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POWER ELECTRONICS CONTROLLED CURRENT SOURCE BASED ON A MULTI-CONVERTER TOPOLOGY

The paper presents the idea of power electronics voltage controlled current source (VCCS) which is able much more precise mapping of its output current in a reference signal, compared to a typical converter solution. It can be achieved by means of such interconnection of two separate converters that one of them corrects a total output current towards a reference signal. An output power of auxiliary converter is much lower than an output power of main one but its frequency response is extended. Thanks to continuous work of this converter also pulse modulation components in a total output current are minimized. In the paper an exemplary application of a current source, as an execution block of active power filter (APF), is presented.

KEYWORDS: active power filter, converter control, interleaved converters, PWM

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 in hardware and substantial modification of their control algorithms are necessary.

The subject of paper is a voltage controlled current source (VCCS) with modified topology uses two converters connected in parallel. The advantage of this conception is possibility of accurate mapping of the VCCS output current in the reference signal. The proposed architecture of converter has been called "multi-converter topology" (MCT).

A conception of cooperation of number interconnected converters is widely used in practical systems, e.g. [1-3, 5, 6, 9, 10-12, 15, 16]. This one is related to electric drives, converters for renewable energy sources, and UPS systems. In particular, this applies to using of two connected in parallel converters, where an output power of one of them is a fraction of power of second one. This idea is also presented in many studies, e.g. [3, 10, 14-16]. A common feature

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of some of these solutions is that activation of an auxiliary converter (ACN) takes place only in transient states of a main converter (MCN) output current. Usually, the role of an auxiliary converter depends on maximization of a system's dynamics, i.e. extension of its frequency response. As consequence a total system output current is better mapped in a reference signal. Unfortunately, system control algorithms, especially in relation to an ACN, are often defined informally. Because of this potential possibilities of a system are not fully utilized. The MCT conception is also related to a common work of two connected in parallel converters but an auxiliary converter operates continuously – not only in system transient states. Also, rules of the system operation are defined in a formal way. Unlike many other works particular attention has been paid to minimization of PWM carrier component in the MCT output current.

In addition to the application of MCT based VCCS in a shunt active power filter (APF) – discussed in this paper – expected other application areas of this one are: FACTS, current modulators, automated test equipment (ATE), and special purpose power electronics converters – especially for the magnetotherapy [8].

This study presents first stage of work on the layout of APF, which includes, among other items, principles of operation of the VCCS based on the MCT and discusses the APF simulation experiment. The following text is divided into three sections. The first one deals with a structure and principles of the MCT operation. The second part presents simulation model researches for the APF. In the third part conclusions are presented.

2. MULTI-CONVERTER TOPOLOGY BASICS

In Fig. 1 the block diagram of a typical VCCS based on a single converter 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 energy efficiency.

The VCCS consists of a control module (CM) and an execution module (EM). A CM includes a signal adder and a controller block (CTR), where a CTR is an output current regulator, while an EM contains: inverter (INV), passive filter (the L inductor), and current transducer (CT). The VCCS output current i_{VCCS} is related to the error signal at the input of the CM:

$$u_{\mathrm{err}} = u_{\mathrm{ref}} - r_{\mathrm{CT}} i_{\mathrm{VCCS}} \quad (1)$$

where r_{CT} =const. In such system a value of error signal (u_{err}) is relatively large.

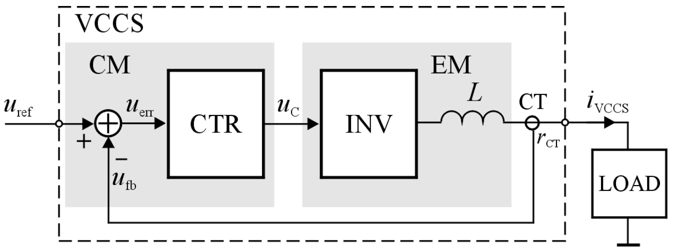

Fig. 1. Block diagram of a typical power electronics current source (VCCS) as a closed-loop electrical system

The general aim of a VCCS operating is fulfilling the following theoretical formula:

$$i_{VCCS} = \frac{1}{r_{CT}}\left(u_{ref} - u_{err}\right) \xrightarrow[-\infty<t<\infty]{\forall\ |u_{err}|\to 0} \frac{1}{r_{CT}} u_{ref} \tag{2}$$

Fulfilling the equation (2) obtains, only theoretically existing, the „ideal case" of a VCCS work. In a real system, even small minimization of an error signal can be a difficult task.

The simplified form of the VCCS, based on proposed the MCT conception, is presented in Fig. 2a. The main converter is supplemented with the auxiliary one. The main converter is high power one but its a frequency response is limited. The auxiliary converter is a low power one but its frequency response is significantly extended, compared to the main one. In the simplified system form the auxiliary converter is equipped with a transconductance amplifier. This amplifier is preceded by the limiter block (LIM) that clips the ACN control signal. This one imposes a maximal value of an ACN output current ($i_{out,A}$), therefore a relationship of the ACN and MCN an output power.

In the small-signal model of system (Fig. 2b) the DELAY block is implemented. This one introduces a τ time delay and reflect delays occurring in a real system, mainly being results of: limited value of a signal sampling period, time needed for signal processing, and a non-zero period of a pulse modulation carrier frequency.

The general formula of the VCCS work is now modified towards the following one:

$$i_{VCCS}(t) = i_{out}(t) + i_{out,A}(t) \tag{3}$$

and, in the relationship to the linear model of the system:

$$\begin{aligned} i_{VCCS}(t) &= i_{out}(t) + i_{out,A}(t) = i_{out}(t) + u_{err}(t) * g_A(t) = \\ &= i_{out}(t) + \left[u_{ref}(t) - r_{CT} i_{out}(t)\right] * g_A(t):\ R_L = 0, L_L = 0 \end{aligned} \tag{4}$$

where $g_A(t)$ is the pulse response of the transconductance amplifier.

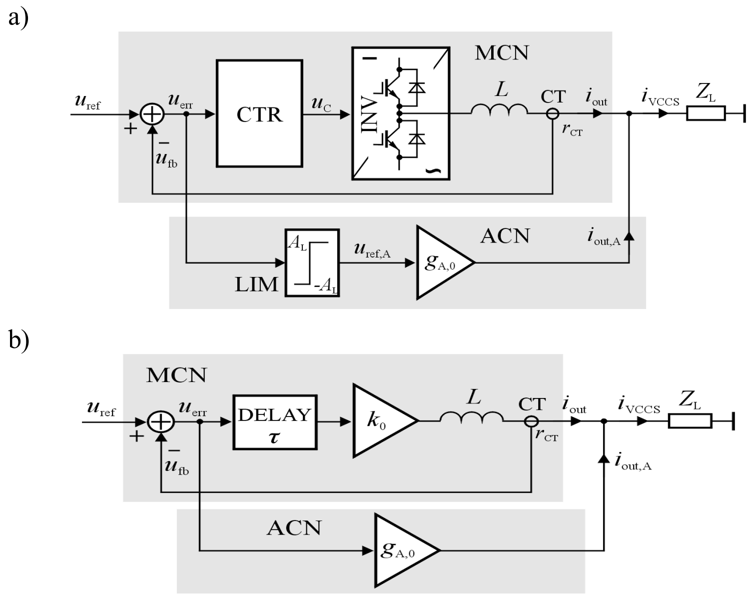

Fig. 2. Block diagram of the VCCS based on the simplified MCT a) and its small-signal model b)

Assuming the transfer function of the transconductance amplifier has the 0-order form, i.e. $g_A(t) = g_{0,A}\delta(t)$, the general equation describing the model work can be obtained:

$$\begin{aligned} i_{VCCS} &= i_{out}(t) + [u_{ref}(t) - r_{CT} i_{out}(t)] * g_A(t) = \\ &= g_{A,0} u_{ref}(t) + (1 - g_{A,0} r_{CT}) i_{out}(t)\Big|_{g_{A,0} r_{CT} = 1} = g_{A,0} u_{ref}(t) \\ &: \ |u_{err}| \subset \langle -A_{LIM}, A_{LIM} \rangle, R_L = 0, L_L = 0 \end{aligned} \quad (5)$$

where $-A_{LIM}$ and A_{LIM} are voltage clipping levels of the LIM block.

The equation (5) indicates that a load current can match a reference signal regardless a degree of mapping in a reference signal a main converter output current (i_{out}) – under the condition that the amplitude of ACN control signal is not limited by the LIM block.

3. SIMULATION MODEL OF AN ACTIVE POWER FILTER BASED ON MCT

For checking theoretical assumptions a simulation model of the shunt Active Power Filter (APF) based on MCT with use of the OrCAD/PSpice tool has been investigated. The model has consisted of the following elements: reference signal generator, main and auxiliary converters, power supply, and load. Ready to use models of power electronics devices that are implemented in OrCAD/PSpice have been modified towards real devices. In the execution part of the main converter IGBT/IPMs could be used. Good choice seems the L1 series 1200 V [17] family of IPMs, manufactured by MITSUBISHI ELECTRIC. In the auxiliary converter the 800 V CoolMOS™ power MOSFETS [18] from INFINEON could be utilized. Models of these just devices have been used in simulation experiments. An interesting alternative for silicon based devices is utilization in the ACN Silicon-Carbide (SiC) MOSFETs, e.g. Z-FET® series from CREE [19] or GaN E-HEMTs e.g. manufactured by GaN Systems [20]. In the result the PWM carrier frequency value could be significantly increased.

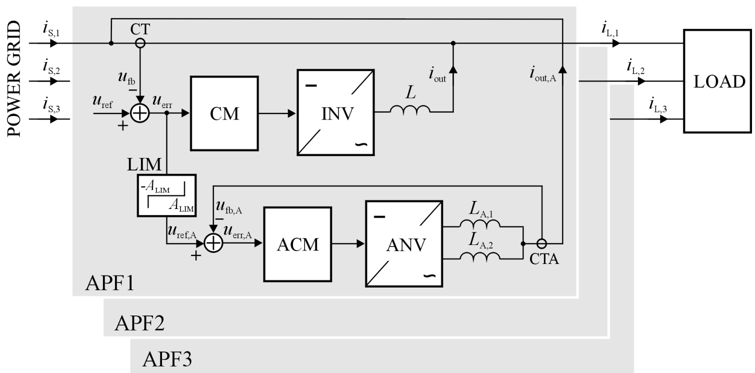

Fig. 3. Simplified block scheme of an APF (only a single phase is shown for clarity)

Basic electrical parameters of the APF simulation model have been as follows:
- power grid parameters: 3x400 V / 50 Hz,
- nominal load power: $P_{L,n} = 36$ kW,
- PWM carrier frequency: $f_c = 2$ kHz, and $f_{c,A} = 100$ kHz,
- number of converter channels: $M = 1$, and $M_A = 2$,
- gain factor: $k_0 = 25$ V/V, $k_{A,0} = 70$ V/V,
- converter output inductance in a single channel: $L = 3$ mH, and $L_{A,1} = L_{A,2} = 0.5$ mH,
- maximal magnitude of the main inverter (INV) output current: $A_{max} = 80$ A,
- maximal magnitude of the auxiliary inv. (ANV) output current: $A_{A,max} = 26$ A.

Values of gain factors have been very close to maximal ones. Due to imposed values of voltage clipping levels in the limiter block the nominal output power of the ACN has been equal to 33% of the MCN.

In following figure selected waveforms in the APF simulation model are presented. In Fig. 4a the waveform of load current is shown. The load is a thyristor based voltage regulator with firing angle equal to 90 el. deg. – with resistors at the output.

a) b) c)

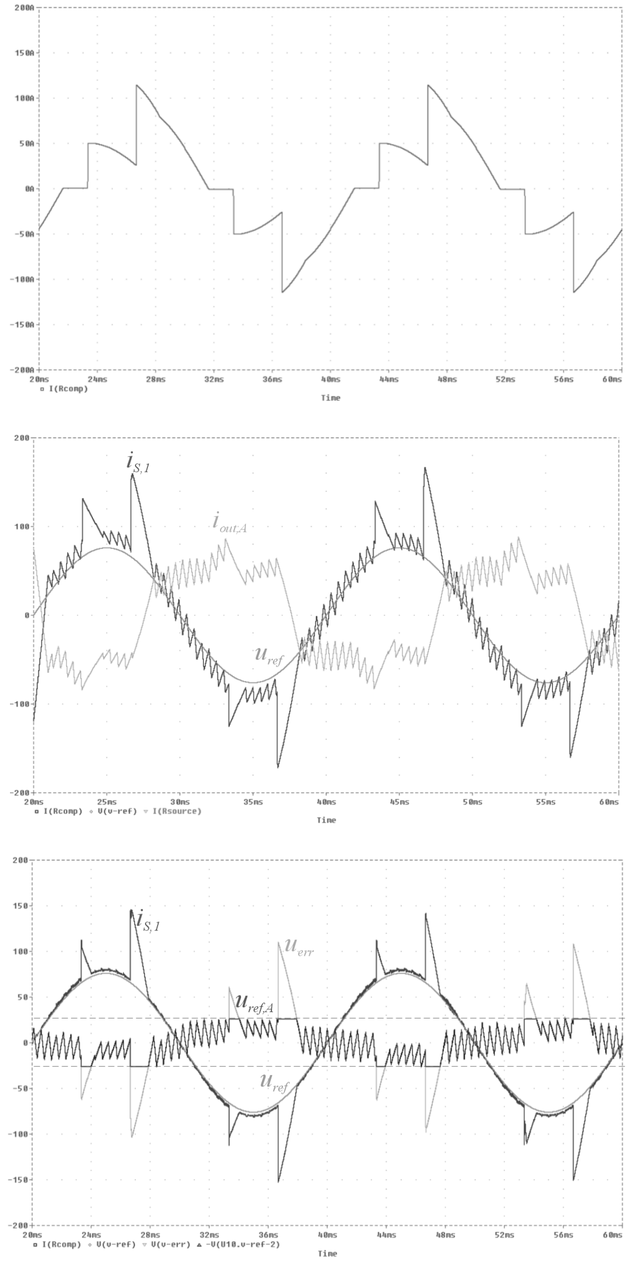

Fig. 4. Waveforms in the simulation model of the APF

In Fig. 4b, among other items, the APF input current $i_{S,1}$ (i.e. power grid current) is shown. In case of typical (i.e. non MCT based) APF structure magnitude of current ripples in this current (caused by a PWM) are relatively large. After including the MCT in an APF power stage, amplitudes of these ones are very limited, what confirms Fig. 4c (under condition, that the magnitude of error signal is lower than the value of voltage clipping level(-s)).

4. CONCLUSIONS

The power electronics controlled current source based on the proposed multi-converter topology is characterized by a much better mapping of its output current in a reference signal, compared to a typical converter solution. Thanks to the operation of the auxiliary converter in a continuous manner also components of pulse modulation in this current can be minimized. Therefore, it is expected that energy transmission losses in a power line can be lowered and, also, a converter can easier meet EMC requirements. These benefits are paid for by a relatively small 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. Thus, it will be further developed towards controlled current (voltage) sources and equipment based on multi-channel (interleaved) converters topology.

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