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A Microcontroller Based Class-D Power Amplifier for Low Frequency Sonar Application

V. N. Panchalai, Bineesh P. Chacko and N. Sivakumar
Naval Physical and Oceanographic Laboratory,
Thrikkakara, Kochi-21

***Abstract*— A processor controlled Switch Mode Power Amplifiers (SMPA) for a frequency (1kHz- 10kHz) to excite electro-acoustic transducers for an active sonar system is explained in this paper. The system uses a low cost digital signal controller, can precisely control various parameters of interest viz. amplitude, frequency, pulse length, pulse repetition rate. The programmability, insertion of programmable dead band and ease of implementing protection schemes make digitally controlled SMPA a attractive system. A Digital method to generate Sine Pulse Width Modulation (SPWM) signal is described. A prototype digital class D power amplifier of 1kW has been fabricated for the above frequency range. An experimental result of prototype power amplifier for a frequency range of 1 kHz- 10 kHz is presented at the end.**

Keywords*— Acoustic Transducer, Switch Mode Power amplifier, Active Sonar, Micro controller, Unipolar PWM, digital, Class D.

I. INTRODUCTION

The detection of objects in the sea viz. a ship, school of fish, submerged wreckage or submarine is achieved most effectively by using sound energy in SONAR systems. Sea water being excellent conductor of electricity, electrical energy rapidly dissipates in it, and electromagnetic waves cannot be deployed for detecting objects in the sea [1]. The basic principle of sending a packet of energy and finding the time delay of the reflected signal to get a measure of range as in radar is used in sonar also. Sea water behaves as a low pass filter for the acoustic waves; hence the choice of frequency for transmission is limited to the audio band, with the actual frequency being a compromise based on the permissible transducer size.

The Sonar transmitter uses power amplifiers (PA) of different classes to excite underwater acoustic transducers through which acoustic signal of required frequency band is transmitted into the water. In some underwater acoustic applications, high power of the orders of tens of kilowatts is required to be delivered out of each unit to generate required power levels from relatively high impedance acoustic transducers[2]. Several such units occupy prohibitive volume where space is limited in a ship and is very critical in the case of a submarine. Hence highly efficient SMPA with flexibility in controlling parameters like frequency, pulse length, pulse repetition interval etc is a real boon in this scenario.

There are many papers [3]-[7] on power amplifiers for low power and high frequency operation. These references analyse many improvements over basic amplifier topology to achieve high efficiency, low distortion, reliable operation etc. A low cost, compact, efficient low frequency active sonar power amplifier using microcontroller described here.

II. SONAR TRANSMITTER

Sonar transmitter needs to transmit different kinds of signals such as Continuous Wave (CW), Linear frequency Modulated (LFM) wave, Hyperbolic Frequency Modulated (HFM) wave etc. for the detection of underwater targets. The underwater electro acoustic transducers offer resistive load at resonance (F_r), becomes capacitive for frequency less than F_r and inductive for frequency between Fr and F_{ar} where F_{ar} is anti-resonance. The impedance of the transducer exhibit complex property even with the power levels, especially at higher level [8]-[9]. The impedance value of the transducer decides the voltage and current for a particular power level. Since the impedance of acoustic transducers are high, the output voltage of power amplifier will be very high (thousands of volts) to generate the designed power levels [2]. The cable capacitance is also added to the impedance of the electro acoustic transducers to form highly complex impedance which limits the Safe Operating Area (SOA) of power electronic devices used in power amplifiers.

One of the alternatives to a linear power amplifier design is a switch mode power amplifier (SMPA). By modulating the duration of the ‘ON’ and ‘OFF’ periods, the output of the switching amplifier (either voltage or current) can be controlled to follow the input reference signal, and thus the circuit can work as a power amplifier, and the expected efficiency will be higher than the linear power amplifiers.

The power amplifiers with high power level requirement use switch mode technology because the cooling requirement is less compared to linear power amplifier. However, the switching frequency of the power electronic devices puts a limitation on the usage of switch mode power amplifiers for high frequency applications. T.Wurtz et.al [10] explains a method to achieve high efficiency with high linearity by dividing the total operating voltages into many and operate the device effectively so that energy wasted can be recovered. Dennis Nielsen et.al [11] proposed a new power amplifier for audio application which can be operated with high voltage for medium power application. The modification of the circuit for active sonar transmission systems wherein power ranges are above 500W for driving impedance from 50Ω-400Ω is difficult. In both the cases the power levels are not sufficient for active sonar as it needs high power at high voltage to drive complex transducer load. A separate signal generation circuitry is essential for generation of sonar signals if the above power amplifiers are used apart from reconfiguration of the system. Bineesh et.al [12] proposed a modified unipolar switching scheme which can be used as an alternative to unipolar switching schemes for full bridge power amplifier. However the switching frequency of the devices is twice as compared to conventional unipolar switching scheme to achieve the benefits claimed.

The proposed system gives comprehensive details of processor based compact SMPA which uses unipolar switching scheme and full bridge converter. It offers high efficiency, low distortion and simple solutions to existing problems in power amplifier for active sonar transmitter.

III. SMPA FOR ACTIVE SONAR TRANSMITTER

A functional block schematic of basic SMPA used in sonar transmitter is given in Fig 1. Signal generator system generates sine wave of sonar frequency with a selected pulse length, pulse repetition rate and power level. This sonar signal (also called as modulating signal) of frequency f_m is compared with a triangular wave (also called as carrier signal) of frequency f_c to generate Sine pulse width modulated (SPWM) signals. There are two comparators one compares the triangular carrier signal with sonar signal and another compares triangular carrier signal with 180^O phase shifted sonar signal for implementation of unipolar SPWM

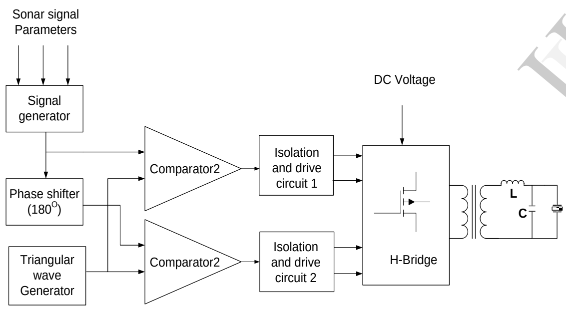
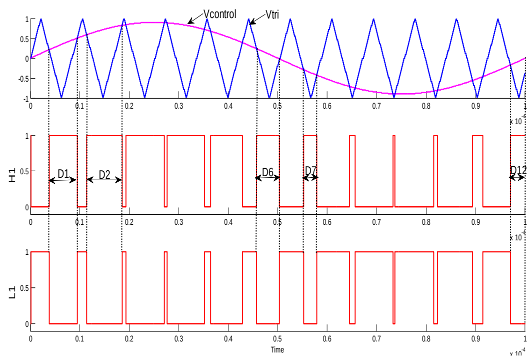


Fig. 1. Block Schematic of SMPA for sonar applications



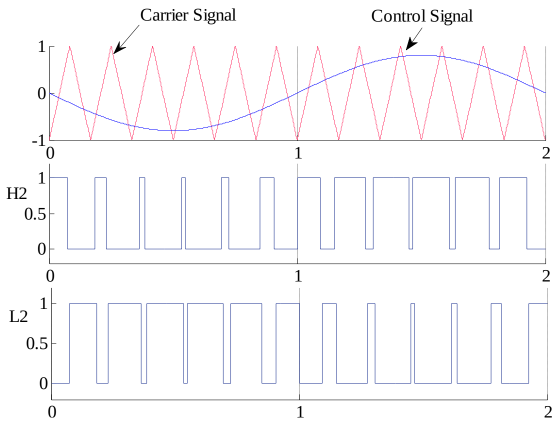


Fig. 2. SPWM with its complementary for full bridge controlled bridge

The output of the comparators is pulses with their widths proportional to the amplitude of input sine signal, also called as Sine Pulse Width Modulation SPWM. The SPWM signal (and its complement as shown in Fig.2) is used to control the ON time of power electronic switch in a controlled full bridge circuit (CFBC). Since the CFBC is operated at high voltage DC supply, the voltage output of CFBC is an amplified version of SPWM signal. The SPWM waveform with peak amplitude of high voltage DC is isolated using a power transformer designed to operate around modulating frequency. The turn's ratio of the transformer is chosen in such a way that the output of secondary should be capable of giving required current to the underwater acoustic transducer, so that it generates sufficient source level underwater.

The power transformer followed by power filter removes carrier frequency components and allows only amplified input sonar signal for exciting the electro acoustic transducer element.

IV. DIGITAL CLASS 'D' PA FOR AN ACTIVE SONAR TRANSMITTER

The functionalities of waveform generator and comparator are assigned to micro controller in the digital power amplifier system. Typical block level schematic of Digital class D power amplifier is given in Fig 3.

Following points are to be considered while designing a digital power amplifier for underwater active sonar transmitter.

A. *Controller and Oscillator frequency*

Considering the sonar signal frequency in the range 1 kHz to 10 kHz, carrier frequency ranges from 12 kHz to 120 kHz The carrier frequency less than 12 times sonar signal generates higher Total Harmonic Distortion (THD) in voltage and current waveforms. So the digital controller should be able to operate at higher clock frequency for the generation of SPWM for sonar frequencies. It is also desirable to have inbuilt PWM modules which can be configured to have complementary waveforms and dead band. Insertion of programmable dead band between complementary signals of SPWM is an added advantage of digital class of power amplifiers.

B. Power Semiconductor Devices Switch and their Switching Frequency

The power semiconductor operating frequency should be sufficiently higher than the carrier frequency. The power filter component values will be small if the carrier frequency is high. But the losses during switching transients of power devices increase with higher switching frequencies. Though IGBTs have higher operating voltage which is suitable for high power sonar transmitter application, MOSFETs have high operating frequencies and hence suitable for high frequency application

C. Power Transformer

The power transformers are the heaviest and bulkiest item of a sonar power amplifier. The transformers are used at the output of H-bridge, to provide isolation and voltage transformation. The design of transformer means, to properly select core material, core dimensions and winding parameters, which can satisfy the operating conditions.

The operation in sonar power amplifier is pulsed one with specified pulse width and a specified repetition interval. The heat produced by the pulsed current can average itself over the time between the pulses, and hence the transformer can be designed with less VA rating than the continuous VA rating [13] in case of sonar power amplifiers.

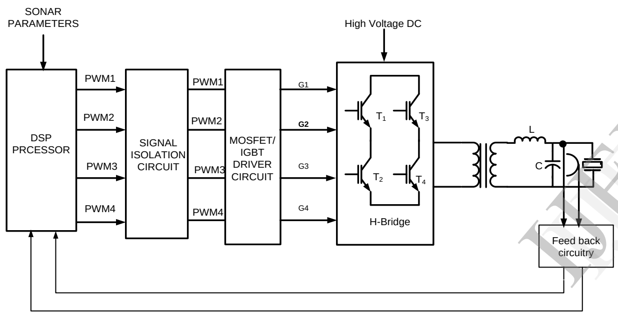


Fig. 3. Block Schematic of proposed Digital Sonar power amplifier

D. Power Filter

The power filter normally consists of inductor and capacitors that suppresses the high frequency harmonics. The filter used in sonar power amplifier can be of second order, which is designed using a single inductor element and a capacitor.

The empirical formula for designing the values of inductor (L) and capacitor (C) are given in [14] is presented in equation 1 and 2.

$$L = \frac{1.414 R_L}{2\pi f} \quad (1)$$

$$C = \frac{0.707}{2\pi f R_L} \quad (2)$$

The switching frequency is inversely proportional with the filter components and hence the smaller size of the components can be achieved, if the switching frequency is higher. However the switching losses at higher switching frequencies and the device's maximum operating frequency leads to the trade-off between switching frequency and values of filter components.

V. SPWM GENERATION USING MICROCONTROLLER

There are many kinds of pulse width modulation schemes out of which the aforementioned sine pulse width modulation (SPWM) is widely used. The unipolar SPWM gives better results as the frequency of output pulses of the unipolar SPWM scheme is twice the switching frequency (carrier frequency) of the power switches. So, the size of the components in the power filter is small, as compared to similar rating of bipolar switching scheme. Digital generation of SPWM involves implementation of control logic explained in the section III into a digital controller/ processor. It needs huge memory for storing sonar signal which has certain pulse lengths of the order of seconds at sufficient sampling rate.

The proposed SMPA uses another simple logic to generate SPWM. The unipolar SPWM generation typically using microchip dsPIC 30F family microcontroller [15]-[16] has the following steps.

i. Time period equivalent to time base of triangular wave (PTPER) at fc Hz in centre aligned mode can be calculated using the formula

$$PTPER = \frac{CrystalFrequency\ (F_{CY})}{(f_c) * 2 * PTMR\ prescalar} - 1 \quad (3)$$

ii. Sine wave is divided into 12 or more in time scale. This no (ratio of carrier frequency to modulating frequency) can be any even number more than 12 which can be implemented using selected microcontroller. For example 360^{O} is divided into 12 equal parts of 30^{O} as shown in Fig 4.

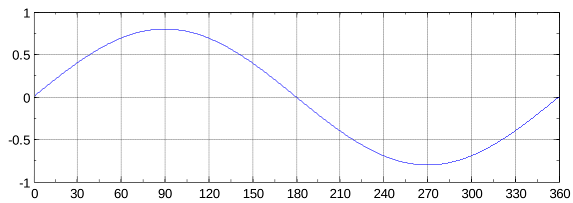


Fig. 4. The Fundamental Sine Wave with 12 Number of Samples

iii. The average value of sine from 0^{O} to 30^{O} can be approximated as sin(0+30/2) = sin(15). The approximate angles for all the 12 values can be calculated as shown in TABLE I.

TABLE I. ANGLES OF A SINE WAVE FOR SPWM GENERATION USING DIGITAL METHOD

P_1	P_2	P_3	P_4	P_5	P_6
15	45	75	105	135	165
P_7	P_8	P_9	P_{10}	P_{11}	P_{12}
195	225	255	285	315	345

iv. The duty cycle value at any point 't', for a modulation index of MI is calculated using the equation (4)

$$D_t = (MI * \frac{PTPER}{2} * \sin(p_t)) + \frac{PTPER}{2} \quad (4)$$

v. Now the pulses are generated digitally using the PWM modules inbuilt in microcontroller with PDC registers are loaded with D_t values (TABLE1) and PTEPER values as time period. The signal so generated will look similar to Fig.2.

vi. The frequency spectrum of SPWM generated using above method is similar to conventional unipolar SPWM. The error in SPWM is only due to approximation in programming from floating values to integer. If carrier frequency is chosen more , then the THD value of output voltage is less and lesser values of filter components are sufficient to filter out unwanted harmonics.

vii. The advantage of processor controlled SPWM is that the harmonic content can also be spread among frequencies by simply changing the parameters (values in the PTPER and PDC registers) on the fly. The ratio of Dt to PTPER is maintained to give equivalent Sin(P_t) for t values from 1 to 12. By maintaining the ratio and changing PTPER value (Sum of 12 PTPER values is maintained constant to keep modulating frequency unchanged) the harmonic contents can be spread.

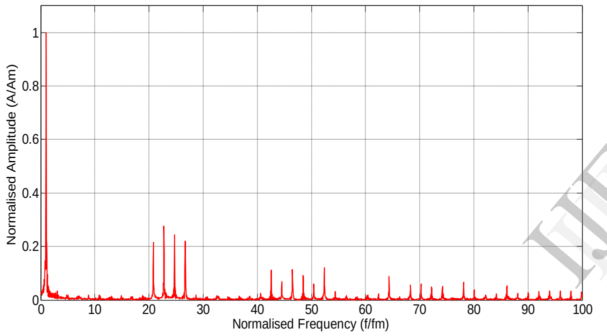


Fig. 5a. FFT of SPWM generated by conventional method

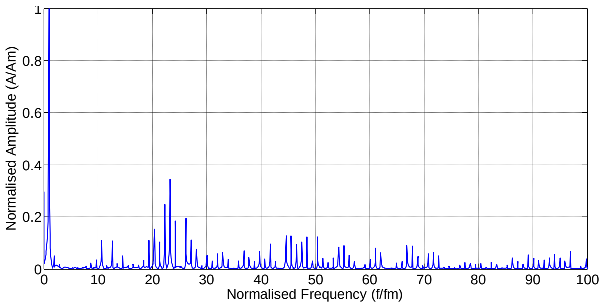


Fig. 5b. FFT of SPWM generated by micro controller

The amplitude values of uni-polar SPWM for different frequencies for both conventional and new digital method are shown in Fig. 5a and 5b. In the conventional method sine wave and triangular wave is generated for the duration of pulse lengths required for sonar transmission. This waveform is stored in a memory for further comparison to generate SPWM. This takes huge memory and limits the no of sample per cycle. Though the harmonic content of conventional method is better at few frequencies the memory requires to save this wave form is huge if it is sampled at higher sampling rate. If the same is sampled at lower sampling rate the harmonic content is high which is undesirable.

The proposed method does not require huge memory as the pulse widths are calculated on the fly. The practical results of this method show that the harmonic con tent is low except few frequencies compared to conventional method. It is also easy to spread the harmonic spectrum keeping the fundamental component at same amplitude.

VI. PROTOTYPE DEVELOPMENT

A prototype of 1kW power amplifier for driving transducer load whose amplitude vary from 50Ω to 300Ω for a frequency range of 1 kHz to 10 kHz was developed using proposed method. In case of conventional power amplifiers that use analog ICs for generating unipolar switching SPWM waveforms, the PWM waveforms are present continuously and hence the MOSFETs of H- bridge are switched at a frequency equal to the triangular wave frequency always. A dedicated circuit is generally designed to switch off the MOSFETs when signal is not present, as the sonar signals normally present only short duration.

In the proposed digital method the micro controller can be programmed in such a way that the SPWM can be generated only if it is required. Remaining duration the signal signals can be made zero (Fig.5). The gain of the amplifier is controlled by generating SPWM signal for different modulation indeces.

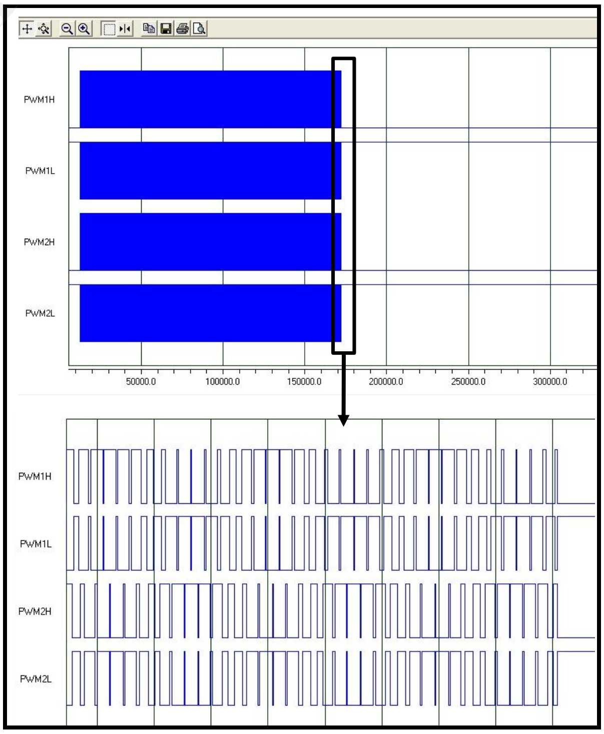


Fig. 6. MPLABSIM output Signals for H-bridge Devices

Microchip's controller dsPIC 30F2010 was used for generation of SPWM signals of sonar waveform. Four SPWM waveforms generated using the PIC microcontroller which consists of gating signal for the high side devices as well as the low side devices of the MOSFET based full bridge, is shown in Fig 6 (MPLABSIM output). Opto-coupler HPCL2630 is used for

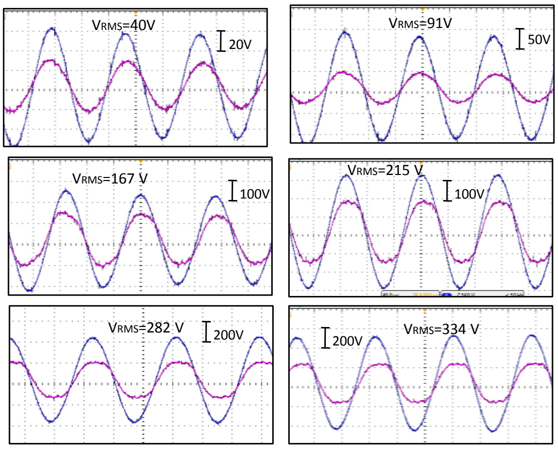


Fig.7. Output Voltage and current of digital SMPA at different power levels when connected across a transducer load

isolating microcontroller output from power circuit in the present design. The isolation circuitry is followed by MOSFET driver circuit (IR2110, FAN 7392) that uses bootstrap technique to drive high side devices

The H-bridge output is isolated using an isolation transformer followed by a low pass filter. The output voltage and output current across actual transducer element for different power level is gin in Fig. 6. It is to be noted that the current waveform shape vary as the power increases because the piezo electric transducer element offers complex load to the power amplifier and the impedance vary with the power.

The output voltage of the power amplifier (after transformer and power filter) for different power levels expressed in dB(which can be achieved by varying MI), is shown in Fig 8. It can be observed that the signal has very less distortion even at low power levels due to the digitally generated SPWM signals. The output voltage waveform across the load (Mark1) and the input current from the HT DC (Mark2) are shown in Fig 9.

Since SPWM with controllable dead time is also possible in microcontrollers, the losses during the switching transitions can be greatly reduced. The loss reduction enhances the efficiency of microcontroller controlled switched mode power amplifier. The protection of the power amplifier and the monitoring of the parameters are easy if the controllers are programmed accordingly.
Since the components are less and the pulses are generated only when transmission is required, micro controller based power amplifier is compact and highly efficient. High power requirement also can be met with only very small modifications in program and modularity in power circuits.

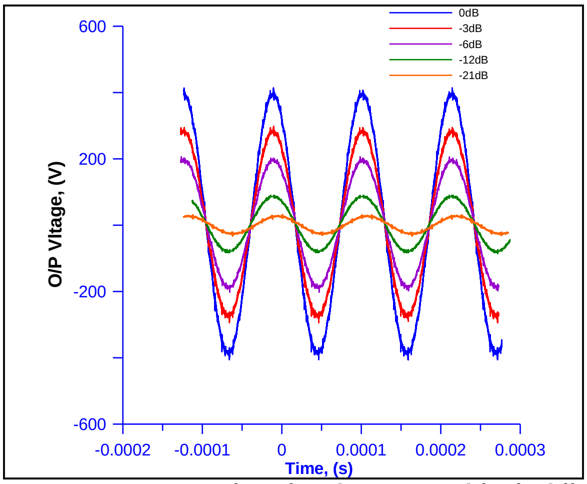


Fig.8. Output waveforms from the Power Amplifier for different power levels

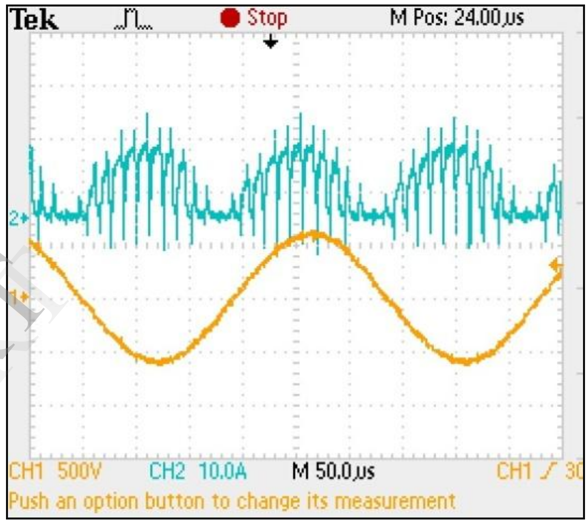


Fig. 9. Output Voltage and Input Current (supply current from the DC source)

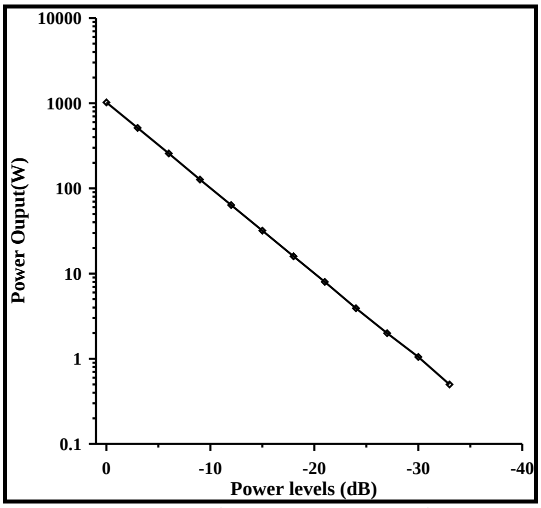


Fig. 10. Linearity of power levels in steps of -3dB measured in prototype

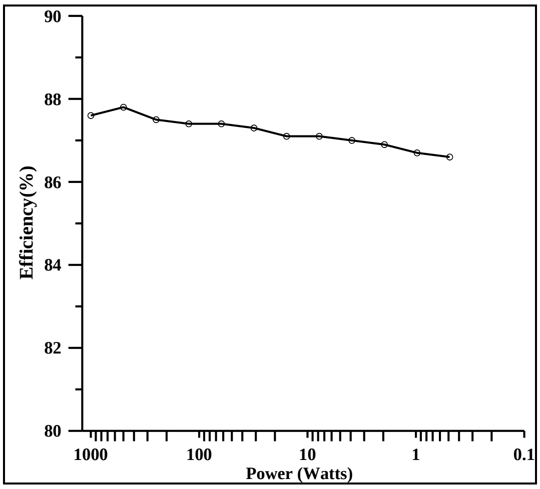


Fig. 11. Efficiency of prototype for different power levels

It can be seen from the experimental data (Fig 10) that the system is very linear over the power ranges of interest. The dynamic range that the sonar transmitter expected to work is well within this linearity range. The efficiency >86% in all power levels (Fig 11) ensure the less heating of the power devices and hence the system is very compact

VII. CONCLUSION

The switch mode power amplifiers are preferred over its linear counterpart in low frequency sonars because they occupy less volume and are compact and need less cooling arrangements, due to high efficiency. Conventional method of design of switch mode power amplifiers use many control circuitries for effective operation and protection of power amplifiers. Microcontroller based switch mode power amplifier incorporates all the control functionalities in programming and gives a cost effective solution to volume, cooling arrangement and complex control. Microcontroller also gives the PWM signals that include dead band control, and minimises the losses during switching transients. A prototype of 1 kW Microcontroller controlled switch mode power amplifier for underwater applications is developed and its performance is evaluated.

VIII. ACKNOWLEDGEMENT

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