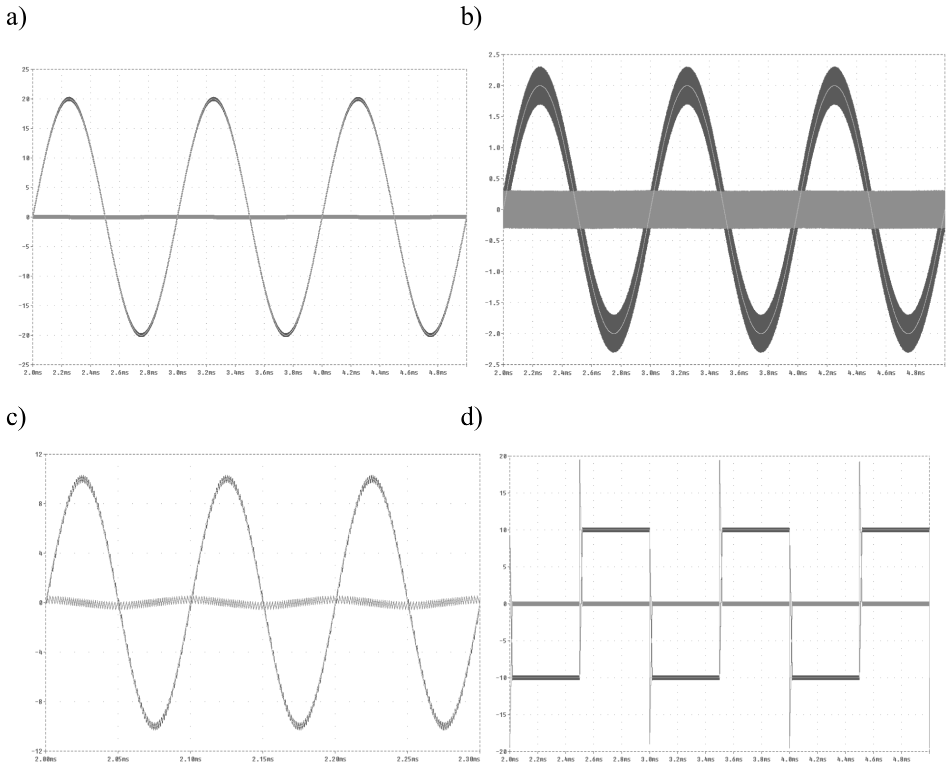


Fig. 4. Waveforms in the simulation model of the current source (green line – input voltage, red line – output current, and blue line – error signal) while: a) input signal is the sinusoidal one, its amplitude is equal to the nominal one, and its basic frequency is equal to 1 kHz, b) as previously but signal's amplitude is equal to 10% of the nominal one, c) input signal is the sinusoidal one about amplitude equal to 50 % of the nominal one, and basic frequency equal to 10 kHz, and d) input signal is the trapezoidal one, its amplitude is equal to 50 % of the nominal one, and its basic frequency is equal to 1 kHz

Value of the control error were as follows: a) $\varepsilon$ = 1.0 %, b) $\varepsilon$ = 10 %, and c) $\varepsilon$ = 3.5 %. Relatively high value of the control error stems from the fact, that this one also respects the carrier component in the output current. Excluding this component the control error can be about even an order lower !.

In case of the trapezoidal shape of the input signal this one differs from the output current (in the transient states) significantly and control error value's reaches 23 %. The reason is the limited dynamics of the power stage of current source (mainly as result of influence of the output inductor and limited value of the supply voltages).

## 4. CONCLUSIONS

The power electronics controlled current source based on the sigma-delta modulator with dynamic hysteresis loop and the output stage with the GaN transistors is characterized by exceptionally wide the pass–band, compared to typical converter's solution. As result the output current is precisely mapped in the input (reference) signal. Thanks to operation of the converter at very high "carrier" frequency also components of pulse modulation in this current are minimized. The structure of control system is simple, mostly analogue one, and can be easily implemented in power electronics equipment where high quality of the output current (or voltage) is necessary. These benefits are not significantly paid by increase in the system complexity (and the system cost).

The presented solution of the power electronics system can find application in many power electronics equipment like: active power filters, converters for RES, and reference currents generators.

## REFERENCES

[1] Kester W., The Data Conversion Handbook, Analog Devices Inc, Newnes, 2005.

[2] de la Rosa J.M., Sigma–Delta Modulators: Tutorial Overview, Design Guide, and State–of–the–Art Survey, Circuits and Systems I: Regular Papers, IEEE Transactions on, Vol. 58 , Issue: 1, 2011.

[3] Palmer R., Design Considerations for Class–D Audio Power Amplifiers, Application Raport (SLOA031), Texas Instruments,1999.

[4] Boudreaux R., Gaboriau J., Hagge M., Melanson J, Zhang L., Real–Time Power Supply Compensation for Noise–Shaped Class D Amplifier, 117th AES Convention, San Francisco, CA, 2004.

[5] Sorensen J., Sigma–delta conversion used for motor control, Technical article, Analog Devices, Inc.: http://www.analog.com/en/products/analog–to–digital–converters/precision–adc–10msps/isolated–ad–converters/ad7405.html#product–reference. Accessed: January 2016.

[6] Jain A., Muthusubramaniam N., Pavan S., Analysis and Design of a High Speed Continuous Time Delta Sigma Modulator Using the Assisted Opamp Technique, IEEE Journal of Solid State Circuits (2012).

[7] Rozanov Y., Ryvkin S., Chaplygin E., Voronin P., Fundamentals of Power Electronics: Operating Principles, Design, Formulas, and Applications, CRC Press, hardcover, 489 pp., ISBN 97814822987961, 2015.

[8] Gwóźdź M., Power electronics wideband controlled voltage and current sources on base of interleaved converters, (in Polish), Przegląd Elektrotechniczny, Nr 10A, 2012, 132–134.

[9] Gwóźdź M., Matecki D., Power Electronics Controlled Voltage Source Based on Modified Sigma–Delta Modulator, Proceedings of the 2016 IEEE International Power Electronics and Motion Control Conference (PEMC), Bulgaria, Varna,

25–30 September, 2016, ISBN: 978–1–5090–1797–3, pp. 186–191. DOI: 10.1109/EPEPEMC.2016.7751995.
[10] Gwóźdź M., Stability of Discrete Time Systems on Base of Generalized Sampling Expansion, Quarterly Elektryka, Silesian University of Technology, Issue 1 (217), pp. 29–40, 2011.
[11] Gwóźdź M. , Krystkowiak M., Wideband power electronics voltage and current sources, Przegląd Elektrotechniczny, No 11/2011, pp. 37–40 (in Polish).
[12] GS61008T: GaN Systems product page: http://www.gansystems.com/gs61008t.php. Accessed: December 2016.

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