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Design and Implementation of Mag-Amp Controlled Dual Output Forward Converter with Input Voltage Feed-Forward Technique for Space Applications

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Abstract: **Power supply modules play a crucial role in modern power electronics by ensuring reliable and stable power delivery across a wide range of systems. In space applications, DC–DC converters are extensively employed to deliver regulated output power with high efficiency and operational stability. This paper focuses on the design and development of a dual-output forward converter operating at 140 kHz and implementing an input-voltage feedforward control technique. The UC2525 PWM controller is utilized for its features, such as, rapid transient response, soft-start capability, undervoltage lockout, and maximum duty cycle limitation. A Magnetic amplifier can also be used as a post regulator along with the Forward converter to improve the output voltage regulation and reduce the ripple (within permissible limit). The proposed system has been modeled and analyzed using LT Spice and TINA simulation tools. A hardware prototype is tested under different input voltages and load conditions at ambient temperature. Both Simulation and experimental results shows that the converter maintains stable operation, provides effective voltage feedforward compensation, and ensures accurate dual-output regulation, making it suitable for space applications.**

Keywords: **DC-DC Converters, Feed-Forward Control, Forward Converter, Magnetic Amplifier, Ouput Voltage Regulation.**

I. INTRODUCTION

Switched Mode Power Supplies (SMPS) address the limitations of traditional linear power supplies, which typically suffer from low efficiency and challenges in achieving voltage step-up. To achieve higher efficiency, compact size and reduced weight, SMPS are well suited for space applications. Current trends in space research emphasize the development of power supplies that are lighter, smaller, more efficient, cost-effective and highly reliable [1].

A DC–DC converter is a device that receives DC input and delivers DC output at a different voltage level. Depending on the configuration, the output voltage can be stepped up or stepped down based on the input voltage. In a basic DC–DC converter, a switching device is used to control the connection and disconnection of the power supply to the load. These converters are commonly employed to provide regulated and stable DC power for various power supply applications [2].Almost every electronic device operates on DC power. Since these devices differ in their characteristics, a single fixed DC source cannot satisfy all requirements. Therefore, a DC power supply unit is placed in between the main source and the load [3].

Basic topologies that are used for DC voltage regulation includes Buck, Boost, Buck-Boost, Cuk and Sepic, Fly back, Forward, Half Bridge and Full Bridge Converters [3]. Among these converters, Forward converter topology is selected for designing the power supply unit as it is most suitable for medium power applications and also has an added advantage of good reliability, compact size and ruggedness [4].

To improve the line regulation and to eliminate output voltage spikes caused by input line voltage variations, voltage feed-forward technique is used in the primary side of converter. In this technique PWM converter is used which automatically adjusts the duty cycle based on the input voltage. This approach offers effective line regulation throughout a large input voltage range and quick reaction to input line transients [5].

To enable proper load regulation, a magnetic amplifier is used in the secondary side of the converter. A magnetic amplifier or Mag-Amp is a type of electronic amplifier that uses the magnetic properties of materials to control the flow of electrical current, shown in Fig 1. It is robust and has radiation tolerance making it suitable for space application [6].

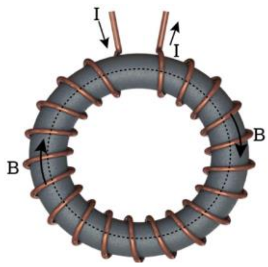

Fig 1: Magnetic Amplifier (Mag-Amp)

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This paper presents the design and implementation of 80W dual output forward converter for power supply applications. Both simulation and hardware have been carried out for a variable input voltage from 32 V to 42V DC. Simulation is carried out using LT Spice and TINA software. Hardware is a bread board model. The general bread board model is shown in Fig 2, which is widely used for hardware implementation. In the present work, the main aim is to build a power circuit using forward converter suitable for power supply applications.

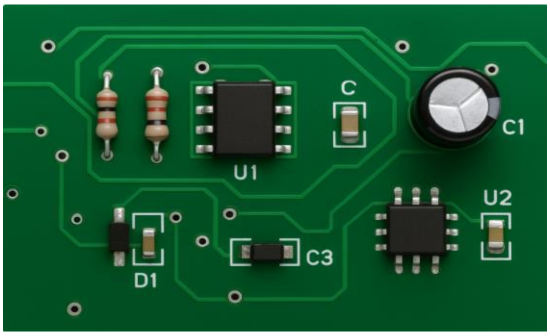

Fig 2: Bread Board Model

II. BLOCK DAIGRAM

The dual output 80W forward converter has been implemented based on the proposed specifications. The detailed block diagram of the proposed forward converter is as shown in Fig 3.

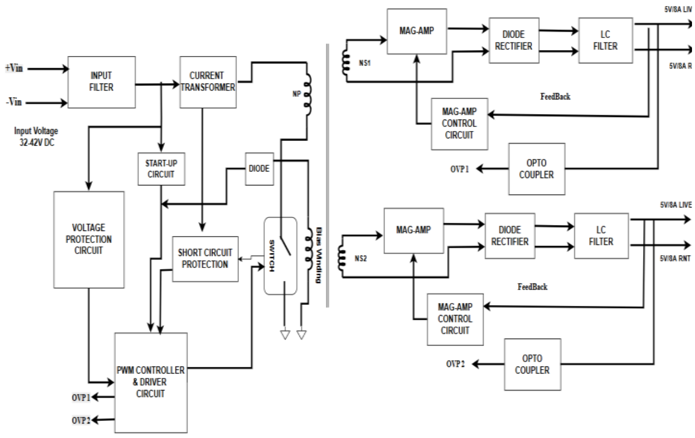

Fig 3: Block diagram of proposed system

Input Filter - In order to protect the converter from instances of overvoltage and overcurrent, relays are utilized on the input side. The relays provide a level of safety for the operation of the entire power system.
An EMI (Electromagnetic Interference) filter is also placed on the input stage to eliminate the unwanted effects of current, harmonics, and electrical noise. The EMI filter enhances the converter's efficiency and reliability by supplying noise-free DC power to the transformer's primary.

Start-up circuit and Bias winding - The start-up circuit provides power to the control ICs till the bias winding generates sufficient voltage needed for converter start-up. Once established, the bias winding provides the bias voltage needed to power the control circuitry, and this voltage must be higher than that of the start-up circuit. As a result, the PWM controller transitions to drawing current from the bias winding instead of the start-up circuit. The bias winding thus serves as a housekeeping supply, ensuring continuous power delivery to the PWM IC and associated circuits.

Current Transformer - A current transformer is employed to sense the input-current and safeguard the converter against overcurrent and short-circuit conditions.

PWM Controller and Driver Circuit - To control the input-side switch of the forward converter under input voltage variations ranging from 32 V to 42 V, a UC2525B PWM controller along with an HS4424B driver is employed. A feedforward voltage control approach is adopted to achieve a fast closed-loop response to line voltage changes at the primary side of the forward transformer, independent of load variations. The converter is designed to operate across the full input voltage range of 32 V to 42 V and regulate each output of 5 V/8 A over load variations from 10% to 100%, maintaining a fixed switching frequency.

Transformer - Transformer provides isolation and helps in energy Transfer. Ensure safety during electronics testing and servicing by preventing hazardous voltage contact. The transformer's turn's ratio determines the output voltage, allowing for flexible voltage regulation.

Magnetic Amplifier and Mag-Amp Controller - A Magnetic Amplifier, commonly referred to as Mag-Amp, does not function as a conventional amplifier despite its name. Instead, it utilizes the magnetic properties of its core to regulate voltage according to the requirement.

Diode Rectifier - Serve as a key component in power supplies, rectifier circuits, and switching applications. Block the negative half cycle of Pulsating DC (AC Component) and allow only the positive half to be converted into DC.

Output filters - It will provide consistent and stable output, removing any interference or fluctuations that could have occurred during the conversion. Typically, inductors and capacitors (LC) are utilized for filtering purposes.

Opto-coupler – Opto coupler is an electronic component that fundamentally acts as an interface between the two partitioned circuits with distinctive voltage levels. It is utilized to supply confinement between input and yield source.

III. WORKING OF PROPOSED SYSTEM

The working principle of proposed forward converter circuit is shown in Fig 4 [7]. It consists of a fast-switching MOSFET device, a transformer with its primary winding in series with the switch to the unregulated input supply and a diode rectifier followed by a filter which is connected to the secondary side. There are two modes of operation i) power transfer function mode ii) freewheeling mode [7].

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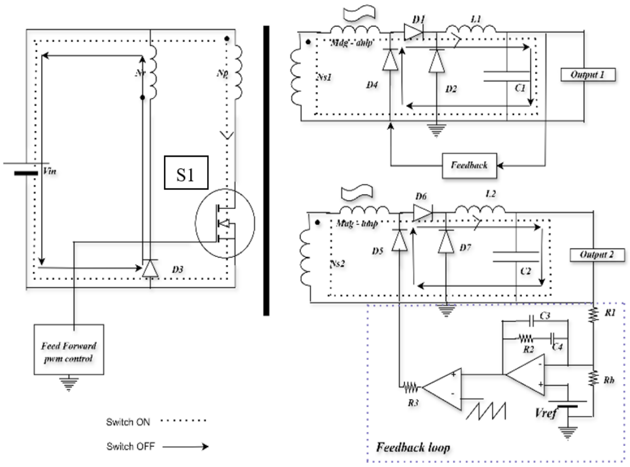

Fig 4: Circuit diagram of proposed forward converter

Mode 1 Operation:
This mode is called the power transfer function mode as shown in Fig 4. The current flows from the input source to the load through the transformer and filter network [7].
In this mode, the main switch (S1) is in ON state. Indicating that the input voltage is applied across the primary side of the transformer. Current flows through the primary side of the transformer as shown in Fig 3.5. With respect to the transformer dot convention, a corresponding voltage is induced on the secondary side which allows energy transfer from the primary to the secondary [7].
While switch (S1) is 'ON', the forward path diodes D1 and D6 become forward-biased and allow the secondary current flows through the low pass filter, which consists of an inductor (L) and a capacitor (C). This low-pass filter allows the majority of high frequency ripple components to be attenuated, allowing the load to be supplied with a steady DC output. Meanwhile, the freewheeling diodes D4 and D5 stay OFF because they are reverse-biased. Similarly, the diode D3 on the primary side, remains off due to the opposite dot position, basically implying reverse biased condition. This mode is called the power transfer function mode, because the energy is flowing from the input source to the load through the transformer and filter network [7].

Mode 2 Operation:
This mode is called the freewheeling mode as shown in Fig 4. It commences when the main switch (S1) is turned OFF and the current in the transformer primary winding goes to zero. Thus, the output filter inductor on the secondary side builds up the current to the load and returns through the freewheeling diodes D4 and D5. While this occurs, the forward path diodes D1 and D6 are reverse-biased. On the primary side, when the dot polarity reverses between the primary and reset windings, diode D3 will conducts, thus allowing the magnetizing current to circulate in the reverse direction and begin the core reset [7].

IV. SPECIFICATION AND DESIGN DETAILS

Table 1 presents the design specifications of the proposed forward converter.

Table 1: Specification of the Proposed Converter

Parameter	Specification
Input Voltage Range	32V – 42V DC
Selected Topology	Isolated Forward Converter
Output Voltage (for each outputs)	5V
Output Current (for each outputs)	8A
Switching Frequency	140 kHz
Output Power	80W
Efficiency	>65%
Line Regulation	<1%
Load Regulation	<2%

A. Transformer design

The transformer design parameters, Area of the conductor and number of turns are shown below [8].

Vin min = 32 V DC
Vin max = 42 V DC
Kw = 0.35
Bm = 0.12 Tesla
J = 6 Amp/mm2
Fsw = 140 K Hz
Pout = 80 Watts

$$A_p = A_c \times A_w \quad (1)$$

$$A_p = \frac{\sqrt{Dmax} \times P_{out} \times (1+\frac{1}{Eff})}{Kw \times J \times 10^{-6} \times Bm \times Fsw} \quad (2)$$

$$N_p = \frac{(Vin\, min \times Dmax)}{Bm \times Ac \times 10^{-6} \times Fsw} \quad (3)$$

$$Tratio = \frac{Vout + (V_D \times Dmax)}{Dmax \times Vin\, min} \quad (4)$$

$$Tratio = \frac{Ns}{Np} \quad (5)$$

$$Ns = Tratio \times Np \quad (6)$$

Selected core: 0R43019UG, material, Ur:5010, AL: 6680mH/1000T [8].

Where,
Kw = Window Factor
J = Current Density A/mm^2
Bm = Maximum Flux Density
Fsw = Switching Frequency Hz
Dmax = Maximum Duty Cycle
Vd = Diode Drop

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B. Magnetic amplifier design

Based on the area of the conductor, the mag-amp is selected as per the following design [8].

$$A_{p\ MA} = \frac{Ax \times Vwithstand}{Bm \times K_w \times 10^{-6}} \quad (7)$$

Where,

Ap ma = Area product of Mag-Amp
Ax = Wire area of conductor
Vwithstand = Withstanding voltage
Bm = Maximum Flux Density
Vd = Diode Drop

Selected Mag-Amp Core:

P/N: 6-L2016-W763 (Nanocrystalline Mag-Amp Core) [8].

C. Selection of Switching Device

Switching devices in power converters undergo extremely high electrical stress levels because there is rapid change in voltage and current. Thus, it is very important to select a proper switching device when designing switching converters. Commonly used devices include diodes, bipolar junction transistors (BJTs), metal-oxide-semiconductor field-effect transistors (MOSFETs) and insulated gate bipolar transistors (IGBTs) [8].

MOSFETs are preferred in:

- Frequency: >200 kHz.
- Wide range of line variations or load variations.
- Device of choice for blocking voltages less than 500V.
- A majority-carrier device: fast switching speed.

The peak voltage of the mosfet is calculated by using below equation,

$$V_{Peak\ MOSFET} = V_{in\ max} \times \left(1 + \frac{Np}{Nmag}\right) \quad (8)$$

Selected MOSFET: IRHM57260, 200V, 0.049 Ohm, 32@ 100 Deg [8].

D. Output Filters

The output voltage of transformer secondary is processed through rectification and filtering to obtain the required output. In the proposed converter, an LC filter is employed and selecting appropriate component values is essential. Proper filter design helps to minimize noise, reduce size and lower costs, which are key considerations for spaceborne applications. The design formulae for output inductor and output capacitor are mentioned in the below equations [8].

$$L1 := \frac{Vout1 \cdot (1 - Dmin1) \cdot Ts}{2 \cdot K1 \cdot Iout1} \quad (9)$$

$$C1 := \frac{K1 \cdot Iout1}{8 \cdot Fsw \cdot DeltaV1} \quad (10)$$

$$L2 := \frac{Vout2 \cdot (1 - Dmin2) \cdot Ts}{2 \cdot K1 \cdot Iout2} \quad (11)$$

$$C2 := \frac{K1 \cdot Iout2}{8 \cdot Fsw \cdot DeltaV2} \quad (12)$$

E. Secondary diode selection

When selecting the output diode for a given application it is determined by the voltage and current levels of the secondary side. Schottky diodes are the preferred choice, because they have a low forward voltage drop (approx. 0.6 V) and can handle substantial current (approx. 35 A) [8].

One advantage of a Schottky diode over conventional p-n junction diodes is that they have negligible reverse recovery time (Trr). While a p-n diode will have a reverse recovery time of several hundred Nano seconds changing from a conduction state to a blocking state, Schottky diodes have virtually no time delay. This makes Schottky diodes well-suited for high-frequency applications where low forward voltage drop, high current handling and very low reverse recovery time are required [8].

Selected Diode is 35CGQ150, Package: TO-254AA having V_F=150 V, I_F= 35 A, VFD= 0.6 V [8]

V. SIMULATION STUDY AND RESULTS

A. Simulation Of Dual Output Forward Converter Using LT Spice Software

The simulation model of closed loop control of Forward converter model in LT-Spice is shown in Fig 5 [9].

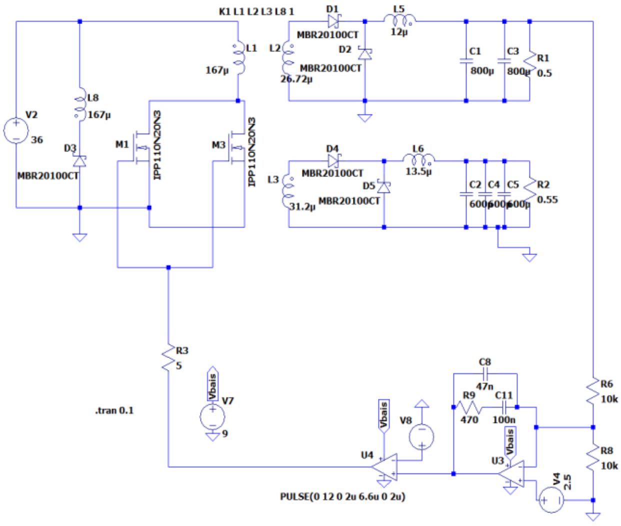

Fig 5: Simulation Model of Dual Output Forward Converter Using LT Spice

Input supply to the Converter is V2, D3 is magnetizing winding Diode, L8 is reset winding, M3 is MOSFET switch, L1&L2 are Transformer Windings Inductance, D1 & D4 are Secondary Diodes. Voltage feed Forward technique is implemented to regulate the output voltage and it is shown in simulation model, it has 2 op-amps U3 and U4.

For an input voltage of 32 V DC, the converter provides an output voltage of 5V with a load current of 8A. At start-up, the output capacitor is initially uncharged, causing the output voltage and current to begin from zero. As the switching action of the converter commences, energy is transferred through the transformer and rectifier stage to charge the capacitor, resulting in a gradual rise in voltage, as illustrated in Fig 6, which shows the corresponding output voltage and output current waveforms (Output I and Output II).

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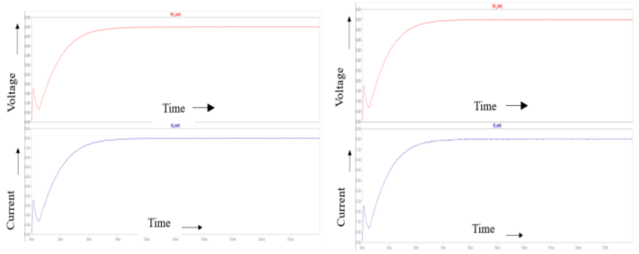

Fig 6: Output voltage and current waveforms (Output I and Output II), When input voltage is 32V DC

For an input voltage of 36 V DC, the converter provides an output voltage of 5V with a load current of 8A as illustrated in Fig. 7, which shows the corresponding output voltage and output current waveforms (Output I and Output II).

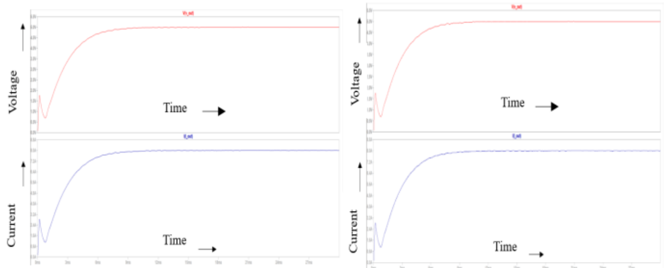

Fig 7: Output voltage and current waveforms (Output I and Output II), When input voltage is 36V DC

For an input voltage of 42 V DC, the converter provides an output voltage of 5V with a load current of 8A as illustrated in Fig 8, which shows the corresponding output voltage and output current waveforms (Output I and Output II).

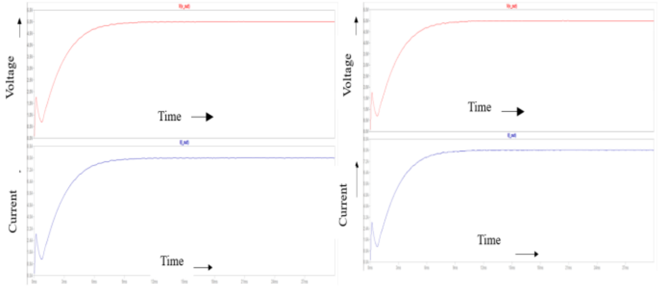

Fig 8: Output voltage and current waveforms (Output I and Output II), When input voltage is 42V DC

The output voltage and output current values (output I and output II) for a variable input voltage range of 32V, 36V and 42 V for above simulation model is tabulated in Table 2.

Table 2: Output voltage and current (Output I and Output II) of simulation model using LT Spice

Sl. No	Input Voltage	Output Voltage (V DC) (Output I&II)	Output Current (A) (Output I &II)
01	32	5	8
02	36	5	8
03	42	5	8

B. Simulation Of Dual Output Forward Converter Using TINA Software

The simulation model of closed loop control of Forward converter model in TINA Software is shown in Fig 9 [11]. From the Circuit model of Forward Converter, V1 is the input supply to the Converter. N1 is the transformer primary winding and N2 & N3 is the transformer secondary windings. Mag-Amp has been implemented on each output to improve load regulation. Voltage feed Forward technique is implemented to regulate the output voltage and it is shown in simulation model.

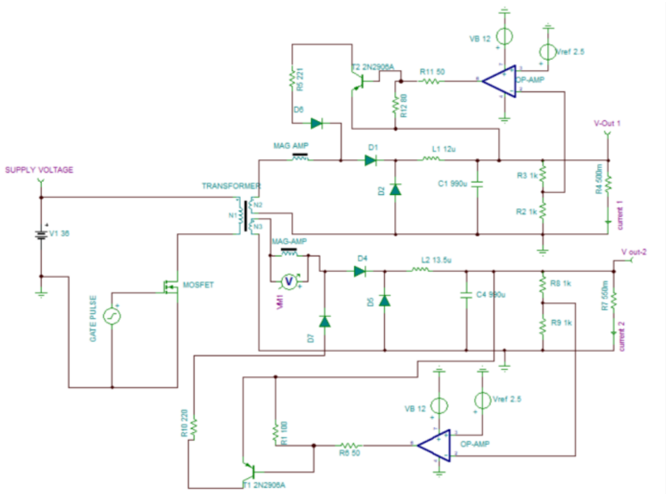

Fig 9: Simulation Model of Dual Output Forward Converter Using TINA Software

For an input voltage of 36 V DC, the converter provides an output voltage of 5V with a load current of 8A as illustrated in Fig 10 and Fig 11 which shows the corresponding output voltage and output current waveform.

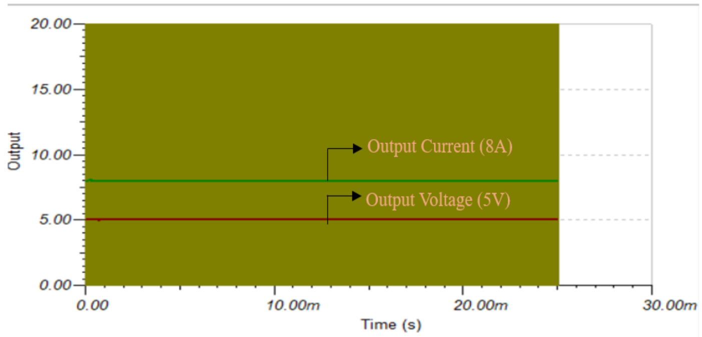

Fig 10: Output voltage and current waveforms (output I), when an input voltage is 36V DC

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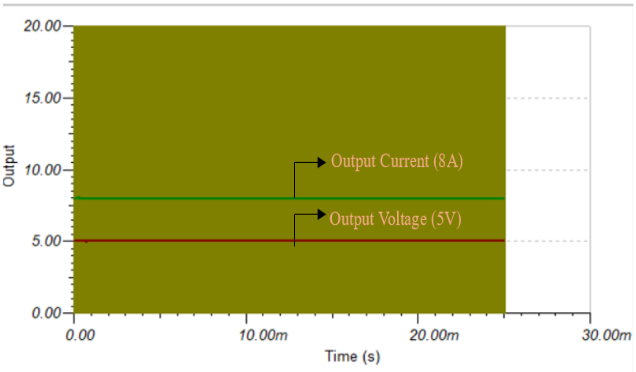

Fig 11: Output voltage and current waveforms (output II), when an input voltage is 36V DC

The hardware model is designed for the same variable input voltage (32 to 42 V DC) are discussed in part V.

V. HARDWARE MODEL AND RESULTS

Fig 12 shows the hardware setup of the proposed forward converter. The converter is connected to a DC voltage source for power and its output is connected to an electronic load. This load measures both the output voltage and the current drawn by the load [7].
The key components of this circuit setup include: Power supply, Cathode Ray Oscilloscope (CRO), Forward dc-dc converter and Electronic load [7].

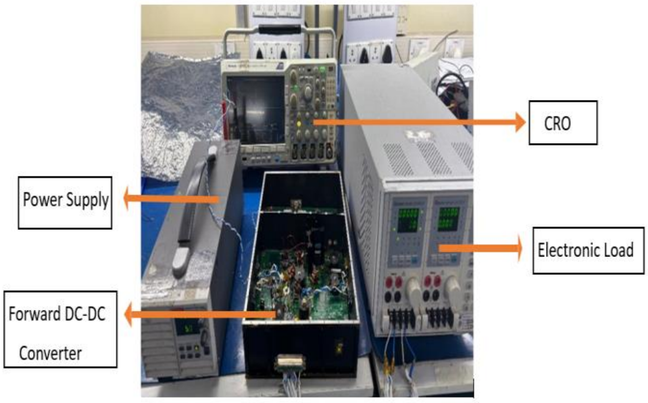

Fig 12: Experimental Setup

The top and bottom view of the proposed forward converter are depicted in Fig 13 and Fig 14 respectively.
The primary key components used in the hardware setup of the proposed forward converter consists of EMI filter (CMI & DMI filters), Transformer, Bias inductor, Input and output connectors, Parallel MOSFETs, Mag-Amps and Secondary diodes, Output Filters (capacitors and inductors) and Snubber circuit [7].

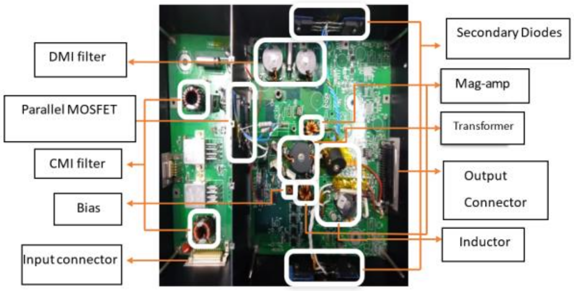

Fig 13: Top view of the converter

Fig 14: Top view of the converter

A. Hardware Results
B. Gate and Drain Voltage:
The gate and drain waveform for different input voltage condition (32V, 36V & 42V) is shown in Fig 15, 16 and 17 which consists of maximum and peak-peak gate voltage and drain voltage [7].

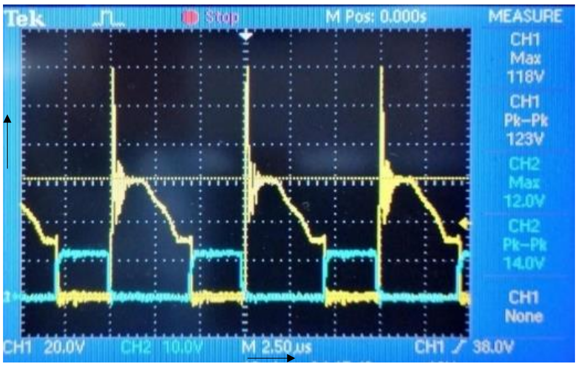

Fig 15: Gate & Drain waveform for input voltage of 32V

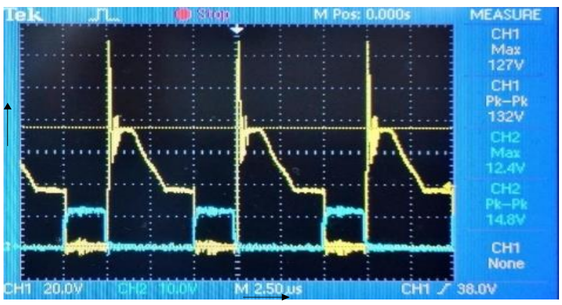

Fig 16: Gate & Drain waveform for input voltage of 36V

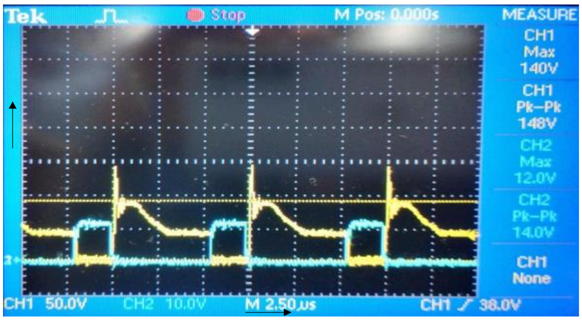

Fig 17: Gate & Drain waveform for input voltage of 42V

Drain Voltage: The peak drain voltage occurs at maximum input voltage and maximum load. The energy regenerative snubber circuit used and the reduction of transformer leakage inductance mitigates the ringing present in the drain voltage. This reduction in voltage ringing across the MOSFET leads to a reduction in switching losses and therefore improves converter efficiency [7].

Table 3: Gate & Drain voltage at different input voltages.

Input voltage Vin (V)	Maximum Gate Voltage (V)	Maximum Drain Voltage (V)	Peak to Peak Gate Voltage (V)	Peak to Peak Drain Voltage (V)
32	12	118	123	14
36	12.4	127	132	14.8
42	12	140	148	14

C. Output Voltage and Efficiency

Output voltage at 100% load condition and input current at different input voltage condition are tabulated in Table 4.

Table 4: Output voltage at 100% load for different input condition and efficiency.

Input Voltage (V)	100% load (Iout = 8A)					
	Iin (A)	Vout-1 (V)	Vout-2 (V)	Pin (W)	Pout (W)	Efficiency (%)
32	3.43	4.98	4.97	102.9	79.6	77.7
36	3.14	4.96	5.0	113.04	79.68	70.4
42	2.81	4.96	4.95	118.02	79.28	67.17

D. Output Voltage Ripple

Ripple voltage refers to the AC component superimposed on a DC output. It is a key parameter in evaluating the quality of the DC voltage. Measurements of ripple voltage were conducted under varying load conditions and input voltage levels. The ripple voltages for output I is presented in Table 5. The measured ripple voltage for output II is similar to output I [7].

Table 5: Ripple voltages for output-I (5V/8A).

Vin (V)	Ripple (mV)		
	Minimum Load (10%)	Nominal Load (50%)	Maximum Load (100%)
32	32.4	27.9	44
36	26.5	28.8	44.8
42	25.2	28	48.8

E. Line and Load Regulation

Line Regulation is defined by,

$$\%\text{Line Regulation} = \frac{V_{out\ max} - V_{out\ min}}{V_{out\ nom}} \times 100 \qquad (13)$$

Line regulation for different input voltage is shown in Table 6

Table 6: Line Regulation

Vin (V)	Output Voltage (V)	%Line Regulation
32	4.97	0.20
36	4.99	
42	4.98	

Load Regulation is defined by,

$$\%\text{Load Regulation} = \frac{V_{out\ min\ load} - V_{out\ max\ load}}{V_{out\ nom\ load}} \times 100 \qquad (14)$$

Load regulation for different input voltage is shown in Table 7.

Table 7: Load Regulation

Load Condition	Vout (V) Vin=32 V	Vout (V) Vin=36 V	Vout (V) Vin=42 V
10%	4.99	4.99	5.0
50%	4.98	4.96	4.97
100%	4.97	4.98	4.98
%Load Regulation	0.40	0.20	0.40

VI. CONCLUSION

The design and implementation of mag-amp controlled dual-output forward converter with voltage feed-forward technique for space applications has been successfully carried out. Both simulation and experimental results show that the converter achieves an efficiency above 65%, thus meeting the design requirements. Implementing magnetic amplifier enables enhanced load regulation (< 2%**)** by independently controlling each output. Furthermore, the voltage feed-forward control method ensures line regulation (< 1%) by delivering a dynamic response. The output voltage ripple remains within the permissible range, with a peak-to-peak value of less than 50 mV, ensuring reliable and noise-free power delivery. Hence the proposed converter is found to be suitable for spaceborne power supply applications.

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