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Analysis and Simulation of Parallel DC-DC Converter fed Sonar Power Amplifiers

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Abstract—* Parallel operation of power amplifiers aims to develop higher output power at low current stress. To improve the reliability of parallel connected converter systems, the load current must be distributed among the converter modules. The total power delivered at the output is the sum of the individual module powers. In parallel operation, the voltage across each module will be the same and it is the current that decides the amount of power delivered to the load. By specifying the required output power from each module and knowing the load impedance, the required output current can be calculated which serves as the reference. The output current from individual modules are extracted and compared with their respective reference current quantity to generate the control signals. These control signals are used to switch the DC-DC converter fed SONAR power amplifier. Thus, the output of the DC-DC converter is adjusted according to the reference current specified and thereby the input to the power amplifier gets adjusted. The feasibility of the proposed control is demonstrated by simulation results. Simulation is done using MATLAB/SIMULINK.

Index Terms—**Digital Control, DC-DC Converter, Power Amplifier (PA), Pulse Width Modulation (PWM).**

I. INTRODUCTION

SONAR an underwater equivalent of radar, exploits acoustic energy for detection, localization, tracking and classification of underwater targets. The term sonar is an acronym for Sound Navigation and Ranging. Sonar system consists of underwater transducers, front-end signal conditioning units, signal processors, and displays. Sonar transducers transmit acoustic power and pick up the echo returns or merely listen to the underwater sounds, process the signal and provide information about targets on the display units. [1] A typical signal generation circuit which consists of a high end processor generates a signal with particular frequency, pulse length and pulse repetition rate. The signal is then given to the power amplifier for amplification. The power amplifiers in turn are connected to sonar transducers element which generally consists of piezo-crystals for excitation. The power amplifier (PA) is a key element in transmitter systems, aimed to increase the power level of the signal at its input up to a predefined level required for the transmission purposes. The power amplifiers are usually provided the DC supply they require from a switch mode power supply. The switch mode power supplies used will have to tolerate variations in its input supply which is common in ships, especially when large loads are turned ON. Reliable supply is of utmost importance to sonar system. An unreliable supply can damage whole system's performance and undermine its usefulness, especially during critical war like conditions. In power supply systems for higher power demand the parallel operation of standard converter modules is taken more and more into consideration. There are two reasons why converters are operated in parallel. One is to provide more current than available from a single unit and will help to reduce the current rating of the devices used. The second reason to connect units in parallel is to provide a back-up when one unit fails. This is also calledN+1 redundancy. The parallel connection offers several advantages like, improve system reliability, enhance redundancy, reduce cost of development, cover wide power range, existing systems extended easily [2]. The main problem occurring with the parallel operation is the accurate distribution of the total power to each module to avoid stress of a single module. The previous methods to equalize the modules inductor currents are presented in literatures [3]-[6].This paper discusses control of current sharing in parallel connected DC-DC converter fed power converter sonar amplifiers using tolerance band control. The simulation of parallel DC-DC converter fed power amplifier is implemented in this paper. The power amplifier circuit is gated using unipolar PWM technique. These signals are external signals for the SONAR application that are provided by an external gating circuit. Hence these signals are not available to provide the control to the power amplifier and thus we control the input to the power amplifier. We control the gating to the DC-DC converter with a feedback loop from the output and obtain the required current sharing property. MATLAB/SIMULINK simulations are carried out to verify the feasibility of the project.

II. CIRCUIT AND WORKING OVERVIEW

To control the output of the power amplifier, we can either adjust the input to the system or we can adjust the duty cycle of the switching signals. For the SONAR application, the PA switching signals are generated from an external source and are readily available as PWM signals. Hence, the only alternative available is to adjust the input to the system for the required current sharing. We use a DC-DC converter at the input side of the PA for this purpose whose gating is adjusted to produce the required output at its terminals that serves as the input to the PA. Parallel system is obtained by connecting together the output terminals of two similar modules. The system consists of control circuits, inverter circuit or full bridge circuit, diode bridge circuit, power transformer and filter circuit.

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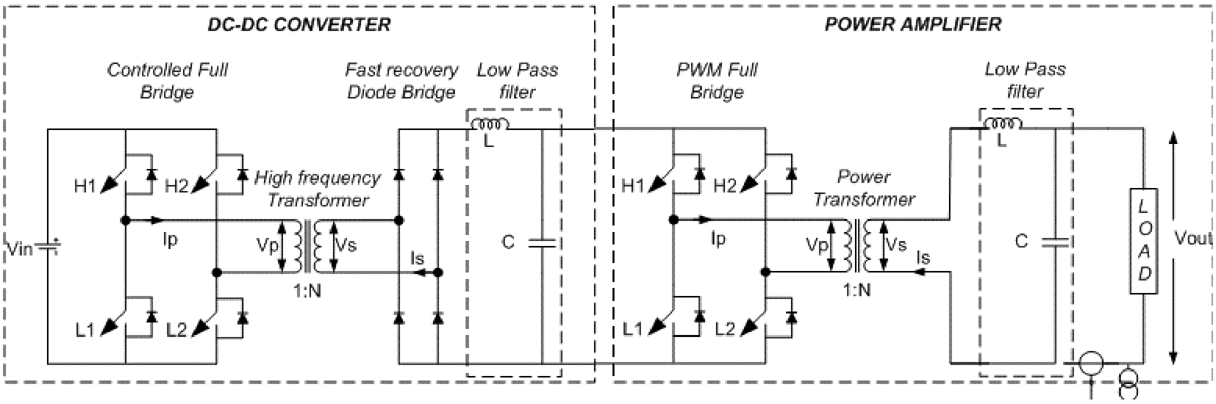

Fig. 1. Circuit diagram of one DC-DC converter fed sonar power amplifier

The feedback from the output is used to drive the DC-DC converter bridge. The controlled output of DC-DC converter is then rectified by a diode bridge circuit and then fed to step up transformer to get the required output level. LC filter is used to reduce harmonic content. The output of the transformer is then fed into the power amplifier bridge whose switching is controlled by externally generated PWM signals. This inverter pulses are stepped up and filtered out to excite the transducer crystals. The total acoustic power radiated by the projector is P, which is less than the electrical power supplied to it, Pe, and the ratio of these is the projector efficiency, E. Thus, increasing Pe can result in increased power radiated by the projector. This is achieved by a power amplifier circuit shown in Fig. 1. The power developed at the terminal is dependent on the supply voltage V_{in}, the modulation index m_a, the transformer turns ratio N, the filter efficiency etc. The PA bridge is controlled by PWM signals that are external signals generated from a separate control card. Hence, we use a DC-DC converter circuit with controllable switches. The DC-DC converter is composed of an inverter and a rectifier. The power amplifier is composed of an inverter. The inverter consists of a transformer and four power MOSFETs used as controllable switches H1, L1, H2 and L2. The transistors in each switching leg are driven by non-overlapping voltages that are out of phase by 180◦. The maximum duty cycle of the gate-to-source voltages is slightly less than 50%. The waveforms of the gate to source voltages should be non-overlapping to avoid cross-conduction. The individual gate control signal for the switches are to be provided across the gate (base) and source (or emitter) terminals of a particular switch. The gate control signals are low voltage signals referred to the source (emitter) terminal of the switch. For an n-channel IGBT, when gate to source voltage is more than threshold voltage for turn-on, the switch turns on and when it is less than threshold voltage the switch turns off. The threshold voltage is generally of the order of +5 volts but for quicker switching the turn-on gate voltage magnitude is kept around +15 volts whereas turn-off gate voltage is zero or little negative (around –5 volts). The isolation transformers of the DC-DC converter and the power amplifier are not required to store energy. Its magnetizing inductance Lm should be large enough to reduce the current through this inductance. On the other hand, if the magnetizing inductance is too large, it requires a large number of turns and is physically large. Ideally, the dc component of the current through the magnetizing inductance is zero. A coupling capacitor may be added in series with the primary winding to achieve zero dc component of the current through the magnetizing inductance and thus remove an imbalance of the magnetic core. The full-bridge converter is well suited to high-power applications, usually from 0.5kW to several kilowatts. It offers the highest power levels among all converters. In very high-power applications, insulated gate bipolar transistors thyristors, or MOSFET-controlled thyristors are used as switching devices. In addition, two or more power switching devices may be connected in parallel to increase current capability of every switch and output power levels [7]. The bridge rectifier is suited for high output voltage applications because the voltage stress of the diodes is V_{in}/n, which is half of the transformer center-tapped rectifier. This rectifier is not suitable for low-voltage applications because two diodes conduct when two switches are ON, and the total forward voltage across the two diodes may become comparable with the output voltage, resulting in low efficiency. [8]-[12]

III. SIMULATION AND RESULTS

MATLAB/Simulink model of the parallel DC-DC converter fed power amplifier is shown in Fig. 2. They are connected in parallel for higher power rating. The design parameters for the simulation circuit are given in the Table I. The filter is designed for a cut off frequency of 2500 Hz. It will allow all the frequencies below 2500 Hz to pass through and reject all the high frequencies. The design is verified using MATLAB bode plot shown in Fig. 3. -3dB point in the magnitude plot gives the cut-off frequency value. The designed value of cut-off frequency 2500Hz is obtained at the -3dB point and hence we can conclude that the designed filter is satisfying the parameters.

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A. Reference Current Calculation

The control signals are generated by comparison of the power amplifier output current with a reference current as shown in Table II. In the proposed DC-DC converter fed power amplifier, the control signals generated are used to control the switching of the DC-DC converter to implement proper current sharing. The control signals for the power amplifier are externally generated and hence the user has no access to it. The magnitude of the reference current specified determines what percentage of the total required power has to be shared between the 2 parallel modules. The total output power required and the individual module powers are governed by the following equation,

$$P_{total} = P_1 + P_2 \quad (1)$$

Where, P_1 is the power output of module 1 and P_2 is the power output of module 2.

$$P_1 = I_1^{\,2} \times R_L \quad (2)$$

$$P_2 = I_2^{\,2} \times R_L \quad (3)$$

If module 1 has to generate P_1 Watts of power and module 2 P_2 Watts, then the RMS currents to be to be produced is calculated from (2) and (3) as below,

$$I_1 = \sqrt{P_1 / R_L} \quad (4)$$

$$I_2 = \sqrt{P_2 / R_L} \quad (5)$$

The reference is specified as the peak value of current to be produced. It is calculated from (4) and (5) as below,

$$I_{ref1} = I_1 \times \sqrt{2} \quad (6)$$

$$I_{ref2} = I_2 \times \sqrt{2} \quad (7)$$

Thus, the equations (6) and (7) give the values of the reference current.

TABLE I. Simulation System and Design Parameters

Input supply	300 V DC SUPPLY
Output power	2000 W
Output frequency	2500 Hz
PA switching frequency, f_s	50 kHz
Dc/dc converter transformer turns ratio	2
PA transformer turns ratio	1.9
Dc-dc filter values	L_1=0.0001nH, C_1=0.000001pF
PA filter values	L_f=7.5mH, C_f=0.375µF
Load impedance	100Ω-200Ω

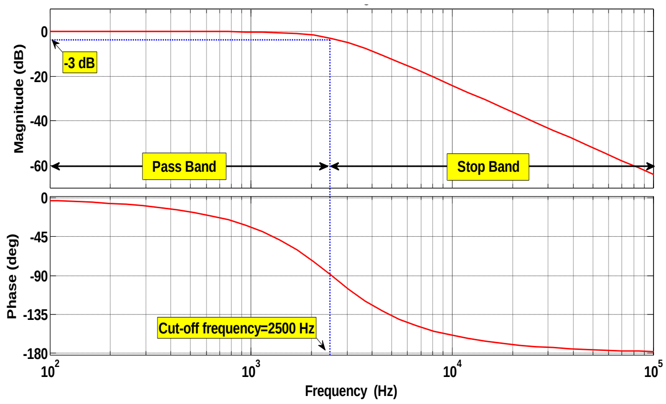

Fig. 3. - MATLAB/Simulink bode diagram of filter transfer

TABLE II. CONTROL ALGORITHM OF THE DC-DC CONVERTER SWITCHING

$I_{ref} \geq I_{act}$	H_1 on, L_1 off
$I_{ref} < I_{act}$	L_1 on, H_1 off
$-I_{ref} \geq I_{act}$	H_2 on, L_2 off
$-I_{ref} < I_{act}$	L_2 on, H_2 off

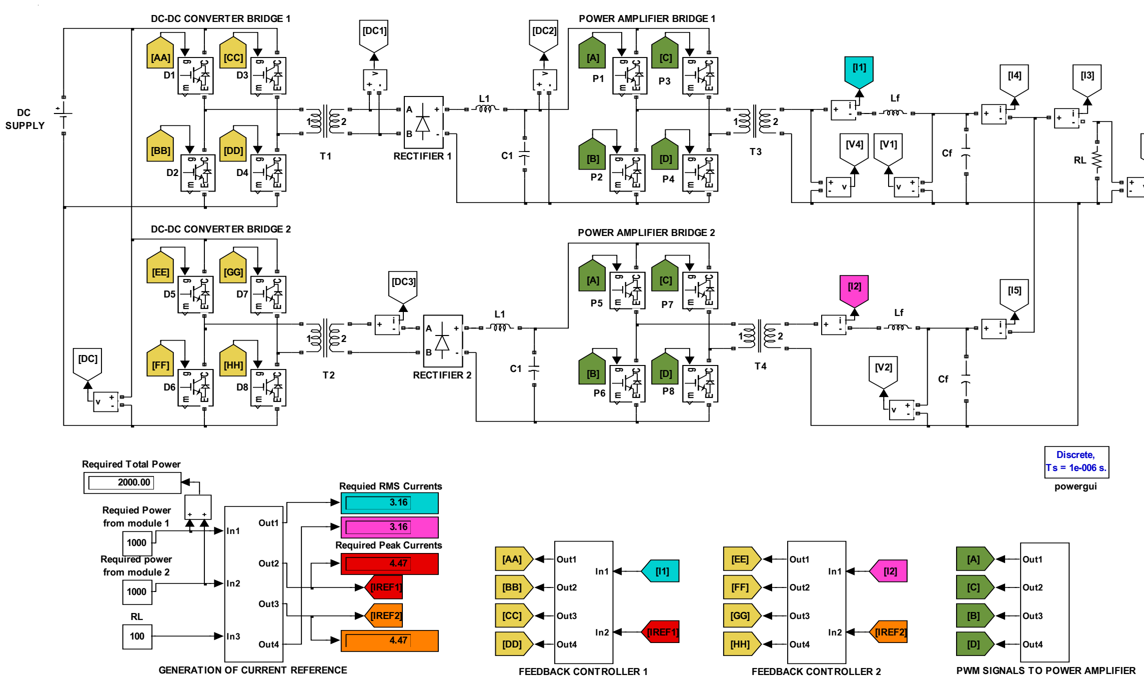

Fig. 2. MATLAB/Simulink model of the DC-DC converter fed power amplifier

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B. Generation of Gating Pulses

The DC-DC converter bridge is driven by signals obtained from the feedback loop. The reference current is made to follow the actual module currents as shown in Fig. 4. The reference current is calculated from the power requirement of each module. PWM with Unipolar voltage switching technique uses two inverted sine waves as modulating signals for the two legs of the inverter. Here, the legs of the full bridge inverter are controlled separately by comparing V_{tri} with $V_{control}$ and $-V_{control}$, respectively as shown in Fig. 5. Unipolar SPWM voltage modulation type is selected because this method offers the advantage of effectively doubling the switching frequency of the inverter voltage, thus making the output filter smaller, cheaper and easier to implement.

C. Output Waves

For the values given in Table I and for a load impedance of 100 Ω, let us specify that each of the modules supply the total power of 2000W equally, ie, each module supply 1000 W. As per the design given in *section A*, the rms reference current is 3.16A and peak is 4.47A for each module. The current waveforms in Fig. 6 show that, the actual current generated from each module equals the reference specified. The voltage waveforms in Fig. 7 show that, the voltage across each terminal is the same. Hence, the problem of the unit with the higher output voltage supplying all the current until it reaches its current limit setting could be avoided. The Power waveforms in Fig. 8 show that, each module generates the amount of power specified. Thus, from the above analysis it is clear that the individual modules can be made to operate at desired power by specifying the reference current to the controller.

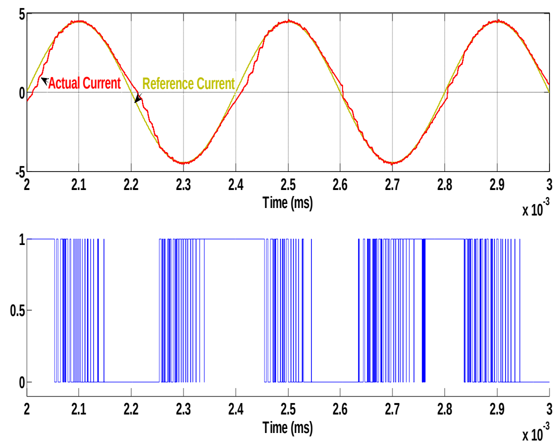

Fig. 4. - Generation of switching pulses DC-DC Converter (a) Comparison of reference and actual current (b) Gating pulses to H1

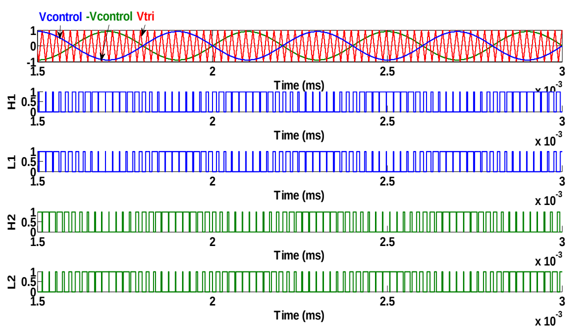

Fig. 5. - Generation of PWM switching pulses for PA (a) Comparison of Reference and Control Signals (b) Gating Pulses to H1 (c) Gating Pulses to L1 (d) Gating Pulses to H2 (e) Gating Pulses to L2

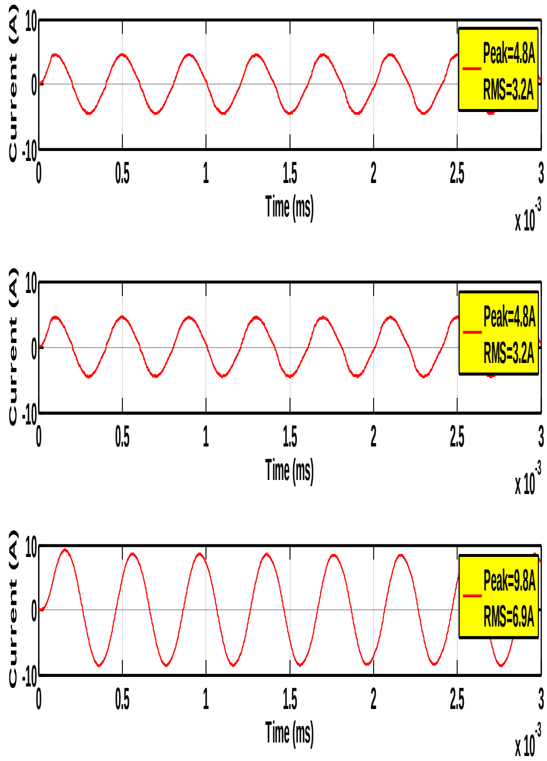

Fig. 6. MATLAB/Simulink waveform of current for a power of 2000W (a) Current from module 1 (b) Current from module 2 (c) Total output current

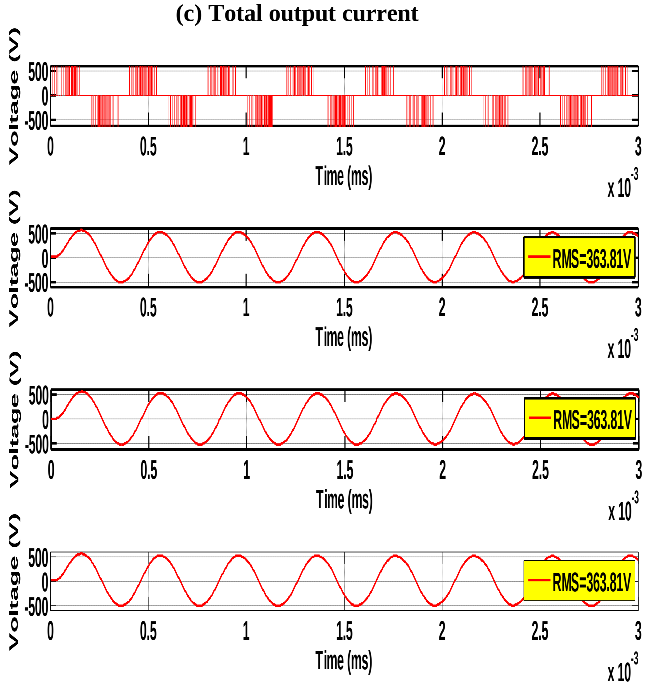

Fig. 7. MATLAB/Simulink waveform of voltage for a power of 2000W (a) Non-filtered PWM output from transformer terminal (b) Voltage of module 1 (c) Voltage of module 2 (d) Total output voltage

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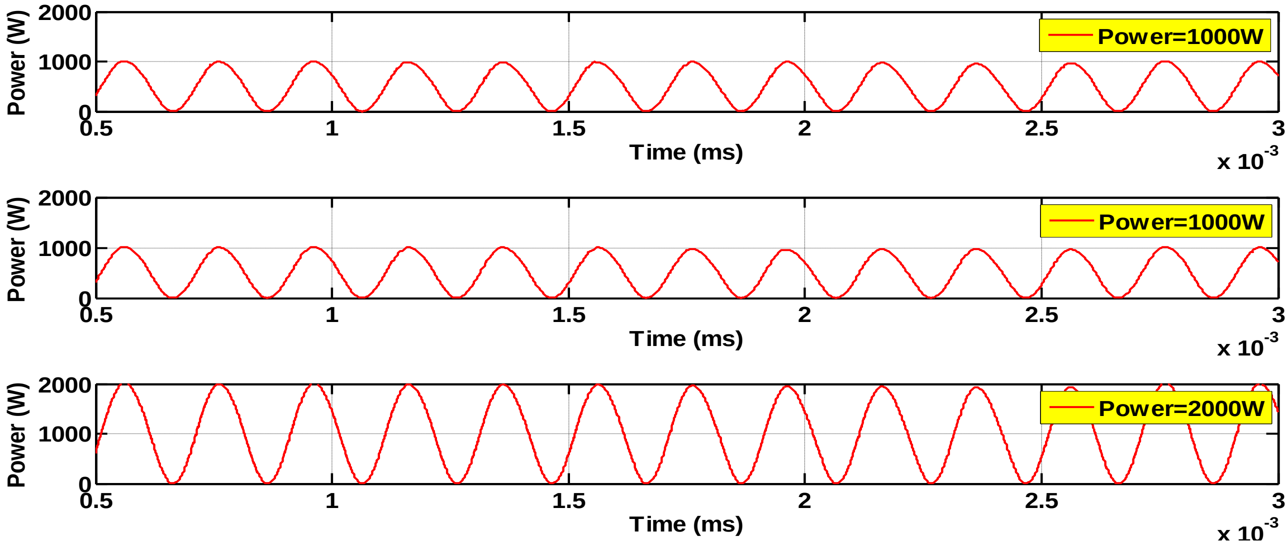

Fig. 8. MATLAB/Simulink waveform of power output of 2000W (a) Power output of module 1 (b) Power output of module 2 (c) Total power output

A. Simulation Analysis

An analysis is done for the results obtained for the following conditions,

1) Constant supply, Varying Load, Varying reference current
2) Constant supply, Varying Load, Constant reference current
3) Varying supply, Varying Load, Constant reference current

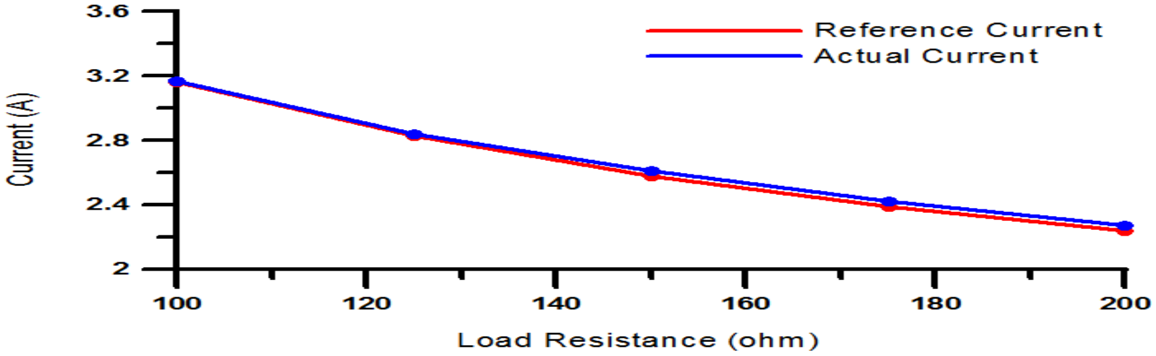

Fig. 9. Plot showing actual current following reference current with varying load

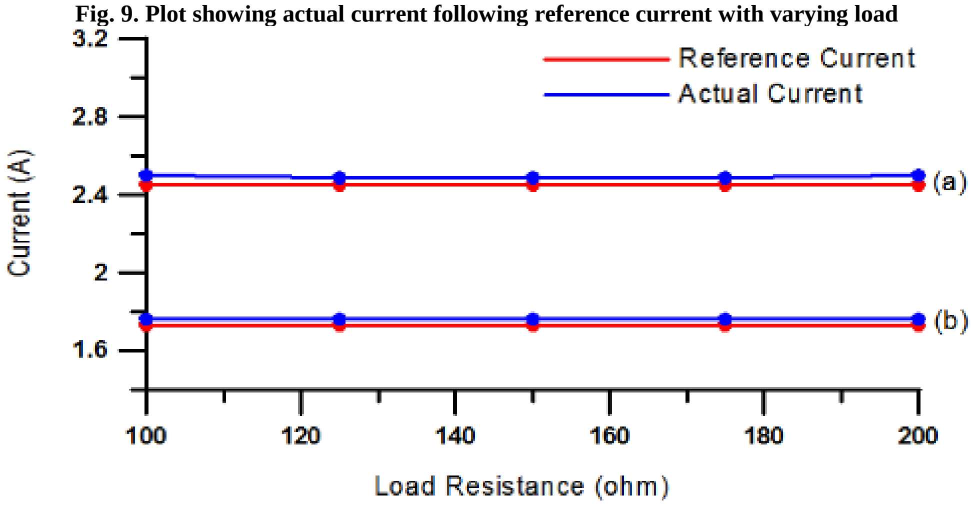

Fig. 10. Plot showing constant current with varying load

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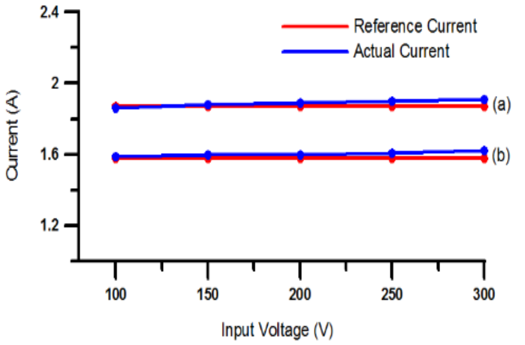

Fig. 11. Plot showing constant current with varying supply

Fig. 9 shows that the reference current is decreased with increasing load. This variation in reference current is fed as input to the controller which controls the gating to the DC-DC converter thereby making the actual current to follow the reference. Fig. 10 shows that the current reference is kept constant and the load impedance is varied. The variations at the output load do not cause the actual current to deviate from the reference. Fig. 11 shows that the current reference is kept constant and the input voltage is varied. The variations at the supply voltage do not cause the actual current to deviate from the reference.

IV. CONCLUSION

The proposed sonar system finds application mainly for underwater navigation and surveillance. Civilian uses include determination of water depth, mapping the ocean floor, locating various objects in the ocean, determining the characteristics of ocean bottom, and even fish finding. Simulation of parallel connected DC-DC converter fed power amplifier modules is discussed in the paper. The parallel connection offers several advantages like, improve system reliability, enhance redundancy, reduce cost of development, cover wide power range, existing systems extended easily. The accurate distribution of the total power to each module is done using tolerance band current control method. The power amplifier is a class D amplifier which is also known as the switching amplifier. It offers high efficiency compared to the linear power amplifier. Control of PA using DC-DC converter switches provides reliable operation to the system. Analytical, simulation results of the power amplifier have been presented.

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