

TITLE OF THE INVENTION

LOW DISSIPATION AMPLIFIER

RELATED APPLICATION INFORMATION

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/155,382 (Attorney Docket 157835-0041) filed on February 25, 2009, hereby incorporated by reference as if set forth fully herein.

BACKGROUND OF THE INVENTION

1) Field of the Invention

[0002] The field of the invention generally relates to amplifiers and, more specifically, to an improved method to minimize distortion and power dissipation in a compact amplifier.

2) Background

[0003] Amplifiers are used for many applications including audio signal processing, video processing, communications, control systems, satellites, and so on. Based on its power consumption characteristics, an amplifier may be categorized into one or more categories including Class A, B, AB, D, G or H. A general background of different amplifier classifications may be found, for example,

in R. Bortoni, et al., "Analysis, Design and Assessment of Class A, B, AB, G and H Audio Power Amplifier Output Stages Based on MATLAB® Software," 110th Convention of Audio Engineering Society (AES), May 12-15, 2001, pp. 1-14, and in "Audio Power Amplification," J. Audio Eng. Soc., Vol. 54, No. 4, April 2006, pp. 319-323, both of which publications are hereby incorporated as if set forth fully herein.

[0004] A Class A amplifier is known to require a relatively large amount of standing power and is inefficient, and thus undesirable in many applications that require low power dissipation. A Class B amplifier can have very low standing power dissipation but introduces distortion. A Class AB amplifier is somewhere between the two, and uses bias currents to reduce the distortion inherent in a Class B amplifier. A Class AB amplifier has a higher power dissipation than a Class B amplifier due to the bias currents.

[0005] As equipment gets smaller, amplifiers become an increasing limitation on the ability to reduce packaging size. The inevitable limited efficiency of an amplifier leads to power dissipation that must be dissipated by a heatsink in order to prevent the amplifier getting too hot; however, a large heatsink can take up an inordinate amount of packaging space. Techniques exist to improve the efficiency over that of a standard Class AB amplifier design, and hence reduce heatsink requirements, but these approaches often lead to compromises in the bandwidth, noise or distortion performance of the amplifier.

[0006] There are at least two aspects to the power dissipation of an amplifier system. The first is commonly known as idle or standing dissipation – that is, power dissipated when the amplifier is delivering no power to the load. With a conventional linear amplifier, this standing dissipation, which includes the bias current applied to

the amplifier, is primarily concentrated in the driver and output stage of the amplifier and is generally required in conventional amplifier designs to minimize crossover distortion. In a high performance audio power amplifier of a nominal 100 Watt sine wave power capability into an 8Ω load, for example, the idle current may be of the order of 100-200 milli-amps per channel. With a quiescent power supply voltage of typically ± 45 Volts, this idle current results in roughly 9-18 Watts of idle power dissipation per channel. This can be a significant problem for a stereo amplifier, but for a multi-channel amplifier it is an even larger problem, as the idle dissipation quickly becomes excessive as the number of amplifiers is increased.

[0007] For home audio amplifiers, large heatsinks can often be used to dissipate the power and keep the temperature of the power devices down, but for size-constrained applications such as automotive entertainment systems, the size and weight of the heatsink cannot be tolerated.

[0008] The idle current for an amplification system must generally be set at the time of production for optimum distortion performance and thus increases production costs. The idle current requirements can also change with temperature and age. Therefore, over time or after prolonged use, the quality of the amplifier output may deteriorate.

[0009] To add to the idle power dissipation problem, an amplifier produces extra dissipation, sometimes referred to as dynamic dissipation, when it is delivering a signal to the load. In practice, a nominal 100 Watt capability linear power amplifier may well dissipate 40 Watt worst case when delivering sine wave signals to a load. With music as the audio source for the amplifier, this figure is lower since music has a higher crest factor than sine waves, but may still approach 30 Watts per channel.

[0010] Various techniques have been employed to reduce both the idle power dissipation and the dynamic power dissipation of linear amplifiers. One technique that can be employed to reduce idle power dissipation is to decrease the output stage bias current. However, this causes crossover distortion to increase which is difficult to eradicate with conventional negative feedback around the amplifier. Also, this technique has little effect on the dynamic power dissipation.

[0011] Another approach that can reduce both idle and dynamic dissipation is to use a 'Class G' amplifier configuration. This 'Class G' nomenclature is commonly attributed to Hitachi (see "Highest Efficiency and Super Quality Audio Amplifier Using MOS Power FETs in Class G Operation," IEEE Transactions on Consumer Electronics, Vol. CE-24, No. 3, August 1978), although the basic technique appears to have been described previously (see, e.g., U.S. Patent No. 3,622,899). A 'Class G' amplifier arrangement maintains a lower voltage across the output devices under idle conditions whilst also reducing dynamic power dissipation by ensuring that the voltage across the power devices is also reduced when driving signals to the load. Thus both the idle and dynamic power dissipation is reduced. However, the switching of the output devices between the power rails often causes glitches in the output waveform that appear as distortion. These glitches have significant high frequency energy and so are difficult to correct by negative feedback. Careful design can reduce this effect but cannot eliminate it and tends to increase high frequency dynamic power dissipation.

[0012] An alternative way of reducing amplifier dissipation is to implement a switching amplifier, and specifically a so-called 'Class D' architecture. With this design, the linear amplifier is replaced by power switches operating at typically

several hundred kilohertz for a high performance audio amplifier. The nominal efficiency of this design into a resistive load can theoretically be very high, although in practice switching losses and output filter losses significantly reduce the actual efficiency. The high switching frequency can cause significant EMI problems which then require bulky inductors to prevent coupling to power supply and output lines, as well as careful screening to avoid radiation. These additions mean that although the basic amplifier components can be small and low cost, the overall size is significantly larger and more costly due to the need for the inductive and filter components. Furthermore, the continual switching causes a significant idle current due to the dynamic switching losses and the pulse width modulation (PWM) process used to generate the switching signal leads to a poor distortion performance compared to a linear amplifier.

[0013] An example of a Class D amplifier is the model TDF8590TH amplifier available from NXP Semiconductors, a company headquartered in the Netherlands. When this amplifier is configured to provide a nominal 100 Watt sine wave power to an 8Ω load, the idle dissipation is in excess of 4 Watts/channel. The total harmonic distortion (THD) is above 0.1% at 10kHz at all levels above 10 Watts output and rises dramatically at higher output levels—and even these figures are an underestimate of the actual distortion due to the use of an AES17 filter to remove the effect of the residual switching frequency components on the measuring equipment. The intermodulation distortion (IMD) performance is much worse than a well-designed linear amplifier. The output inductors also generally must be large, in order that they do not saturate or introduce further distortion, and typically measure 4 to 5 cubic centimeters, which is a barrier to overall circuit and package miniaturization.

[0014] There remains a need therefore for an amplifier topology that can be readily miniaturized while providing low power dissipation. There further is a need for an amplifier that is capable of providing low idle and dynamic power dissipation levels, requires no bias setting, and no inductors for EMI or filtering. There further is a need for an amplifier that delivers very low distortion levels.

SUMMARY OF THE INVENTION

[0015] According to one or more embodiments, a power amplifier system and method is provided that may include one or more of the following features: a distortion reducing topology; a Class AB driver stage; a current protection mechanism; distortion reduction, especially when configured as a Class G or Class H amplifier; and a nested distortion reduction architecture.

[0016] According to an aspect of one or more embodiments, a low power, low distortion amplifier comprises a first amplifier configured as or including a driver stage, and a second amplifier configured as or including a main output stage, with a plurality of impedance networks providing feedback paths from outputs of said first amplifier and said second amplifier to an input of said first amplifier, a first coupling path from the output of said second amplifier to a load, and a second coupling path from the output of said first amplifier to the load. The impedance networks may be resistors, capacitors, or network combinations thereof. An additional feedback path may be provided from the load to the input of the first amplifier. One or more intermediate amplifier stage(s) may also be disposed between the first amplifier and the second amplifier.

[0017] According to another aspect of one or more embodiments, a method for amplifying an input source signal comprises the steps of receiving the input source signal at a first amplifier and generating a driver signal thereby; providing the driver signal to the input of a second amplifier acting as a main output stage; operating the first amplifier in a Class AB or low power dissipation mode; operating the second amplifier in a Class B, Class G, Class H and/or low power dissipation mode; and providing selective coupling or feedback connections from the outputs of said first and second amplifiers to the inputs of said first and second amplifiers and to a load to maintain operation of said first and second amplifiers in their respective modes.

[0018] According to yet another aspect of one or more embodiments as disclosed herein, a low power, low distortion amplifier includes a plurality of cascaded stages with a driver stage biased to operate in Class AB mode, a main output stage operating in a low power dissipation mode, and a plurality of impedance networks providing feedback paths or couplings between the outputs and inputs of the cascaded stages or the load so that the amplifier provides low distortion and maintains a substantially constant frequency response over a wide range of frequencies. The low power amplifier may be configured to have very low standing and dynamic power dissipation.

[0019] According to certain embodiments or variations, the first amplifier may operate in Class G or Class H mode.

[0020] Further embodiments, alternatives and variations are also described herein or illustrated in the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] FIG. 1 is a generic schematic diagram of a conventional linear amplifier as known in the prior art.

[0022] FIG. 2 is a schematic diagram of an amplifier showing, among other things, an arrangement of impedance networks in accordance with one embodiment as disclosed herein.

[0023] FIG. 3 is a schematic diagram of another embodiment of an amplifier similar to that of FIG. 2, but having an additional feedback loop.

[0024] FIG. 4 is a graph showing an example of distortion performance that can be achieved by an amplifier built according to the principles disclosed herein, under certain load parameters.

[0025] FIG. 5 is a block diagram of another amplifier design using an amplifier cascading technique.

[0026] FIG. 6 is a block diagram illustrating another example of an amplifier design in accordance with various embodiments as disclosed herein.

[0027] FIG. 7a is a schematic diagram of a current limiting circuit as known in the prior art, while 7b is a schematic diagram of an alternative current limiting circuit as may be used in connection with various embodiments as disclosed herein.

[0028] FIGS. 8a and 8b are diagrams comparing the frequency responses of different amplifier designs.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0029] According to one or more embodiments, a low power amplifier is provided having at least a first amplifier configured as or including a driver stage and

a second amplifier configured as or including a main output stage, biased into operating modes in which they draw very little idle power, yet also consume very little dynamic power when active. A plurality of impedance networks provide, among other things, feedback paths from the outputs of the first amplifier and the second amplifier to the first amplifier, enabling in part the ability of the low amplifier to combat distortion. The impedance networks may also provide a coupling path from the output of the second amplifier including the main output stage to the load, and another coupling path from the output of the first amplifier including the driver stage amplifier to the load. The impedance networks are preferably resistors, capacitors, or network combinations thereof.

[0030] An additional feedback path may also be provided from the load to the input of the first amplifier. The additional feedback path may include a low pass filter and more specifically a T-network of two resistors and a capacitor, and may help flatten out the frequency response of the amplifier at low frequencies. An intermediate amplifier stage may also be added between the driver stage amplifier and the main output stage to provide additional versatility and distortion reduction.

[0031] The first and second amplifiers are both preferably operated in low power dissipation modes, although in some embodiments where power dissipation is not as critical, one or both of the amplifiers can be operated in a higher power dissipation mode in order to, e.g., simplify the design, further reduce distortion (if necessary), or for other reasons. As used herein a low power dissipation mode or low dissipation mode generally includes those operating modes in which standing or idle current dissipation is kept low, and thus would generally include Class B, G and H modes, and potentially Class AB mode in certain configurations.

[0032] As one example, the first amplifier including the driver amplifier stage may be operated in a Class AB mode, while the second amplifier including the main output stage may be operated in a Class B and/or Class G or H mode. Thus, the overall power draw of the amplifier may be kept very low. The second amplifier may alternatively be operated in Class AB mode at the expense of increased power dissipation, which may lower distortion even further. As another example, both the first and second amplifiers can be operated in Class G mode, or both operated in Class H mode, or one in Class G mode and the other in Class H mode. The novel amplifier designs disclosed and taught herein therefore provide a great deal of flexibility and versatility in terms of operating mode selection and overall design configuration. The amplifier design can be tailored for specific purposes including extremely low power dissipation, very low distortion, compact structure, etc., or combinations thereof.

[0033] Figure 1 is a generic schematic diagram of an example of a conventional linear amplifier 100 as known in the prior art. As shown in Figure 1, the linear amplifier 100 includes an input stage 110, a driver stage 120, and an output stage 150 that may include, for example, a pair of transistors 131 and 132 (also labeled as Q1 and Q2 in Figure 1) coupled to positive and negative voltage rails 130, 135 (also labeled as +V and -V in Figure 1). The input stage 110, driver stage 120, and output stage 150 are connected in a serial arrangement. The input stage 110 receives an input signal 106 from an input signal source 105. The output stage transistors Q1, Q2 are normally biased by a voltage source 128 (also labeled V_b) into either Class B or Class AB operation. While shown in Figure 1 as single transistors, the output stage transistors Q1 and Q2 may be embodied as different types of circuit such as

single transistors, compound transistor arrangements or FETs. The output stage 150 provides an amplified output signal 140 to a load 145 (represented as an impedance in Figure 1).

[0034] Also in Figure 1, a feedback capacitor 124 (also labeled as Z2 in Figure 1) applies local feedback around the driver stage 120 whilst ensuring stability by introducing a 6dB/octave roll-off to the open loop frequency response of the amplifier 100. Driver stage 120 is typically biased into Class A operation. Input stage 110 is typically implemented as a transconductance stage. Additional resistors 115 and 112 (also labeled as R4 and Rg in Figure 1) provide overall negative feedback around the complete amplifier.

[0035] As mentioned earlier, an amplifier of this generic type generally suffers from poor idle and dynamic dissipation performance when biased into Class AB operation, and poor distortion performance when biased into Class B operation. Dissipation can be reduced by operating in Class G mode, but then more distortion mechanisms are introduced which are difficult to address by means of conventional negative feedback.

[0036] According to one or more embodiments disclosed herein, and as explained for example in connection with Figure 2, distortion is significantly reduced over the conventional linear amplifier of Figure 1 by providing a signal path from the gain/driver stage X1 to the output by means of an impedance network Z3 whilst also introducing another impedance network Z1. Figure 2 is a schematic diagram of a novel amplifier design in accordance with one embodiment as disclosed herein, illustrating a useful arrangement of impedance networks and other amplifier circuitry by way of one example. In Figure 2, an amplifier 200 includes, among other things,

a gain/driver stage 210 (also labeled as X1 in Figure 2) and an output stage 250 that may include, for example, a pair of transistors 231 and 232 (also labeled as Q1 and Q2 in Figure 2) coupled, similar to Figure 1, to positive and negative voltage rails +V and -V (not shown in Figure 2). The gain/driver stage 210 receives an input signal 206 from an input signal source 205. While shown in Figure 2 as single transistors, as with Figure 1 and all other embodiments that will be described herein, the output stage transistors Q1 and Q2 may be embodied as different types of circuit such as single transistors, compound transistor arrangements or FETs. The output stage 250 provides an amplified output signal 240 to a load 245 (represented as an impedance in Figure 2).

[0037] More generally, the gain/stage 210, while conceptually shown as a single amplifier in Figure 2, may be constructed from multiple amplifier stages or may be included as part of a larger amplifier block. Likewise, the output stage 250, while shown as primarily consisting of transistors Q1 and Q2, may be included as part of a larger amplifier block which may contain one or more stages, and would also be understood to include bias components, protection elements, and other conventional features that are not shown in detail in Figure 2 for the sake of simplicity. Those skilled in the art will appreciate that there are many different ways to implement the gain/driver stage 210 and output stage 250 of amplifier 200.

[0038] As noted above, an impedance network 290 (also labeled as Z3 in Figure 2) is provided between the output of the gain/driver stage 210 and the load 245. Another impedance network 280 (also labeled as Z1 in Figure 2) is provided between the output stage 250 and the load 240. Another impedance network 270 (also labeled as Z2 in Figure 2) is provided from the output of the gain/driver stage

210 to one of the differential inputs of the gain/driver stage 210. A fourth impedance network 260 (also labeled as Z4 in Figure 2) is provided from the output stage 250 to the same differential input of the gain/driver stage 210. Impedance networks 260 and 270 are coupled to ground (or some other reference potential) by another impedance network 212 (also labeled as Zg in Figure 2).

[0039] In the example of Figure 2, impedance network 290 is embodied as a capacitor 291 and resistor 292 connected in parallel. Impedance network 280 is embodied as a resistor 281. Impedance network 270 is also embodied as a resistor 271. Impedance network 260 is embodied as a resistor 262 and capacitor 261 connected in series.

[0040] Choosing the values of the impedance networks Z1, Z2, Z3, Z4 such that they satisfy the relationship $Z1(s) \cdot Z2(s) = Z3(s) \cdot Z4(s)$, the distortion on the amplifier 200 can be significantly reduced compared to a standard feedback amplifier of the type shown in Figure 1. As noted above, in this example impedance network Z1 is preferably embodied as a resistor, impedance network Z2 is preferably embodied as a capacitor, impedance network Z3 is preferably embodied as a parallel combination of resistor and capacitor, and impedance network Z4 is preferably embodied as a series combination of resistor and capacitor, although other equivalent impedance networks may be used. The time constant of the impedance network Z3 preferably matches that of impedance network Z4. At low frequencies, below the frequency at which the impedance of Z3 become capacitive, impedance network Z3 appears resistive in nature and impedance network Z4 appears to be capacitive. The presence of impedance network Z3 softens the crossover knee of the output stage

250 by virtue of the driver stage to load output connection through impedance network Z3.

[0041] In order to gain maximum distortion reduction, impedance network Z4 is preferably capacitive in nature so that the ratio of impedances of Z2:Z4 equals Z3:Z1. However, this means that the open loop gain of the feedback loop around the output stage 250 no longer falls off with frequency. Incorporating a series resistor within Z4 reinstates the fall in gain with frequency above the breakpoint at which Z4 stops appearing capacitive and becomes resistive in nature. The resistor 262 in impedance network Z4 is chosen to set a unity loop gain frequency that ensures stability.

[0042] To retain full distortion reduction, impedance network Z3 should be made to appear capacitive in nature at high frequencies; hence the matching of the time constants of impedance networks Z3 and Z4. There is generally a free choice of time constant for the components of impedance networks Z3 and Z4. However, the larger the time constant, the larger the capacitor has to be in impedance network Z3, and the greater the current that will be drawn from the gain/driver stage 210 (i.e., X1) at high frequencies. To minimize size of the amplifier 200, the time constant for impedance networks Z3 and Z4 should be kept low.

[0043] The balancing of the impedance networks will work even in the presence of parasitic elements in the impedance networks. For instance, a parasitic inductance in series with resistor 281 can be balanced by placing a suitable value resistor in series with capacitor 291. As reflected by the example of Figure 2, all of the components of impedance networks Z1 – Z4 can be realized as resistors, capacitors or combinations thereof (excluding parasitic elements). This design

approach can lead to a very compact amplifier package. The term “resistor” in this context includes any resistive element that displays a substantially constant impedance relationship over the applicable operating frequency range, and will typically, but not necessarily, involve a conventional discrete resistor component.

[0044] By itself, the choice and arrangement of impedance networks in Figure 2 works adequately but can be improved. For example, the incorporation of the series capacitor 262 within impedance network Z4 means that below the break frequency formed by its series resistor/ capacitor combination of elements 261 and 262, the closed loop gain of the complete amplifier 200 increases at 6dB/octave as frequency decreases. Additionally, the open loop gain around transistors Q1, Q2 due to the arrangement of impedance networks Z2 and Z4 and gain/driver stage 210 becomes constant at low frequencies rather than rising at 6dB/octave with decreasing frequency as with a conventional feedback amplifier. Thus, the distortion reduction around transistors Q1 and Q2 by means of negative feedback will be lowered as compared to a conventional amplifier with this choice of impedance networks. Additional distortion reduction will still be achieved by virtue of the incorporation of impedance network Z3 into the amplifier 20, but there is still room for improvement, as will be explained in more detail below. Also, the output resistance of the amplifier 200 is approximately equal to the parallel combination of the impedance networks Z1 and Z3. In the case where the first impedance network Z1 is embodied as a resistor, the output resistance of the amplifier 200 at low frequencies is generally higher than would be the case for a purely conventional feedback amplifier such as illustrated in Figure 1.

[0045] Figure 3 illustrates how further improvements can be made to distortion performance and closed loop response in the foundational amplifier design of Figure 2. In Figure 3, elements labeled 3xx generally correspond to the similar elements labeled 2xx in Figure 2. In Figure 3, an amplifier 300 receives an input signal 306 from an input signal source 305. Similar to the amplifier 200 of Figure 2, the amplifier 300 of Figure 3 includes a gain/driver stage 310, an output stage 350 comprising transistors 331 and 332 (also labeled as Q1 and Q2), and impedance networks 360, 370, 380 and 390 (also respectively labeled as Z4, Z2, Z1 and Z3 in Figure 3). A network 356 comprising resistors 352, 353 (also labeled as R5, R6 in Figure 3) and a capacitor 354 (also labeled as C7 in Figure 3) has been added to the amplifier 300 to form an additional feedback loop. The feedback is taken from the final output 340 of the amplifier 300 rather than the output stage 350 directly although it is then fed into the same feedback input terminal of gain/driver stage 310 as the existing feedback loop that is based upon impedance networks Z2 and Z4. Notwithstanding this, this connection of the extra feedback loop does not upset the conditions required for maximum distortion reduction.

[0046] Simply adding another resistive feedback path to the amplifier arrangement of Figure 2 would generally result in a non-flat frequency response because extra feedback loop is placed around the closed loop system of Figure 2, and the closed loop gain is not large enough to ensure that the final closed loop response of the amplifier is independent of the value of the Figure 2 closed loop gain. However, by designing the extra feedback network 356 to have a low pass filter response with a cut-off frequency that matches the breakpoint frequency of impedance networks Z3 and Z4 and with an appropriate gain, then the overall

amplifier 300 can be designed to have a flat response. Thus the rising low frequency response of the amplifier system of Figure 2 is perfectly compensated by the design additions of Figure 3.

[0047] The extra feedback loop of Figure 3 provided by the addition of feedback network 356 also additionally reduces distortion at low frequencies, compensating for the compromised low frequency distortion performance of the Figure 2 amplifier implementation. Furthermore, this extra feedback loop also reduces the output impedance of the amplifier at low frequencies since the feedback is taken from directly across the load 345 and hence impedance network Z1 is within this feedback loop.

[0048] Having the extra overall frequency dependent feedback loop to lower the output impedance of the amplifier 300 allows the bridge impedance network Z1 to have a higher impedance than would otherwise be possible, within the constraints of power losses within the resistor 381 of the impedance network Z1; thus, the impedance of element Z3 can be similarly increased to lower the value of the parallel capacitance and with it the high frequency current that must be sourced from the gain/driver stage 310.

[0049] The available choices of capacitor and resistor values for impedance networks Z1-Z4 means that balancing at high frequency ranges can be more accurately attained, since capacitors and resistors of the values used for the amplifier design of Figure 3 can be readily obtained with close manufacturing tolerances. The voltage that appears across the capacitor 391 within impedance network Z3 is quite small (it is only the gain/error loss in the output stage plus the product of the output current times the impedance of Z1) and so its package size,

given the low voltage requirements of the capacitor 391, is also commensurately small, allowing for miniaturization of the amplifier 300. Multiple amplifiers using the design shown in Figure 3 can be placed in close proximity with little interaction between the impedance networks, because the lack of balancing inductors means that there is less possibility of magnetic coupling among the amplifiers.

[0050] The use of the additional impedance networks Z1, Z3 and Z4 and the extra feedback loop provided by the addition of feedback network 356 allows the high frequency distortion of the amplifier 300 to be significantly lower than a conventional feedback amplifier and so the output stage 350 could potentially be operated, for example, in Class B mode whilst still avoiding crossover distortion. Thus, idle power dissipation that normally occurs due to the quiescent current required to bias a conventional amplifier output stage into Class AB mode is eliminated by the design of Figure 3. This might be of limited use if the gain/driver stage 310 of amplifier 300 were required to have a high idle current drain. However, the gain/driver stage 310 in this example operates at much lower power than the main output stage 350 based around transistors Q1 and Q2, and so the gain/driver stage 310 can be configured with a Class AB output stage 350 having linear, fast output devices (transistors Q1 and Q2) and so still operate with low distortion compared to the main output stage 350. Thus the dissipation in the gain/driver stage 310 can also be very low.

[0051] By incorporating a low power Class AB output stage internally within the gain/driver stage 310, the distortion introduced into the error signal by the Class AB operation of the gain/driver stage 310 can be made exceedingly small. Typically, for an audio power amplifier according to the design shown in Figure 3 capable of

delivering 100 Watts nominal output power into a 16 ohm load, the gain/driver stage 310 can be configured to operate for instance with only 1-2 milliamps of quiescent current, which is quite low.

[0052] Given the significant reduction in high frequency distortion of the output stage 350, the dynamic power dissipation of the amplifier 300 can also be reduced by employing a Class G or Class H architecture. Unlike with a conventional feedback amplifier, the high frequency distortion components introduced by the Class G rail switching transitions or Class H tracking scheme will be reduced by using the amplifier feedback configurations of some of the embodiments disclosed herein so that a very low distortion, very low idle power dissipation, low dynamic power dissipation amplifier can be realized. One example of a tracking power supply that can be used in conjunction with the amplifier designs disclosed herein to provide additional power savings is described in co-pending U.S. Patent Application Ser. No. 12/253,047 filed on October 16, 2008, assigned to the assignee of the present invention, and hereby incorporated by reference as if set forth fully herein. The use of a Class G or H architecture for the first amplifier containing the gain/input stage may have the potential to introduce non-linearities into the system, which could need to be controlled or otherwise taken account of.

[0053] Where a Class G or H architecture is applied to both the first and second amplifiers, different power rails (with different voltage levels) may be provided to the first amplifier and the second amplifier to, e.g., help isolation, reduce non-linearities, and minimize power dissipation.

[0054] Figure 4 shows an example of the distortion performance that can be achieved by an amplifier built according to the principles outlined above, when

capable of driving a 56 Volt peak signal into a 16 ohm load using an amplifier design constructed according to Figure 3. As shown in Figure 4, the total harmonic distortion is quite low at relatively low frequencies (generally ranging from about 0.0003 to 0.0010 percent distortion level at 1 kHz), and remains low even at higher frequencies (generally ranging from about 0.0020 to 0.0050 percent distortion level at 10 kHz).

[0055] Figures 8a and 8b are idealized frequency response graphs showing the effect of the additional feedback loop 356 in the embodiment of Figure 3. Figure 8a shows that at relatively low frequencies, the overall amplifier gain drops off, then flattens out at a shelf region, and then later drops off again with increasing frequency. By using the additional feedback loop of Figure 3, this frequency response can be altered as shown in Figure 8b. The low frequency response is perfectly compensated by the outer feedback loop, resulting in a flat frequency response out to relatively high frequencies. The outer frequency loop can also be used for additional purposes, such as to extend the operating range of the amplifier through the introduction of an additional zero and pole at high frequencies.

[0056] Further modifications or enhancements can also be made to the amplifier architectures described above. For example, although the distortion of the Class AB gain/driver stage 310 can be made to be low compared to that of the output stage 350, it will still generate some residual distortion. To overcome this, the Class AB gain/driver stage 310 can itself employ the same distortion reduction technique as used around the output stage 250 as previously outlined in connection with Figure 2.

[0057] This "cascaded" approach is illustrated in the amplifier design shown in Figure 5. Elements in Figure 5 labeled "5xx" generally correspond to the similar

elements labeled "3xx" in Figure 3. In Figure 5, an amplifier 500 receives an input signal 506 from an input signal source 505. Similar to the design of Figure 3, the amplifier 500 includes a gain/driver stage 510, an output stage 550 comprising transistors 531 and 532 (also labeled as Q1 and Q2), and impedance networks 560, 570, 580 and 590 (also respectively labeled as Z4, Z2, Z1 and Z3 in Figure 5). An additional feedback network 556 comprising resistors 552, 553 (also labeled as R5, R6 in Figure 5) and a capacitor 554 (also labeled as C7 in Figure 5) is included in the amplifier 500, having the same general purpose as in Figure 3, with feedback being taken from the final output 540 of the amplifier 500 and fed into the feedback input terminal of gain/driver stage 350. Also added in Figure 5 is an intermediate stage 542, which in one aspect may act as a second or supplemental driver stage, comprising transistors 543 and 544 (also labeled as Q3 and Q4) and voltage bias components 546 and 547. The transistors 543 and 544 are coupled to the positive voltage rail +V and negative voltage rail -V respectively, and may be biased into Class AB operating mode by bias components 546 and 547.

[0058] The output of the intermediate stage 542 is coupled to the input of the output stage 550 via a resistor 529 (also labeled as Z1i in Figure 5). An additional resistor 528 (also labeled as Z3i) is connected from the input of the output stage 550 to the input of the intermediate stage 542. The feedback taken from impedance network 590 (Z3) thus passes through resistor 528 for purposes of intermediate stage 542, although it is still applied directly to the input of the output stage 550. An additional capacitor 548 (also labeled Z2i in Figure 5) is provided from the output of the gain/driver stage 510 to the feedback input terminal thereof. The feedback derived from impedance network 570 (Z2) is taken from the output of the

intermediate stage 542 instead of the output of the gain/driver stage 510. The additional elements 529, 548 and 528 (Z1i, Z2i and Z3i) form part of an inner feedback loop, while impedance network 570 (Z2) shares its operation between the inner and outer feedback loops.

[0059] Both the gain/driver stage 510 and the intermediate stage 542 provide some aspect of feed-forward operation, in that both provide current to the load when the main output stage 550 is relatively idle, and hence both may be viewed as having a driver function to some degree. Both stages may also supply gain. In this respect, the designation of particular stages as “gain” or “driver” stages is not intended to be limiting.

[0060] In the example shown in Figure 5, the inner loop components 529, 548 and 528 (Z1i, Z2i and Z3i) have been chosen, along with impedance network 570 (Z2), such that the inner loop realizes the distortion reduction condition described for the Figure 3 amplifier design, with the Class AB stage (i.e., the internal output stage of gain/driver stage 510, in certain embodiments) retaining an integrator type response in respect of the action seen by the outer loop. A resistor 572 (R2) has been added to impedance network 570 (Z2) to help ensure stability of the inner feedback loop around transistors Q3 and Q4, while another resistor 592 (R3i) has been added to impedance network 590 (Z3) to compensate the outer feedback loop for the zero introduced into the integrator response by resistor 572. This arrangement makes it possible for the other outer loop components of impedance networks Z1 - Z4 to remain the same as the example illustrated in Figure 3. The retention of the high frequency roll-off of the improved driver stage comprising gain/driver stage 510 and intermediate stage 542 allows stability of the feedback

loop around the output stage 550, and the final overall feedback loop still allows for low output impedance of the amplifier 500 at audio frequencies.

[0061] Other arrangements of the inner loop impedance networks are also possible. For example, if an extra gain stage is introduced before gain/driver stage 510, then capacitor 571 (C2) in impedance network 570 (Z2) could be dispensed with and resistor 528 (Z3i) replaced with a capacitor. The gain of this inner loop would then be flat with frequency, so the extra gain stage could be given an integrator response and the outer bridge and loop components Z4, R5, R6, C7, Zg could be connected to the input of the additional integrator gain stage.

[0062] Such an arrangement is detailed in Figure 6. Elements in Figure 6 labeled "6xx" generally correspond to the similar elements labeled "5xx" in Figure 5. In Figure 6, an amplifier 600 receives an input signal 606 from an input signal source 605. Similar to Figure 5, the amplifier 600 includes a gain/driver stage 610B, an intermediate stage 642 comprising transistors 643 and 644 (also labeled as Q3 and Q4) and voltage bias components 646 and 647, and an output stage 650 comprising transistors 631 and 632 (also labeled as Q1 and Q2), along with impedance networks 660, 670, 680 and 690 (also respectively labeled as Z4, Z2, Z1 and Z3 in Figure 6). An additional gain stage 610A (also labeled X2 in Figure 6) has been added before the gain/driver stage 610B. The amplifier 600 further includes an outer feedback network 656 comprising resistors 652, 653 (labeled as R5, R6) and capacitor 654 (labeled as C7), having a similar purpose as in Figures 3 and 5, with feedback being taken from the final output 640 of the amplifier 600 and fed into a feedback input terminal of gain stage 610A. In this case, the impedance network 670 (Z2) is positioned between the output of the gain stage 610A and the feedback

input terminal of gain stage 610A. Similarly, the impedance network 660 (Z4) is positioned between the output of the driver stage 650 and the feedback input terminal of gain stage 610A.

[0063] The feedback from the output of gain/driver stage 610B continues to run through capacitor 648 (Z2i) into the feedback input terminal of the gain/driver stage 610B. A feedback connection is also made from the output of the intermediate stage 642 to the feedback input terminal of the gain/driver stage 610B. In this case, the feedback element is a resistor 619 (also labeled as R2), and another resistor 618 (also labeled Rgi) has been added coupling the feedback input terminal of the gain/driver stage 610B to ground (or some other reference potential). Capacitor 628 and resistor 629 (also labeled as Z3i and Z1i respectively) perform similar functions to their counterparts in Figure 5, both of them forming part of the inner feedback loop.

[0064] In the design of Figure 6, the added gain stage 610A is configured with an integrator response (using the capacitor 671 of impedance network Z2), and the outer bridge and loop components Z4, R5, R6, C7, Zg are connected to the feedback input of the added gain stage 610A instead of the gain/driver stage 610B. The gain of the inner feedback loop including resistors 618 and 619 (Rgi and R2) is flat with frequency.

[0065] As with Figure 5, in the example of Figure 6 the other inner loop components 629, 648 and 628 (Z1i, Z2i and Z3i) have been chosen, along with impedance network 670 (Z2), such that the inner loop realizes the distortion reduction condition described for the Figure 3 amplifier design, with the Class AB stage (i.e., the internal output stage of gain/drive stage 510, in some embodiments)

retaining an integrator type response in respect of the action seen by the outer loop. The choice of outer loop impedance network values to ensure maximum distortion reduction now has to take account of the gain of the inner loop which increases the effective impedance of Z2 by the ratio $[R2+R_{gi}]/R_{gi}$. A resistor in impedance network 670 (Z2) is not needed for stability of the inner feedback loop around transistors Q3 and Q4. This arrangement again makes it possible for the other outer loop components of impedance networks Z1-Z4 of the Figure 3 amplifier design to remain the same. The retention of the high frequency roll-off of the inner amplifier subsystem comprising gain stage 610A, gain/driver stage 610B, and intermediate stage 642 allows stability of the feedback loop around the output stage 650, and the final overall feedback loop still allows for low output impedance of the amplifier 600 at audio frequencies.

[0066] If the output impedance of the inner amplifier subsystem is an appreciable value in comparison to the impedance of Z3, then impedance network Z3 can be modified (i.e., increased) to ensure correct distortion reduction.

[0067] By utilizing these extra network arrangements in the amplifier designs of Figures 5 and 6, the dissipation of the Class AB driver stage (that is, the internal output stage of the gain/driver stage 510 or 610B, in some embodiments) can be made even lower by reducing the Class AB quiescent current further, since its distortion can be greatly reduced by the techniques described. The Class AB stage of the gain/driver stage 510 or 610B could itself be biased in Class B, resulting in a reduction of idle dissipation.

[0068] A further reduction in idle dissipation can be obtained by operating the gain/driver stage 210, 310, 510 or 610B in Class G or H mode, since the quiescent

power supply voltage to the gain/driver stage will be lower than would be the case otherwise. This could be done also without the extra network(s) of Figure 5 or 6, but extra care would be needed in order to eliminate any power supply switching spikes from affecting the output of the gain/driver stage. The extra network circuitry allows any switching distortion introduced into the gain/driver stage to be significantly reduced.

[0069] Amplifiers generally incorporate small current sensing resistors in series with the output transistors in order to provide for current limiting protection circuits. Impedance network Z1 employed in the various amplifier designs of Figures 2, 3, 5 and 6 can be used to replace these current sensing resistors as depicted in Figures 7a and 7b. Figure 7a shows a conventional current limiting circuit arrangement in which a push-pull output stage 700 comprises n-type transistor 711 and p-type transistor 712 (also labeled as Q1 and Q2) that are inter-connected with a combination of circuitry including transistors 721, 722 and 723 (also labeled as Q3, Q4 and Q5 respectively), current source 724 (also labeled as I1), and resistors 714 and 715 through which the output signal passes to reach the final output 720 of the output stage 700. The amount of current that can be output from transistor 711 is limited by the current that passes through resistor 714, and that amount of current is in turn determined by the base-to-emitter voltage of transistor 721. Resistor 715 and transistor 722 operate in a similar fashion to protect transistor 712 from excessive output current.

[0070] Figure 7b, on the other hand, shows a modified current limiting circuit arrangement that takes advantage of the presence of impedance network Z1 to dispense with resistors 714 and 715. In Figure 7b, output stage 750 comprises n-

type transistor 731 and p-type transistor 732 (also labeled as Q1 and Q2) that are again inter-connected with a combination of circuitry including transistors 751, 752 and 753 (also labeled as Q3, Q4 and Q5 respectively), current source 754 (also labeled as I1), and, in this case, resistor 781 which may be the resistor in impedance network Z1 of any of the previous embodiments described herein. In this case, when transistor 731 (Q1) is ON, then resistor 781 serves to limit the output current in the same way as resistor 714, i.e., using the relatively fixed base-to-emitter voltage of n-type transistor 751 to limit the output current, and when transistor 732 (Q2) is ON, then resistor 781 limits the output current in the same way as resistor 715, i.e., using the relatively fixed emitter-to-base voltage of p-type transistor 752 to limit output current.

[0071] The invention has generally been illustrated or discussed with particular reference to an audio power amplifier but is by no means limited to this application area. The disclosed techniques apply also, for example, to low power audio amplifiers, video amplifiers and radio frequency amplifiers, among others.

[0072] According to various embodiments as disclosed herein, a power amplifier is provided having low power dissipation and, more specifically, is capable of having low idle and dynamic power dissipation levels. The power amplifier may not require a bias setting, and further may not require inductors for EMI or filtering. The power amplifier may also deliver very low distortion levels.

[0073] In certain embodiments described herein, a low-power, low-distortion amplifier includes a gain/driver stage, an optional intermediate stage, and an output stage in a cascaded arrangement. A coupling path, which may in one aspect be viewed as a feed-forward path, is provided from the output of the gain/driver stage to

the load, via a feed-forward impedance network that may include a capacitor and a resistor connected in parallel. The output stage may be coupled to the load by another impedance network such as a resistor. The output stage may also be coupled to the input of the gain/driver stage by another impedance network, which may take the form of a capacitor and a resistor in a series arrangement. The output of the gain/driver stage may also be coupled to its input by another impedance network, which may take the form of a capacitor.

[0074] In addition, a feedback network may be provided from the load to the input of the gain/driver stage for stabilization, which may have the affect of flattening the overall frequency response at low frequencies will leaving the response unchanged at higher frequencies. The additional feedback network may take the form of a low pass filter and, more specifically, a T-network of two series resistors and a capacitor connected between their common node and a reference potential (such as ground). The additional feedback network may be used to counter-act the resistive nature of the frequency response of the feed-forward impedance network at low frequencies. Because the additional feedback network is fed into the negative input of the gain/driver stage, it effectively cancels out the low frequency component of the amplifier's frequency response contributed by the feed-forward impedance network.

[0075] In some embodiments, an additional intermediate amplifier stage may be provided, which functions in certain respects as a driver stage, and has a feed-forward path coupling to the load via the third impedance element.

[0076] In certain embodiments, the main output stage is operated in Class B mode, while the gain/driver stage is operated in Class AB mode, thus leading to a

low power dissipation configuration. At low signal levels, the gain/driver stage (and/or an intermediate amplifier stage) may provide the drive for the output signal via the feed-forward or coupling between the gain/driver stage (and/or the intermediate amplifier stage) and the load, (through impedance network Z3, while at higher signal levels the main output stage drives the load. In alternative embodiments, one or both of the gain/driver stage and the main output stage may be operated in Class G or H mode, with the addition of an appropriate power supply for the amplifier. In alternative embodiments, the main output stage may be operated in Class AB mode, or else in Class A mode. While doing so may increase power dissipation, this configuration may still take advantage of other benefits provided by the novel designs discussed herein.

[0077] The novel power amplifier embodiments of Figures 2, 3, 5 and 6 may be realized in a very small package and, in particular, may be implemented entirely on a single chip, with the possible exception of the capacitive component of impedance network Z3 which may, in some cases, be large but still relatively small as compared to an inductor, hence allowing smaller overall packaging size. Because of the amplifier's low power dissipation, multiple amplifiers (such as four, eight, or possibly more) may be included on a single chip without the risk of over-heating. Such a chip can be particularly convenient for multi-channel amplifier system such as used in audio applications or for other purposes.

[0078] As noted above, the amplifier designs disclosed herein may be suitable for many different types of applications, including audio or sound reproduction, communications, satellites, and other applications. The novel amplifier designs can potentially have very wide frequency range with substantially flat or constant gain,

while maintaining low power dissipation and low distortion. For example, the amplifier may provide relatively flat or constant gain over the range of 20 Hz to 20 KHz for audio applications, but is not so limited, and conceptually may provide flat or constant gain over a much larger pass-band, depending upon the specific application.

[0079] While preferred embodiments of the invention have been described herein, many variations are possible which remain within the concept and scope of the invention. Such variations would become clear to one of ordinary skill in the art after inspection of the specification and the drawings. The invention therefore is not to be restricted except within the spirit and scope of any appended claims.

CLAIMS

What is claimed is:

1. An amplifier, comprising:
a first amplifier for receiving an input source signal;
a second amplifier downstream from the first amplifier; and
a plurality of impedance networks providing (i) feedback paths from outputs of said first amplifier and said second amplifier to an input of said first amplifier, (ii) a first coupling path from the output of said second amplifier to a load, and (iii) a second coupling path from the output of said first amplifier to the load;
wherein all of said impedance networks are comprised of resistors, capacitors, or network combinations thereof.
2. The amplifier of claim 1, wherein a first impedance network providing said first coupling path comprises a resistor connected between the output of said second amplifier and the load.
3. The amplifier of claim 2, wherein a second impedance network of said plurality of impedance networks providing a first feedback path from the output of said first amplifier to the input of said first amplifier comprises a capacitor.
4. The amplifier of claim 3, wherein a third impedance network of said plurality of impedance networks providing said second coupling path comprises a resistor and capacitor connected in parallel between the output of the first amplifier and the load.

5. The amplifier of claim 4, wherein a fourth impedance network of said plurality of impedance networks providing a second feedback path from the output of said second amplifier to the input of said first amplifier comprises a capacitor and resistor connected in series.

6. The amplifier of claim 1, wherein a fifth impedance network of said plurality of impedance networks providing a third feedback path from the load to the input of said first amplifier comprises a low pass filter.

7. The amplifier of claim 1, wherein said second amplifier is operated in Class AB mode, Class G or Class H mode.

8. The amplifier of claim 7, wherein said first amplifier is operated in Class AB mode.

9. The amplifier of claim 1, wherein the power amplifier has a frequency response that is substantially constant over a low frequency band.

10. An amplifier, comprising:
a first amplifier receiving an input signal to be amplified and supplied to a load;
a second amplifier downstream from the first amplifier, said second amplifier being operated in a low power dissipation mode;

a feed-forward network coupling an output of said first amplifier to the load, said feed-forward network comprising a capacitor and a resistor connected in parallel;

a resistor coupling said second amplifier to the load; and

a plurality of negative feedback paths from the respective outputs of said first and second amplifiers to an input of said first amplifier.

11. The amplifier of claim 10, further comprising an additional feedback path from the load to the input of said first amplifier.

12. The amplifier of claim 10, wherein said additional feedback path comprises a low pass filter, and serves to cancel out the frequency response of the power amplifier at low frequencies without the additional feedback path thus providing a constant frequency response over low frequencies.

13. The amplifier of claim 10, wherein said second amplifier is operated in Class B mode.

14. The amplifier of claim 13, wherein said first amplifier is operated in Class AB mode.

15. The amplifier of claim 10, wherein said second amplifier is operated in Class G or Class H mode.

16. The amplifier of claim 15, wherein said first amplifier is operated in Class AB mode.

17. The amplifier of claim 10, wherein said negative feedback paths each comprise a feedback network comprising only one or more resistors, capacitors, or network combinations thereof.

18. The amplifier of claim 10, further comprising an intermediate amplifier stage disposed between the first amplifier and the second amplifier.

19. A low dissipation amplifier, comprising:

- a driver amplifier for receiving an input signal;
- an output amplifier;
- a first impedance network Z1 coupling the output amplifier to a load;
- a second impedance network Z2 providing a feedback signal indicative of an output of the driver amplifier to an input of the driver amplifier;
- a third impedance network Z3 coupling the output of the driver amplifier to the load; and
- a fourth impedance network Z4 providing a feedback signal indicative of an output of the output amplifier to the input of the driver amplifier;

wherein the third impedance network Z3 comprises a capacitor and a first resistor connected in parallel; and

wherein the first impedance network comprises a second resistor.

20. The low dissipation amplifier of claim 19, wherein the second impedance network Z2 comprises a third resistor, and wherein the fourth impedance network Z4 comprises a fourth resistor and a second capacitor connected in series.

21. The low dissipation amplifier of claim 20, wherein each of said first, second, third or fourth impedance networks Z1, Z2, Z3 and Z4 consists of one or more resistors, capacitors or network combinations thereof.

22. The low dissipation amplifier of claim 19, wherein said low dissipation amplifier does not include a balancing inductor in any of the impedance networks Z1, Z2, Z3 and Z4.

23. The low dissipation amplifier of claim 19, further comprising a fifth impedance network providing a feedback path from the load to the input of said driver amplifier.

24. The low dissipation amplifier of claim 19, wherein the values of the first, second, third and fourth impedance networks Z1, Z2, Z3, and Z4 satisfy the relationship $Z1(s) \cdot Z2(s) = Z3(s) \cdot Z4(s)$.

25. The low dissipation amplifier of claim 19, wherein a time constant of the third impedance network Z3 approximately matches a time constant of the fourth impedance network Z4.

26. The low dissipation amplifier of claim 25, wherein at high frequencies an impedance characteristic of impedance network Z3 appears capacitive in nature.

27. The low dissipation amplifier of claim 26, wherein at low frequencies below which the impedance characteristic of said third impedance network Z3 appears capacitive, the impedance characteristic of the third impedance network Z3 appears resistive.

28. The low dissipation amplifier of claim 19, wherein the fourth impedance network Z4 comprises a series resistor and a series capacitor, and wherein a value of the series resistor is selected to provide a unity loop gain frequency to facilitate stability of the low dissipation amplifier.

29. The low dissipation amplifier of claim 19, wherein said output amplifier is operated in Class B mode.

30. The low dissipation amplifier of claim 29, wherein said driver amplifier is operated in Class AB mode.

31. The low dissipation amplifier of claim 19, wherein said output amplifier and said driver amplifier are both operated in Class G or Class H mode.

32. The low dissipation amplifier of claim 19, further comprising an intermediate amplifier stage disposed between said driver amplifier and said output amplifier.

33. A method for amplifying an input source signal, comprising:
receiving the input source signal at a first amplifier and generating a driver signal thereby;
providing the driver signal to the input of a second amplifier acting as a main output stage;
operating the first amplifier in a Class AB mode;
operating the second amplifier in a Class B, Class G or Class H mode; and
providing selective coupling or feedback connections from the outputs of said first and second amplifiers to the inputs of said first and second amplifiers and to a load to maintain operation of said first and second amplifiers in their respective modes, while alternately driving the load from the first amplifier and the second amplifier.

34. The method of claim 33, further comprising the step of providing the driver signal to an intermediate amplification stage prior to providing it to the second amplifier.

35. The method of claim 33, wherein the step of providing selective coupling or feedback connections includes coupling the load to the output of the first amplifier through a capacitor and resistor connected in parallel.

36. The method of claim 35, wherein the step of providing selective coupling or feedback connections includes coupling the load to the output of the second amplifier through a resistor.

37. The method of claim 36, wherein the step of providing selective coupling or feedback connections includes providing a feedback path from the load to the input of the first amplifier via a feedback network.

38. The method of claim 37, wherein said feedback network comprises a low pass filter.

39. The method of claim 37, wherein said feedback network compensates for a low frequency response boost related to the parallel connected resistor and capacitor between load and the output of the first amplifier by making the frequency response substantially constant over low frequency ranges.

40. The method of claim 33, wherein the method provides low idle power dissipation.

41. The method of claim 40, wherein the input signal remains substantially distortion-free.

42. The method of claim 33, wherein the coupling or feedback connections from the outputs of said first and second amplifiers to the inputs of said first and second amplifiers and to a load are formed of resistors, capacitors or combinations thereof, without a balancing inductor.

43. The method of claim 33, wherein the second amplifier is operated in a Class B mode.

44. A low dissipation amplifier, comprising:
a driver amplifier coupled to an input signal;
an output amplifier;
a first impedance network Z1 coupling the output amplifier to a load;
a second impedance network Z2 providing a feedback signal indicative of an output of the driver amplifier to an input of the driver amplifier;
a third impedance network Z3 coupling the output of the driver amplifier to the load; and
a fourth impedance network Z4 providing a feedback signal indicative of an output of the output amplifier to the input of the driver amplifier;
wherein the values of the first, second, third and fourth impedance networks satisfy the relationship $Z1(s) \cdot Z2(s) = Z3(s) \cdot Z4(s)$; and
wherein all of said impedance networks are comprised of resistors, capacitors, or network combinations thereof.