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Class-G series audio power amplifier for subwoofer

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ABSTRACT

An audio power amplifier is an electronic device used to amplify a small signal source power at the input into a large signal power at the output that is speaker. In general, audio power amplifiers use class-AB amplifiers. In the process of amplifying the signal power, there will be power losses in the amplifiers which results in relatively lower amplifier power efficiency because there is a difference between the supply and output voltage levels. In this paper a class-G series audio power amplifier for subwoofers is designed to minimize these power losses and increase the power efficiency of the amplifier. The designed amplifier voltage supply is 40 V with a maximum output power of 80 W at an 8 Ω load. The amplifier has frequency response from 20–200 Hz and gain twice. Realization of the power amplifier and measurements were carried out using the circuit maker simulator, and the measurement results of the class-G power amplifier were compared with the class-AB power amplifier. The measurement results show that both power amplifiers meet the design specifications. The proposed class-G amplifier has 0.14% larger total harmonic distortion (THD) but has 10.4% greater power efficiency advantages over the class-AB amplifier.

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1. INTRODUCTION

An audio power amplifier is an electronic device used to boost the voltage, current, or sound power produced by a sound source such as a microphone or music player. This is used to amplify sound signals so that they are stronger and clearer when received by a receiver such as a speaker or recording console. There are two types of audio power amplifiers, namely analog power amplifiers and digital power amplifiers. One of the things desired in an audio power amplifier is high power amplifier efficiency to minimize the resulting heat dissipation.

The efficiency of an audio power amplifier is the ratio between the output power produced by an audio power amplifier compared to the input power received by the power amplifier. Higher efficiency means less power lost as heat or less heat dissipation in the power amplifier's power transistors. Higher efficiency can also reduce operating costs and improve battery life in applications that use batteries as a power source.

Heat dissipation of power transistors in audio power amplifier can be caused by the difference in voltage supply and output signal amplitude. This difference is referred to as voltage drop, which is the power lost during the signal passing through the transistor. This voltage drop is converted into heat by the transistor and resistors.

In audio power amplifiers, the amount of heat dissipation in the power transistor and resistors are determined by the voltage drop across the transistor, resistors, because the current passing through the transistor. The current passing through the transistor is the same as the load current of the power amplifier. The greater the voltage drop on the transistor, the greater the heat dissipation produced. Therefore, the design of the audio power amplifier must pay attention to the balance between the output signal amplitude and the voltage supply to reduce the resulting heat dissipation.

Audio power amplifiers have several types or classes [1], and each class has advantages and disadvantages. If viewed in terms of power efficiency, most types of audio power amplifiers are less efficient than class-B, forexample, class-AB is very less efficient when using power at low levels of its power capability. Class-A power amplifiers dissipate almost all the energy put into them. Building a power amplifier with higher efficiency and fidelity is difficult. Class-D power amplifiers, for example, use several hundreds of kHz to a few MHz pulse width modulation, promise high efficiency, but this class has several drawbacks such as more complicated design, worse linearity than class-B [2], [3] requires an inductor-capacitor (LC) filter with large dimensions [4], bus-pumping effects [5], total harmonic distortion (THD) that greater than class-AB [6], requires additional filters to reduce electromagnetic interference (EMI) [7], and the total cost of class-D power amplifier systems remains higher than a class-AB amplifier [8].

The general picture states that class-D has superior efficiency than class-G and class-H [9]. In the [7] paper, these three classes are implemented into three class-D or fixed boost, integrated with class-G, and class-H modes on the TAS2562 integrated circuit. Class-G and class-H can extend the usage of a 1000 mAh battery by around 10.2% and 15.5% compared to class-D. Class-H requires a power supply circuit that is able to continuously follow the amplitude of the output signal [10], [11]. Meanwhile, in class-G, there are only a few discrete comparison points that are used to change the value of the voltage supply.

The circuit concept in class-G looks simpler, allows the use of charge-pump [12], less quiescent power [13], and has quality equivalent to class-AB. Class-AB itself has the ability to produce high fidelity (Hi-Fi) audio quality [14]. As far as we have investigated, the design of a complete class-G circuit with discrete components for a subwoofer has not been published yet, although some have been fabricated into an integrated circuit [7], its application is for low power audio [11] or for radio frequency (RF) [15]–[23]. Therefore, we raised this topic specifically on hi-fi and efficient power amplifier circuits for subwoofers.

2. METHOD

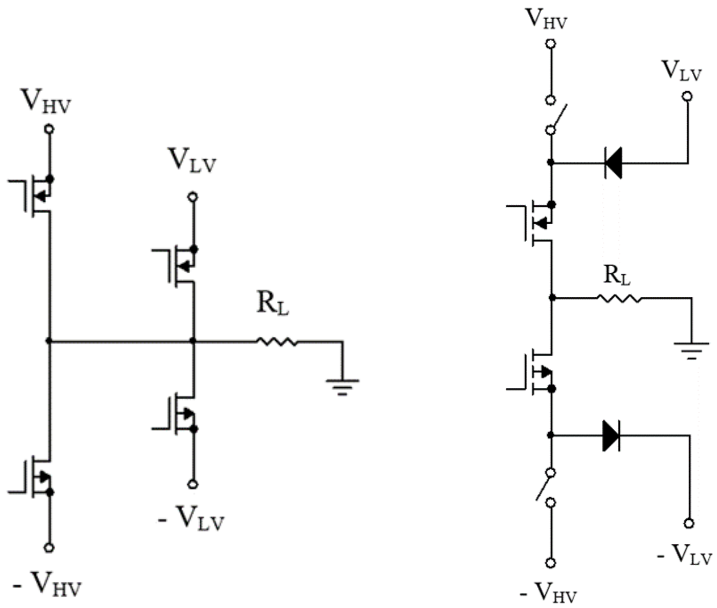
Among several types of power amplifiers, there are two classes of power amplifiers whose working principle is to achieve high power efficiency by changing the supplied voltage. The two amplifiers are class-G and class-H power amplifiers. Class-G and class-H power amplifiers are based on a class-AB amplifier, but have adjustable supplied voltage, to which these values are adapted according to the output voltage level amplifier [24].

Class-H amplifiers use power supplies adapted to input signal level and adjust the voltage level for a large input signal level, providing the required output power while minimizing power dissipation. Class-H amplifiers modulate the supplied voltages, thereby minimizing transistors power loss in the amplifier. A class-H amplifier provides the supply with variable levels adjusted to the load power. The voltage drop across the power transistor is kept constant to maximize efficiency [25].

A class-G power amplifier is a combination of an ideal high-fidelity speaker drivers class-AB amplifier and several power supply units [1], [26]. This amplifier will take the power from the high or low voltage (LV) rail corresponding to the high or low signal level. Power efficiency in class-G power amplifiers is improved by optimizing the power supply. Class-G power amplifiers use dual or more power supply rails [27], [28]. For the use of dual supply rails, LV and high voltage (HV) are provided by the power supply unit. The output stage of the power supply is selected between the two supply rails (LV and HV). Class-G power amplifiers have the goal of maximizing power efficiency while maintaining high linearity.

There are two types of class-G power amplifiers, parallel class-G power amplifiers and series class-G power amplifiers [2]. A parallel class-G power amplifier is a type of power amplifier that has two or more transistors working together to increase the output power. In a parallel class-G power amplifier, the input power is shared between the transistors so that each transistor only needs to amplify part of the signal. Figure 1(a) shows a parallel class-G power amplifier consisting of a voltage supply V_{HV} in parallel with a voltage supply V_{LV} where $V_{HV}>V_{LV}$ [29]. If the input signal is small, then the voltage supply V_{LV} works as a power amplifier supply, and if the input signal V_i is large, then the voltage supply V_{HV} works as a power amplifier supply. This allows the power amplifier to achieve higher output power with good efficiency [30].

A power amplifier is a type of amplifier where the signal enters through one transistor and is then transferred to another transistor before being amplified. Series class-G power amplifiers use a single connected output stage to the V_{LV} and V_{HV} supply rails respectively through a diode and switch as shown in Figure 1(b). The output power is increased through many successive stages of gain. This allows the power amplifier to achieve very high output power with fairly good efficiency.



(a) (b)

Figure 1. Two basic types of class-G power amplifier; (a) parallel and (b) series [29]

In this paper, a class-G series audio power amplifier for subwoofers is designed with two power supply rails with an output power of 80 W at an 8 Ω load. The amplifier gain is designed two times. Efficiency testing was carried out by comparing it to a class-AB power amplifier at a frequency of 1 kHz. A subwoofer amplifier as an application of the amplifier will be tested at frequencies of 20 Hz and 200 Hz to determine whether its frequency response meets the requirements as a subwoofer amplifier [31]. The box diagram of the designed class-G audio power amplifier is shown in Figure 2.

The power amplifier receives input in the form of a small power input signal, which will be amplified by a power amplifier with a certain power and produce an output signal with a large power. The amplifier output drives a load in the form of a speaker. The output signal is sampled and detected by an output voltage sampler and compared with the reference voltage. If the output voltage level is smaller than the reference voltage, then the power amplifier gets a LV supply from the voltage supply, and if the output voltage level is greater than the reference voltage, then an electronic switch will connect the power amplifier to a HV supply from the voltage supply. There are two output voltage samplers, each to sample the positive level and negative level output voltage. The voltage supply consists of low and HV for positive and negative polarity.

The design of each circuit of a class-AB and class-G amplifier is explained in the following subsections. These two circuits aim to produce a subwoofer speaker power output of around 80 W at a load R of 8 Ω for subwoofer's speaker. The brief design and circuit used by class-AB are explained in the first subsection. Meanwhile, the following subsections describe the design of the box diagram as mentioned in Figure 2.

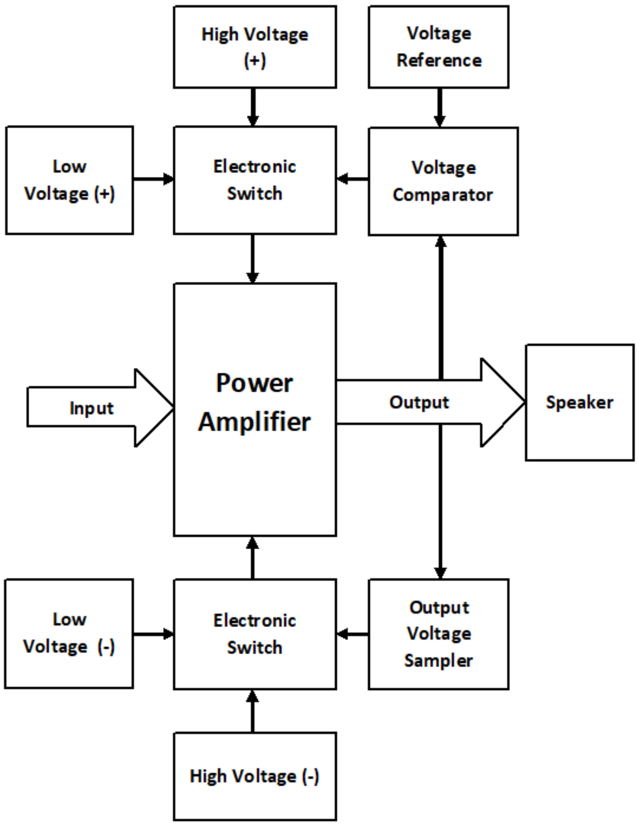


Figure 2. Class-G amplifier box diagram

2.1. Power amplifier

The power amplifier used in this subsection is a class-AB power amplifier as shown in Figure 3. The boost voltage factor is determined by the resistance of the voltage divider R17 and R25 or R18 and R26. If the values R17=R25 and R18=R26, then the power amplifier has a voltage gain of two times ideally [2]. Taking into account the non-ideality of the transistor amplifier and the presence of a load on the amplifier output, the amplifier battery is made slightly larger than twice, and the value of R17 and R18 are not the same as R25 and R26. In this case, R17 and R18 are determined as 47 Ω and the value R25=R26=56 Ω. The amplifier efficiency is calculated by (1), and the amplifier output power is calculated by (2) and (3) are as [9] [32]:

$$\eta = \frac{P_{out}}{P_{dc}} \quad (1)$$

$$P_{out} = \frac{V_{out}^2}{2R_{load}} \quad (2)$$

$$P_{out} = \frac{V_{eff}^2}{R_{load}} = \frac{V_{out}^2}{2R_{load}} \quad (3)$$

where P_{out} is the output power of an amplifier (W), P_{dc} is the input power from a power supply (W), V_{out} is the output voltage of an amplifier (V), R_{load} is the load of power amplifier output (Ω), and V_{eff} is the effective output voltage (V).

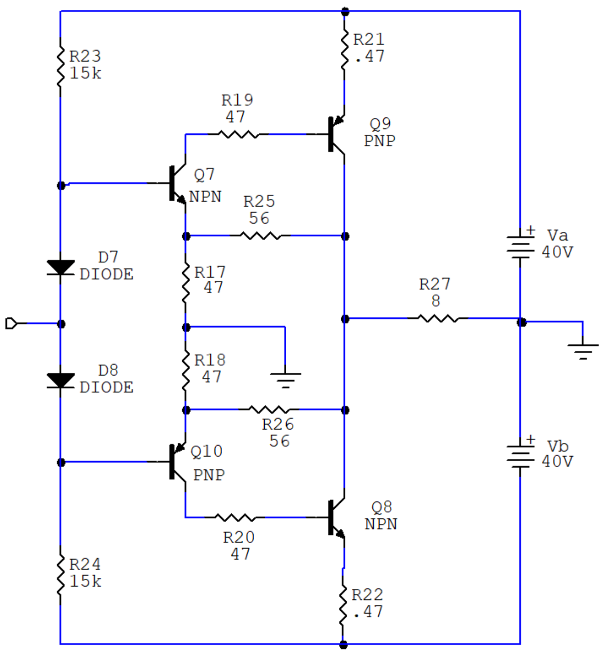


Figure 3. Class-AB power amplifier

2.2. Comparator circuit

The comparator circuit functions to compare the output voltage of the amplifier with the reference voltage. The comparison circuit using the TL072 operating amplifier is shown in Figure 4. The reference voltage is the result of dividing the voltage by the 18 kΩ, and 22 kΩ resistances to the 40 V voltage supply, which is 18 V. If the amplifier output at the inverting input of the operating amplifier is smaller than the reference voltage at the non-inverting input, then the output of the comparison circuit produces a level of "1" (high), and if the amplifier output is greater than the reference voltage then the comparison circuit output produces the level "0" (low). The output of the comparator circuit will trigger an electronic switch.

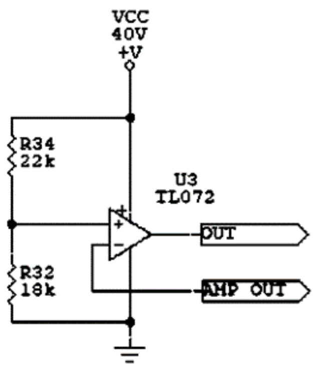
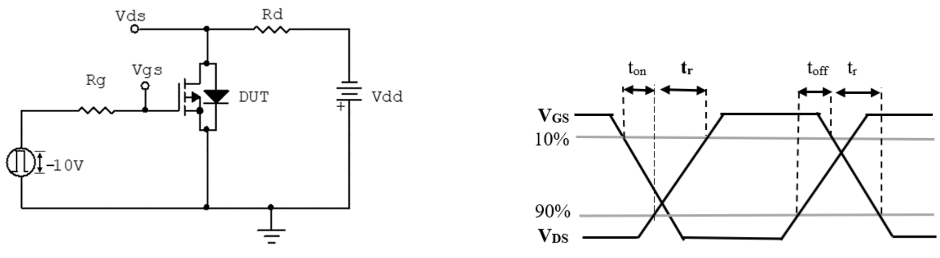


Figure 4. Comparator circuit

2.3. Electronic switch

The electronic switch functions to select the voltage supply which has LV or HV. In this design, the LV=22 V and the HV=40 V. The electronic switch uses P-MOSFET IRF9540 [33] for positive polarity voltage supply and N-MOSFET IRF540 [34] for negative polarity voltage supply. Figure 5(a) is the P-MOSFET IRF9540 which is triggered in the form of a pulse and Figure 5(b) is the switching waveform. The trigger level must be below -4 V so that the P-MOSFET is saturated. In this design, a trigger of around -13 V will be given.



(a) (b)

Figure 5. Switching test circuit of: (a) P-MOSFET IRF9540 and (b) switching waveform [16]

2.4. Class-G power amplifier circuit

The complete class-G amplifier circuit is shown in Figure 6. The trigger input on the pin gate of the P-MOSFET IRF9540 (Q5) is given resistance R12=500 Ω and R13=1 kΩ which functions as a voltage divider from the output of the comparison circuit. The voltage divider formula is shown in (4) [35]:

$$V_n = \frac{R_n}{R_1 + R_2 + R_3 + ... + R_n} V_s \quad (4)$$

where V_s is the voltage source (V) [17], V_n is the voltage across n resistance (V), N is the number of resistances in R series, and R_n is the n^{th} resistor.

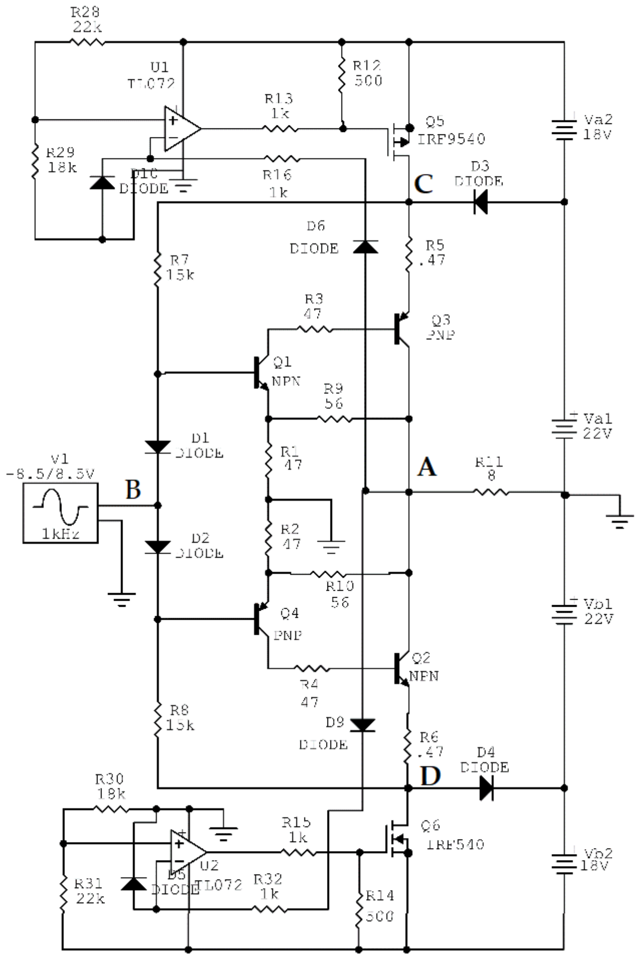


Figure 6. A complete circuit of class-G power amplifier

In this case, the output of the comparison circuit (U1) is “1” (high) and “0” (low) when U1=40 V and U1=0 V respectively. With the voltage divider resistance, according to (4), the voltage drops across the resistance R12=500 Ω is 13.3 V so that the P-MOSFET IRF9540 will get a trigger voltage of -13.3 V. The same thing also happens to the N-MOSFET IRF540, but the polarity is opposite. So the N-MOSFET IRF540 will get a trigger voltage of +13.3 V.

3. RESULT AND DISCUSSION

The experimental results of each class-AB and class-G amplifier circuit are discussed in this section. The circuit of the proposed class-G will be compared with the reference class-AB. All circuits and measurements use circuit maker software. Both circuits produce a signal gain of two times. There are two sub-sections that will be discussed here, namely, comparison of power consumption at several test points and direct current (DC) sweep, THD and frequency response.

3.1. Comparison of power consumption and DC sweep

The power amplifier measurement results in Table 1 state that for a class-G amplifier, the output power Po=81 W when the output voltage Vo=36 V. Meanwhile, the supply power drawn from Va1 is Pva1=73.9 W and from Va2 is Pva2=52.5 W so that the total power drawn from the supply is Pva=126.4 W. Therefore, the efficiency of the class-G power amplifier is obtained Eff=η=64.1%. On the other hand, for the class-AB amplifier, the output power Po=81 W when the output voltage Vo=36 V. The supply power drawn from Va is Pva=133 W and the efficiency of the class-AB power amplifier is Eff=η=60.9%. It is noted that Ptr is the heat dissipation in the transistor from the measurement results.

Table 1. Results of measuring the power consumption of class-G and class-AB power amplifier

Vcc=±40 V	Class-G						Class-AB		
Vo (peak)	Po (W)	Pva1 (W)	Pva2 (W)	Pva (W)	Ptr (W)	Eff (%)	Pva (W)	Ptr (W)	Eff (%)
0	0.00	0.0	0.0	0.0	0.0	-	0.0	0.0	-
2	0.25	4.3	0.0	4.3	3.3	5.8	7.2	6.7	3.5
9	5.00	18.0	0.0	18.0	10.9	27.8	32.0	11.8	15.6
17	18.00	34.4	0.0	34.4	10.8	52.3	62.0	39.7	29.0
19	22.50	38.6	9.0	47.6	17.9	47.3	69.5	41.5	32.4
26	42.20	53.2	32.0	85.2	30.3	49.5	95.6	43.2	44.1
36	81.00	73.9	52.5	126.4	22.0	64.1	133.0	32.2	60.9

It also shows that the efficiency of the proposed class-G amplifier is greater than that of the class-AB amplifier [9]. In addition, the highest efficiency is achieved when the output voltage is closer to the voltage supply. In class-G power amplifiers, the efficiency is swung up two times and proportional to the Vo. The first higher efficiency than class-AB is achieved when the output voltage Vo=17 V because it is close to the LV 22 V, and second is when the output voltage Vo=36 V, because it is close to the HV of 40 V supplied voltage. Meanwhile, class-AB power amplifiers achieve highest efficiency once, when the output voltage Vo=36 V because it is close to the voltage supply of 40 V. The integration between class-D and class-G produce in peak output efficiency of around 80% but at a maximum power 5 W which is much less than our proposed 80 W power output [7].

We also conduct the DC sweep simulation to show the broad areas where the class-G outperforms or is similar to class-AB. The designed amplifier has twice the gain with a power supply limit of 40 V. Therefore, DC sweep is regulated from -20 V to +20 V. Class-G and class-AB utilize four and two power supply sources respectively. Class-G is designed to have a positive and negative power supply, each having two power supplies. In class-AB two power supplies are required. The total value of positive (va1[p]+va2[p]) and negative (vb1[p]+vb2[p]) current power in class-G is compared with class-AB power (va[p]+vb[p]). Figure 7 displays the output power of class-G and class-AB as a function of DC sweep. The gray area is the area where class-G outperforms class-AB. Based on the ratio of gray area to area under class-AB during the DC sweep experiment from -9 V to +9 V and -18.5 to +18.5, it is clear that our proposed class-G yields 43.8% and 10.4% more efficient than class-AB, respectively.

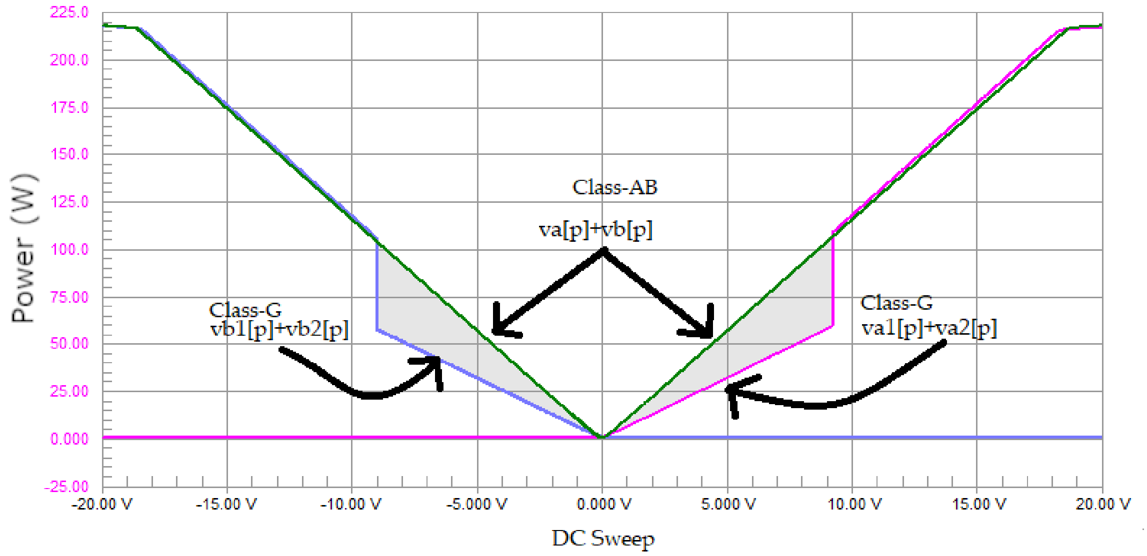


Figure 7. Power of class-G and class-AB as a function of DC sweep from -20 V to 20 V

3.2. THDs and frequency response

Audio signal quality can be measured from the THD of the output signal. Here, measurement of the output signal from the amplifier is carried out using measurement points as shown in Figure 6 for signal frequencies of 20 Hz, 200 Hz, and 1 kHz. Figure 8 shows the output signal (□) which is very similar to the input signal frequency of 20 Hz (△). Meanwhile, the low and high positive (◇) and negative (▭) power supply changes following the movement of the output signal as expected in class-G.

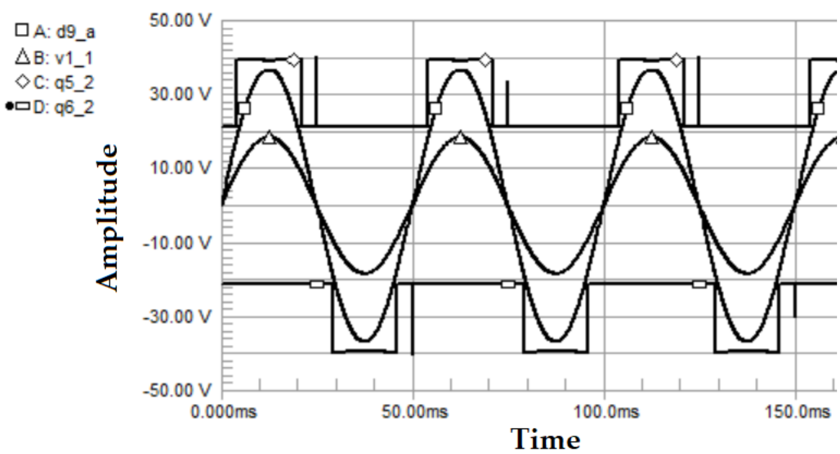


Figure 8. Response of the low and high positive and negative power supply, and the output signal, (◇), (▭), and (□), respectively, to the input signal (△), at a voltage of 36 Vpp, and an input signal frequency of 20 Hz

To test the THD of class-G and class-AB at a fundamental frequency of 1kHz, an experiment is carried out with an input of 13 Vpp as an example. The THD of class-G and class-AB are both below than 1% which is considered as hi-fi [36]. Both classes yield THD of 0.70% and 0.56% respectively. In this case, class-G has 0.14 % higher distortion than class-AB.

The frequency response of the amplifier is measured from 20 Hz to 1 kHz with the same input amplitude. Figure 9 shows the results of measuring the frequency response of a flat power amplifier for the frequency range 20 Hz–200 Hz. Thus, this amplifier qualifies as a subwoofer power amplifier which has a frequency range of 20 Hz–200 Hz [31].

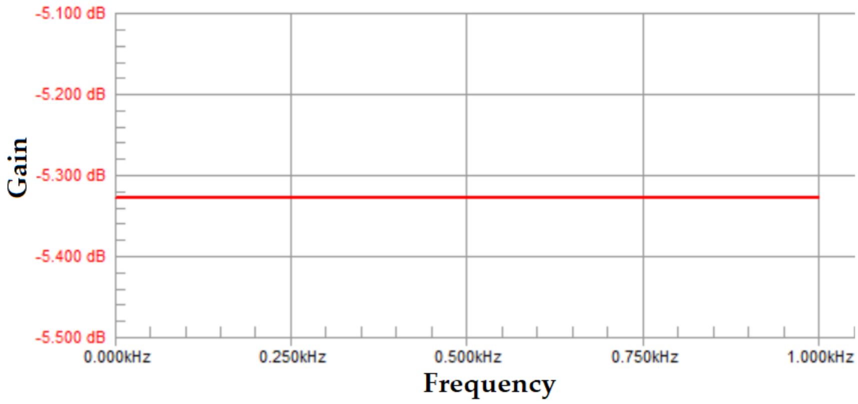


Figure 9. Frequency response of a class-G power amplifier for a subwoofer

4. CONCLUSION

The design of a class-G power amplifier for a subwoofer meets the specifications, namely 80 W amplifier power at a load of 8 Ω with a voltage gain of two times and a frequency response of 20 Hz-200 Hz. The power efficiency of a class-G amplifier is greater than the class-AB. The difference in efficiency between the two amplifiers becomes larger as it approaches the reference voltage limit of the comparator circuit and becomes smaller as both outputs approach the highest output voltage.

This design can be developed more efficiently by increasing the number of voltage rails. Varying rail voltage is useful for minimizing the difference between the voltage supply level and the output voltage level. Thus, the dissipation due to the voltage difference has an impact on increasing the efficiency of the power amplifier.

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