

An Amplifier Apparatus and Method

Field of the Invention

The present invention relates generally to an amplifier system and method for amplifying a signal, for use, for example in an audio amplifier circuit.

5 Background of the Invention

Environmental considerations are becoming an increasingly important design parameter for product developments. For amplifier designs, considerable research has been directed towards high efficiency amplifiers which have less energy loss and various topologies exist that perform at a higher efficiency than conventional Class B amplifiers. Examples of such amplifiers are Class D, Class G and Class H amplifiers. Such amplifiers require smaller heat sinks than conventional Class B amplifiers, resulting in lighter and more compact products.

For a Class B amplifier having a fixed primary power supply, the theoretical maximum efficiency is 78.5% when it is driven to saturation by a sine wave, but in actual practice the efficiency does not exceed 70%.

The basic concept of conventional Class D amplifiers is to convert the input signal into a Pulse Width Modulated (PWM) signal and to recover the analog output signal through a low pass filter before delivering the signal to the load. A theoretical efficiency of 100% may be achievable with conventional Class D amplifiers and, in practice, over 90% efficiencies have been achieved using Class D Digital Amplifiers. Disadvantages of Class D amplifiers are the EMI issues which arise from the high level switching of the PWM signal. Furthermore, the typical requirement of the output low pass filter adds costs to the implementation of Class D amplifiers. At the same time, this output low pass filter also affects the output characteristics of the amplifier as a fixed load impedance of, for example, 6 ohms has to be assumed during its design. This is not, however, the case for typical loudspeaker loads. In typical loudspeaker systems, when connected to a load which may range from 2

ohms to some tens of ohms for typical loudspeakers, the output characteristics will deviate from the target design.

Conventional Class G amplifiers generally achieve higher efficiencies than conventional Class B amplifiers by switching the power supply level at different fixed levels to have the power supply closer to the output signal. In theory, 100% efficiency may be achieved by increasing the number of fixed power supply levels indefinitely. However, as several devices have to be used to switch among the different supply voltages, this will create losses in practice.

Conventional Class H amplifiers use the input signal to control the power supply and vary the power supply by Pulse Width Modulation (PWM) to form an envelope over the output signal. Although a very high efficiency may be achieved in such amplifiers, such as theoretically up to 100%, the transient response of conventional Class H amplifiers may be poor and the bandwidth may be extremely limited due to the slow response of the power supply. Moreover, EMI issues will be a major concern in such amplifiers.

Summary of the Invention

In general terms, the invention provides an amplifier apparatus and method in which the voltage signal level in an amplifier is reduced by applying a voltage at various fixed levels to a first side of a load, obtaining a difference signal derived by subtracting a proportion of the voltage applied to the load from the input signal, and applying the difference signal to the other side of the load through the amplifier. This results in the reconstruction of the signal across the load. The voltage swing obtainable across the load is greater than the output voltage swing obtainable from the amplifier alone, thus the efficiency of the amplifier apparatus and power handling capacity of the apparatus are improved.

According to a first aspect of the invention, there is provided amplifier apparatus comprising:

an amplifier;

a comparator connectable to the amplifier to compare an incoming signal with a number of reference potentials, the comparator having an output;

a switching stage controllable by the output of the comparator to select a voltage level to be applied to one side of a load; and

5 a subtractor for subtracting from the incoming signal a percentage of the selected voltage level to be applied to the load to provide an output signal of the subtractor;

the amplifier being arranged to receive the output signal of the subtractor and to amplify the output signal to be applied to a second side of the load.

10 The amplifier may comprise a differential amplifier.

The amplifier may include the subtractor.

The amplifier may be a linear amplifier.

In one embodiment, the amplifier has a gain associated therewith, and the percentage of the selected voltage subtracted by the subtractor is inversely
15 proportional to the gain of the amplifier.

In one embodiment, the input signal varies between a first potential and a second potential, the reference potentials being obtainable from one or more supplies having a range of or between the first and second potentials of the input signal.

The load may comprise a loudspeaker system.

20 According to a second aspect of the invention, there is provided an audio system comprising amplifier apparatus according to the first aspect of the invention.

According to a third aspect of the invention, there is provided a method for amplifying a signal in an amplifier apparatus, the method comprising the steps of:

25 comparing, in a comparator, an incoming signal with a number of reference potentials, the comparator having an output;

selecting, in a switching stage, a voltage level to be applied to one side of a load, the switching stage being controllable by the output of the comparator;

subtracting from the incoming signal a percentage of the selected voltage level to be applied to the load to provide an output signal of a subtractor;

5 receiving, in an amplifier, the output signal of the subtractor;

amplifying the output signal of the subtractor; and

applying the amplified signal to a second side of the load.

The step of amplifying the signal may comprise amplifying the signal using a differential amplifier.

10 The step of amplifying the signal may comprise amplifying the signal using a linear amplifier.

In one embodiment, the amplifier has a gain associated therewith, and the step of subtracting the percentage of the selected voltage comprises subtracting a percentage which is inversely proportional to the gain of the amplifier.

15 In one embodiment, the input signal varies between a first potential and a second potential, and the method further comprises obtaining the reference potentials from one or more supplies having a range of or between the first and second potentials of the input signal.

Brief Description of the Drawings

20 Preferred features of the invention will now be described, for the sake of illustration only, with reference to the following Figures in which:

Figure 1 is a schematic circuit diagram of a conventional Class B amplifier;

Figure 2 is a schematic circuit diagram of an amplifier according to a preferred embodiment of the invention;

Figure 3 is a waveform of an input signal in the form of a sine wave;

Figure 4 is a waveform of a signal at node 1 in the circuit of Figure 2 for a sine wave input signal of the type shown in Figure 3;

5 Figure 5 is a waveform of a signal at node 3 in the circuit of Figure 2 for a sine wave input signal of the type shown in Figure 3;

Figure 6 is a graph of the efficiency against normalised power for the amplifier of Figure 2 compared with a conventional Class B amplifier;

Figure 7 is a graph of power loss against normalised output power for the amplifier of Figure 2 compared with a conventional Class B amplifier;

10 Figure 8 is a schematic circuit diagram according to a further preferred embodiment of the invention;

Figure 9 is a waveform of a signal at node 1 in the circuit of Figure 8 for a sine wave input signal;

15 Figure 10 is a waveform of a signal at node 3 in the circuit of Figure 8 for a sine wave input signal;

Figure 11 is a graph of the efficiency against normalised power for the amplifier of Figure 8 compared with a conventional Class B amplifier;

Figure 12 is a graph of power loss against normalised output power for the amplifier of Figure 8 compared with a conventional Class B amplifier;

20 Figure 13 is a graph of the efficiency against normalised power for the amplifiers of Figures 2 and 8 compared with a conventional Class B amplifier; and

Figure 14 is a graph of power loss against normalised output power for the amplifiers of Figures 2 and 8 compared with a conventional Class B amplifier.

Description of Preferred Embodiments

Figure 1 shows a circuit diagram of a conventional Class B amplifier. An input signal 10 is applied between ground and the positive input terminal of an amplifier 12 which has a gain of G_v . Negative feedback is applied to the amplifier 12 by dividing the output signal therefrom in a potential divider comprising two resistors 14, 15 connected in series from the output of the amplifier 12 to ground. The junction 16 of the two resistors 14, 15 is connected to the negative terminal of the amplifier 12, the two resistors 14, 15 defining the gain of the amplifier 12. The amplifier 12 is powered by twin power supplies having power supply voltages which are fixed at V_{cc} and $-V_{cc}$ respectively. Thus, the output signal from the amplifier 12 will vary within the range $-V_{cc}$ to $+V_{cc}$.

Assuming that there is no clipping, if the peak amplitude of the input signal 10 is V_{ref} , giving a corresponding peak output of V_{cc} , the gain of the amplifier 12 may be denoted by $G_v = \frac{V_{cc}}{V_{ref}}$. The theoretical efficiency of such an amplifier 12 based on a

sinusoidal input of amplitude V_0 may be denoted as $\frac{\pi V_0}{4V_{cc}}$ and the power loss as

$$\frac{2V_{cc}V_0}{\pi R} - \frac{V_0^2}{2R}, \text{ where } R \text{ is a resistive load.}$$

An amplifier circuit 18 according to a first preferred embodiment of the present invention is shown in Figure 2. In this embodiment, the amplifier circuit 18 comprises an input signal 19, a comparator 20, a control circuit 21, a multi-way switch 22 and a differential amplifier 23. The input signal 19 is applied via a resistor R7 to the negative input of the differential amplifier 23. A resistor R8 is connected between the output of the differential amplifier 23 at node 3 and the negative input of the differential amplifier 23. The input signal 19 is also applied to the input of the comparator 20. The output terminals of the comparator 20 are connected to the multi-way switch 22 and the output of the multi-way switch is connected at a node 1 to the positive terminal of a loudspeaker 24 and also to a potential divider comprising two resistors R9 and R10 connected in series between node 1 and ground. The

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junction (node 2) of the resistors R9 and R10 is connected to the positive input of the differential amplifier 23.

The comparator 20 compares the input signal 19 with the reference voltages $-2/3V_{ref}$, $-1/3V_{ref}$, $+1/3V_{ref}$ and $+2/3V_{ref}$, which are fixed by resistors R1, R2, R3, R4, R5 and R6 within the comparator 20. Preferably,

$$R1=R2=R3=R4=R5=R6$$

$$V_{cc1} = V_{cc} / 3$$

$$V_{cc2} = 2 \times V_{cc1}$$

$$R8/R7 = Gv$$

$$R10/(R9+R10) = 1/Gv$$

Also, $|V_{ref}|$ corresponds to the peak amplitude of the input signal 19.

When the amplitude of the input signal 19 is below $|V_{ref}/3|$, the ground potential is applied to node 1 at the positive terminal of the load 24. When the input signal 19 amplitude exceeds the reference voltages, a corresponding signal is sent to the control circuit 21 to indicate the level of the input signal 19. Via the multi-way switch 22, the control circuit 20 then switches on the appropriate DC voltage, at $-V_{cc2}$, $-V_{cc1}$, V_{cc1} or V_{cc2} respectively, to the positive terminal of the load 24, where $|V_{cc1}| = \frac{V_{cc}}{3}$,

$|V_{cc2}| = \frac{2V_{cc}}{3}$ and V_{cc} refers to the peak output voltage, which is also the power supply voltage of a conventional Class B amplifier delivering the same output power as the embodiment of the present invention illustrated in Figure 2.

Figure 3 shows an input waveform 19 comprising a sinusoidal waveform, the peak amplitude of which is equal to the maximum voltage present in the comparator 20.

When the waveform of Figure 3, namely a sinusoidal input of amplitude V_{ref} , is applied to the comparator 20, a stepped waveform resembling the sinusoidal waveform will appear at the positive terminal of the load, as shown in Figure 4.

The gain of the differential amplifier 23 is chosen such that $|G_v| = |V_{cc}|/|V_{ref}|$ and its power supply voltages are $+V_{cc1}$ and $-V_{cc1}$. A proportion of the DC voltage applied to the load from node 2, the amplitude of which may be fixed by selecting appropriate values for the resistors R9 and R10, is fed to the positive input of the differential amplifier 23. This amplitude may be selected to be $1/G_v$ of the supplied DC voltage to the load. As the DC voltages are fixed at $-V_{cc2}$, $-V_{cc1}$, GND, V_{cc1} and V_{cc2} , the signal to the positive input of the differential amplifier 23 will be correspondingly $-2/3 V_{ref}$, $-1/3 V_{ref}$, GND, $+1/3 V_{ref}$ and $+2/3 V_{ref}$.

The input signal 19 is fed to the negative input of the differential amplifier 23 through resistor R7. The difference between the positive input and the negative input of the differential amplifier 23 is amplified and fed to the negative terminal, Node 3, of the load, as shown in Figure 5. The differential amplifier 23 essentially compensates for the difference between the signal fed to the positive terminal of the load and the desired signal. Thus, the overall signal as seen by the load will be equivalent to the input signal amplified by a gain of G_v .

On the positive side of the load 24, which is essentially switching among several DC voltage levels, the efficiency is theoretically 100%. On the negative side of the load, a conventional Class B amplifier design may be used for the differential amplifier 23. The efficiency of such a differential amplifier will be the same as a conventional Class B amplifier. However, since the supplied voltage is $+V_{cc}/3$ and $-V_{cc}/3$, the overall efficiency of the amplifier circuit of Figure 2 as compared to a conventional Class B amplifier delivering the same output power, may be seen to be significantly higher. The efficiency and power loss calculations are described as follows.

It is proposed that amplifiers embodying the present invention are to be named the Class μ Amplifier because of the resultant shape of the curve when the graph of Efficiency against Output Power is plotted (as shown in Figure 6 described below).

Symbol Definitions

	ε	Efficiency
	ε_B	Efficiency of normal (conventional) Class B Amplifier
5	ε_1	Efficiency of Stage 1 of Class μ Amplifier
	ε_2	Efficiency of Stage 2 of Class μ Amplifier
	ε_3	Efficiency of Stage 3 of Class μ Amplifier
	f	Frequency
	I	Current
10	P_{in}	Input power
	P_{out}	Output power
	$P_{total-in-2+}$	Total input power for positive side of Stage 2 of Class μ Amplifier
	$P_{total-in-2-}$	Total input power for negative side of Stage 2 of Class μ Amplifier
	$P_{total-in-3+}$	Total input power for positive side of Stage 3 of Class μ Amplifier
15	$P_{total-in-3-}$	Total input power for negative side of Stage 3 of Class μ Amplifier
	P_{ave-in}	Average input power
	$P_{ave-out}$	Average output power (same for both Class B and μ in this application)
	$P_{ave-in-B}$	Average input power of normal Class B Amplifier
20	$P_{ave-in-1}$	Average input power of Stage 1 of Class μ Amplifier

	$P_{\text{ave-loss-1}}$	Average power loss of Stage 1 of Class μ Amplifier
	$P_{\text{ave-in-2}}$	Average input power of Stage 2 of Class μ Amplifier
	$P_{\text{ave-loss-2}}$	Average power loss of Stage 2 of Class μ Amplifier
	$P_{\text{ave-in-3}}$	Average input power of Stage 3 of Class μ Amplifier
5	$P_{\text{ave-loss-3}}$	Average power loss of Stage 3 of Class μ Amplifier
	R	Impedance, assumed resistive for this case
	t	time
	t_1	Moment (or the time) that V_{cc1} is switched on
	t_2	Moment (or the time) that V_{cc2} is switched on
10	T	Period
	V_{out}	Output voltage
	V_0	Amplitude of output voltage ($= V_{\text{out}} $)
	V_{cc}	Peak output voltage, which is also the supply voltage for a normal Class B Amplifier
15	V_{cc1}	First stage output voltage to positive side of load for Class μ Amplifier
	V_{cc2}	Second stage output voltage to positive side of load for Class μ Amplifier
	V_{ref}	Reference voltage, which corresponds to the peak input voltage to give the peak output voltage at V_{cc}
20	ω	Angular frequency ($= 2\pi f$)

In the calculations below, the positive side of the load 24 refers to the side with the DC voltage switching between $-V_{cc1}$, $-V_{cc2}$, GND, $+V_{cc1}$ and $+V_{cc2}$ and the negative side of the load 24 is connected to the differential amplifier 23 with a supply voltage of $+V_{cc1}$ and $-V_{cc1}$. The load R is taken to be resistive.

- 5 The following calculations are based on sinusoidal inputs.

Output voltage,

$$V_{out} = V_0 \sin \omega t$$

Current,

$$I = \frac{V_{out}}{R}$$

Input power,

$$P_{in} = V_{cc} I = \frac{V_{cc} V_{out}}{R}$$

Output power,

$$P_{out} = V_{out} I = \frac{V_{out}^2}{R}$$

- 10 Average input power for 1 period,

$$P_{ave-in} = \frac{1}{T} \int_0^T P_{in} dt$$

Average output power for 1 period,

$$P_{ave-out} = \frac{1}{T} \int_0^T P_{out} dt$$

Efficiency,

$$\varepsilon = \frac{P_{ave-out}}{P_{ave-in}}$$

For both an amplifier of the type illustrated in Figure 2 (hereinafter referred to as a Class μ amplifier) and a conventional Class B Amplifier:

Average output power,

$$\begin{aligned}
 P_{ave-out} &= \frac{1}{T} \int_0^T \frac{V_{out}^2}{R} dt \\
 &= \frac{1}{TR} \int_0^T V_o^2 \sin^2 \omega t dt \\
 &= \frac{V_o^2}{TR} \int_0^T (1 - \cos 2\omega t) dt \\
 &= \frac{V_o^2}{2TR} \left[t - \frac{1}{2\omega} \sin 2\omega t \right]_0^T \\
 &= \frac{V_o^2}{2TR} \left[t - \frac{1}{2\omega} \sin \frac{4\pi t}{T} \right]_0^T \\
 &= \frac{V_o^2}{2R}
 \end{aligned}$$

For a conventional Class B Amplifier:

Average input power ,

(for ½ period, T/2)

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$$\begin{aligned}
 P_{ave-in-B} &= \frac{2}{T} \int_0^{\frac{T}{2}} \frac{V_{out} V_{cc}}{R} dt \\
 &= \frac{2V_{cc}}{TR} \int_0^{\frac{T}{2}} V_o \sin \frac{2\pi t}{T} dt \\
 &= \frac{2V_{cc}V_o}{TR} \left(\frac{T}{2\pi} \right) \left[-\cos \frac{2\pi t}{T} \right]_0^{\frac{T}{2}} \\
 &= -\frac{2V_{cc}V_o}{2\pi R} \left[\cos \frac{\pi}{2} - 1 \right] \\
 &= \frac{2V_{cc}V_o}{\pi R}
 \end{aligned}$$

20 Average efficiency,

$$\begin{aligned}
 \varepsilon_B &= \frac{P_{ave-out}}{P_{ave-in}} \\
 &= \frac{V_o^2}{2R} \times \frac{\pi R}{2V_{cc}V_o} \\
 &= \frac{\pi V_o}{4V_{cc}}
 \end{aligned}$$

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Average power loss,

$$\begin{aligned}
 P_{ave-loss-1} &= P_{ave-in-1} - P_{ave-out} \\
 &= \frac{2V_{cc}V_o}{\pi R} - \frac{V_o^2}{2R}
 \end{aligned}$$

For a Class μ Amplifier - Stage 1: For sinusoidal output voltage $|V_o| < |V_{cc1}|$:

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For this stage of operation, the ground potential will be supplied to the positive side of the load 24. Thus, only the differential amplifier 23 is supplying the signal to the load 24 at the negative side thereof.

5 Thus, average input power,

$$P_{ave-in-1} = \frac{2V_{cc1}V_0}{\pi R}$$

$$= \frac{2V_{cc}V_0}{3\pi R} \quad \because V_{cc1} = \frac{V_{cc}}{3}$$

Efficiency,

$$\varepsilon_1 = \frac{\pi V_0}{4V_{cc1}}$$

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$$= \frac{3\pi V_0}{4V_{cc}}$$

Comparing the above with a conventional Class B Amplifier, during this stage of operation,

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$$\begin{aligned} \frac{\varepsilon_1}{\varepsilon_B} &= \frac{3\pi V_0}{4V_{cc}} \times \frac{4V_{cc}}{\pi V_0} = 3 \\ \Rightarrow \varepsilon_1 &= 3\varepsilon_B \end{aligned}$$

Average power loss,

$$\begin{aligned} P_{ave-loss-1} &= P_{ave-in-1} - P_{ave-out} \\ &= \frac{2V_{cc}V_0}{3\pi R} - \frac{V_0^2}{2R} \end{aligned}$$

Class μ Amplifier Stage 2: For sinusoidal output voltage $|V_{cc1}| < |V_0| < |V_{cc2}|$:

For this stage, it is necessary to determine the time t_1 , when $V_{out}=V_{cc1}$, which is the
5 moment that V_{cc1} is switched on.

Output voltage, $V_{out} = V_0 \sin \omega t$

At t_1 , $V_{out}=V_{cc1}$,
$$\Rightarrow V_{cc1} = V_0 \sin \frac{2\pi}{T} t_1$$

$$\frac{2\pi}{T} t_1 = \sin^{-1} \frac{V_{cc1}}{V_0}$$

$$t_1 = \frac{T}{2\pi} \sin^{-1} \frac{V_{cc}}{3V_0} \text{-----}(1)$$

10

For positive side, total input power for $\frac{1}{4}$ period,

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$$P_{total-in-2+} = \int_{t_1}^{\frac{T}{4}} \frac{V_{cc1} V_0 \sin \omega t}{R} dt$$

$$= \frac{V_{cc1} V_0}{R} \int_{t_1}^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt$$

$$= \frac{V_{cc} V_0}{3R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_{t_1}^{\frac{T}{4}}$$

$$= \frac{V_{cc} V_0 T}{6\pi R} \cos \frac{2\pi}{T} t_1$$

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For the negative side, total input power for $\frac{1}{4}$ period,

$$\begin{aligned}
 P_{total-in-2-} &= \int_0^{\frac{T}{4}} \frac{V_{cc1} V_0 \sin \omega t}{R} dt \\
 &= \frac{V_{cc1} V_0}{R} \int_0^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt \\
 &= \frac{V_{cc} V_0}{3R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_0^{\frac{T}{4}} \\
 &= \frac{V_{cc} V_0 T}{6\pi R} \quad \text{-----(2)}
 \end{aligned}$$

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Average input power,

$$\begin{aligned}
 P_{ave-in-2} &= \frac{P_{total-in-2+} + P_{total-in-2-}}{\frac{T}{4}} \\
 &= \frac{2V_{cc} V_0}{3\pi R} \left(1 + \cos \frac{2\pi}{T} t_1 \right)
 \end{aligned}$$

10

Efficiency,

$$\begin{aligned}
 \varepsilon_2 &= \frac{V_0^2}{2R} \times \frac{3\pi R}{2V_{cc} V_0 \left(1 + \cos \frac{2\pi}{T} t_1 \right)} \\
 &= \frac{3\pi V_0}{4V_{cc} \left(1 + \cos \frac{2\pi}{T} t_1 \right)}
 \end{aligned}$$

15

Comparing the above with a conventional Class B Amplifier,

$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{3\pi V_0}{4V_{cc} \left(1 + \cos \frac{2\pi}{T} t_1 \right)} \times \frac{4V_{cc}}{\pi V_0}$$

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$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{3}{(1 + \cos \frac{2\pi}{T} t_1)}$$

Average power loss,

$$\begin{aligned} P_{ave-loss-2} &= P_{ave-in-2} - P_{ave-out} \\ &= \frac{2V_{cc}V_0}{3\pi R} (1 + \cos \frac{2\pi}{T} t_1) - \frac{V_0^2}{2R} \end{aligned}$$

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Class μ Amplifier Stage 3: For sinusoidal output voltage $|V_{cc2}| < |V_0| < |V_{cc}|$:

From Equation (1) above,

$$t_1 = \frac{T}{2\pi} \sin^{-1} \frac{V_{cc}}{3V_0}$$

At the time t_2 , when $V_{out} = V_{cc2}$,the moment that V_{cc2} is switched on, is given as follows:

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$$\begin{aligned} V_{out} &= V_0 \sin \omega t \\ \Rightarrow V_{cc2} &= V_0 \sin \frac{2\pi}{T} t_2 \\ \frac{2\pi}{T} t_2 &= \sin^{-1} \frac{V_{cc2}}{V_0} \\ t_2 &= \frac{T}{2\pi} \sin^{-1} \frac{2V_{cc}}{3V_0} \end{aligned}$$

For the positive side of the load 24, the total input power for $\frac{1}{4}$ period may be denoted as follows:

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$$\begin{aligned}
P_{total-in-3+} &= \int_{t_1}^{t_2} \frac{V_{cc1} V_0 \sin \omega t}{R} dt + \int_{t_2}^{\frac{T}{4}} \frac{V_{cc2} V_0 \sin \omega t}{R} dt \\
&= \frac{V_{cc1} V_0}{R} \int_{t_1}^{t_2} \sin \frac{2\pi}{T} t dt + \frac{V_{cc2} V_0}{R} \int_{t_2}^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt \\
&= \frac{V_{cc1} V_0}{R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_{t_1}^{t_2} + \frac{V_{cc2} V_0}{R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_{t_2}^{\frac{T}{4}} \\
&= \frac{V_0 T}{2\pi R} \left\{ V_{cc1} \left(\cos \frac{2\pi}{T} t_1 - \cos \frac{2\pi}{T} t_2 \right) + V_{cc2} \left(\cos \frac{2\pi}{T} t_2 \right) \right\}
\end{aligned}$$

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$$\begin{aligned}
\text{But } \because V_{cc2} &= 2V_{cc1}, \quad \therefore P_{total-in-3+} = \frac{V_0 T}{2\pi R} V_{cc1} \left(\cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right) \\
&= \frac{V_0 V_{cc} T}{6\pi R} \left(\cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right)
\end{aligned}$$

10

For the negative side of the load 24, from equation (2), $P_{total-in-3-} = \frac{V_{cc} V_0 T}{6\pi R}$

Average total input power,

$$\begin{aligned}
P_{ave-in-3} &= \frac{P_{total-in-3+} + P_{total-in-3-}}{\frac{T}{4}} \\
&= \frac{4}{T} \left\{ \frac{V_0 V_{cc} T}{6\pi R} \left[\left(\cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right) \right] + \frac{V_{cc} V_0 T}{6\pi R} \right\} \\
&= \frac{2V_0 V_{cc}}{3\pi R} \left(1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right)
\end{aligned}$$

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Efficiency,

$$\begin{aligned}
\varepsilon_3 &= \frac{V_0^2}{2R} \times \frac{3\pi R}{2V_{cc} V_0 \left(1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right)} \\
&= \frac{3\pi V_0}{4V_{cc} \left(1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right)}
\end{aligned}$$

Comparing the above with a conventional Class B Amplifier,

$$\frac{\varepsilon_3}{\varepsilon_B} = \frac{3\pi V_0}{4V_{cc} (1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2)} \times \frac{4V_{cc}}{\pi V_0}$$

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$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{3}{(1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2)}$$

Average power loss,

$$P_{ave-loss-3} = P_{ave-in-3} - P_{ave-out}$$

$$= \frac{2V_{cc}V_0}{3\pi R} (1 + \cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2) - \frac{V_0^2}{2R}$$

Figure 6 shows a graph of Efficiency against Normalized Output Power for the amplifier circuit of Figure 2, and, for comparison, a graph of Efficiency against Normalized Output Power for a conventional Class B amplifier. The graphs shown are for amplifiers operating at maximum output power with a sinusoidal input, without clipping, normalized to 1.

Figure 7 shows a graph of Power Loss in the amplifier of Figure 2 against Normalized Output Power and, for comparison, a graph of Power Loss in a conventional Class B amplifier against Normalized Output Power. As with Figure 6, the graphs shown are for amplifiers operating at maximum output power with a sinusoidal input, without clipping, normalized to 1.

Figure 8 shows an alternative preferred embodiment of a Class μ Amplifier according to the present invention. The same reference numerals as those used in respect of the embodiment of Figure 2 have been used to denote identical components.

The circuit shown in Figure 8 is identical to that shown in Figure 2, the difference being that V_{cc1} , which is the voltage step between inputs on the switching unit 22, is $V_{cc}/5$ in the circuit of Figure 8 and the DC voltages output to the positive terminal at node 1 of the load 24 will therefore be $-4V_{cc1}$, $-2V_{cc1}$, GND, $2V_{cc1}$ and $4V_{cc1}$ accordingly.

The resistor values in the circuit of Figure 8 are chosen as follows:

$$R_3/(R_1+R_2+R_3) = R_4/(R_4+R_5+R_6) = 1/5$$

$$(R_2+R_3)/(R_1+R_2+R_3) = (R_4+R_5)/(R_4+R_5+R_6) = 3/5$$

$$V_{cc1}=V_{cc}/5$$

$$R_8/R_7=G_V$$

$$R_{10}/(R_9+R_{10})=1/G_V$$

Figure 9 shows the waveform at the positive terminal (node 1) of the load 24 of the circuit of Figure 8.

Figure 10 shows the signal at node 3 of the negative terminal of the circuit of Figure 8.

In the embodiment of Figure 8, on the negative side of the load 24, the differential amplifier, instead of giving a half swing (as shown in Figure 5), gives a full swing as shown in Figure 10.

Figure 11 shows a graph of Efficiency against Normalized Output Power for the amplifier of Figure 8, and, for comparison, a graph of Efficiency against Normalized Output Power for a conventional Class B amplifier. The graphs shown are for the amplifiers operating at maximum output power with a sinusoidal input, without clipping normalized to 1.

Figure 12 shows a graph Power Loss in the amplifier of Figure 8 against Normalized Output Power and, for comparison, a graph of Power Loss in a conventional Class B

amplifier against Normalized Output Power. As with Figure 11, the graphs shown are for amplifiers operating at maximum output power with a sinusoidal input, without clipping normalized to 1.

Figure 13 shows a graph of Efficiency against Normalized Output Power for each of the amplifiers of Figures 2 and 8 and, for comparison, a graph of Efficiency against Normalized Output Power for a conventional Class B amplifier. The graphs shown are for amplifiers operating at maximum output power with a sinusoidal input, without clipping normalized to 1.

Figure 14 shows a graph Power Loss in the amplifiers of Figures 2 and 8 against Normalized Output Power and, for comparison, a graph of Power Loss in a conventional Class B amplifier against Normalized Output Power. As with Figure 13, the graphs shown are for the amplifiers operating at maximum output power with a sinusoidal input, without clipping normalized to 1.

Although in terms of efficiency and power loss, the performance of the embodiment of Figure 8 is not as good as that of Figure 2, an advantage of the embodiment of Figure 8 is that a differential amplifier having lower output voltage and also a lower output power may be used. If the maximum output voltage of the differential amplifier 23 is 12V, then the overall output voltage to the load 24 will be 60V.

The efficiency and power loss calculations for the embodiment of Figure 8 are described as follows.

As before, a conventional Class B amplifier with a supply voltage of V_{cc} and capable of delivering a maximum output voltage of amplitude V_{cc} is used as comparison. The symbols used have been kept the same, except for V_{cc1} , which is changed to $V_{cc}/5$.

Output voltage, $V_{out} = V_0 \sin \omega t$

Average output power, $P_{ave-out} = \frac{V_{out}^2}{2R}$

Class μ Amplifier Stage 1: For sinusoidal output voltage $|V_0| < |V_{cc1}|$:

For this stage of operation, the ground potential will be supplied to the positive side of the load 24. Thus, only the differential amplifier 23 is supplying the signal to the load 24 at the negative side thereof.

5

$$\begin{aligned} \text{Average input power, } P_{ave-in-1} &= \frac{2V_{cc1}V_0}{\pi R} \\ &= \frac{2V_{cc}V_0}{5\pi R} \quad \because V_{cc1} = \frac{V_{cc}}{5} \end{aligned}$$

$$\begin{aligned} \text{Efficiency, } \varepsilon_1 &= \frac{\pi V_0}{4V_{cc1}} \\ &= \frac{5\pi V_0}{4V_{cc}} \end{aligned}$$

10 Comparing the above with a conventional Class B Amplifier, during this stage of operation,

$$\begin{aligned} \frac{\varepsilon_1}{\varepsilon_B} &= \frac{5\pi V_0}{4V_{cc}} \times \frac{4V_{cc}}{\pi V_0} = 5 \\ \Rightarrow \varepsilon_1 &= 5\varepsilon_B \end{aligned}$$

15 Average power loss,

$$\begin{aligned} P_{ave-loss-1} &= P_{ave-in-1} - P_{ave-out} \\ &= \frac{2V_{cc}V_0}{5\pi R} - \frac{V_0^2}{2R} \end{aligned}$$

Class μ Amplifier Stage 2: For sinusoidal output voltage $|V_{cc1}| < |V_0| < |3V_{cc1}|$

For this stage, it is necessary to determine the time t_1 when $V_{out}=V_{cc1}$, which is the moment that V_{cc1} is switched on.

Output voltage, $V_{out} = V_0 \sin \omega t$

5 At t_1 , $V_{out}=V_{cc1}$,

$$\Rightarrow V_{cc1} = V_0 \sin \frac{2\pi}{T} t_1$$

$$\frac{2\pi}{T} t_1 = \sin^{-1} \frac{V_{cc1}}{V_0}$$

$$t_1 = \frac{T}{2\pi} \sin^{-1} \frac{V_{cc}}{5V_0} \quad \text{-----(3)}$$

For the positive side of the load 24, the total input power for $\frac{1}{4}$ period is:

24

$$\begin{aligned}
 P_{total-in-2+} &= \int_{t_1}^{\frac{T}{4}} \frac{2V_{cc1}V_0 \sin \omega t}{R} dt \\
 &= \frac{2V_{cc1}V_0}{R} \int_{t_1}^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt \\
 &= \frac{2V_{cc}V_0}{5R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_{t_1}^{\frac{T}{4}} \\
 &= \frac{V_{cc}V_0T}{5\pi R} \cos \frac{2\pi}{T} t_1
 \end{aligned}$$

5

For the negative side of the load 24, the total input power for $\frac{1}{4}$ period is:

$$\begin{aligned}
 P_{total-in-2-} &= \int_0^{\frac{T}{4}} \frac{V_{cc1}V_0 \sin \omega t}{R} dt \\
 &= \frac{V_{cc1}V_0}{R} \int_0^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt \\
 &= \frac{V_{cc}V_0}{5R} \frac{T}{2\pi} \left[-\cos \frac{2\pi}{T} t \right]_0^{\frac{T}{4}} \\
 &= \frac{V_{cc}V_0T}{10\pi R} \quad \text{-----(4)}
 \end{aligned}$$

10

15 Average input power,

$$\begin{aligned}
 P_{ave-in-2} &= \frac{P_{total-in-2+} + P_{total-in-2-}}{\frac{T}{4}} \\
 &= \frac{2V_{cc}V_0}{5\pi R} \left(1 + 2 \cos \frac{2\pi}{T} t_1 \right)
 \end{aligned}$$

20

Efficiency,

$$\varepsilon_2 = \frac{V_0^2}{2R} \times \frac{5\pi R}{2V_{cc}V_0(1 + 2\cos\frac{2\pi}{T}t_1)}$$

$$= \frac{5\pi V_0}{4V_{cc}(1 + 2\cos\frac{2\pi}{T}t_1)}$$

5

Comparing the above with a conventional Class B Amplifier,

$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{5\pi V_0}{4V_{cc}(1 + 2\cos\frac{2\pi}{T}t_1)} \times \frac{4V_{cc}}{\pi V_0}$$

$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{5}{(1 + 2\cos\frac{2\pi}{T}t_1)}$$

10 Average power loss,

$$P_{ave-loss-2} = P_{ave-in-2} - P_{ave-out}$$

$$= \frac{2V_{cc}V_0}{5\pi R}(1 + 2\cos\frac{2\pi}{T}t_1) - \frac{V_0^2}{2R}$$

Class μ Amplifier Stage 3: For sinusoidal output voltage $|3V_{cc1}| < |V_0| < |V_{cc}|$

From (3),

$$t_1 = \frac{T}{2\pi} \sin^{-1} \frac{V_{cc}}{5V_0}$$

The time t_2 , when $V_{out}=V_{cc2}$, the moment that $3V_{cc1}$ is switched on, is given as

15 follows.

26

$$\begin{aligned}
 V_{out} &= V_0 \sin \omega t \\
 \Rightarrow 3V_{cc1} &= V_0 \sin \frac{2\pi}{T} t_2 \\
 \frac{2\pi}{T} t_2 &= \sin^{-1} \frac{3V_{cc1}}{V_0} \\
 t_2 &= \frac{T}{2\pi} \sin^{-1} \frac{3V_{cc}}{5V_0}
 \end{aligned}$$

5

For the positive side of the load 24, the total input power for $\frac{1}{4}$ period is:

$$\begin{aligned}
 P_{total-in-3+} &= \int_{t_1}^{t_2} \frac{2V_{cc1}V_0 \sin \omega t}{R} dt + \int_{t_2}^{\frac{T}{4}} \frac{4V_{cc1}V_0 \sin \omega t}{R} dt \\
 &= \frac{2V_{cc1}V_0}{R} \int_{t_1}^{t_2} \sin \frac{2\pi}{T} t dt + \frac{4V_{cc1}V_0}{R} \int_{t_2}^{\frac{T}{4}} \sin \frac{2\pi}{T} t dt \\
 &= \frac{2V_{cc1}V_0}{R} \frac{T}{2\pi} [-\cos \frac{2\pi}{T} t]_{t_1}^{t_2} + \frac{4V_{cc1}V_0}{R} \frac{T}{2\pi} [-\cos \frac{2\pi}{T} t]_{t_2}^{\frac{T}{4}} \\
 &= \frac{V_{cc1}V_0T}{\pi R} \left\{ \cos \frac{2\pi}{T} t_1 - \cos \frac{2\pi}{T} t_2 \right\} + \frac{2V_{cc1}V_0T}{\pi R} \left(\cos \frac{2\pi}{T} t_2 \right)
 \end{aligned}$$

10

$$\text{But } \therefore V_{cc1} = \frac{V_{cc}}{5}, \quad \therefore P_{total-in-3+} = \frac{V_{cc}V_0T}{5\pi R} \left(\cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right)$$

15 For the negative side of the load 24, from equation (4),

$$P_{total-in-3-} = \frac{V_{cc}V_0T}{10\pi R}$$

Average total input power,

$$\begin{aligned}
 P_{ave-in-3} &= \frac{P_{total-in-3+} + P_{total-in-3-}}{\frac{T}{4}} \\
 &= \frac{4}{T} \left\{ \frac{V_0 V_{cc} T}{5\pi R} \left(\cos \frac{2\pi}{T} t_1 + \cos \frac{2\pi}{T} t_2 \right) + \frac{V_{cc} V_0 T}{10\pi R} \right\} \\
 &= \frac{2V_0 V_{cc}}{5\pi R} \left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right)
 \end{aligned}$$

5

Efficiency,

$$\begin{aligned}
 \varepsilon_3 &= \frac{V_0^2}{2R} \times \frac{5\pi R}{2V_{cc} V_0 \left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right)} \\
 &= \frac{5\pi V_0}{4V_{cc} \left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right)}
 \end{aligned}$$

10

Comparing the above with a conventional Class B Amplifier,

$$\frac{\varepsilon_3}{\varepsilon_B} = \frac{5\pi V_0}{4V_{cc} \left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right)} \times \frac{4V_{cc}}{\pi V_0}$$

$$\frac{\varepsilon_2}{\varepsilon_B} = \frac{5}{\left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right)}$$

Average power loss,

$$\begin{aligned}
 P_{ave-loss-3} &= P_{ave-in-3} - P_{ave-out} \\
 &= \frac{2V_{cc} V_0}{5\pi R} \left(1 + 2 \cos \frac{2\pi}{T} t_1 + 2 \cos \frac{2\pi}{T} t_2 \right) - \frac{V_0^2}{2R}
 \end{aligned}$$

15

As mentioned above, it is proposed that amplifiers embodying the present invention are to be named the Class μ Amplifier because of the resultant shape of the curve

when the graph of Efficiency against Output Power is plotted (as shown in Figure 6). From the graph of Figure 6, it will be seen that for a Class μ amplifier implementing 3 stages of operation, during a proposed typical operation at 1/8 to 1/3 of the maximum output power, an efficiency of about 62% to 75% may be achieved. This
5 is typically 1.5 times more efficient than conventional Class B amplifiers.

The difference in the actual power loss between the Class μ amplifier and the conventional Class B amplifier is evident from the graph of Power Loss against Output Power shown in Figure 7. During an operation at 1/8 to 1/3 of maximum output power, the power loss of the Class μ amplifier may be seen to be less than
10 1/3 of that of a conventional Class B Amplifier. For the whole range of output power, the maximum power loss of the Class μ Amplifier may be seen to be less than half of that of a conventional Class B Amplifier.

If more stages of operation are used for the Class μ amplifier, higher efficiencies may be achieved.

15 In summary, one or more preferred embodiments of the invention may provide an amplifier circuit that achieves considerably greater efficiency than a conventional Class B amplifier. Another advantage of one or more preferred embodiments of the invention is that errors generated in the switching circuit may be substantially eliminated as the differential amplifier will apply the errors to the opposite side of the
20 load 24, thereby canceling them out.

Claims:

1. Amplifier apparatus comprising:

an amplifier;

a comparator connectable to the amplifier to compare an incoming signal with a number of reference potentials, the comparator having an output;

a switching stage controllable by the output of the comparator to select a voltage level to be applied to one side of a load; and

a subtractor for subtracting from the incoming signal a percentage of the selected voltage level to be applied to the load to provide an output signal of the subtractor;

the amplifier being arranged to receive the output signal of the subtractor and to amplify the output signal to be applied to a second side of the load.

2. Amplifier apparatus according to claim 1, wherein the amplifier comprises a differential amplifier.

3. Amplifier apparatus according to claim 1 or claim 2, wherein the amplifier includes the subtractor.

4. Amplifier apparatus according to any one of the preceding claims, wherein the amplifier is a linear amplifier.

5. Amplifier apparatus according to any one of the preceding claims, wherein the amplifier has a gain associated therewith, and wherein the percentage of the selected voltage subtracted by the subtractor is inversely proportional to the gain of the amplifier.

6. Amplifier apparatus according to any one of the preceding claims, wherein the input signal varies between a first potential and a second potential, the reference

potentials being obtainable from one or more supplies having a range of or between the first and second potentials of the input signal.

7. Amplifier apparatus according to any one of the preceding claims, wherein the load comprises a loudspeaker system.

8. An audio system comprising amplifier apparatus according to any one of the preceding claims.

9. A method for amplifying a signal in an amplifier apparatus, the method comprising the steps of:

comparing, in a comparator, an incoming signal with a number of reference potentials, the comparator having an output;

selecting, in a switching stage, a voltage level to be applied to one side of a load, the switching stage being controllable by the output of the comparator;

subtracting from the incoming signal a percentage of the selected voltage level to be applied to the load to provide an output signal of a subtractor;

receiving, in an amplifier, the output signal of the subtractor;

amplifying the output signal of the subtractor; and

applying the amplified signal to a second side of the load.

10. A method according to claim 9, wherein the step of amplifying the signal comprises amplifying the signal using a differential amplifier.

11. A method according to claim 9, wherein the step of amplifying the signal comprises amplifying the signal using a linear amplifier.

12. A method according to any one of claims 9 to 11, wherein the amplifier has a gain associated therewith, and wherein the step of subtracting the percentage of the

selected voltage comprises subtracting a percentage which is inversely proportional to the gain of the amplifier.

13. A method according to any one of claims 9 to 12, wherein the input signal varies between a first potential and a second potential, the method further comprising obtaining the reference potentials from one or more supplies having a range of or between the first and second potentials of the input signal.