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Design of high efficiency, low noise power supply for automotive audio systems

***Abstract**. The paper deals with proposal and simulations of the high efficiency and high-power switching power supply suited for hi-fi audio amplifiers in automotive applications. Main focus is given on specific requirements, which are needed in the automotive segment, low voltage input must be considered. The presented article describes design of the main topology and its parameters. Key operational characteristics are very high efficiency in full spectrum of operation and high-power density. The performance of proposed design is condition by high-current operation, thus thermal management is key indicator related to requirements on high-efficiency operation. Secondary features of proposed converter must consider high-end requirements of audio systems, which are fast dynamics to load change and low noise of output voltage. Almost switched-mode power supplies are defined by high noise of the output voltage, presented approach proposes also solution of the low noise output filter.*

***Streszczenie**. Zaprezentowano projekt wysokiej jakości i mocy układ zasilania wzmacniacza hifi w zastosowaniu do samochodów. Ze względu na duży pobór prądu zadbano w właściwości termiczne układu. Zadbano też o mały poziom szumów. (**Projekt zasilacza o dużej skuteczności i małych szumach w zastosowaniu do samochodowych systemów audio**)*

Keywords: switching converter, interleaving, current fed push-pull, high-end audio, low noise filter, automotive amplifier power supply, soft switching
Słowa kluczowe: zasilacz, samochodowe systemy audio, małe szumy

I. Introduction

The audio systems in modern premium cars are currently part of its systems where focus related to the quality of the sound reproduction is highly requested. Audio system is part of comfort equipment, while the quality is dependent on the quality of individual components from which audio system consists. Nowadays, main trend is cost reduction as well as dimensions and weight reduction. On the other side, very strict requirements are putted on efficiency of the audio system. If audio application is considered, then the only solution how to overcome specified requirements is to use amplifier from D class whose quality of the audio output is in most cases worse compared to amplifiers from class AB. It is because of switching action which is reproduced within output signals which are fed into speakers. On the other side, class AB amplifiers requires symmetric supply, while if car supply network is considered, only non-symmetric voltage 12 V is available.

In this article, the main focus is given on the design switching power converter with the application for class AB audio amplifier for automotive conditions. Current requirements from car industry are to have at least 10 speakers, thus 10 individual audio outputs are requested, while average power for each is approximately 100 W and for subwoofer speaker more power. As a result, the total power of converter supplying amplifier shall be around 1 kW in the peak output. The audio signal dynamically changes output load, so the power supply has to have fast dynamic response. Even high system efficiency will be expected, the second issue which designers must count is very high current taken from the input source (around 100A in full power output). Based on this description it is clear that proposal on the power supply, i.e. power converter must consider requirements on high-efficiency performance, while system cooling must also pass high expectations on operational conditions. This paper proposal presents introduction of dual interleaved current fed push-pull converter whose operational characteristics gives expectation to reach required demands from automotive audio application. [1]

II. Main circuit topology – operational conditions, design of main circuit components

Due to above-mentioned requirements on the operational characteristics, the current fed push-pull converter with active clamp is proposed (Fig. 1). The capacitor active clamp provides efficiency increase as soft commutation is reached. In order to minimize noise and ripple of the output voltage, interleaving technique of power circuit is used, and two identical power converters are connected in parallel. Interleaving provides also more efficient power delivery if high power/high current operation is considered [2][3][5] because the current stress of individual power semiconductor components is reduced. As thermal management is key design issue, the magnetic components are supposed to be designed by planar technology. This technology is also defined by small dimensions and low parasitic properties. Unwanted interference between on-board network of the car and speakers is eliminated using galvanic isolation of the secondary side of power supply. The main circuit parameters of are listed in Table I.

Table 1. The main circuit parameters of proposed automotive audio amplifier supply

Nominal output power [kW]	1
Switching frequency [kHz]	80
Output voltage range [V]	30 - 40
Noise/output voltage ripple [mV]	Max. 20
Input voltage range [V]	9- 16
Efficiency [%] in range 20% - 100% of output power	> 90

III. Design of main circuit components

Fig. 1 shows principal circuit schematics of the power stage of proposed current fed interleaved push-pull converter with active clamp circuit. At the output, the modified filter circuit is connected output filter (L_2-C_3-C_5-C_4-C_6-L_3), whose task is filtering high frequency switching noise caused by function of converter. The active clamp circuit is composed by transistors T_3 and T_4, which are connected in series with capacitors C_1 and C_2. The main function of the clamping circuits is absorption and recuperation of the energy from transformer´s parasitic inductances on the primary side of the transformer. The second task is providing soft-switching conditions for the main transistors T_1, T_2, which improves overall efficiency. For the transformer construction is used planar technology, thus improving efficiency is performed. The output rectifier is realized by the fast switching SiC Schottky diodes. The output voltage has symmetrical character, which is required by the target application. As was already mentioned, the output part of the converter exhibits a symmetrical enhanced sinusoidal filter in CLC topology. Electrolytic capacitors C_3 and C_4 filter rectifier voltage which is consequently being supplied into first LC filter operating as low-pass band filter of 2nd order. The task of the first LC stage is to reduce high-frequency noise. The filter is composed of individual de-coupled inductors L_2 and L_3 and electrolytic capacitors C_5 and C_6, whose function is to store the energy, which may be needed for fast dynamic load changes (mostly subwoofer tones of the amplifier). The phase shift of the gate driving signals between converters is 90º thus additionally improving ripple of the output voltage and current feed into output load.

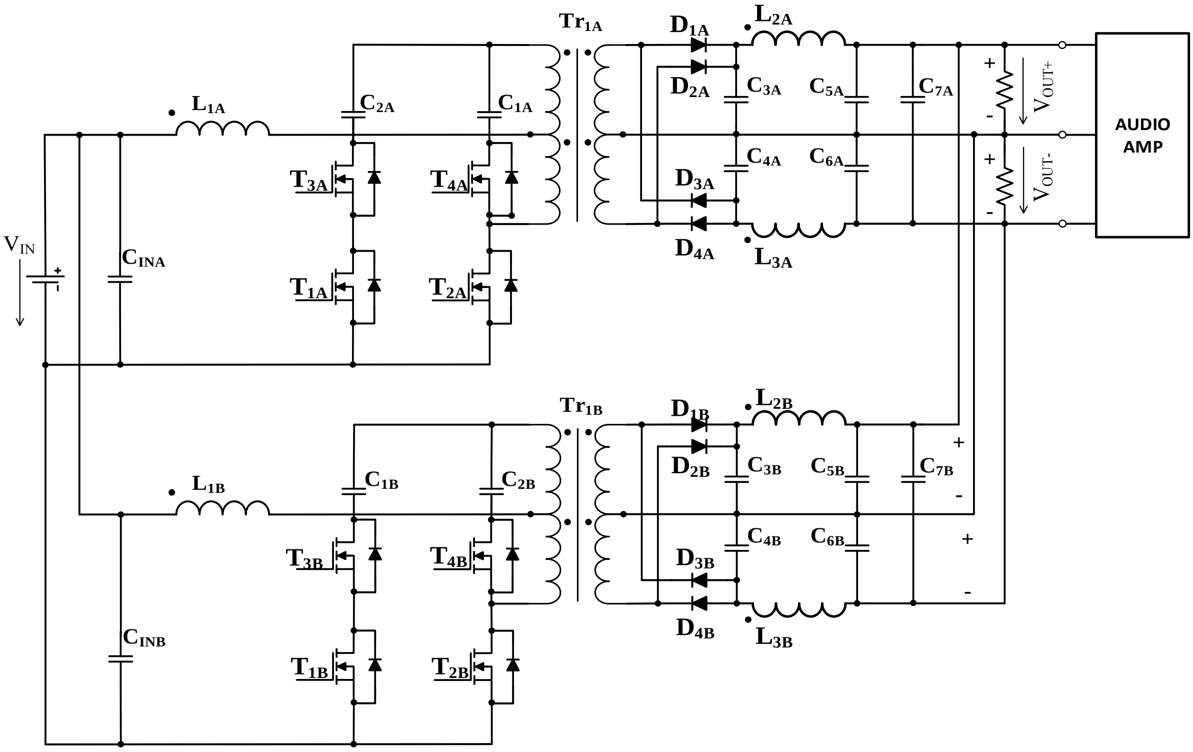

Fig.1. Principal schematics of the proposed current fed interleaved push-pull converter with active clamp for automotive audio amplifier system

A. Design of filter and transformer parameters

Since the inductance L_1 of the proposed converter operates similarly to standard boost converter, the calculation of its value is realized as for the boost converter. For the calculation of this component, it must be considered, that L_1 operates with double frequency compared to switching frequency of the converter, due to interleaved operation of primary transistors. The value of the inductance is given by the equation:

(1) $$L[H] = \frac{V_{in}.(V_{out}-V_{in})}{\Delta i_L.2.f_{sw}.V_{out}}$$

where: V_{in} – input converter voltage [V]; V_{out} – output converter voltage [V]; f_{sw} – switching frequency [Hz]; Δi_L – ripple of inductor current [A]; I_{out_max} – maximum output current [A]

The design procedure of the galvanically isolated transformer design is like the design of the push-pull transformer, while the only difference is higher operational voltage because of the boosting performance of input inductor L_1. The transformer turns ratio for proposed converter is given by equation (2) as follows:

(2) $$n[turns] = \frac{V_{in\_boost}}{V_{out}} = \frac{N_{prim}}{N_{sec}}$$

where: V_{in_boost} – input voltage of converter boosted by L_1 [V]; V_{out} – output converter voltage [V]; N_{prim} – number of primary turns [-]; N_{sec} – number of secondary turns [-]

The minimal effective area of the transformer core can be determined by the empiric equation:

(3) $$A_{e\min} = 25.\sqrt{\frac{P}{f_{sw}}}$$

where: A_{e_min} – minimal area of the transformer core [mm^2]; P – output power per transformer [W]; f_{sw} – switching frequency [Hz]

The minimal number of the primary turns required for the proper transformer operation avoiding its saturation is defined by equation (4):

(4) $$N_{prim\_\min} = \frac{V_{in\_nom}.D_{nom}}{f_{sw}.\Delta B.A_e}$$

where: V_{in_nom} – input converter voltage [V]; D_{nom} – nominal duty cycle [-]; f_{sw} – switching frequency [Hz]; ΔB – ripple of inductor current [T]; A_e – effective core area [mm^2]

Because the inductor L_1 increases input voltage, the whole voltage gain of the transformer should be specified within 20% – 30% lower compared to standard push-pull converter. The number of secondary turns is therefore given by (5).

(5) $$N_{sec} = \frac{N_{prim}}{n} 0,8$$

where: N_{prim} – number of primary turns [-]; N_{sec} – number of secondary turns [-]; n – transformer turns ratio [-]

The summary of the transformer design is listed in Table 2.

Table 2. The main circuit parameters of proposed automotive audio amplifier supply

Nominal output power [W]	500
Ferrite core shape	E43
Noise/output voltage ripple [mV]	3F3
Primary turns	2
Secondary turns	5
B_{max} [mT] (at POUT = 100%)	~ 100

Also, the important part of proposed converter is output low-pass filter. The design of the filter is derived from the frequency spectrum of music, while attention must be given on the transmission of the low frequencies, which are the most challenging from dynamic load change. The audio system is composed of amplifier and power supply, whereby related to the above-mentioned specifics, the reproduction of audio signals must be as most authentic as possible.

The design of the output filter includes functionality, which is defined by the reduction of the noise and reduction of the output ripple. The cut-off frequency of the filter must be defined based on spectrogram of the music (Fig. 2) [4][7]. From Fig. 2 is visible that the highest amplitude is visible for low-frequency sound, i.e. in the range from 50 Hz – 1,4 kHz. Based on this fact, the cut-off frequency of the filter is designed to 1 kHz.

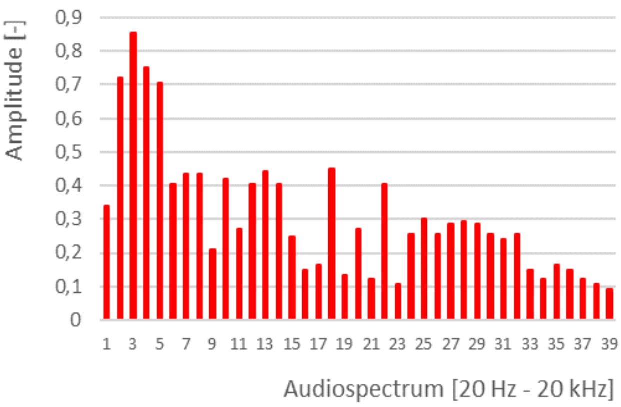

Fig.2. Music spectrogram for the output filter cut-off frequency design

Output filtering capacitors are placed at the output of the secondary side rectifier and they have 1000 μF value. The cut-off frequency between L_2 and C_5 is f_0 = 1000 Hz, while the angular frequency is defined by (6):

(6) $$\omega_0 = 2 * \pi * f_0$$

For the calculation of filtering inductor formula (7) must be used:

(7) $$L_2 = \frac{1}{(2 * \pi * f_0)^2 * C_5}$$

B. Power semiconductor devices selection

Table III. and IV. as well as display main electrical parameters of used power semiconductor devices. The electronic components in both sub-converters have the same parameters.

Table 3. The main parameters of active clamp transistors

Input clamp transistors BSZ037N06LS5ATMA1	
Drain – source voltage [V]	60
RDS ON [mΩ]	3.7
Drain current [A]	40
Power dissipation [W]	69

Table 4. The main parameters of secondary diodes

Output diodes VS-40CPQ100-N3	
Forward current [A]	E43
Reverse voltage [V]	3F3
Drain current [V]	2

Based on the previous design of main circuit components which influence qualitative parameters of proposed audio amplifier, the results from simulation analysis are provided, while focus is given in efficiency and noise evaluation.

IV. Simulation analysis

The simulation analysis was realised in PSpice Orcad software. Simulations have been realized for three different values of the input voltage, i.e. 9V, 12 V and 14 V, while output load was replaced by the signal source simulating the waveform of bass tone within the spectrum of 0% of P_{OUT} up to 100% of P_{OUT}. The converter was connected in closed regulations loop and the feedback value of output voltage was taken from the auxiliary winding of transformer. On the fig. 3 we can see the current waveforms and gate drive signals of main switching transistors from sub-converter A for the 100 % output power (1 kW). Tue to used active clamp circuitry, there are no current spikes on the waveforms and the soft switching is successfully achieved. For the right function of the converter, the duty cycle has to be over 50%. In this case, the duty cycle is 75 %.

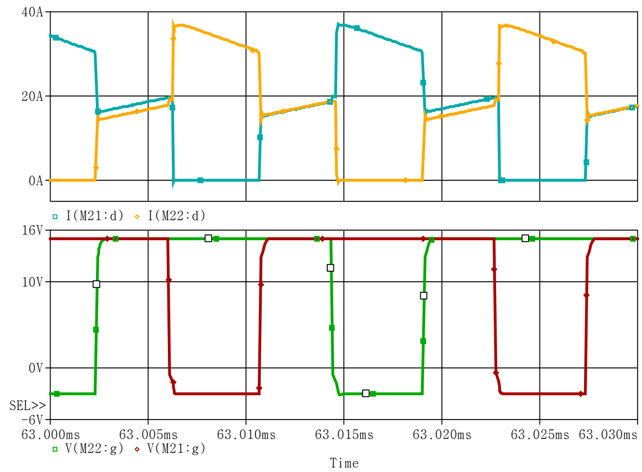

Fig.3. Waveforms switching transistors currents (yellow and grey), and switching transistors gate signals (red and green)

The fig. 4 shows the waveforms of boost inductor, which working frequency is 2 times higher than switching frequency of converter and the waveforms of primary winding of the transformer. The working frequency is 2 times bigger due to interleaving function on input transistors Also, on these waveforms the current spikes are dumped by the function of active capacitor clamp.

On the fig. 5 the current waveforms of switching transistors from sub-converter A and B are shown. From this picture is clear that converters are interleaved by the angle 180° which helps to achieve lower output voltage and current noise and the better thermal management is achieved.

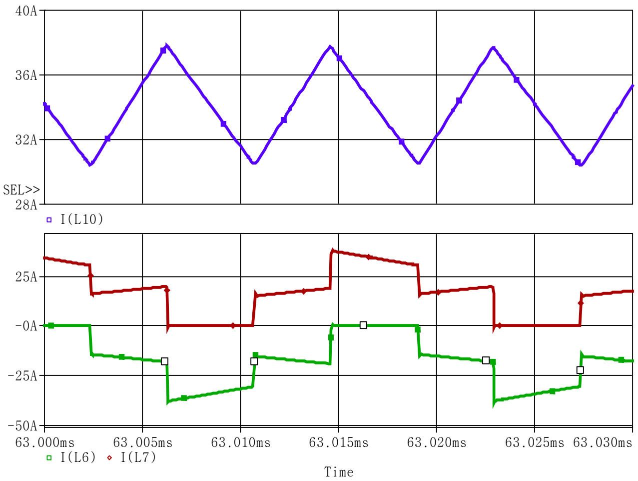

Fig.4. Waveforms of boost inductor curent (blue), and primar transformer coils currents (red and green)

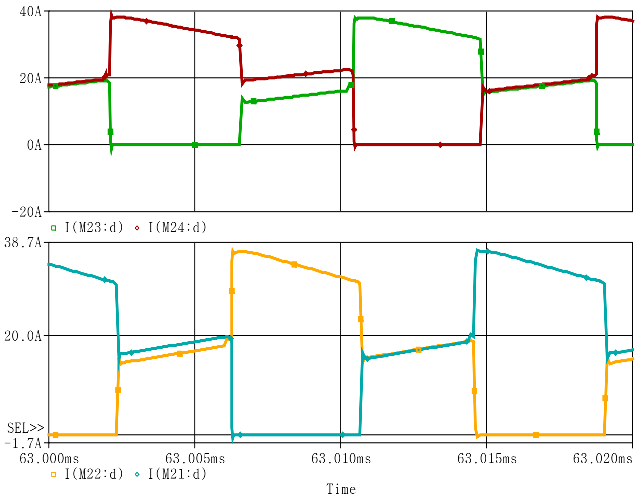

Fig.5. Waveforms switching transistors for converter A (red and green) and waveforms switching transistors for converter B (yellow and grey)

The first evaluation is the efficiency performance within the full power range from 100 W up to 1000 W. From fig. 6 is seen, that during input voltage change from 14 V to 9 V, the efficiency decrease is in the range from 1.5% to 3% depending on the load. Maximal achieved value of efficiency is 94 % while the flat region of efficiency is located within 20 % – 80 %. The visible decrease is evident if 9 V of input voltage, while conduction losses takes major part causing visible efficiency decrease. Since the proposed power supply is primarily designed for supplying class AB audio amplifiers with relatively high bias current, the operating area under 10% of output load is not important for this application. More than 8 channels of audio channels will be used, and the significant bias current will be caused by them. Thus significant current will be sourced from the supply in the zero music output condition.

Fig. 7 is showing the evaluation of the output voltage ripple in dependency od output power, whereby also 3 different values of input voltages have been considered. It is seen that the highest ripple is visible if full power is applied with 14 V at the input of converter. On the other side the lowest output voltage noise is produced at the lowest value of the input voltage i.e. when 9V is applied. The difference between voltage ripple is within 0.015 % for full load to 0.003 % for low load conditions.

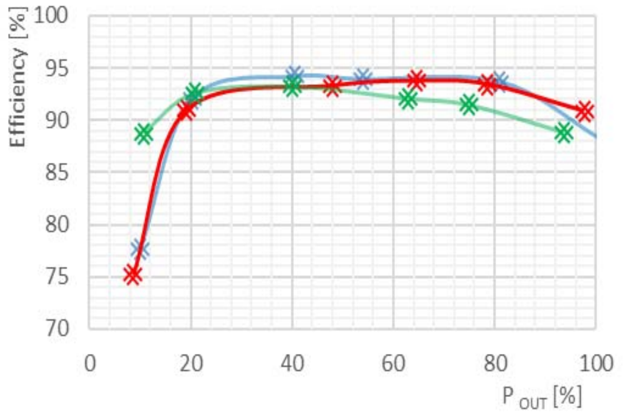

Fig.6. Efficiency in dependency on output power change for three different values of input voltage (red – 14V, blue – 12V, green – 9V)

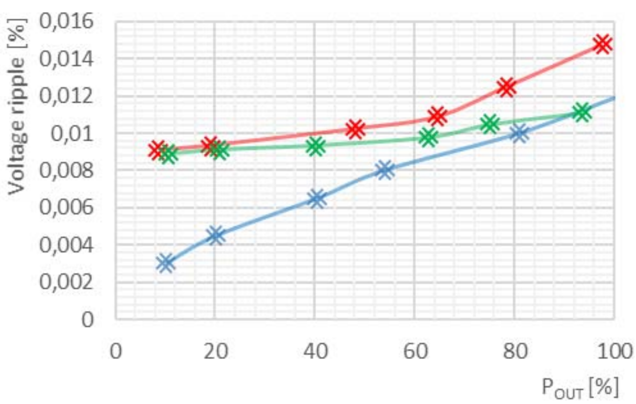

Fig.7. Output voltage ripple in dependency on output power change for three different values of input voltage (red – 14V, blue – 12V, green – 9V)

V. Conclusion

In this this article, the design proposal and simulation analysis for power converter suited for automotive audio applications was presented. The specific parameters for proposed solution are its power rating (1 kW), while low values of input voltages must be considered. The design uses combined solution of boost converter, while its functionality is implemented with the topology of proposed solution, which is the dual interleaved current fed push-pull converter. The topology is suitable for applications where low input voltage and high currents are necessary. Initially circuit description was provided followed with design of the transformer and the output low pass filter. The requirements on the system performance and efficiency are very strict because it is battery sourced converter. Therefore, very high efficiency was one of the important parameters as well as output AC voltage ripple, which is the main source of the noise degrading quality of the audio signal. Improving the quality of audio signals, the simplified procedure for output filter design is also provided. At the end of the article, the system was experimentally verified from efficiency and voltage ripple point of view. Various scenarios considering change of input voltage and change of load replaced by source of audio signal have been applied. It was found that proposed converter exhibits very high operational system efficiency achieving 90 % for most output power spectrum.

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