Design and Implementation of Efficient DC to DC Converter with Forward Converter Topology For Low Power Applications

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***Abstract-** The power supply module in the space application use Forward Converter topology due to its advantage such as reduction in weight and providing the isolation on input & output of the converter. The Forward Converter having the high switching frequency of 140KHz to reduce the size of the converter with the feed forward technique and PWM controller UC2525 IC. MOSFET is used for the switching and RCD snubber are used to decrease the stress of MOSFET. The driver IC used to control the gate pulse of MOSFET and LM358 IC are used. The proposed converter is of 5V/2A single output for the input range of 30V-44V. Output of the converter is controlled by Mag-amp connected across the secondary winding of the transformer with some output filters. The paper describes about design, analysis, hardware implementation of efficient DC DC converter with Forward converter for low power application. The converter requires some major protection such as under voltage protection, over voltage protection, over current protection and short circuit protection. The proposed converter provides the lesser output ripple and better efficiency at the nominal voltage along with full load condition. The hardware of this converter is tested for the various input voltage and different load condition with nearly constant output voltage*

***Keywords—**Forward converter, PWM controller, Mag amp, Protection Circuit, Filters*

I. INTRODUCTION

Switched-mode power converters are now extensively utilized because they are smaller and more efficient than conventional power sources. Reduced size and weight are the advantages of SMPS which is required for space applications. The present space research organizations drive towards lighter, smaller, more efficient, low-cost and high-reliable power supply[1]. Satellites employ a variety of dc/dc converters in their electrical power systems. The heritage design features of the dc/dc converter topologies utilized in satellites differ from those of the dc/dc converters used on Earth[2].The most popular topologies for isolated output voltage and low power applications are forward converter due to their tiny transformer size, simple structure, and efficiency[3].With these converters, transformer demagnetization is a potential risk. Different transformer resetting strategies, such as (i) adding an additional reset winding or (ii) utilizing a snubber circuit, can be used to demagnetize transformers[4].

The use of magnetic amplifiers, or "Mag-amps," is an easy and affordable way to manage auxiliary outputs. A saturable inductor used for a controlled switch is called a mag-amp[5]. Unsaturated coils have a high impedance and block the entire voltage, while saturated coils have zero voltage and carry the full current. Mag-amps provide several benefits, including low noise, excellent precision, power savings, and dependability[6][7]. An interesting approach to enable output voltage regulation at constant frequency is to increase the energy stored by the inductor and follow a conventional PWM control strategy[8].The most crucial components of the power supply unit are the protection circuits. In addition to input under-voltage and output over-voltage protection, the proposed converter also includes output over current protection. The protective circuit activates when the output current surpasses 125% of the intended output current, shutting down the converter and preventing a serious failure of the power supply unit[9]. The core saturation theory underlies the operation of the Mag-amps. These are saturable inductor, meaning that the entire voltage appears across the mag-amp coil, drops to zero, and carries the entire current when the core hits the saturation level. The coil blocks the entire voltage and no current passes through it when unsaturated[10][11]. Magnetic amplifiers work incredibly well and are simple to utilize as post regulators to control the secondary side's output voltage[12].A resistor, capacitor, and diode (RCD) clamp can be used as an alternate technique for resetting a forward converter transformer .The resistor, capacitor, and diode are the only three parts of the straightforward RCD clamp circuit, which only needs a more straightforward two winding transformer. The clamp absorbs the magnetizing inductor energy as well as provides a discharge path for the leakage inductance[13][14].Therefore, compared to the reset-winding approach, RCDclamp completely resets the transformer and greatly reduces voltage stress on the power switch. These factors make RCD clamp forward converters popular in the power supply sector[15].

II. CONVERTER SPECIFICATION

Table 1 Converter Specification

Input voltage	30V – 44 DC
Topology	Forward DC-DC Isolated Converter
Switching frequency	140 kHz
Time period	7.14 uSec
Output voltage & current	5V / 2A
Line regulation	<1%
Output Voltage Ripple	<50mV
Duty cycle	27%-40%
Output Power	10 W
Operating Temperature Range	−55°C to 125°C
Efficiency	>70%

The converters required details are given in the table 2.1. As mentioned in the table the input voltage varies from 30V to 44V DC supply with the constant output of 5 Volts and 2 Amps for the range of input. Forward converter topology is used with the converter having the switching frequency of 140 KHz.

The converter should have the Line regulation and the Load regulation less than 1% of the converter.

The efficiency of the converter should be atleast of 70% or more than 70% which can be done by minimizing various loss . The output voltage should be maintained of constant 5 volts with the voltage ripple of less than 50m Volts for the various load condition.

Other than all this specification the converter should have some protection circuit such as Under voltage protection, Overvoltage protection , Short circuit protection & Over current protection for the better operation the converter.

All the above specification and details are used for designing of the required converter.

III. BLOCK DIAGRAM

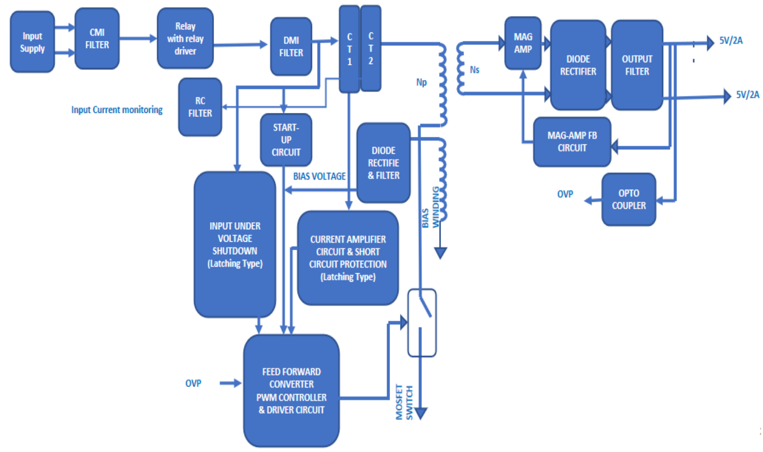


Fig 1 : Block Diagram of the Forward converter

The Above figure show the complete block diagram of the forward converter topology with all the essential components such as cmi filter, dmi filter, current transformer ,under voltage protection ,start up circuit, short circuit protection, diode rectifier and filters, mag-amp, opto coupler, output filter etc.

Principle Of Operation Of Designed Forward Converter

A forward converter is a kind of power converter that uses a transformer to provide electrical isolation between the input and output and to transition a direct current (DC) voltage from one level to a lower level. To put it simply, it safely transforms a greater voltage to a lower voltage and makes sure that the electrical components on the input and output sides are kept apart, which is essential for both safety and noise reduction. The proposed converter consists of a Forward Converter controlled by voltage feed forward technique with Mag-Amp as post regulator as shown in Fig 2.

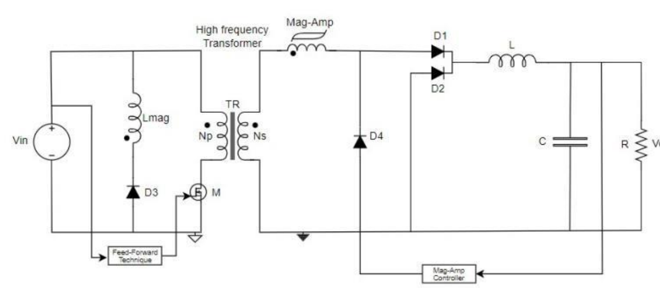


Fig.2: Circuit diagram of Forward Converter with voltage feed-forward technique and mag-amp controller.

As shown in the above Figure, Vin is input supply to the Converter whose voltage varies in range (30V to 44V). TR is High frequency Transformer of the Converter for Isolation purpose. Lmag is the reset or demagnetizing winding of

Transformer. D3 is a reset winding Diode. M is the Mosfet, controlling switch of the converter. Mag-Amp is on the secondary side which is usually represented as Inductor with a small BH-curve symbol on top as shown in the above diagram. It is connected in series with Secondary winding following the Output rectifying diode D1 and D2. L and C are Output Filters. R is the load then the voltage across R is Vout (Output Voltage) and then the current flowing is Iout (Output Current). Output is regulated by Mag-Amp Controller Feedback. D4 is to block the current from flowing into mag-amp controller.

The operation of the proposed converter can be explained in 4 modes, then the related circuit diagram and waveform is given below:

MODE 1:

In this mode, Converter Switch M is turned ON, and the input voltage has been applied to the primary winding of the transformer. Current starts flowing on the primary side of Transformer, This generates a magnetic field in the transformer's core, storing energy. Simultaneously, the voltage induced in the secondary winding and then the current starts builds up slowly on secondary side due to the same polarities. D3 is reverse biased so no current will flow through Lmag winding. Due to the current on Secondary, Mag-amp slowly starts saturating and it blocks the current to flow through it. Entire Secondary side voltage is appeared across mag-amp and then no output voltage. This is called as Blocking state. Corresponding Circuit diagram with current flow is shown in Fig.3 (a).

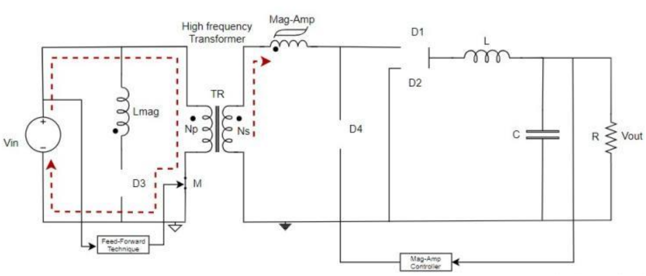


Fig.3 (a): Circuit diagram of Mode1 operation (Blocking State).

MODE 2:

In this mode, M is on conduction Mode, mag-amp is fully saturated acts as a short circuit/ switch when closed. Current starts flowing in Diode D1, which is forward biased. The secondary voltage is rectified by diode D1 and filtered by LC filters then appeared across the load R. This is called as Conducting state. Corresponding Circuit diagram with current flow is shown in Fig.3 (b).

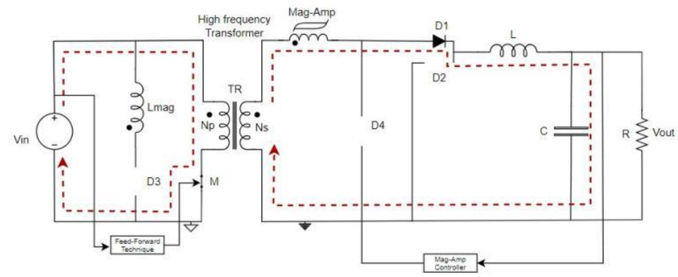


Fig.3 (b): Circuit diagram of Mode2 operation (Conducting State).

MODE 3:

In this mode, M is on conduction Mode, Output reached the required value. When output voltage goes more than desired value the mag controller regulates output voltage to the appropriate value by desaturating the core of mag-amp, thereby blocking the voltage of secondary. Now Diode D4 becomes forward biased and allows the current to flow through it. This we can call it as controlling state. Corresponding Circuit diagram with current flow is shown in Fig.3 (c).

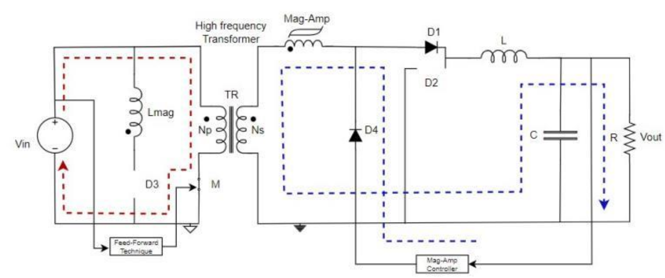


Fig.3 (c): Circuit diagram of Mode3 operation (Controlling State).

MODE 4:

In this mode, M is turned OFF, the magnetic field in the transformer starts to collapse, and voltage across the primary winding reverses polarity. The diode connected in series with the primary winding i.e D3 (often taken as "freewheeling diode") becomes forward-biased, providing a path for the magnetizing current to flow, thus resetting the transformer's core. On the secondary side, the output diode D1 becomes reverse-biased. Diode D2 is Forward Biased providing a path for current to flow and the energy is stored in the output inductor L continues to supply the load through the output capacitor C. This we can call it as resetting state. Corresponding Circuit diagram with current flow is shown in Fig.3 (d).

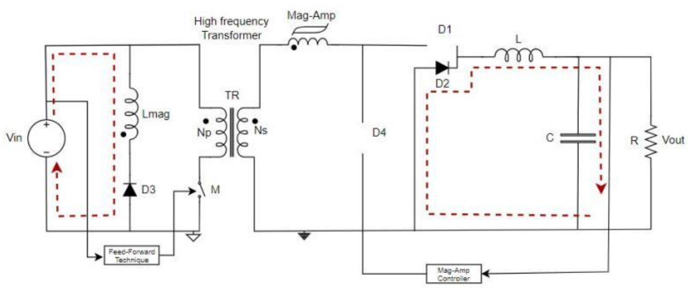


Fig.3 (d): Circuit diagram of Mode4 operation (Resetting State).

Working of Magnetic Amplifier:

Magnetic Amplifier in short called as Mag-Amp. It is not exactly amplifying any gain as the name suggests but the magnetic property of the core is used to regulate the voltage as per the requirement. Mag-Amp is also known as Saturable Inductor. In the normal Transformer and Inductor ferrite based high impedance cores are used and they shouldn't saturate, because the necessity of these in circuit is energy transfer. When it comes to mag-amp they are used in circuit as a switch, they should offer high impedance when it is un-saturated and then when saturated it should offer zero impedance/ resistance similar to an Ideal Switch. The working of Mag-Amp can be explained using the equivalent model as shown in Fig.e.

Fig.4: Equivalent model of working of Mag-Amp.

As shown in above Fig.4, the circuit has SPST switch (SW), mag-amp (MA), DC voltage supply (Vs), and Load resistance (RL). Mag-Amp working like a programmable controlled

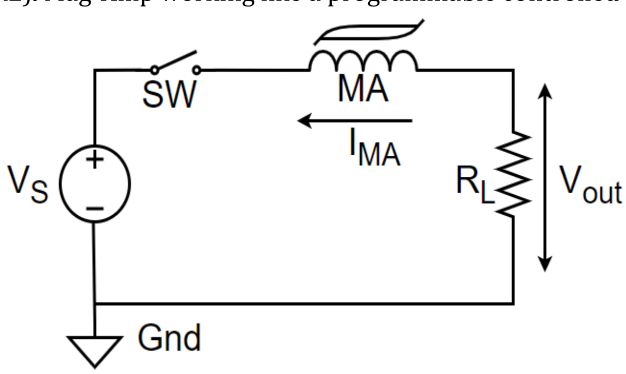


Fig.4: Equivalent model of working of Mag-Amp.

switch. When the switch closes, it offers high relative permeability Ur, and thus high impedance. Due to its nature of not allowing any sudden change in current the voltage across Mag-Amp is equal to input supply voltage (Vs) and no current will be flowing through it. As the core is made of perm-alloy or Cobalt, the current in the core builds up rapidly which saturates the core and acts as a Short circuit in turn providing a path for current to flow. The relative permeability is shift from Ur to 1 and input voltage Vs will appear across load resistor RL. The interruption required because saturation of the MA coil is designed by opposite current IMA applied by the feedback loop.

Mag-Amp Controller:

Mag-Amp feedback controller will have a voltage feedback from Output which is connected to error amplifier. Non-inverting pin of this is connected to reference voltage of 2.5 V and inverting pin is connected to voltage divider from output. When output voltage goes above the required value a negative error signal is generated which is amplified by error amplifier. This error signal is connected to base of the PNP transistor which will be turning the transistor to conduction mode and a current starts flowing through it, this current is limited by Rlimit resistor. Now the Diode D is Forward Biased and then a large current starts flowing through Mag-Amp in the reverse direction and desaturates the core thereby regulating the output voltage to appropriate value. The Mag-Amp Control Circuit is as shown in Fig5.

Voltage Feed-Forward Control:

Variations in input voltage affect the overall performance of the circuit through duty cycle variations. In order to avoid that there must be a loop which corrects the duty cycle, so that even though there is a change of the input voltage the output voltage is not affected. The voltage feed forward mode of PWM control is used which adjusts the duty ratio according to the changes in the input voltage. This type of feed forward technique uses RC network to generate saw tooth waveform using input voltage which is shown in the Fig 5(a) and also the expected waveform is shown Fig 5(b).

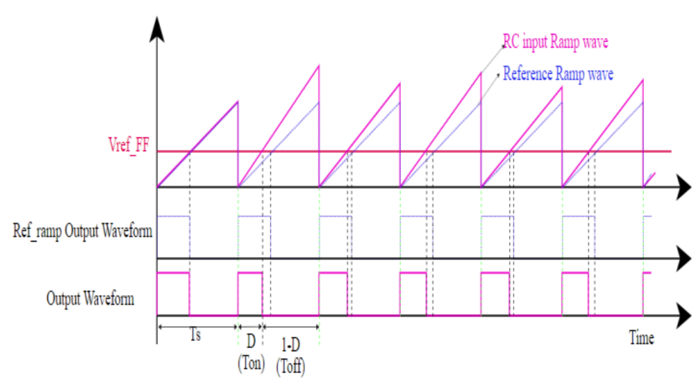
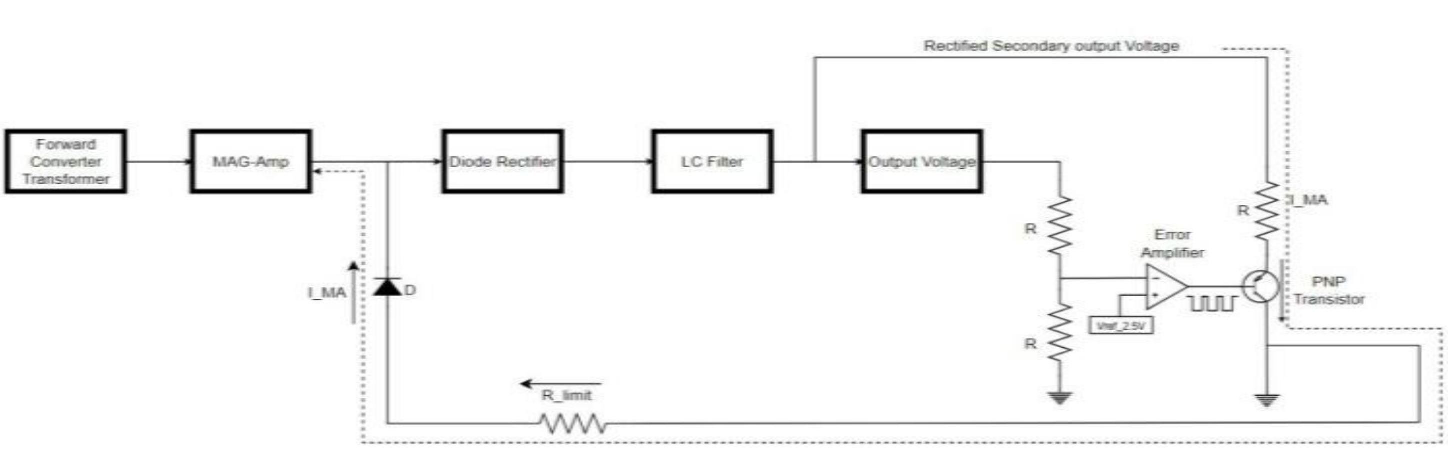


Fig.5 (a) & (b): Voltage Feed Forward Circuit and its waveform.



As the input goes high or doubles, the slope of the comparator will also doubles which causes the duty cycle will immediately be halved. This type of duty cycle correction is very much important for circuit in order to wait for an error amplifier to detect the error in the output voltage.

IV. Design Procedure

Design of Transformer,PWM Controller, MOSFET, Diode, Filter. Efficient Converter design depends on optimum selection of all the required components.

A. *Abbreviations and Acronyms*

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B_M : Flux density
$V_{IN\,(min)}$: Minimum input voltage
V_{OUT} : Output voltage
ΔV : Output Ripple Voltage
T_S : Switching period
P_{OUT} : Output power
Eff : Efficiency
V_D : Diode drop
Fsw : Switching frequency
D_{max} : Maximum duty cycle
D_{min} : Minimum duty cycle
N_P : Primary no. of turns of transformer
A_P : Area product of the core
A_C : Cross-sectional area of the selected core
N_S : Secondary no. of turns of transformer
K_W : Window factor: 0.4
J : Current density
$I_{(SFT)}$: Secondary winding flat topped pulsed Current
$V_{IN\,(max)}$: Maximum input voltage
K : Ripple factor =0.4

B. *Equations*

i. Core Selection:

The optimum design is decided by the small size and lower dissipation of transformer, so Kw, Bm & J values are assumed, for optimal design.

Kw = 0.35
Bm = 0.12 Tesla
J = 6 Amp/mm2
Efficiency = 70%
Dmax = 0.4
Fsw = 140 kHz
P_{OUT} = 10 W

$$Ap = \frac{\sqrt{D_{max}} * P_{Out} * \left(1 + \frac{1}{Eff}\right)}{Kw * J * 10^{-6} * Bm * F_{sw}} = 453.36\ mm^4$$

The right core will be chosen according area product where the selected core must have the area product more than the calculated value
Ap = 435.36 mm^4

Selected pot core: 0R42213UG which will have

$$Ac = 63.4\ mm^2$$

$$Aw = 28.39\ mm^2$$

$$Ap = Ac * Aw$$

$$Ap = 1799.92\ mm^4$$

$$N_P = \frac{V_{in}(min) * D_{max}}{Bm * Ac * 10^{-6} * F_{SW}} = 11.266$$

$$T_{ratio} = \frac{(|V_{out1}| + V_{L1}) + V_{D1} * D_{max}}{D_{max} * V_{in}(min)}$$

$$T_{ratio\_bias} = \frac{(|V_{Bias}|) + V_{D\,Bias} * D_{max}}{D_{max} * V_{in}(min)}$$

Turns ratio Calculation :
Number of Primary Turns is calculated using the formula
$N_p = 11.266 \approx 12$ Turns
Transformer ratio of primary and secondary is given
Therefore, Tratio = 0.5643.
Number of Secondary Turns is: $N_s = T_{ratio} * N_p = 6.772 \approx 6$ Turns
Transformer ratio of bias winding is T_{ratio_bias} =1.0133.
Number of Demagnetizing or reset winding will be equal to number of primary winding.
So, $N_{mag} \cong N_p = 12$ Turns.

ii. Output Filter Design:

Output filters are used to rectify and filters the output voltage and output current to obtain the desired output parameter. The LC filter are used in the proposed converter and these values need to be chosen optimally, so that converters have low noise, less bulky and economical which is the main requirement in Space application.
The filter capacitor has a linear relation between output voltage and the switch Duty ratio, so we need to decide on capacitor value so that output voltage ripples are reduced. The output current needs to be continuous, so choose Inductor accordingly.

$V_{out_s} = 6.5$ V
$I_{out_s} = 1.538$ A
$D_{min_s} = 0.8 * D_{min} = 0.218$
$K = 0.25$
$V_{D1} = 0.6$ V
$V_{D_{Delta}} = 0.6 * 30 * 10^{-3} = 0.018$ V

$$L = \frac{V_{out_s} * (1 - D_{min_s}) * T_s}{2 * K * I_{out_s}}$$
$L = 31.46\ \mu$ Henry

$$C = \frac{K * I_{out_s}}{8 * F_{sw} * V_{D_{Delta}}}$$
$C = 19.07\ \mu$ Farad

iii. MOSFET Selection:

The MOSFET selection depends on the Drain-Source voltage (VDS), Drain current (Id), Drain-Source ON resistance (Rds_on), Gate charge (Qg) and Output Capacitance (Coss). The package and size of MOSFET depends on losses takes place in it. Normally it'll have two types of losses:
Conduction loss: It is the power losses occurring in MOSFET when it is conducting, it mainly depends on rms current flowing in the switch and ON resistance drop between drain to source. As the Current is not controllable so the designer is left with selecting the low resistance value so losses can be minimized.
Switching loss: It is the losses associated with transition of switches from ON state to OFF state and vice-versa. It depends on Gate charge (Qg), switching frequency, voltage required for Gate to turn ON Mosfet switch, then voltage and Peak current flowing in Switch when they're taking transition from OFF and ON. The designer needs to choose the Mosfet in an optimal way, so that losses are minimized.

The Mosfet must withstand a peak voltage of about 100V and inrush current of about 5A- 10A.
Selected MOSEFT; JANSR2N759413 [Vds= 250V, Rds_on= 0.022ohm, Id= 32A @100deg].

iv. Protection Circuits

The proposed converter has protection circuit such as under voltage protection (UVP), over voltage protection (OVP).

Under Voltage Protection (UVP)

Fig.6 shows the design for the undervoltage protection. The UVP threshold voltage is established using a resistor divider and is then compared to the reference value. For the 30V–44V input range, the threshold would always be greater than the reference value. When the input falls below 28V, the comparator output goes high and latches the PWM IC's shutdown pin since the threshold is smaller than the reference. If the input voltage is raised back to 30V, the converter is activated.

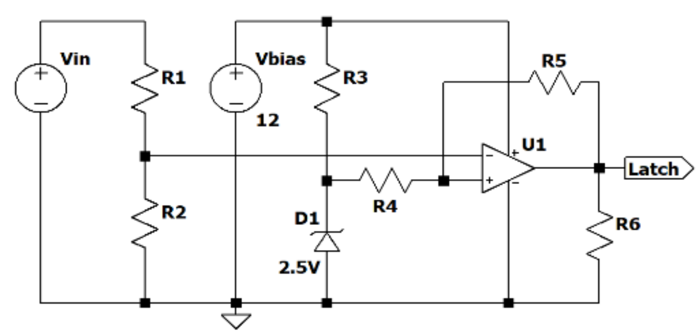

Fig.6: UVP circuit

Over Voltage Protection (OVP)

The over voltage protection circuits are used to prevent harm to devices from exceeding the maximum voltage or over voltage. If the voltage exceeds the specified limits, components may sustain damage. Based on the greatest differential voltage at the highest anticipated current, the resistor's value is designed. The device will have a voltage detecting element. If the voltage rises beyond the maximum voltage or 125% of the rated primary voltage, the PWM IC's shutdown pin go high. shutting off the device.

Over Current Protection (OCP)

The converter is protected from damage using the over current protection. The converter's components may be harmed if the current exceeds the allowed level. In this case, the input voltage supply's input voltage range is between 30 and 44 volts, so the voltage divider resistor's value is planned accordingly. Once the current reaches 125% of the planned amount, a current limiting resistor is created according to the input and output current. PWM IC's shutdown pin goes high, turning off the converter.

V. Hardware results

EXPERIMENTAL RESULTS

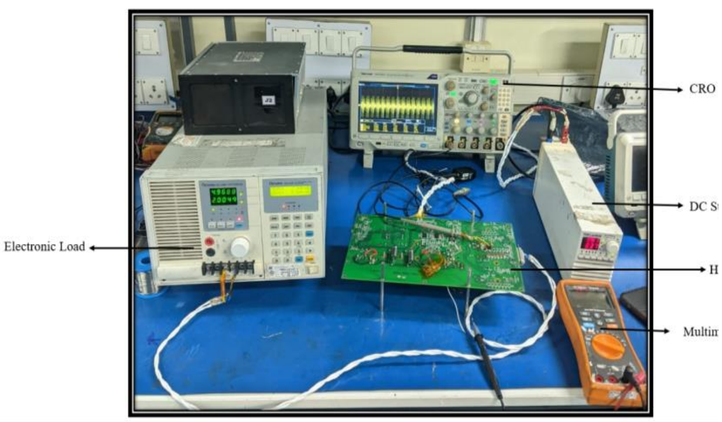

Fig 7 : Complete Hardware setup for Testing

A. Output Voltage

Vin(V)	Output Voltage(V)		
	10% Load (0.2A)	50% Load (1A)	100% Load (2A)
34	5.03	5.04	5.04
36	5.03	5.03	5.03
42	5.03	5.03	5.03

Table 2: Output voltages of different loads and different voltages

B. Efficiency

Input Voltage (V)	Pin (W)	Pout (W)	Efficiency(%)
34	13.8	10.078	73.02
36	13.68	10.08	73.68
44	14.08	10.082	71.6

Table 3 : Efficiency of the Forward converter

C. Output ripple Voltage

Input Voltage (V)	At Min Load (10%)	At Half Loa d (50%)	At Full Load (100%)
34	2.560mV	3.350mV	5.600mV
36	2.400mV	3.200mV	6.400mV
44	2.800mV	3.360mV	5.680mV

Table 4 : Ripple voltage for varies load and input

D. Load regulation and Line regulation

Load	Output Voltage [Vout (Volts)]			Line regula tion %
	Vin=30V	Vin=36V	Vin=44V	
100% (2A)	5.039	5.04	5.041	0.04
50% (1A)	5.039	5.04	5.041	
10% (0.2A)	5.04	5.041	5.042	
%load regu lation	0.02			

Table 5 : Regulation of line and load

E. MOSFET Voltage

Input Voltage	Gate to Source Voltage (VGS)	Drain to Source Voltage (VDS)
30V	12.6V	70.4V
36V	12.6V	79.2V
44V	12.7V	80.4V

Table 6 : Voltage of VDS and VGS for different input voltage

MOSFET Gate to Source and Drain to Source at the nominal voltage 36 with full load of 2A is shown in Fig 8.

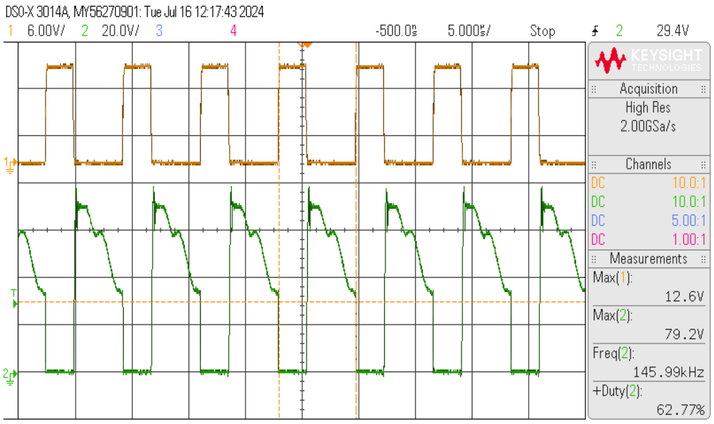

Fig 8 : Gate & Drain Waveform

V. Conclusion

The Efficient DC DC Converter with Forward Converter for Low Power Application is designed. The main topology used is Forward converter with the single out of 5V and 2A with the total power of 10 watts. The main components used are Driver circuit , PWM Controller IC , Transformer , MOSFET . The hardware implementation results show results are obtained as per the specification with efficiency of 73% .The voltage ripple less than 50 mV and the line regulation is below 1% even the Load regulation is also below 1%. The efficiency and the feed forward PWM technique can be improved in future.

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