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Design and Implementation of 40W Magnetic Amplifier Controlled Dual Output Forward Converter for Space Application

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Abstract: **The forward converter is widely used in space- grade DC-DC power supplies due to its electrical isolation, high efficiency, and simple voltage step-down capabilities. However, traditional PWM control on the primary side cannot accurately regulate multiple output voltages due to the complexity of the feedback, and changes to duty cycle to achieve regulation. This paper proposes a dual-output forward converter employing a Magnetic Amplifier (Mag-Amp) to achieve regulation of volts as well as feed-forward control at the input to improve transient response. The converter has a switching frequency of 140 kHz with a maximum of 0.4 duty cycle and total output power of 40 Watt. The Mag-Amps regulate on the secondary side using reactor saturation to eliminate active switching devices and improves reliability. This also reduces electromagnetic interference (EMI). In addition to the Mag-Amps, a feedforward control loop regulates transients in the output voltage and stabilizes the output in the case of input voltages varying, significantly improving the transient response. The converter included some auxiliary features, such as current sensing, input undervoltage protection. Experimental results showed that voltage ripple was less than 30 mV, line and load regulation was within 0.2 percent for a variety of loading conditions, demonstrating that the combination of Mag-Amp and feedforward control could provide a stable, accurate, and efficient multi-output DC-DC power supply**

Keywords: **Forward converter, Magnetic Amplifier, Line-load regulation, Feed-forward**

I. INTRODUCTION

In satellite and aerospace applications, space grade DC-DC converters are required when efficiency, high reliability, and compact design are critical. Forward converters, as shown in Figure 1, are the most common topologies used in these applications due to their electrical isolation, good step-down voltage capability, and simplicity of control [1]. Although, conventional primary-side PWM control do not provide precise regulation over several outputs because of feedback and cross regulation [2].

Design of space grade converters has focused on improving regulation performance by using either very high frequency switching or non-conventional converter topologies, which also allow for lower switching losses and higher efficiencies. Modified boost and forward converter geometries have the potential to alleviate EMI and switching stress [3]. In the satellite power systems sector, commonly implemented solutions have been Magnetic Amplifier (Mag-Amp) post regulators, or in some instances, better passive post-regulators with a forward converter, as they want to achieve the output they desired out of power systems precisely. Both are examples to demonstrate systems that provide precise control, as they are not operating with active switching devices, which are acutely desirable in the space surrounding by severe radiation [4].

Additionally, voltage feedforward control methods have been proposed and applied in space-grade converters to improve line regulation and dynamic performance. The voltage feedforward methods produce a duty cycle adjustment in response to input voltage changes in a timely manner, and have faster transient responses compared to feedback control [5]. In further developments there are self-resonant forward converters and discrete PWM controllers, with the aid of recent developments, will help mitigate the shortage of high-frequency radiation-hardened PWM ICs and improve reliability and overall efficiency for space applications [6].

This paper reports on a dual-output forward converter design and implementation for space applications that utilizes Magnetic Amplifiers on the secondary-side for regulation, and a voltage feedforward control loop on the primary-side for regulation. The converter operates at 140 kHz with a duty-cycle of 0.4 and has a total output power of 40 W, the converter incorporates current sensing and input undervoltage as part of its protection features. Experimental results verify that the voltage ripple is less than 30 mV and that the line and load regulation is under 0.2% which demonstrates that it can be an efficient, compact, and stable power source for space systems [7].

II. BLOCK DAIGRAM

The Fig-1 describes the block diagram for proposed forward converter system. A dual-output forward converter topology using Magnetic Amplifier (Mag-Amp) regulation that provides isolated and stable DC outputs for space-grade systems. The converter operates within a 30–42 V input range and supplies two regulated 5 V outputs with different load currents. The system contains relatively simple protection, regulation, and filtering blocks to provide a reliable output across a broad range of the input voltage and loads.

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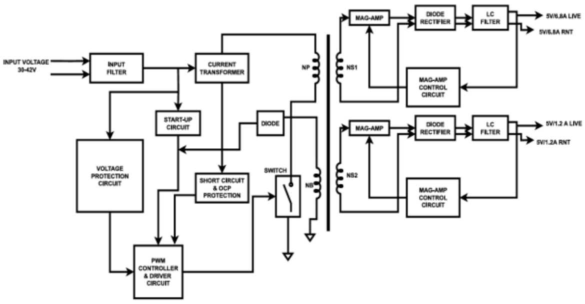

Fig 1 Block diagram of proposed system

Input Filter - This block attenuates high-frequency noise on the converter input while limiting any electromagnetic interference (EMI) that can be passed into the converter.

Voltage Protection Circuit- Monitors the input voltage and interrupts operation when the voltage signal exceeds the safe limits for operation. Start-Up Circuit- Manages the condition of the initial turn-on to avoid high inrush currents, which would otherwise compromise the safety of the converter operation.

Short Circuit and Overcurrent Protection- Recognizes faults at the output, e.g., short circuit or overload, and turns off the converter to protect the system. PWM Controller and Driver Circuit- This generates gate signals to command the switching of the power transistor, which in turn manages energy transfer into the transformer on each switching cycle.

Current Transformer- Monitors switching current in the primary side and provides feedback for condition monitoring of protection and control.

Main Transformer- Its purpose is to transfer energy from the primary winding to the secondary winding while maintaining isolation. There is one primary winding N_P and there are two secondary windings - N_{S1} & N_{S2}, designed to both outputs. Mag-Amp Units- Mag -amp Located on each of the secondary paths, these units are directly connected to a saturable inductor to regulate the pulse width of the output, allowing for precise

Mag-Amp Control Circuits- For both Mag-Amps, the control circuits are used to trim the magnetic saturation level of both Mag-Amps, in order to find a level that can provide stable voltage to the common output load.

Diode Rectifiers- It convert the AC waveform from the transformer secondary into a DC voltage.LC Filters- Further smooth out the rectified voltage to mitigate ripple from reaching the output.

Feed-forward Control- It Provides a response to line regulation variations for a given input voltage, allowing for improved stability of the output voltage when load demand shifts. For example, as the input voltage varies after it crosses a threshold, specific dynamic parameters of control can be altered by the feedforward control signal

III. WORKING OF PROPOSED SYSTEM

The Fig-2 shows that system set forth is a dual-output forward converter with Magnetic Amplifier (Mag-Amp) regulation for post-output voltage regulation. The designed system delivers isolated, regulated outputs from a single DC input supply, and is intended for space/aerospace applications where simplicity, stability, and low-noise is required.

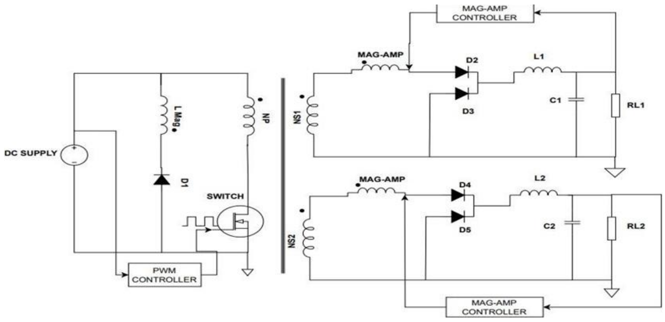

Fig 2 Circuit diagram of proposed system

The converter has a DC input power supply that feeds the primary winding (N_P) of a high frequency transformer through a switch (generally a MOSFET).
The switch is controlled by a PWM controller, which decides the pulse width and switching frequency based on system needs. It should be noted that there is a freewheeling diode (D_1) and reset winding (L_{Mag}) located so that the transformer core is reset each cycle, to repeat this process and continue converting power. On the secondary side, the transformer has two windings (N_{S1}& N_{S2}), where each winding (N_{S1}or N_{S2}) is dedicated to each of the output voltage rails.

These Mag-Amps are passive magnetic devices (saturable reactors) that simply delays the conduction of current to the output until the Mag-Amp saturates, trims the pulse width, and can therefore control output voltage very accurately, due to the paramount control of the time a magnetic field remains constant.

Output 1 Path: - N_{S1} outputs AC voltage and is controlled by the Mag-Amp. D_2 and D_3 provide rectification of the regulated waveform. Then through inductance L_1 and capacitance C_1 we can have a smooth DC voltage output across the load RL_1.The Mag-Amp Controller detects the output voltage and adjusts the saturation of the Mag-Amp to maintain regulation.

Output 2 Path: - N_{S2} performs a similar function; the AC output drives a second Mag-Amp. The rectification is done by D_4 and D_5. The filters L_2 and C_2 remove any ripple and provide a DC voltage output to load RL_2. A second Mag-Amp Controller regulates and monitors the output voltage at that output

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IV. SPECIFICATION AND DESIGN DETAILS

The design specification of the proposed forward converter is shown in Table 1.

Table 1 Specification of the Converter

Parameters	Specification
Topology	Forward Converter
Input range	30-42V
Output-1	5V/6.8A
Output-2	5V/1.2A
Switching frequency	140k Hz
Maximum duty cycle	0.4
Efficiency	>70%
Load & line regulation	<0.01%
Total power	40W

A. Transformer design

The forward converter's transformer isolates input and output, an important function for space applications. It operates at a high frequency (140 kHz) which also means a smaller transformer for the same output power, accommodating small design spaces and being a highly attractive feature in all designs. The area product method is employed to assess core size, wire size, and turns.

The optimum design is decided by the small size and lower dissipation of the transformer, so Window Factor (K_W), Flux Density (B_M) & Current Density (J) values are assumed, for optimal design.

K_W = 0.35

B_M = 0.12 Tesla

J = 6 Amp/mm^2

Efficiency = 70%

Maximum duty cycle (D_{MAX}) = 0.4

Switching Frequency (F_{SW}) = 140 kHz

Output Power (P_{OUT}) = 40 W

$$A_P = \frac{\sqrt{D_{MAX}} \times P_{OUT} \times (1+\frac{1}{Efficiency})}{K_W \times J \times 10^{-6} \times B_M \times F_{SW}} \quad (1)$$

An appropriate core will be selected which have an area product (A_P) greater than the calculated A_P.Hence, selected Pot Core: OR42213UG which will have a Cross-sectional Area, Ac=63.4mm^2,Window Area, Aw=28.39 mm^2, AL=4040 mH/1000 Turns.

Number of primary turns is calculated by using formula

$$N_p = \frac{V_{in(min)} \times D_{max}}{Bm \times A_c \times 10^{-6} \times F_{sw}} \quad (2)$$

$$N_p = \frac{V_{in(min)} \times D_{max}}{Bm \times A_c \times 10^{-6} \times F_{sw}} \quad (3)$$

$$T_{ratio} = \frac{N_s}{N_p} = \frac{V_{out}}{V_{in} \times D_{max}} \quad (4)$$

$$N_{s1} = N_{s2} = T_{ratio} \times N_p \quad (5)$$

$$N_{bais} = N_p \quad (6)$$

Demagnetizing or reset winding is equal to a number of primary winding since it has to demagnetize the flux in the primary winding before the next cycle starts.

$$N_{bais} = N_p \quad (7)$$

B. Magnetic amplifier design

Magnetic amplifier core selection using

$$A_{p_{mag}} = \frac{A_{x1} \times V_{withstand}}{B \times K_f} \quad (8)$$

selected Core: 2-L2016-W723 made of Nano crystalline.

C. Output filter design

The output inductor is responsible for storing energy and smoothing the current supplied to the load. It is designed based on the peak-to-peak ripple current requirement.

$$L = \frac{V_0 \times (1-D_{max})}{\Delta I_L \times F_{sw}} \quad (9)$$

$$C = \frac{\Delta I_L}{8 \times F_{sw} \times \Delta V_0} \quad (10)$$

D. Selection of MOSFET switch

There are several key parameters when selecting a MOSFET, the two main parameters are the Drain-Source voltage (V_{DS}), Drain current (I_D), ON resistance (R_{DS_ON}), gate charge (Q_G), and output capacitance (C_{OSS}). Each of these parameters will have an impact on the switching losses and conduction losses due to R_{DS_ON}. Both the size and type of MOSFET are chosen to minimize these losses. Proper selection of the MOSFET will provide the most efficient and reliable converter operation.

MOSFET 2N759213 250V, 0.022 Ohm, 32A@ 100° has been selected

E. Secondary diode selection

The selection of the output diode depends on the level of current and voltage on the secondary. The basic requirement on these diodes is their ability to operate at high frequencies. In switching action from a state turning ON to OFF, a standard signal or p-n diode's reverse recovery time is typically at the order of hundreds of nanoseconds. Conversely, fast recovery diodes give you the same transition time of under 100 nanoseconds. Schottky diodes exhibit minimal reverse recovery time, basically zero; therefore, Schottky diodes are particularly useful, since they have a low forward voltage drop (VFD), high current capability (IF), and low reverse recovery time (T_{rr}).

The selected diode is a 35CGQ100, 100V, 35A, TO-254AA, VFD: 0.6V.

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V. HARDWARE IMPLEMENTATION

The Fig 3 shows that hardware test setup incorporates a fabricated PCB board with the forward converter circuit. A DC power supply serves as the input source to supply power to the converter. An oscilloscope is used to view several switching waveforms, voltage ripples, and when necessary, validation of the monitoring timing.

An electronic load is connected at the output which supports the testing of the load regulation accuracy, efficiency, and overall performance during various operating conditions. The hardware test setup component utilizes the power supply, oscilloscope, electronic load, and PCB board, which allows for proper verification of the converter to ensure intended functionality.

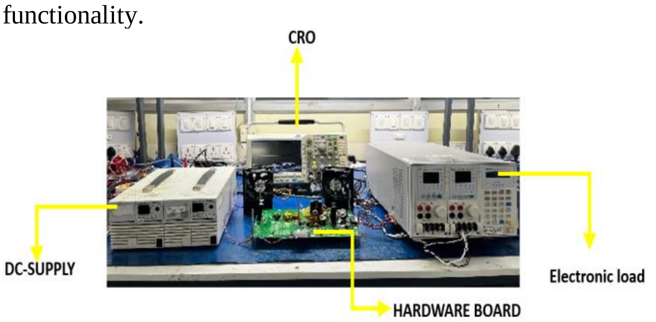

Fig 3 Hardware testing setup

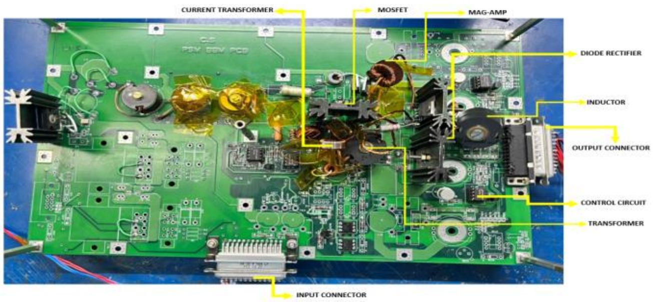

Fig 4 PCB board top view

Fig 4&5 shows the top and bottom view of the PCB provides an overview of the main power components of the forward converter, including the MOSFET switch, rectifier diodes, and output inductors. The input connector is used to connect the DC input voltage to the PCB and the output connector is used to connect the load.

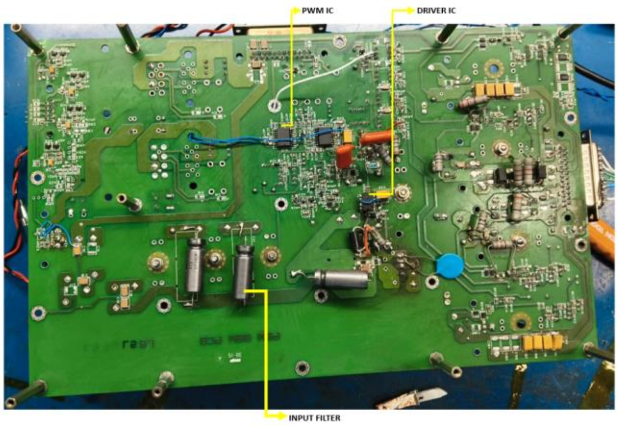

Fig 5 PCB board bottom view

VI. RESULT AND DISCUSSION

The forward converter discussed above was simulated with the TINA software to show the voltage and current waveforms in ideal conditions. The converter simulation was operational and stable to verify functionality before hardware testing. The Fig 6 shows that simulation waveform presented indicates the performance of the proposed forward converter in a steady-state using TINA software; the first and second traces demonstrate Output Voltage 1 and Output Voltage 2 respectively, which both reach a final voltage of 5 V after an initial oscillation period due to typical switching transients as indicated by the smooth voltage waveforms, demonstrating good voltage regulation and transient response. The third and fourth traces are representative of Output Current 1 and Output Current 2 respectively, stabilizing at ~6.8 A and ~1.2 A respectively. Both current outputs display an initial overshoot with a fair amount of ripple, but both started settling quickly indicating that control was achieved and that the loads were being handled properly.

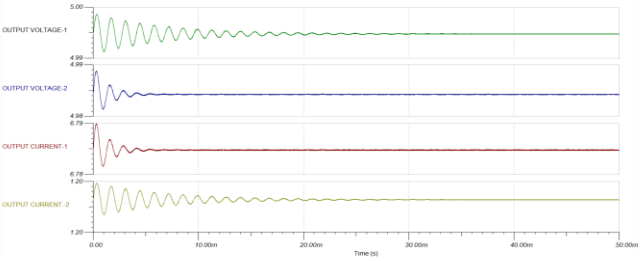

Fig 6 Simulation output of voltage and current

In the results from hardware section, critical waveforms, such as the MOSFET gate signals and V_{DS}, are captured in order to analyze the switching behavior and efficiency. Ripple voltage is captured to assess output stability and confirmation of design limits. Output voltage is captured for various load conditions to confirm regulation performance. In addition, input variation tests are performed in order to confirm line disturbance rejection and reliability of the converter.

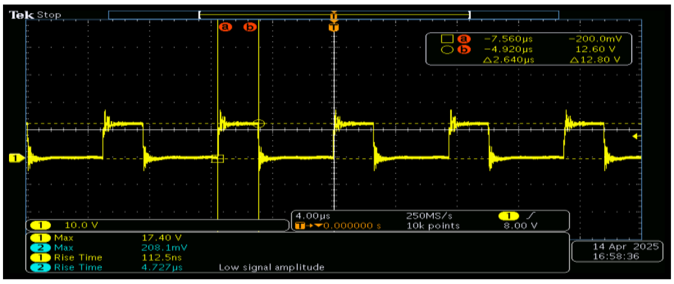

Fig 7 Gate pulse @30V input

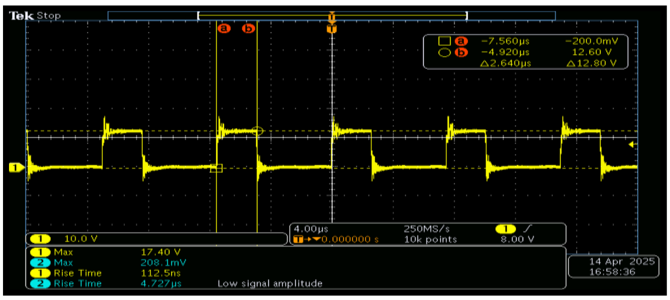

Fig 8 Gate pulse @36V input

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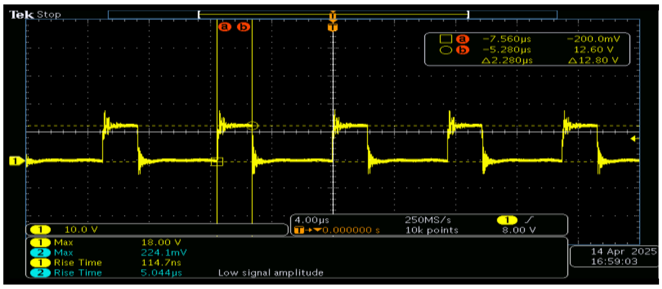

Fig 9 Gate pulse @42V input

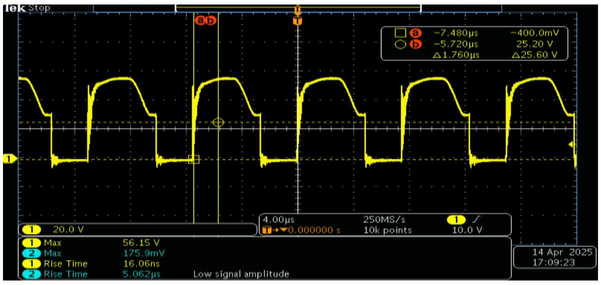

Fig 10 V_{DS}@ 30V input

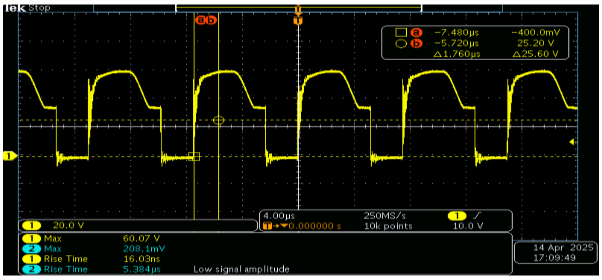

Fig 11 V_{DS}@ 36V input

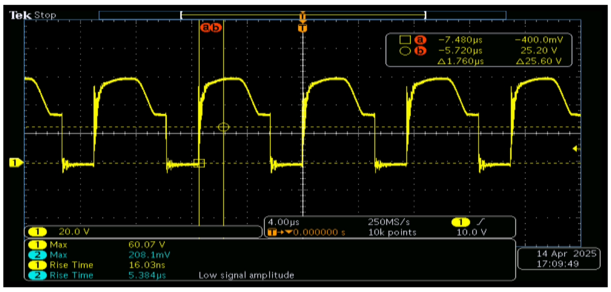

Fig 12 V_{DS}@ 42 V input

Table 2 V_{DS} , V_{GS} & duty cycle for various input

Input voltage	*Gate to source voltage*	*Drain voltage*	*Duty cycle*
30 V	17.40 V	56.15V	0.36
36V	18V	60.07V	0.31
42V	19.04V	68.63V	0.26

The table 2 shows the changes to gate voltage, drain-source voltage, and duty cycle at varying input voltage levels. Input voltage was raised from 30 V to 42 V, which reflected a small increase in gate voltage, suggesting stable driver operation. The drain to source voltage also changed proportionally to the input voltage level.

It is noteworthy that even though V_{DS} increased with the input voltage, the duty cycle decreased, as would be expected in a forward converter, to keep the output voltage constant. The converter's capability for feedforward control was demonstrated, and along with our attempts to model regulation stability across a wide variety of input voltages, it appears to work well together.

The output voltage ripple for both outputs at different input voltages is shown in Tables 3. The results for the 5V/6.8A output (Output-1) show that the ripple decreases from 25.6 mV when the input voltage is equal to 30 V to 20 mV when the input is equal to 42 V. The result for the 5V/1.2A output (Output-2) indicates that the voltage ripple goes from 27.2 mV at 30 V to 25.6 mV at 42 V.

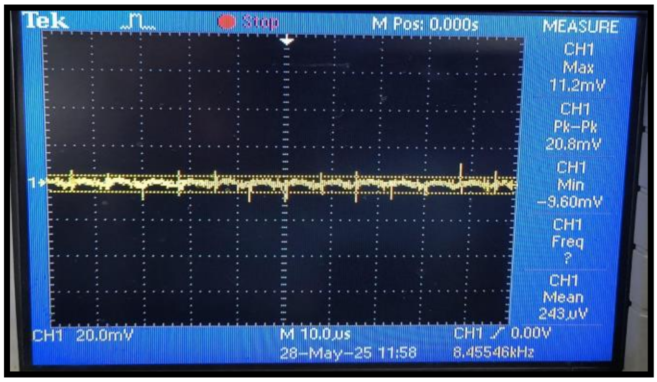

Fig 13 Ripple voltage @36V input for output-1

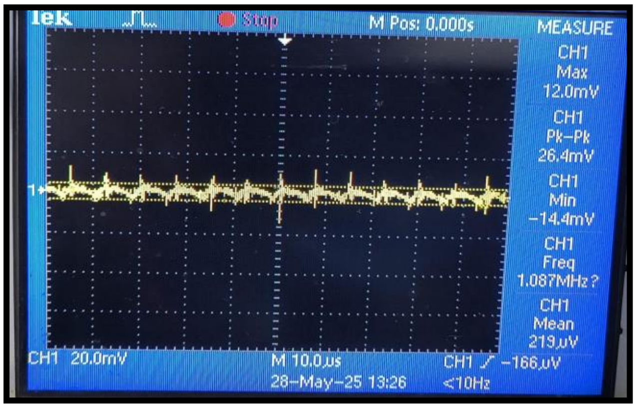

Fig 14 Ripple voltage @36V input for output-2

Table 3 Output ripple value for both output

Input voltage	*Ripple @output-1*	*Ripple @output-2*
30V	25.6 mV	27.2 mV
36V	20.8 mV	26.4 mV
42V	20 mV	25.6 mV

Table 4 load and line regulation for both output

Load	*Output voltage*			*Line Regulation in %*
	$V_{IN\,MIN} = 30V$	$V_{IN\,NOM} = 36V$	$V_{IN\,MAX} = 42V$	
100%	5.025V	5.025V	5.027V	0.01%
50%	5.025V	5.025V	5.027V	
10%	5.026V	5.026V	5.027V	
Load regulation in %	0.01%			

Table 5 Efficiency for output-1

Input voltage	*Input power*	*Output power*	*Efficiency*
30 V	46.9 W	34.17 W	72.85 %
36V	46.3 W	34.17 W	73.8 %
42V	46.3 W	34.18 W	72.69 %

Table 6 Efficiency for output-2

Input voltage	*Input power*	*Output power*	*Efficiency*
30 V	8.27 W	6.03 W	72.93 %
36V	8.17 W	6.03 W	73.8 %
42V	8.27 W	6.03 W	72.9 %

Table 7 Efficiency for both output

Input voltage	*Input power*	*Output power*	*Efficiency*
30 V	54.9 W	40.2 W	72.93 %
36V	54.2 W	40.2 W	73.8 %
42V	54.8 W	40.2 W	72.9 %

From the table 5,6 and 7 the efficiency of a converter is 73.8% at nominal input voltage and slightly dropped at minimum and maximum input voltage. But overall efficiency of an converter is greater than 70%.

VII. CONCLUSION

In summary, a 40 W dual-output forward converter that provides 5 V at 6.8 A and 5 V/1.2 A was successfully conceptualized and realized for space application specifications. The converter includes magnetic amplifier regulation and feedforward control to improve stability and response. The results of the experiment show excellent performance with line and load regulation within 0.01% for both outputs, guaranteeing precision voltage control. The system also achieves efficiency greater than 73.80% at nominal input voltage, proving its importance to high reliability space qualified power supply systems.

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