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Switch Mode Power Amplifier with Feedback Control for Electro Acoustic Projectors

Shahana P saith, K Radhakrishnan, Krishnakumar P

Abstract*— A digital high power switch mode (Class D) power amplifier with feedback control for electro acoustic projector is introduced in this paper. These amplifiers have extremely low switching losses, reduced RF interference and enhanced efficiency. It is extremely reliable, compact, light weight and has the provision for controlling its output power linearly. The full bridge amplifier topology is used in this design. Solid state high side low side drivers replace input driver transformers that make the amplifier truly compact. Advanced current protection safeguards not only the amplifier, but also the load. Amplifier can be tailored for any load impedance, and are capable of driving acoustic projectors without any secondary breakdown problems, and hence becomes an attractive product. Electro acoustic transducer is the load utilized for the proposed power amplifier. Transducer's impedance varies in accordance with the frequency of information signal (Since they are either capacitive or inductive in nature). The resulting load voltage variation affects the performance of the power amplifier system. Therefore, a voltage feedback system is employed in this paper, to reduce the variations of the output voltage with variations in impedance. Experimental results show that feedback circuit can reduce the output voltage variations with the variations in load impedance.

***Index Terms*—Acoustic Transducer, Analog feedback controller, Coefficient table, Unipolar Pulse width modulation.**

I. INTRODUCTION

The main function of Power amplifiers is to deliver power, which is the product of the voltage and current applied to the load, with the output signal power being greater than the input signal power. Power amplifiers are classified into linear and switched mode amplifiers. Among these two classes, switched mode power amplifiers are more efficient. Electro-acoustic projectors require very high electrical power to achieve the desired source level to enhance the detection of modern quiet submarines and torpedoes. The requirement for the increased range, to counter the enhanced weapon range of present day scenario, is also a key factor while designing a sonar transmitter. This large amount of power is to be supplied by a set of highly reliable power amplifiers, which shall have the following salient features such as reduced power wastage as heat dissipation and hence smaller heat sinks, Reduction in size and weight of the amplifier, Reduction in cost due to smaller heat sink and compact circuitry, Compact (1/5th of an equivalent Linear Amplifier) & Energy efficient ($\eta \cong$ 85%), No secondary breakdown & thermal runaway, Advanced current protection, Facility to control output power, it can be tailored to wide frequency range (1 to 10 kHz) & high power output.

A. The Digital Power Amplifier

The class D power amplifier presented here overcomes most of the problems in various existing classes of amplifiers. It is a kind of switching amplifier in which unipolar Pulse Width Modulation (PWM) technique is used. Judicious selection of the switching frequency and appropriate filters results in faithful reproduction of the signal. The amplifiers are switched at 16 times higher the frequency than that of the input signal, reducing the effort of filtering. MOSFET based full bridge amplifier topology used here prevents stored energy being pumped back towards the power supply. EMI/EMC problems are reduced to minimum by using appropriate filters and shielding techniques wherever they are prone to.

B. Selection of Power Device

The choice of power device in a given application depends greatly on the application needs and requirements. With proliferation of choices between different kinds of power devices, it is becoming increasingly difficult for today's sonar designers to select the best power device for their sonar transmitters. MOSFETs offered significant performance improvements as compared to BJTs. The IGBT has overcome the performance limitations of MOSFET. One of the challenges present sonar designers face is the question of which device is better for their application.

C. Amplifier Topology

Full bridge topology is used in the output stage of the proposed switching amplifier. The full bridge topology and current flow for each half cycle using four MOSFETs is shown in Figure 1 given below.

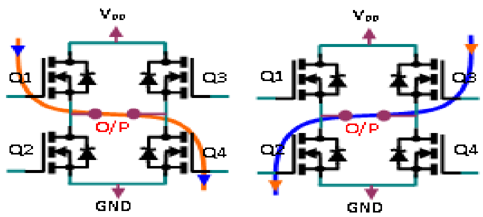

Fig.1. Full bridge topology

In brief, a half-bridge is potentially simpler. In the half-bridge topology, the power supply might suffer from the energy being pumped back from the amplifier, resulting in severe bus voltage fluctuations when the amplifier outputs low frequency audio signals to the load. The full-bridge topology requires two half-bridge amplifiers, and thus, more

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components. The differential output structure of the bridge topology inherently cancels out even order of harmonic distortion components and DC offsets. This kickback energy to the power supply is a fundamental characteristic of switching amplifier. Complementary switching legs in the full-bridge tend to consume energy from the other side of the leg, so there is no energy being pumped back towards the power supply. The switching elements work in pair to reverse the polarity of the drive even though only one polarity supply is used and hence providing bipolar load current from a single supply. Due to the above advantages, MOSFET based full bridge (H bridge) topology is used in the amplifier [2].

D. Unipolar PWM scheme

This technique uses two inverted sine waves as modulating signal for the two legs of the amplifier. The generation of PWM signal can be explained with the help of full bridge circuit shown in the figure 1. Here the two legs of the full bridge circuit are controlled separately by comparing V_{tri} with V_{sin} and $-V_{sin}$ respectively. In this type of PWM scheme, when a switching occurs, the output voltage changes between zero and + V_{dc} or between zero and -V_{dc} voltage levels. For this reason, this type of PWM scheme is called PWM with a unipolar voltage switching [1]. PWM signals are generated in an analog circuit employing comparators, unity gain inverting amplifier and XR2206 monolithic function generator [9].

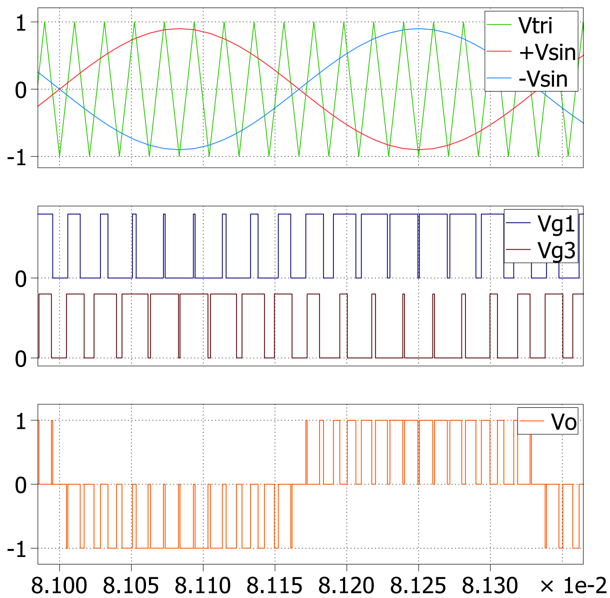

Fig.2. Unipolar PWM signals

Unipolar PWM scheme reduces overall harmonic distortion of the load voltage waveform and doubles the frequency of the ripple voltage in the load waveform. In the sine PWM technique using two inverted modulating waves, the load voltage has double the number of pulses per carrier time period, thus doubling the ripple frequency. Now, higher the frequencies of unwanted ripple voltage, easier it is to filter out the ripple current. Also, the load voltage now has three levels (+0.5$V_{dc,}$ Zero, and -0.5Vdc). Presence of zero duration reduces the rms magnitude of the overall load voltage (Fundamental component along with harmonics), while keeping the magnitude of fundamental component of load voltage same as in the previous case (The rms value of the overall load voltage for the two-level waveform equals V_{dc}). Thus the distortion of the load voltage waveform is less. The waveform given in figure 2 shows the unipolar pulse width modulated signals applied to the gate of MOSFETs in the full bridge topology [1].

E. Solid State Driver Stage

The two fundamental categories for gate drive are high and low side drivers. High side means that the source of the power element can float between ground and high voltage power rail. Low side means that source or emitter is always connected to ground. During the ON and OFF switching operation, gate of MOSFET which is a capacitor need to be charged and discharged. The concept of high side and low side driver can be explained by considering the half bridge topology as shown in the figure 3. In this configuration, Q_1 and Q_2 are always in opposite states. When Q_1 goes from being off to on, the voltage at the sources of the MOSFET goes from ground up to the high voltage rail. This means that the voltage applied to the gate must float up as well. This requires some form of isolated or floating gate drive circuitry. $Q_{2,}$ however, always has its source or emitter connected to the ground so the gate drive voltage can also be referenced to ground. This makes the gate drive much simpler.

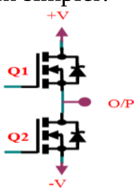

Fig.3. Half bridge topology

Monolithic solid state MOSFET/IGBT driver ICs with independent high and low side referenced channels and matched propagation delay are used in the driver stage. Amplifier performance is enhanced drastically due to the usage of these driver ICs. In order to provide such a gate drive requirement various schemes are used. They include single ended or double ended gate drive transformers, high voltage bootstrap driver ICs, floating bias voltages and opto-isolator drive. The proposed project uses IR2110 IC in the driver stage. It is a high voltage high speed power MOSFET and IGBT driver with independent high and low side referenced output channels.

F. Need of Isolation

The individual gate control signals for the switches are to be provided across the gate and source terminals of a particular MOSFET. When a switch is on its emitter and collector terminals are virtually shorted. Thus with upper switch on, the emitter of upper switch is at positive dc bus potential. Similarly with the lower switch on, the emitter of upper switch of that leg is virtually at the negative dc bus potential. Emitters of all the lower switches are solidly connected the negative line of dc bus. Since gate control signals are applied with respect to the emitter terminals of the switches, the gate voltages of all the upper switches must be floating with respect to the dc bus line potentials. This calls for the isolation between the gate control signals of upper switches and between upper and lower switches[1]. Only the emitters of lower switches of all the legs are at the same potential and hence the gate control signals of lower switches need not be isolated among themselves. Gate signal isolation for the power amplifier is generally achieved by means of opto- isolator circuits. HCPL 2630 opto- isolator is used in the proposed power amplifier.

G. Hardware Configuration

The functional block diagram of the proposed power amplifier without feedback system is shown in the Figure 4.

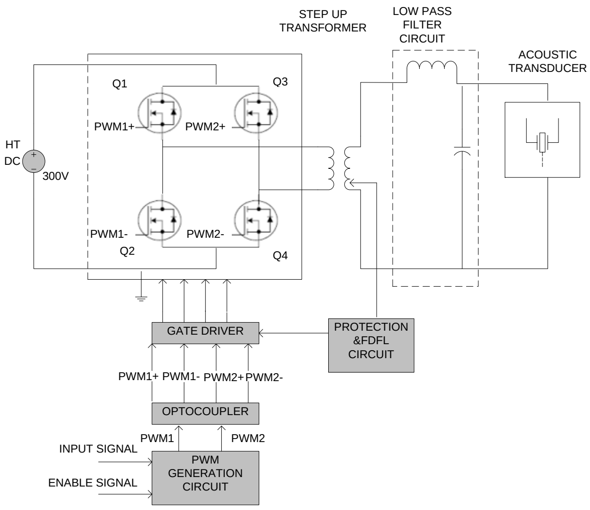

Fig.4. Block diagram of Digital Power Amplifier without feedback system

The amplifier requires four PWM drive signals to power MOSFETs in the bridge. The frequencies of the drive signals are 16 times the frequencies of transmit signal that is easily generated or derived as per the system requirement from the transmitter controller. The high side drivers modify the TTL compatible input PWM signals into signals suitable for driving high side MOSFETs. The high side driver output is referenced to the sources of Q1 and Q3 while low side output is referenced to system ground or to the sources of Q2 and Q4 shown in Figure 1. The primary of the transformer is designed to accept a maximum of twice $V_{DD.}$ This impedance matching ferrite core based step up transformer transforms the high impedance of the electro acoustic projector suitable to the H bridge amplifier to deliver the desired output power from the DC supply.

H. Power Filter

To retrieve the signal frequency, the harmonics present at the output waveform should be attenuated with a low pass filter. The cut off frequency of the filter is the highest signal frequency of interest. Higher harmonics are to be sufficiently attenuated to obtain a very good sine wave output with negligible distortion. To accomplish this task, a filter is used, which assumes low amplifier output impedance, as compared to the load impedance and that the combined impedance of the load plus matching network constant over frequency is used. If 3rd, 5th and 7th harmonics are sufficiently attenuated, one can expect a very good sine wave output, with negligible distortion [11].

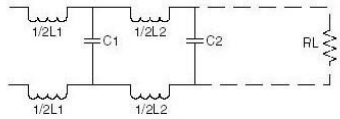

Fig.5. 4th order low pass filter

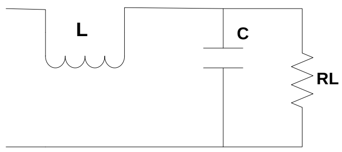

Fig.6. 4th order low pass filter

With full bridge circuits the common mode voltage applied to both load terminals is minimized by using a technique of simply splitting the inductor values in to half as shown in figure 5. I.e. applying half the voltage to each side of the output. The inductance values can be realized using iron powdered toroidal cores, which have very high saturation flux density. Filter analysis begins by developing general mathematical equations to describe the filters. Each filter equation can be reduced to a set of coefficients. Filter coefficient tables are usually in normalized form. Normalized coefficients are calculated at a frequency of 1 radian per second and an impedance of 1 ohm. The coefficient table also assumes very low source impedance and higher load impedance [11].

I. Output transformer

Most of the power circuits contain transformers for providing isolation between input and output and for impedance matching. The transformers give an additional benefit of scaling the voltages and currents, apart from providing isolation. It also helps in optimizing the device operating voltage in the power electronic circuits. The output transformer is an integral part of power amplifiers used in sonar transmitters. For the proposed power amplifier, core material used for the transformer is PM 87/70 and is designed by area product approach method [4].

The design of a transformer means, to arrive at the selection of proper core material, core dimensions and winding parameters, which can satisfy the operating conditions. Selection of a core material is usually based on the frequency of operation [4]. Ferrite core materials higher frequency materials and have lower eddy current losses. However, the permeability is generally lower, resulting in greater magnetizing current. Metal alloy cores are high frequency

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materials and require very thin lamination. Although saturation flux density is usually very much greater than that of ferrite materials, this is usually irrelevant, because flux swing is greatly limited by eddy current losses. Materials made of silicon provide the highest flux. This can result in smaller size, but the losses are greater, leading to a decrease in efficiency. So, in the choice of the material, we need to have a compromise between the size and the efficiency. Ferrite is usually the best choice in transformer applications, except for mechanical ruggedness. The Pot cores and PQ cores have small window area in relation to core size, and the window shape is almost square. One advantage of pot core is that they provide better magnetic shielding than E-E cores, reducing EMI propagation. Variations of the pot core geometry such as PM and RM allow more air flow thus allowing them to operate at cooler temperature. PM cores are particularly suitable for use in transformers handling high powers in the frequency range up to 300 kHz [4].

J. Protection circuit

These circuits protects power amplifier from overload and over temperature. Fault detection and fault localization (FDFL) circuit provided in each module monitor the health of PA module and report back to the health monitoring system. FDFL circuit monitors the status of various power supplies and reports the magnitude of the load current to the system. It receives two sets of PWM signals and control signals from the Transmitter signal generator. Control signals include power amplifier enable, temperature override (to override the PA shutdown due to over temperature) and clock pulse to refresh FDFL data.

Ac voltage corresponding to output current through the load is received in this card. This voltage is rectified and compared with a preset voltage. If it exceeds the limit, it is sensed by the comparator and it triggers a monoshot. This disables high and low side driver in the PA card for some time, after which the amplifier is enabled again. If the load current is still exceeding the limit, PA is again disabled for some time. A four bit counter monitors these events and disables the amplifier permanently if this happens more than eight times.

II. IMPLEMENTATION OF CONTROL STRATEGY

Electro acoustic transducers are the load to the sonar power amplifier. These transducers are reactive in nature. So, according to the frequency of the information signal, the transducer's impedance varies. This results in the variation of output voltage of the power amplifier. Since the power filter is designed for a particular load, it changes the filter characteristics. It causes a change in the current drawn by the secondary of the transformer, which in turn affects the performance of the whole power amplifier system. Also, in case of beam formers, the impedance change property of transducer results in the reduction in quality of each beam. The solution to this problem is to employ a feedback circuit that will take corrective action at the output stage, with respect to the load variations [7]. The figure 7 shows the block diagram of high power switched mode power amplifier with an analog feedback controller. Feedback controller contains a scaling unit, precision rectifier unit, a difference amplifier, variable gain amplifier and an analog multiplier IC. Analog multiplier IC is the important component of the feedback circuit. The output voltage from the low pass filter is first scaled down to a voltage by using a potential divider. The precision rectifier unit rectifies the scaled down voltage and it is then compared with the reference value. The output of difference amplifier is then amplified by an inverting amplifier. The output of this stage and sinusoidal input is then multiplied using an analog multiplier. i.e., according to the load voltage change, the proposed analog controller changes the amplitude of input sinusoidal signal and thus it varies the width of PWM signals. i.e., as the load voltage increases analog controller reduces the width of PWM signal and vice versa. From the experimental results, it is clear that the feedback circuit can reduce the output voltage variation, with change in impedance.

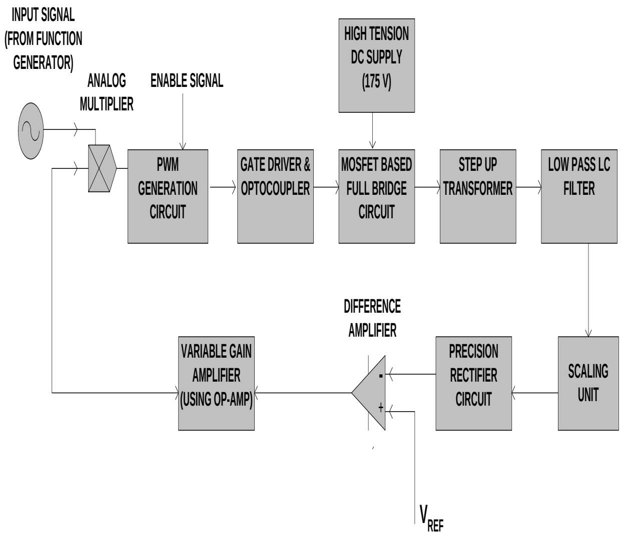

Fig.7. Power amplifier with analog feedback controller

III. EXPERIMENTAL RESULTS

The impedance of the transducer element is in between 100-200 ohms. The power amplifier is designed for 1KW power rating. The experimental results are obtained from Tektronix MSO 2014 mixed signal oscilloscope. The input signal is obtained from Tektronix AFG3022B dual channel arbitrary or function generator. DC input voltage to the system is 175V. The values chosen for the power filter are L=0.0176H & C=0.22uF. The output voltage and current waveforms taken from the oscilloscope are given below. The output signals given in figures 10, 12 show that the voltage variations can be reduced to about half, if we use a feedback system (For the load variation of 225 Ω to 250 Ω) in the proposed power amplifier. Figure 8, given below, shows the unipolar PWM signals for the two legs of for the proposed power amplifier.

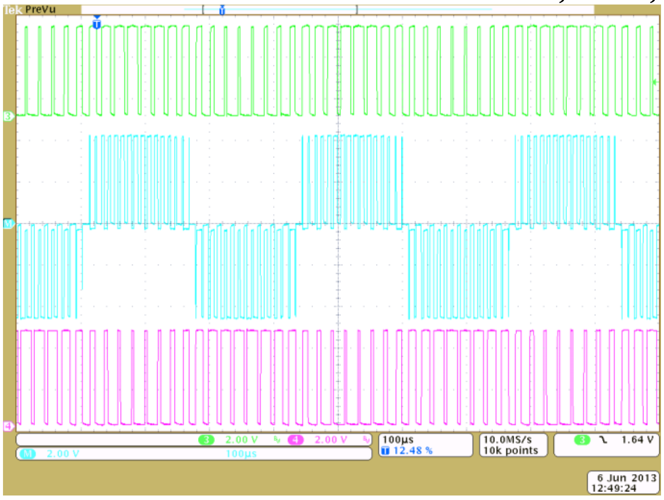

Fig.8. Unipolar PWM signals

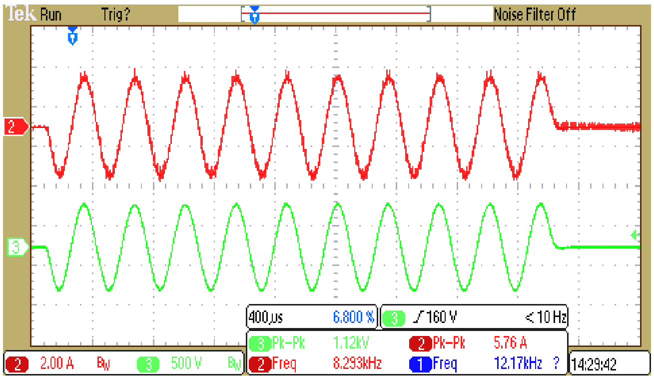

Fig.9. Output voltage and current waveform of power amplifier without feedback for 225Ω load.

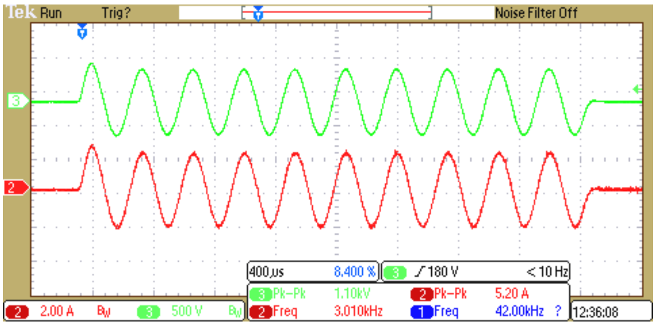

Fig.10. Output voltage and current waveform of power amplifier with feedback for 225Ω load

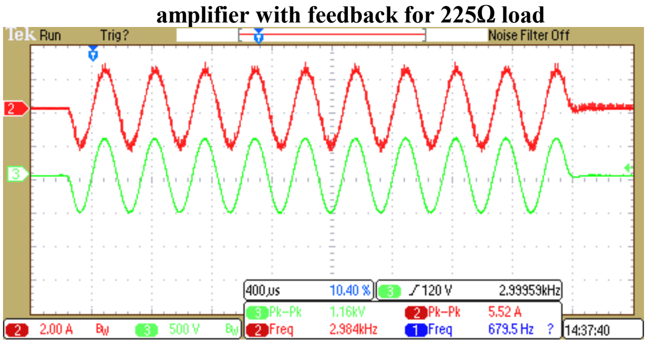

Fig 11. Output voltage and current waveform of power amplifier without feedback for 250Ω load

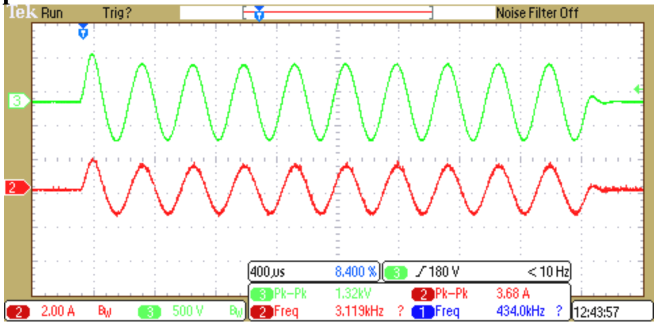

Fig 12. Output voltage and current waveform of power amplifier with feedback for 250Ω load

For the proposed power amplifier, graphs plotted between input and output parameters are depicted below. Figures 13, 14 and 17, 18 enumerate the linearity property of the proposed power amplifier i.e. the variation of output voltage with variation in the input voltage. So, we can vary the output power by varying the input signal amplitude and dc input voltage. Figures 15 and 16 depict the frequency response of the proposed power amplifier. As the frequency deviates from the rated value, there will be a variation in the output voltage and current values (due to changes in the filter characteristics). The given characteristics plotted for the power amplifier without feedback system. From the experimental results, it is clear that the presence of feedback system in the proposed power amplifier does not change these characteristics.

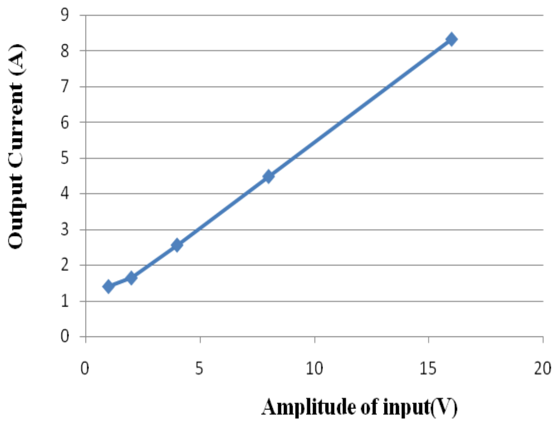

Fig 13. Amplitude of Input Vs output current

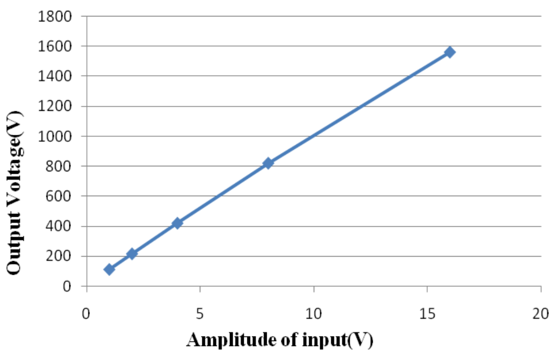

Fig 14. Amplitude of Input Vs Output voltage

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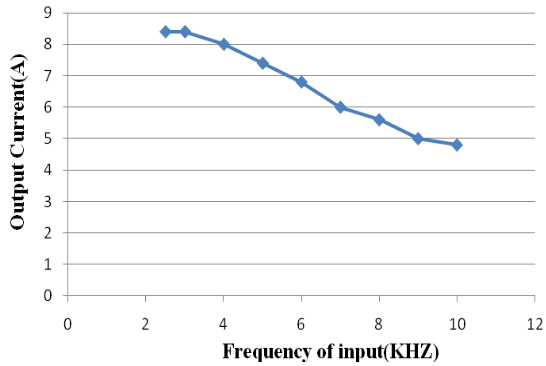

Fig 15. Frequency of Input Vs Output current

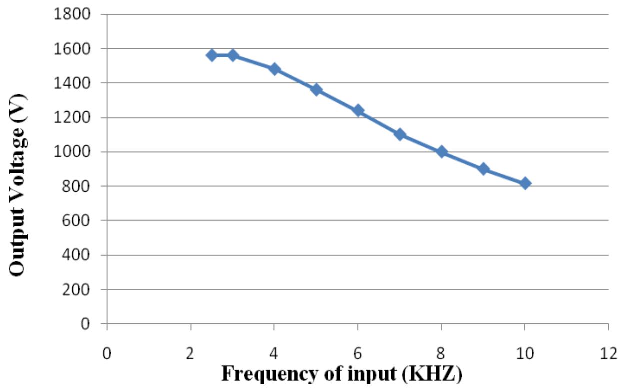

Fig 16. Frequency of Input Vs Output voltage

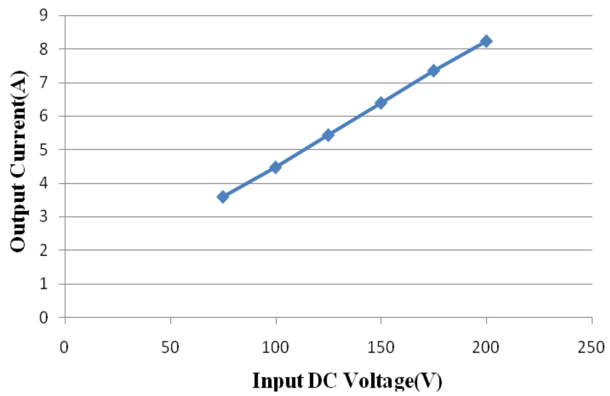

Fig 17. Input dc voltage Vs Output current

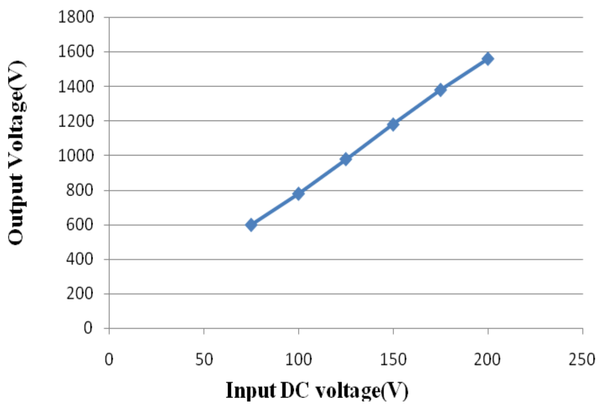

Fig 18. Input dc voltage Vs Output voltage

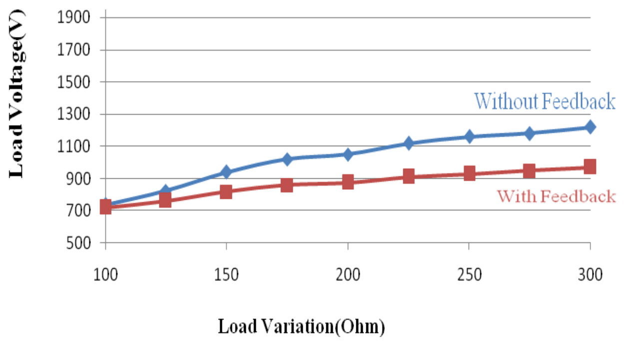

Fig 19. LoadVsoutput voltage

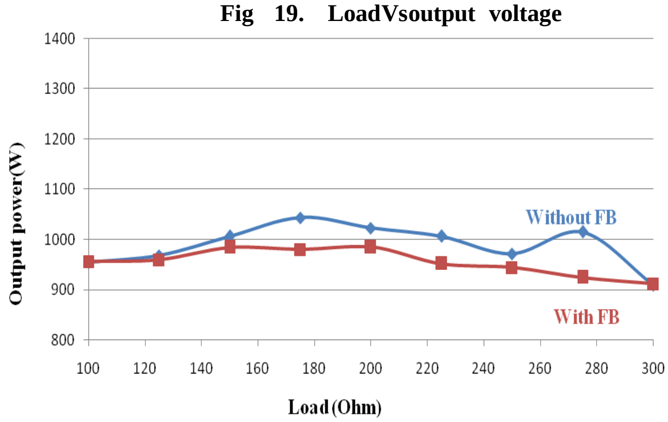

Fig 20. Load Vs output power

Figure 19 shows the variation of output voltage with load variation, when feedback is present and feedback is not present. It can be seen that, the output voltage is maintained constant within allowed tolerance with the feedback present. Figure 20 shows the variation of output power with load variation. From the characteristics, it is clear that the output power variation is reduced when feedback system is present.

IV. CONCLUSION

This paper presents a high power switch mode power amplifier with an analog feedback circuit. Since the total losses are extremely low, the heat sink size requirements are considerably reduced and resulting in a highly compact and light weight amplifier. Impedance changing property of the acoustic transducer necessitates a feedback circuit in the proposed power amplifier. The analog feedback circuitry implemented in the proposed power amplifier is very simple, cheap and easy to implement. Even though the feedback system causes some voltage drop in the system it can reduce the output voltage and power variations with the variation in load impedance.

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AUTHOR BIOGRAPHY

Shahana p saith received the B.Tech (Electrical & Electronics Engineering) degree from Sree Narayana Gurukulam College of Engineering, India in 2011. She is currently pursuing M.Tech (Power Electronics) degree in Mar Athanasius College of Engineering, India.

K Radhakrishnan he is currently the professor in Electrical &Electronics department of Mar Athanasius College of Engineering, India.

Krishnakumar P he is currently the Scientist of Naval Physical and Oceanographic Laboratory, DRDO, India. He has more than 10 year experience in the power electronics and sonar field.