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CONFIGURABLE MULTI OUTPUT DC-DC CONVERTER FOR WIDE INPUT VOLTAGE RANGE FOR SPACE APPLICATION

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ABSTRACT

This paper deals with the design of EPC (Electronic power Conditioner) for space application (Satellites & launch vehicle) with wide input voltage range and variable output voltages. The nominal input voltage of space application are 28V, 42V and 70V DC bus. The EPC need to be designed for this entire input voltage range. The end use of such power supply will be for supplying various RF and digital circuits. Hence the output voltages are need to be modified accordingly if the end requirement is varied slightly. In earlier available designs, the converter itself need to be redesigned each time when the Digital or RF requirements is varied.

Keywords—DC-DC converter; Magnetic Amplifier; Voltage Feed Forward Control; Converter, EPC.

I.INTRODUCTION

The main source of energy for satellite is the output of the solar array which is a varying voltage source. The higher voltage (Raw bus) is converted to lower useful voltage through DC-DC converters using various topologies. DC-DC converter is a device that converts direct current (DC) voltage into lower or higher DC voltage. Several methods are exist to achieve DC-DC voltage conversion. Each of these methods has its own advantages and disadvantages depending upon the operating conditions, load and other requirements. The nominal input voltage of space application are 28V, 42V and 70V DC.

In multiple output design, converter need to be redesigned every time due to the different input voltage requirement as well as the variation in output voltage. There are many basic topologies used in power supply design. Basic topologies like buck, boost and buck-boost are non-isolated. Isolation is required between the power circuit and the control circuit for protection as well as to prevent noise in the ground loop. Transformer is a must for space designs which provides the required isolation as well as power transfer. Multiple outputs can be obtained in an inexpensive way, by adding multiple outputs on the transformer. Voltage mode feed forward converter is selected in this design considering the wide input voltage range.

UC2525 IC is selected as PWM IC which can be easily used for feed-forward design [3]. The line voltage variations are instantly sensed by the PWM controller and corrects immediately. Feed forward technique reduces the effect of sudden spikes in output voltage which arises from input line voltage changes and provide better line regulation by varying the duty cycle in accordance with the input voltage change.. In this technique, instead of using a fixed slope ramp, a ramp whose slope varies according to input voltage is made use at the PWM controller. This method provides excellent line regulation over wide input voltage range and fast response to input line transients.

The duty range is selected from 20% to 65%, to accommodate the wide input voltage range. But still the design for 20V to 75V is very much challenging as the minimum duty reduces to below 10% which is not advisable as the efficiency will be very poor. Hence transformer is also made configurable with two options in the primary. The primary with lower number of turns will be used for input voltage range from 20V to 45V and higher turns will be used for 45V to 75V. This option will limit the duty cycle in the range from 20% to 60% for the complete range without any redesign in the circuit. A single transformer with configurable option is used to incorporate both lower and higher number of primary turns. The design of transformer is given in 3rd section showing the difference in number of turns in primary winding.

Opto-coupler based usual feedback is not suggested due to low reliability. Hence an auxiliary winding is used in the transformer which supplies 12V bias to entire primary section is taken as feedback winding. Then each of the outputs will be partially regulated. The solution to regulate the outputs is to use post regulators in each outputs. There are various ways with which the outputs can be post regulated [1]. Most popular among them are a) Linear regulator b) Buck / Boost regulators c) Magnetic amplifiers. Using any form of regulator in series with the output will cause additional power loss. Thus the post regulators have to be selected carefully based on their performance.

Linear regulators are the simplest form of post regulators. They are best suited for output currents below 1A. But, linear regulators trade efficiency for simplicity. There should always be minimum input - output differential voltage or headroom. There is always a power loss associated with linear regulator which is a product of the headroom voltage and the output current. This power loss is significant for output currents greater than 1A. Buck / Boost regulators can be used at the output side to regulate the output voltage, but additional controller and switching devices are required, which will increase cost. Synchronization between input and output is also required, which will complicate the regulator design.

Magnetic Amplifiers (Mag-amp) are simple and cost effective way of providing secondary side control and regulation of the outputs [1] [2]. Mag-amp is actually a saturable inductor used as a controlled switch. When saturated, the voltage across the coil drops to zero and carries full current and when unsaturated it presents very high impedance thus blocking the complete voltage. The advantages of Mag-amp are low noise, high reliability, high precision and power saving. The synchronization between input and output will be achieved automatically as the Mag-amp works in synchronization with input frequency.

The usual output voltage requirement is from 5V to 18.3V and currents up to 1A for the space applications. Hence two of the outputs are designed for 20V/1A and 3rd output is designed for 10V/5A. But at a time power in any combination is limited to 48W to avoid overdesign. The configurability of the output is achieved by using the best compensation techniques which provides high stability over the entire output range with optimum dynamic performance. Type-3 compensation is used at the outputs and stability is ensured practically using loop analyzer.

In this paper, Mag-amp operation, voltage feed forward control for achieving regulation for wide input voltage range is explained along with the experimental results.

II.SPECIFICATIONS

This converter is designed for the following specifications:

- Input voltage range : 20 V to 75V
- Total output power : 48watts
- No. of outputs : 3 outputs
- Output-I : 5V to 10V/5A
- Output –II : 5V to 20V/1A
- Output- III : -5V to -20V/1A
- Efficiency : $\geq$ 60%
- Line regulation : 3%
- Load and Cross regulation : 3%
- Operating frequency : 100kHz
- Input under-voltage protection
- Input overcurrent protection
- Input over voltage

III.MAGNETIC AMPLIFIER WORKING

Magnetic amplifier is basically a saturable inductor [4]. The principle of Mag-amp can be explained using a simple LR circuit shown in Fig 1.

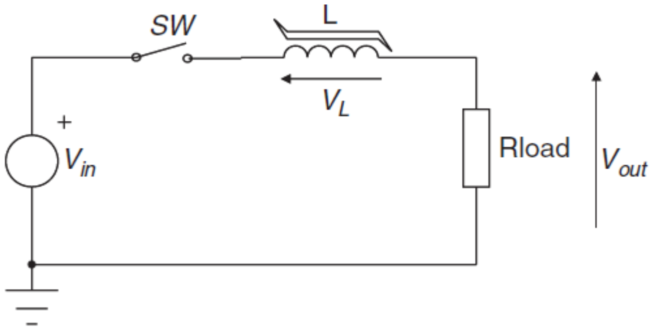

Fig. 1.Mag-amp circuit model

Mag-amp works like a programmable switch. When the series switch closes, the inductor offers a high permeability μ_r and thus a high impedance due to its inherent property of not allowing any sudden change in current. Whole input voltage applied appears across the coil terminals. Because of the saturable core, the current builds up very quickly and saturates the core. Now, the inductor works like a short circuit and the permeability is brought from μ_r to 1. After the saturation of the core, whole input voltage appears across the resistor R. The delay required for saturation of the coil is programmed by the reverse current applied by the feedback network.

A post regulated forward converter is shown in Fig 2. The Mag-amp is connected in series with diode D1. Diode D_f, connected from feedback circuit is used to reset the Mag-amp. The resistor R_{limit} limits the Mag-amp reset current. The feedback network with proper compensation circuit ensures the stability during the variation in output voltage. Output side voltage divider circuit is implemented using potentiometers. Hence the output can be programmed as per the requirement, by varying the resistance of potentiometer.

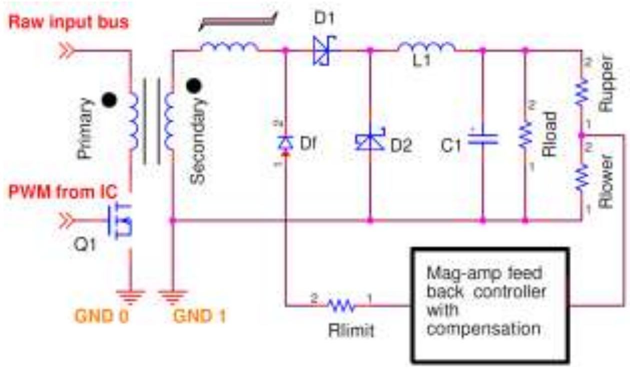

Fig. 2.Baisc forward converter with Mag-amp regulator circuit

IV.VOLTAGE FEED FORWARD CONTROL

In the conventional feedback voltage mode PWM control, any change in the input which will results as a change at the output, which is eventually sensed and feedback to the PWM controller for correcting the PWM duty cycle. Even though this method is very simple, this results in poor dynamic performance in the output against input line voltage variations.

In voltage feed forward mode of PWM control, the duty ratio is adjusted directly according to changes in input voltage before propagating to output side. A saw-tooth wave is generated from input voltage using an RC network as shown in Fig. 3. The ramp and hence the peak of the saw-tooth wave varies in direct proportion to the input voltage as shown in fig 4 in accordance with equation 1.

(1)

Where τ = RC.

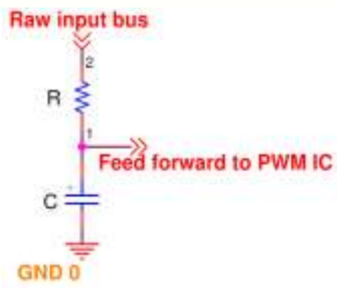

Fig. 3.RC network to generate saw-tooth waveform for feedforward

With the frequency being constant, the value of t in the above equation will be constant. With fixed values of RC, τ is also constant. Thus the capacitor voltage V_o is directly proportional to V_{in}. The PWM IC will take this feed forward also for controlling the duty cycle, along with the normal feedback. Fig.4 shows the variation of feed forward ramp and corresponding change in the duty cycle. The ramp is slow for lower input voltages and steeper for higher input voltages.

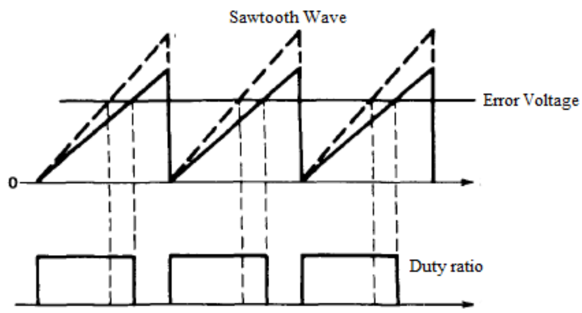

Fig. 4.Dutyty cycle variation with variation in input voltage

V.TRANSFORMER DESIGN PROCEDURE

The transformer for 3 output forward converter is designed below for two different range of inputs. The first design is done for the input voltage range from 20V to 45V and second design is done for the 45V to 75V range. The design includes 3 output winding and an auxiliary winding for primary side sensing and regulation. The design shows that the variation is only in the primary turns of the transformer. All other turns are same for both the cases. Hence the wide input voltage range of 20V to 75V is done with small tapping in the primary of the transformer and entire circuits remains same.

A. 20V to 45V Design

Minimum input voltage, Vin(min) = 20 V

Maximum input voltage, Vin(max) = 45 V

Switching frequency, Fsw = 100 KHz

Duty cycle maximum, Dmax = 0.6

Efficiency, Eff = 0.75 Flux density, Bm = 0.1 T

Vout1 = 20 V Iout1 = 0.5A

Vout2 = 20 V Iout1 = 0.5A

Vout1	= 10 V	Iout1	= 2.8A
Vaux	= 12 V	Iaux	= 0.1A

Total output power,

Pout = Vout1xIout1+ Vout2xIout2+ Vout3xIout3

Pout = 48 W

Pot core transformer with core area Ac= 136mm^2 is selected

Minimum turns in the primary, Npmin = = 8.82

Turns should be integer. Hence Np = 9 turns is selected

Number of turns on the secondary of the transformer are,

Naux =	= 9	Ns1 =	= 15
Ns2 =	= 15	Ns3 =	= 7.5

B. 45V to 75V Design

Minimum input voltage, Vin(min) = 45 V

Maximum input voltage, Vin(max) = 75 V

Switching frequency, Fsw = 100 KHz

Duty cycle maximum, Dmax = 0.6

Efficiency, Eff	= 0.75	Flux density, Bm = 0.1 T	
Vout1	= 20 V	Iout1	= 0.5A
Vout2	= 20 V	Iout1	= 0.5A
Vout1	= 10 V	Iout1	= 2.8A
Vaux	= 12 V	Iaux	= 0.1A

Total output power,

Pout = Vout1xIout1+ Vout2xIout2+ Vout3xIout3

Pout = 48 W

Pot core transformer with core area Ac= 136mm^2 is selected

Minimum turns in the primary, Npmin = = 19.8

Turns should be integer. Hence Np = 20 turns is selected

Number of turns on the secondary of the transformer are,

Naux =	=8.88 = 9	Ns1 =	= 15
Ns2 =	= 15	Ns3 =	= 7.5

That means in both cases only primary turns is varying. Remaining secondary turns and auxiliary turns remains same. Hence transformer is designed with 20 turns in primary with a tapping in the center to take 9 turns option. The wire gauge is selected for the maximum input current which is at 20V input. The testing of transformer with this configurability option is tested with the EPC and found satisfactory for the entire input range from 20V to 75V and found satisfactory. The results are shown in the next session. Hence concept is validated.

VI.EXPERIMENTAL RESULTS

The proposed converter is designed, and implemented with mag-amp as post regulator. The testing for the entire input voltage range from 20V to 75V is done and the results are attached TABLE I-II. The results for nominal load conditions are taken with the load condition of 20V/0.5A, 20V/0.5A, 10V/2.8A for input voltages of 20V, 28V, 42V, 60V, 70V and 75V and shown in TABLE I.

TABLE I. EFFICIENCY READINGS FOR LOAD COND1

Vin (V)	Output Voltage (V)			Efficiency (%)
	Vout1	Vout2	Vout3	
20	19.992	20.061	10.015	75.53
28	19.994	20.063	10.016	75.78
42	19.997	20.064	10.016	73.86
60	20.016	20.038	10.020	80.25
70	20.014	20.039	10.022	79.29
75	20.013	20.040	10.020	78.72

The results for lower output conditions are taken with the load condition of 5V/1A, 5V/1A, 5V/5A for input voltages of 20V, 28V, 42V, 60V, 70V and 75V and shown in TABLE II. This is the condition where all the output voltages are configured to the lowest voltage levels.

TABLE II. EFFICIENCY READINGS FOR LOAD COND2

Vin (V)	Output Voltage (V)			Efficiency (%)
	Vout1	Vout2	Vout3	
20	5.019	5.033	5.017	61.40
28	5.019	5.033	5.016	61.78
42	5.019	5.033	5.016	59.45
60	5.010	5.022	4.996	68.92
70	5.011	5.020	4.993	67.50
75	5.010	5.020	4.996	66.59

Figures 5-6 shows the waveforms captured to ensure the stability of the outputs. The waveform is captured using loop analyzer for output1 and output3, which shows a phase margin more than 45 degree. Cross over frequency also kept low for getting higher stability along optimum dynamic performance. Output2 is same as output1, hence closed loop response is not attached. The blue color line shows the closed loop gain (dB), whereas the red one is the phase (degree).

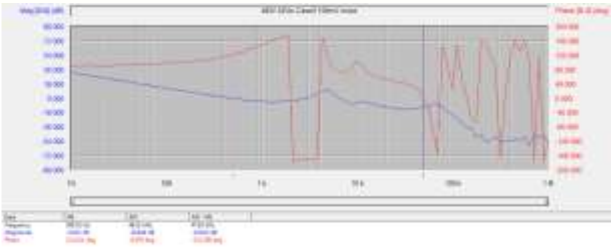

Fig. 5.Closed loop response showing phase margin of 123 degree at 500 Hz for output1

Fig. 5 is the closed loop response of output1 at 20V/1A condition at 42Vin where the cross over frequency is at 500 Hz with a phase margin of 123 degree which shows the highly stable condition. Similar way the output3 is shown in fig. 6, where the cross over frequency is around 415 Hz and the phase margin is 118 degree.

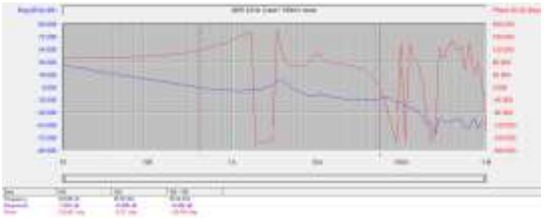

Fig. 6.Closed loop response showing phase margin of 118 degree at 415 Hz for output3

VII.CONCLUSION

A configurable type multiple output Forward converter with voltage feed forward control for wide input voltage variation for space application is designed, developed and implemented. The results proves the validation of the concept. The configurability in the output is achieved by highly stable feedback control circuit and wide input voltage variation is achieved by transformer tapping. Hence the user can configure any output voltage combination in the specification range by simply varying the potentiometer.

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