

Letters

2.1-Channel Switching Amplifier With DC/High-Frequency-AC Mixed Power Supply for Efficiency Improvement and Bus Voltage Pumping Elimination

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Abstract—Compared with traditional two-stage class-D audio amplifier, audio amplifier based on cycloconverter-type single-stage inverter (CSSI) has advantages of high efficiency and no bus voltage pumping (BVP). However, CSSI requires complex active clamp circuits for the current commutation of cycloconverter, especially for multichannel amplification. In this letter, a 2.1-channel switching amplifier with dc/high-frequency-ac (HFAC) mixed power supply is proposed, where CSSI is used as low-frequency audio channel amplifier and two class-D amplifiers are used as high-frequency audio channel amplifiers. With dc/HFAC mixed power supply, the proposed 2.1-channel switching amplifier does not require additional active clamp circuits for current commutation of cycloconverter. Besides, wide range soft switching of cycloconverter switches can be achieved. Benefiting from single-stage power conversion of low-frequency audio channel and wide range soft switching of cycloconverter switches, high efficiency of the proposed 2.1-channel amplifier is achieved. Without BVP, low voltage stress of switches and low distortion of low-frequency audio signal are realized in the proposed 2.1-channel amplifier. A 200-W prototype is presented to verify the analysis results.

Index Terms—2.1-channel, active clamp, bus voltage pumping (BVP), class-D amplifier, high-frequency link inverter.

I. INTRODUCTION

SWITCHING amplifier, e.g., class-D amplifier, has been widely used for audio amplification due to higher efficiency than class-A, class-B, and class-AB amplifiers [1]–[7]. For class-D amplifier directly supplied by battery, full bridge (FB) architecture is widely used [1], whereas for class-D amplifier supplied by front-end switching mode power supply (SMPS), half bridge (HB) is more popular due to simple circuit architecture, especially for multichannel amplification [6], [7]. However, the efficiency of class-D amplifier system is low due to the two-stage cascaded power conversion of SMPS and class-D amplifier [8]–[10]. Besides, for the HB class-D amplifier with front-end SMPS, there exists bus voltage pumping (BVP) phenomenon when the audio frequency is low, which results in high voltage stress across switches and distortion of output voltage [11], [12].

In recent years, cycloconverter-type single-stage inverter (CSSI) has been used for audio amplification [13]–[16]. For CSSI, SMPS and class-D amplifier are integrated into a single power conversion stage and BVP can be eliminated. However, CSSI suffers from the current commutation of cycloconverter, which may result in high voltage spikes and large output voltage distortion. To overcome this problem, various

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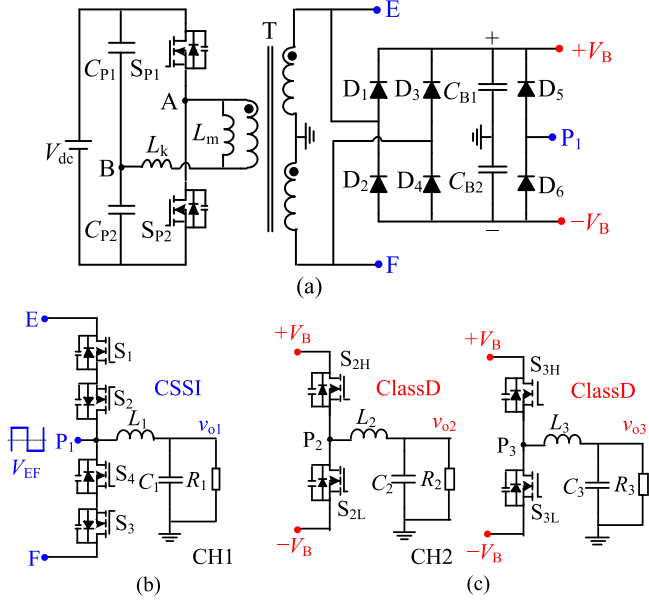


Fig. 1. Circuit diagram of the proposed 2.1-channel switching amplifier. (a) DC/HFAC-mixed power supply. (b) Low-frequency audio channel. (c) High-frequency audio channels.

is composed of bidirectional switches S_1/S_2 and S_3/S_4 , as shown in Fig. 1(b). Fig. 1(c) shows HB class-D amplifiers for high-frequency audio channels CH2 and CH3. v_{o1} , v_{o2} , and v_{o3} are the output voltage of CH1, CH2, and CH3, respectively.

The modulation principles of CSSI and class-D amplifier are shown in Fig. 2(a) and (b), respectively. The driving signals of primary-side switches $S_{P1}-S_{P2}$ are complementary square wave synchronized to sawtooth carrier V_{saw} . The magnitude of carrier V_{saw} is V_H . HFAC square voltage V_{EF} with magnitude $V_{dc}/(2n)$ is generated at secondary side. Cycloconverter switches S_1/S_2 and S_3/S_4 are modulated by input audio signal v_{in1} with phase shift to S_{P1} and S_{P2} . It can be seen that switching period T_S of cycloconverter switches S_1-S_4 is equal to $2T$, i.e., to obtain the same pulsewidth modulation (PWM) wave, the switching frequency of S_1-S_4 is half the switching frequency of class-D amplifier switches, as shown in Fig. 2(b). As switching frequency of audio amplifier should be high to obtain low THD, frequency doubling of PWM wave in CSSI is meaningful for switching loss reduction.

For CSSI, the relationship between output voltage v_{o1} and duty ratio d_1 is

$$v_{o1} = \frac{V_{dc}(2d_1 - 1)}{2n} \quad (1)$$

and the amplification gain between input audio signal v_{in1} and output voltage v_{o1} is [18]

$$\frac{v_{o1}}{v_{in1}} = \frac{V_{dc}}{2nV_H}. \quad (2)$$

It can be seen from Fig. 2(a) and (b) that, although switching frequency of class-D amplifier is twice that of CSSI, PWM waveforms of class-D amplifier and CSSI are the same in nature. In other words, audio amplification principle of HB class-D amplifiers is the same as that of CSSI and there is $v_{o2}/v_{in2} = V_{dc}/(2nV_H)$.

DC supply voltages $\pm V_B$ with magnitude $V_{dc}/(2n)$ is derived by rectification of HFAC square voltage V_{EF} . During dead time of cycloconverter switches S_1/S_2 and S_3/S_4 , freewheeling of filter inductor current i_{L1} is provided by diodes D_5-D_6 and voltage V_{P1} is clamped to $\pm V_B$. The energy in filter inductor is recycled by capacitors $C_{B1}-C_{B2}$

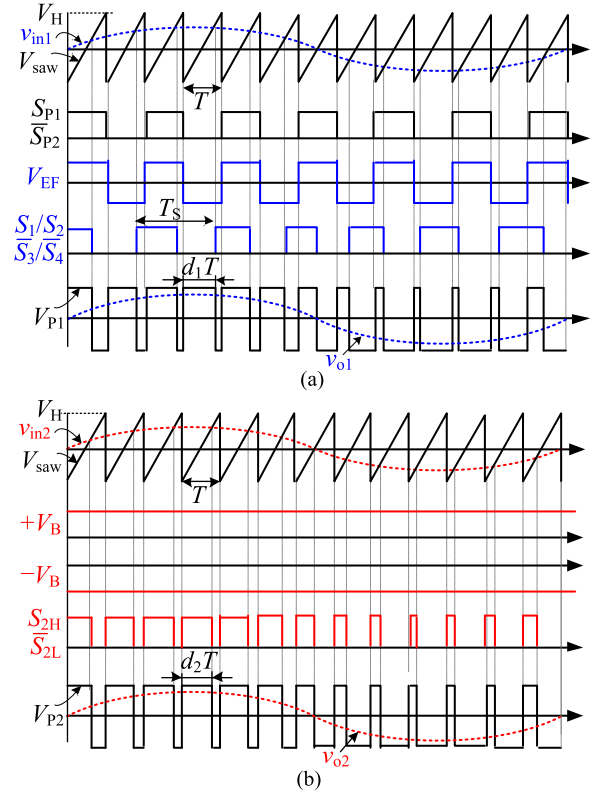


Fig. 2. Modulation principles of low-frequency audio channel and high-frequency audio channels. (a) Low-frequency audio channel. (b) High-frequency audio channels.

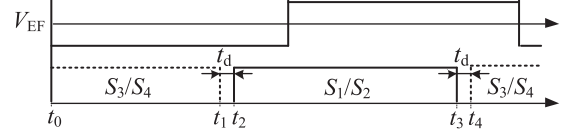


Fig. 3. Operation sequence of cycloconverter switches.

and utilized by class-D amplifiers of CH2 and CH3. Furthermore, by using dc/HFAC mixed power supply, voltage V_{EF} is clamped by diodes D_1-D_4 . As voltages at points E, F, and P1 are all clamped by voltages $\pm V_B$ and the recycled energy from inductor L_1 is utilized by CH2 and CH3, complex active clamp circuit used in [13]–[16] is not required here. With voltage clamp of cycloconverter switches, low distortion of CSSI can be obtained [18]. Besides, wide range zero voltage switching (ZVS) of cycloconverter switches S_1-S_4 can be achieved, which is analyzed in the following section.

B. ZVS of Cycloconverter Switches

Fig. 3 shows the operation sequence of cycloconverter switches, where t_d is dead time between S_1/S_2 and S_3/S_4 . Fig. 4 shows the equivalent circuit of CSSI during t_1-t_2 , where class-D amplifiers of CH2 and CH3 are not shown. During dead time t_d , diodes D_5-D_6 provide flowing path for output current i_{o1} and voltage at point P1 is clamped by capacitors C_{B1} or C_{B2} .

As shown in Fig. 4(a), when the output current $i_{o1} > 0$, diode D_6 will be turned ON during t_1-t_2 . In this case, both diodes D_2 and D_6 are ON during t_1-t_2 and voltage V_{EP1} across S_1/S_2 is zero. Thus, ZVS of S_1/S_2 can be achieved at t_2 . As shown in Fig. 4(b), when the output current $i_{o1} < 0$, diode D_5 will be turned ON during t_1-t_2 . In this case,

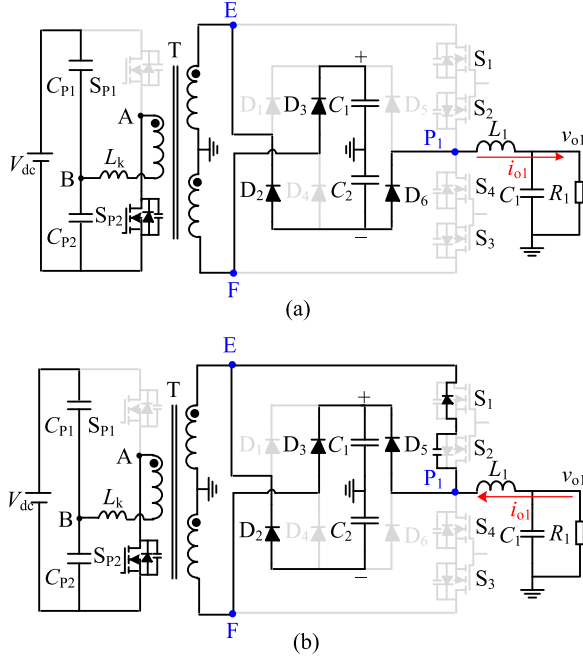


Fig. 4. Equivalent circuits of CSSI during t_1-t_2 . (a) $i_{o1} > 0$. (b) $i_{o1} < 0$.

TABLE I
ZVS OF CYCLOCONVERTER SWITCHES S_1-S_4

Condition	$i_{o1} > 0$				$i_{o1} < 0$			
Switches	S_1	S_2	S_3	S_4	S_1	S_2	S_3	S_4
ZVS	Yes	Yes	Yes	Yes	Yes	No	Yes	No

voltage V_{EP1} across S_1/S_2 is $-V_{dc}/n$ during t_1-t_2 and body diode of S_1 is forward bias. Thus, ZVS of S_1 can be achieved at t_2 , but ZVS of S_2 cannot be achieved. Similarly, ZVS of S_3/S_4 can be achieved at t_4 when $i_{o1} > 0$ and ZVS of S_3 can be achieved at t_4 when $i_{o1} < 0$. ZVS of S_1-S_4 is summarized in Table I.

However, instead of CSSI, if class-D amplifier is used in low-frequency audio channel, both the switching loss and conduction loss will increase evidently due to doubled switching frequency and two-stage power conversion. In one aspect, switches of class-D amplifier operate at hard switching during half-cycle of output current [1], which is similar to CSSI switches S_2 and S_4 . However, the switching frequency of class-D amplifier switches is two times that of CSSI switches. As a result, the switching loss of class-D amplifier is much higher than that of CSSI. In another aspect, the output current of class-D amplifier flows through rectifier diodes D_1-D_4 while CSSI is directly powered by primary-side dc source. When conduction loss of rectifier diodes is considered, the total conduction loss of class-D amplifier is also much higher than that of CSSI.

C. Elimination of BVP

For HB class-D amplifier with dc-bus power supply, pumping voltage $\Delta V_B = V_B/(8\pi f_o R_1 C_1)$ [12], where f_o is the frequency of audio signal. The pumping voltage ΔV_B decreases with the increase of audio frequency, i.e., BVP is only serious when audio frequency is low, e.g., lower than 100 Hz [11]. For two high-frequency audio channels in the

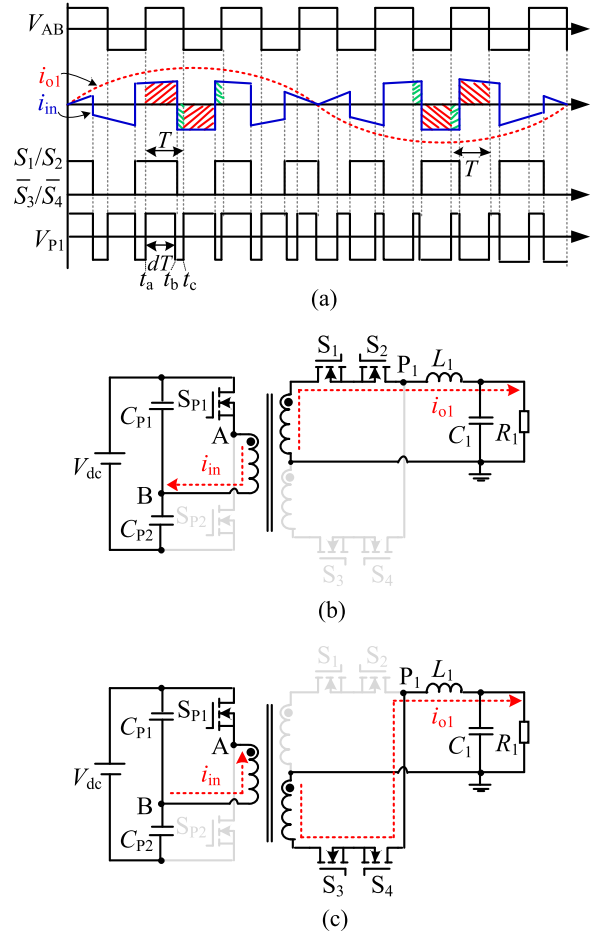


Fig. 5. Diagram of charging and discharging process of primary-side capacitors $C_{P1}-C_{P2}$ by input current i_{in} reflected from CSSI. (a) Operation waveforms. (b) Equivalent circuit during t_a-t_b . (c) Equivalent circuit during t_b-t_c .

proposed 2.1-channel amplifier, although HB class-D amplifiers are used, pumping voltage is small due to high audio frequency. Thus, BVP does not exist at secondary-side dc voltages $\pm V_B$.

For primary-side dc voltage V_{dc} , it cannot be pumped up by currents reflected from CH2 and CH3 with unidirectional power flow. Thus, only the CSSI of CH1 with bidirectional power flowing is analyzed here. The waveforms of primary-side voltage V_{AB} , output current i_{o1} , input current i_{in} , and driving signals of S_1-S_4 are shown in Fig. 5(a). The equivalent circuits during t_a-t_b and during t_b-t_c are shown in Fig. 5(b) and (c), respectively. Output current i_{o1} can be considered as constant during carrier period T . As shown in Fig. 5(b) and (c), when switch S_{P1} is ON, $V_{AB} = V_{dc}/2$. Input current i_{in} is equal to i_{o1}/n during t_a-t_b and is equal to $-i_{o1}/n$ during t_b-t_c . Time intervals t_a-t_b and t_b-t_c are equal to dT and $(1-d)T$, respectively. Thus, the average current $i_{in,av}$ of input current i_{in} during T is equal to $(d_1 i_{o1}/n - (1-d_1) i_{o1}/n)$. According to (1), there is $i_{o1} = V_{dc}(2d_1 - 1)/(2nR_1)$. Thus, during carrier period T with $V_{AB} = V_{dc}/2$, average input power $P_{in,av}$ is

$$P_{in,av} = \frac{(2d_1 - 1)^2 V_{dc}^2}{4n^2 R_1}. \quad (3)$$

Similarly, $P_{in,av}$ during carrier period T with $V_{AB} = -V_{dc}/2$ can also be derived, which is the same as (3). As (3) is always positive, primary-

TABLE II
COMPARISON OF DIFFERENT CIRCUIT ARCHITECTURES FOR 2.1-CHANNEL SWITCHING AMPLIFIER

Circuit architectures		In [7]	In [23]	In [24]	In [17]	In [18]	In this letter
CH1	Amplifier	HB class-D	FB class-D	HB class-D	CSSI	CSSI	CSSI
	Conversion stage	Two	Two	Two	Single	Single	Single
	Switching frequency	$2f_s$	$2f_s$	$2f_s$	f_s	f_s	f_s
	THD	High	Low	Low	High	Low	Low
CH2	Amplifier	HB class-D	HB class-D	HB class-D	CSSI	CSSI	HB class-D
	Conversion stage	Two	Two	Two	Single	Single	Two
CH3	Switching frequency	$2f_s$	$2f_s$	$2f_s$	f_s	f_s	$2f_s$
	THD	Low	Low	Low	High	Low	Low
BVP		Yes	No	No	No	No	No
Number of transformer		1	1	1	3	3	1
Number of switches		8	10	12	18	26	10
Voltage stress		High	Low	Low	High	Low	Low
Efficiency		Low	Low	Low	High	High	High

side capacitors C_{P1} and C_{P2} will never be pumped up during carrier period T , i.e., BVP does not exist at primary-side dc voltage V_{dc} .

D. Comparison of Different 2.1-Channel Audio Amplifiers

Comparison between different circuit architectures to build 2.1-channel switching amplifier is given in Table II, where $f_s = 1/T_s$. It can be seen from Table II that 2.1-channel amplifier with HB class-D amplifier architecture [7] has the simplest circuit structure. However, it suffers from BVP, which results in high voltage stress of switches and increased THD of output voltage when audio frequency is low. When HB class-D amplifier in low-frequency channel is replaced by FB class-D amplifier [23] or bidirectional SMPS [24] is used, BVP with corresponding distortion can be avoided. However, two-stage power conversion and high switching loss in [23] and [24] are still inevitable, which results in low system efficiency.

For 2.1-channel amplifier built by two-channel CSSI in [17], single power conversion stage of all the three channels can be achieved. However, high voltage stress, evident output voltage distortion, and severe electromagnetic interference (EMI) may occur as there is no voltage clamp across cycloconverter switches [25]. For two-channel CSSI with active clamp circuits [18], low voltage stress and low THD of output voltage can be obtained. Besides, wide range ZVS of primary-side switches, clamp switches, and cycloconverter switches can be achieved in [18]. Power loss of clamp switches in [18] is low in nature as small power is handled and soft switching is achieved. Thus, high efficiency can also be achieved with circuit architecture in [18]. However, this circuit is very complex as 3 transformers and 12 clamp switches are required for 2.1-channel amplification.

For the proposed 2.1-channel amplifier, CSSI is used in low-frequency channel and HB class-D amplifiers are used in high-frequency channels. With this combined circuit structure, simple circuit structure is realized without utilization of active clamp switches. Efficiency improvement is also achieved as a large amount of output power is handled by CSSI in low-frequency channel. Wide range ZVS of primary-side switches can be achieved by utilization of magnetizing current [18]. As two class-D amplifiers are used in high-frequency channels, the efficiency of the proposed 2.1-channel amplifier may be lower than that in [18] with single-stage power conversion of all the

three channels. However, much simpler circuit structure is realized in the proposed 2.1-channel switching amplifier.

Except circuit architecture in [17], voltages across switches are all clamped in the circuits in Table II. Thus, lower THD and EMI can be achieved in these circuits than the one in [17]. As BVP exists in [7], its THD at low audio frequency is higher than that in [18], [23], [24], and in this letter. For FB class-D amplifier in [23], besides bipolar PWM (also called as AD modulation) as shown in Fig. 2(b), unipolar PWM (also called as BD modulation) can also be used, where odd harmonics can be removed in the output spectrum and the differential mode voltage can be reduced, while the common mode voltage is increased compared with bipolar PWM [1], [25].

It should be pointed out that this letter only focuses on audio amplifier where front-end SMPS is required. For audio amplifiers directly powered by battery, FB class-D amplifier is a better choice [1]. In this case, high output power and high efficiency can be achieved with FB class-D amplifier, especially for integrated circuit application [25], [26].

III. EXPERIMENTAL VERIFICATION

A 200-W prototype of the proposed 2.1-channel audio amplifier is built and the output power of CH1/CH2/CH3 is 100 W/50 W/50 W. The switching frequency of CSSI and the two class-D amplifiers is 200 and 400 kHz, respectively. The load resistance R_1 , R_2 , and R_3 for CH1, CH2, and CH3 is $4\ \Omega/8\ \Omega/8\ \Omega$, respectively. Input dc voltage $V_{dc} = 310\ \text{V} \pm 15\%$ and turn ratio is 4:1:1. Capacitance of C_{B1} and C_{B2} is 330 μF . MOSFET FDPF20N50 is used for S_{P1} and S_{P2} , MOSFET BSC520N15NS3 is used for $S_1 - S_4$, $S_{2H} - S_{2L}$, and $S_{3H} - S_{3L}$. Schottky diodes MBR10200 and ES1D are used for $D_1 - D_4$ and $D_5 - D_6$, respectively. The frequency range of low-frequency audio signal channel CH1 and high-frequency audio signal channels CH2/CH3 are designed as 20 Hz–1 kHz and 1–10 kHz, respectively.

Fig. 6(a) shows output voltage v_{o1} and driving signals of primary-side switch S_{P1} and cycloconverter switches S_3/S_4 . Fig. 6(b) shows HFAC voltage V_{EF} and dc voltages $\pm V_B$. Fig. 6(c) shows voltages $\pm V_B$ and output voltages v_{o2} and v_{o3} of high-frequency audio signal channels at 1 kHz. It can be seen from Fig. 6(c) that there is no pumping voltage on dc voltages $\pm V_B$. Fig. 6(d) shows input dc voltage V_{dc} , voltages $\pm V_B$, and output voltage v_{o1} at 20 Hz. It can be seen from

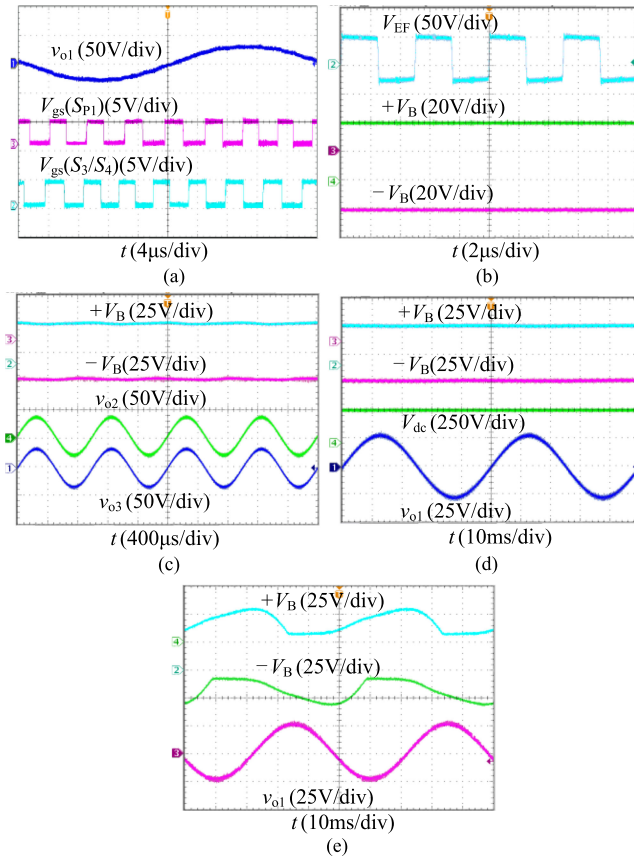


Fig. 6. Experimental waveforms of 2.1-channel amplifier with dc/HFAC mixed power supply and dc-bus power supply. (a) Voltage v_{o1} and driving signals of S_{P1} and S_3/S_4 . (b) Voltages V_{EF} and $\pm V_B$. (c) Voltages $\pm V_B$, v_{o2} , and v_{o3} . (d) Voltages $\pm V_B$, V_{dc} , and v_{o1} (CSSI). (e) Voltages $\pm V_B$ and v_{o1} (Class-D).

Fig. 6(d) that no voltage pumping occurs on dc voltages V_{dc} and $\pm V_B$. Fig. 6(e) shows voltages $\pm V_B$ and v_{o1} at 20 Hz when CSSI for low-frequency audio channel is replaced by HB class-D amplifier supplied by dc voltages $\pm V_B$. It can be seen from Fig. 6(e) that when HB class-D amplifier is used as low-frequency audio channel amplifier, very large pumping voltages occur on dc voltages $\pm V_B$.

Fig. 7 shows the switching waveforms of cycloconverter switches S_1 and S_2 . It can be seen from Fig. 7(a) and (b) that ZVS of S_1 is achieved both when $i_{o1} < 0$ and when $i_{o1} > 0$, and it can be seen from Fig. 7(c) that ZVS of S_2 is achieved when $i_{o1} > 0$.

Efficiency of the proposed 2.1-channel amplifier is measured and 91.2% peak efficiency is achieved, as shown in Fig. 8(a). When HB class-D amplifier is used as low-frequency audio channel amplifier, the peak efficiency of 2.1-channel amplifier is 87.8%, as shown in Fig. 8(a). At 25-W output power, THD plus noise (THD + N) of high-frequency audio channels output voltages v_{o2} and v_{o3} is given in Fig. 8(b). It can be seen that THD + N of v_{o2} and v_{o3} is lower than 0.3% from 1 to 10 kHz. Fig. 8(c) shows THD + N of low-frequency audio channel output voltage v_{o1} at 50-W output power, with CSSI and with HB class-D amplifier supplied by dc voltages $\pm V_B$. From Fig. 8(c), it can be seen that THD + N of v_{o1} with CSSI is below 0.2% from 20 Hz to 1 kHz, which is lower than THD + N of HB class-D amplifier with dc-bus power supply. Lower THD + N of v_{o1} with CSSI is due to elimination of BVP, especially when audio frequency is low.

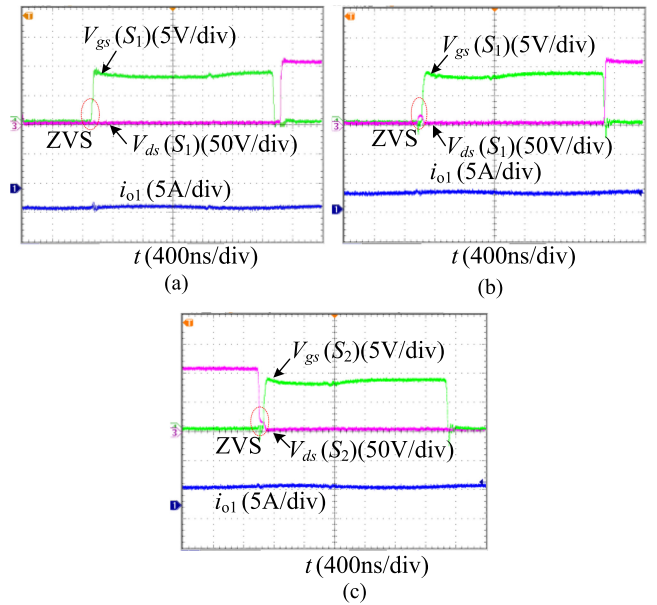


Fig. 7. Switching waveforms of cycloconverter switches S_1 and S_2 . (a) Switch S_1 ($i_{o1} < 0$). (b) Switch S_1 ($i_{o1} > 0$). (c) Switch S_2 ($i_{o1} > 0$).

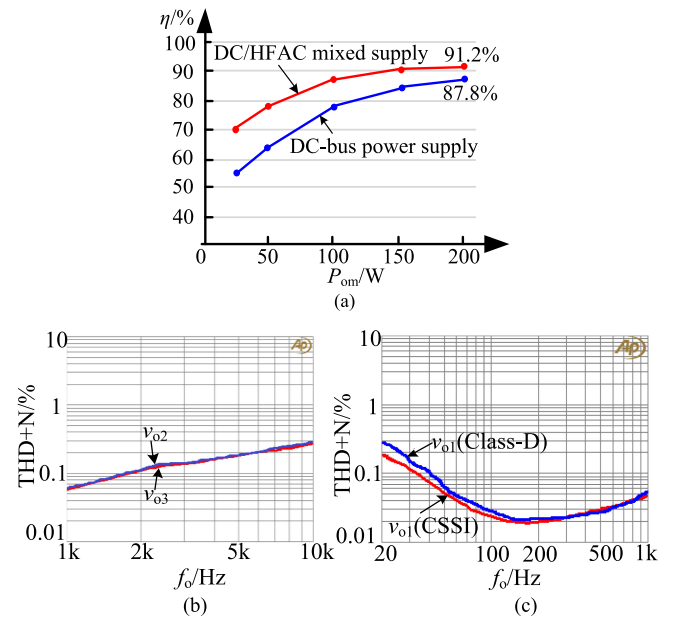


Fig. 8. Efficiency and THD + N results. (a) Efficiency comparison. (b) THD + N versus f_o (CH2/CH3). (c) Comparison of THD + N versus f_o (CH1).

IV. CONCLUSION

High efficiency BVP-free 2.1-channel switching amplifier with dc/HFAC mixed power supply has been proposed. The circuit structure, modulation strategy, soft switching, and BVP elimination of the proposed 2.1-channel switching amplifier have been presented. A 200-W prototype is built and experimental results are analyzed. Efficiency and THD + N comparison between the proposed 2.1-channel switching amplifier and 2.1-channel HB class-D amplifier with dc-bus power supply has been performed. The proposed 2.1-channel amplifier has advantages of high efficiency, simple circuit structure, low voltage stress of the switches, and low THD + N of low-frequency audio signal channel. The proposed circuit architecture is attractive in applications

when front-end converter is required, such as television, home theater, and active loudspeaker with mains voltage supply.

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