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Design and Development of Multiple Stage High Efficiency Synchronous Buck Converter System

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***Abstract*—Switch Mode Power Supplies (SMPS) are extensively used in space and military applications. A single low weight converter board can accommodate multiple outputs and topologies. The project is focused on the design and development of a high efficiency 8-stage synchronous buck converter with continuous, regulated output range using voltage mode control. The Pulse Width Modulated signals are generated using LT3845 controller IC to drive MOSFETS. The proposed converter operates at 100kHz switching frequency. By varying input command circuit reference voltage linearly from 1.5-5V; output voltage of 15-20V can be delivered from each converter. Efficiency of the proposed system can reach up to 94% and each converter has its own protection circuits. The hardware prototype model functionality and results obtained match the designed specifications.**

***Index Terms*— Switch Mode Power Supply (SMPS), Synchronous buck converter, Voltage mode control, Command circuit, High efficiency, Controller IC, PWM signals.**

I. INTRODUCTION

In recent days' advancements in electronics, the exigency for power supplies for use in IC and digital circuits has been increased manifold. Electronic devices require a DC power source to supply infallible and controlled DC voltage. Power supplies are the intermediate stage between the power source and the electric load. Besides, common goals of any power supply design are to reduce the size, weight and to increase the efficiency [1], [2].
The regulated power supply technology is classified into two advances; first one linear or series regulator and second one, the switch mode power conversion. Conventionally linear power supplies have been employed for power conversion. However, the advancements in semiconductor technology led to switching power supplies, that are smaller in size and much more efficient compared to linear power supplies [3].
In this work, 8-stage synchronous buck converter system designed for a total of 638W power output. All stages are identical to each other in every aspect. The objective is to attain high efficiency after integrating 8 synchronous buck converters on a board. All stages are individually powered by a single 100V input bus after passing through EMI filter circuit. By changing reference voltage in each converter from 1.5-5V linearly; output of 15-20V can be produced. Every stage consists its own over and under voltage and current protection circuits.

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A. Voltage Mode Control

A fraction of output voltage obtained using divider circuit is compared with linear reference voltage (desired voltage) to produce the error signal. This error signal is compared with a saw tooth waveform of fixed frequency to generate Pulse Width Modulated(PWM) signals. The signals are weak in nature; which are boosted by high power gate drivers to drive the MOSFETs. A single feedback loop is easier to design and analyse. So signals for MOSFETs are generated in terms of voltage variation [4], [5], [6]. LT3845IFE PWM controller IC is utilized for pulse generation. NCP5183DRG is a high voltage and high current MOSFET driver which provides two outputs.

B. Synchronous Buck Converter

A synchronous buck converter is a modified version of basic buck converter topology in which freewheeling diode is replaced by a semiconductor switch. This is a compromise between increased cost and improved efficiency. Systems designed for low duty cycle operation will bear higher losses in the freewheeling diode or lower switch (basic buck converter), and for such systems it is lucrative to consider a synchronous buck converter design. This topology design always revolves around two major criterions: quality of output load and power dissipation of the converter [7-13].

II. PROPOSED SYSTEM

The proposed system consists of 8–stages of identical synchronous buck converter. Input voltage of 85-110V is applied through an Electro Magnetic Interference(EMI) filter circuit to each converter. An additional 12V bias voltage(Vcc) applied to each converter's top and bottom MOSFET collector pin. Delay sequencing circuit produces signal to create delay between ON time of top and bottom MOSFET. Again each converter provided with command circuit to generate reference voltage (TC_Vdd).

After applying input and bias voltage converters will turn ON. The fraction of output voltage is compared with the reference voltage (1.5-5V) and create an error signal. The error signal is again compared with fixed frequency standard waveform to create PWM signal using LT3845IFE controller. These weak signals could not drive MOSFET. Hence a high current driver NCP5183DRG incorporated to boost signal strength. The signals then drive top and bottom MOSFETs with a proper time delay to produce regulated output voltage.

The output voltage linearly dependent on reference voltage. i.e. when applied reference voltage is 1.5V then output is 15V and when reference is 3.3V the output will be around 17.5V. When Over Voltage Protection circuit of any converter triggers it will turn off that particular converter. But if Over Current Protection circuit triggers it will turn off complete system to prevent damage to any converter. Due to incorporation of well-designed space and military grade components losses are reduced to a greater extent.

The block diagram for proffered converter system is illustrated in Fig 1.

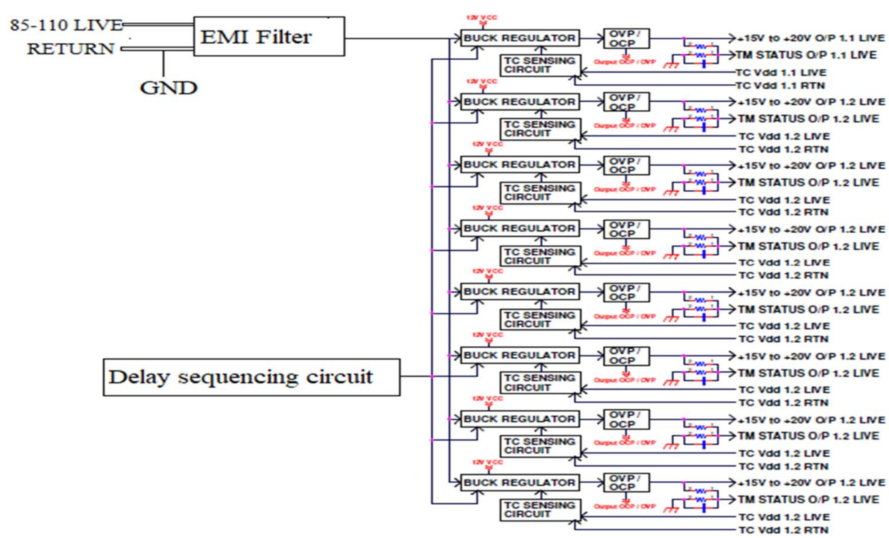

Fig 1. Block diagram of proffered converter system

The functions of different blocks are illustrated in below Table I.

TABLE I: FUNCTIONS OF DIFFERENT BLOCKS

BLOCK	FUNCTION
EMI filter	To reduce conducted emission from the equipment To limit level of interferences entering the equipment
PWM controller	To generate PWM signals
Sequencing circuit	To create delay between top and bottom MOSFET ON time
Vcc supply	12V bias voltage to the MOSFET collector pin
Output filter circuit	To eliminate voltage ripple content.
Gate driver	A high current and high voltage power MOSFET driver IC
OVP circuit	Over Voltage Protection. To protect circuit from instant or long duration voltage surges.
OCP circuit	Over Current Protection. To protect circuit from inrush current spikes.
TC Command circuit	To provide reference voltage (TC_Vdd) for pulse generation.

III. SPECIFICATIONS AND DESIGN

The specifications of proposed converter are mentioned as follow:

Minimum input voltage(Vinmin)	:90V
Nominal input voltage(Vnom)	:100V
Maximum input voltage(Vinmax)	:110V
Output voltage (Vout)	:15-20V
Output current(Iout) for 15V output	:1.4A-3.2A
Output current(Iout) for 20V output	:1.4A-3.9A
Tuning command (TC_Vdd)	:1.5-5V
Switching frequency (Fsw)	:100kHz
Duty cycle (D)	:0.2
Output over voltage protection	:21-23V
Maximum Transient voltage	:1000mV
Maximum ripple voltage	:300mV
System efficiency (η)	:>92%

A. Components Design

Equation (1) is used to calculate current ripple.

$$I_{ripple} = K * I_{out} \tag{1}$$

Where *K*-current ripple factor=0.3.

$$I_{ripple}=1.17$$

Equation (2) and Equation (3) is used for calculation of output inductor and capacitor value respectively which act as filter circuit.

$$L=\frac{|Vout|*(1-D)*Ts}{Iout*K} \tag{2}$$

Where *D*-duty cycle

Ts-switching time.

$$L=136\mu H$$

$$C=\frac{K*Iout}{8*Fsw*\Delta V} \tag{3}$$

Where ΔV=0.03.

$$C=48.75\mu F$$

Equation (4) is used to calculate the number of turns of the output inductor [14].

$$N=\frac{L*Iout*(1+\frac{K}{2})}{B_{max}*Ac*10^{-6}} \quad (4)$$

Where B_{max} is Maximum flux density.
A_c is cross-sectional area.

$$N=48\ turns.$$

IV. HARDWARE IMPLEMENTATION

The converter system is implemented on 10-layer PCB board with heat sinks to dissipate switching losses. Fig 2 illustrates top view of the 6 stage converter board.

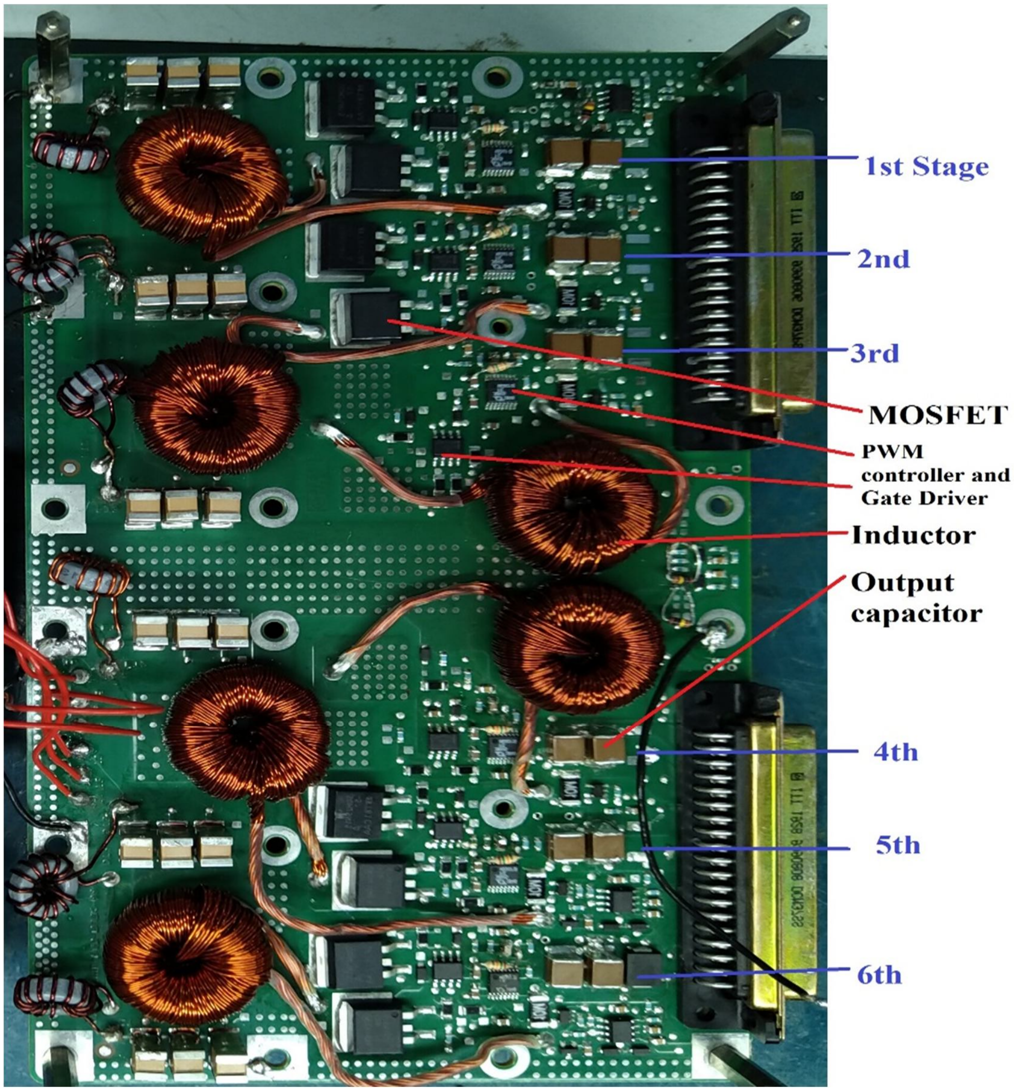

Fig 2:Top view of the 6 stage converter board

The hardware setup is illustrated in below Fig III.

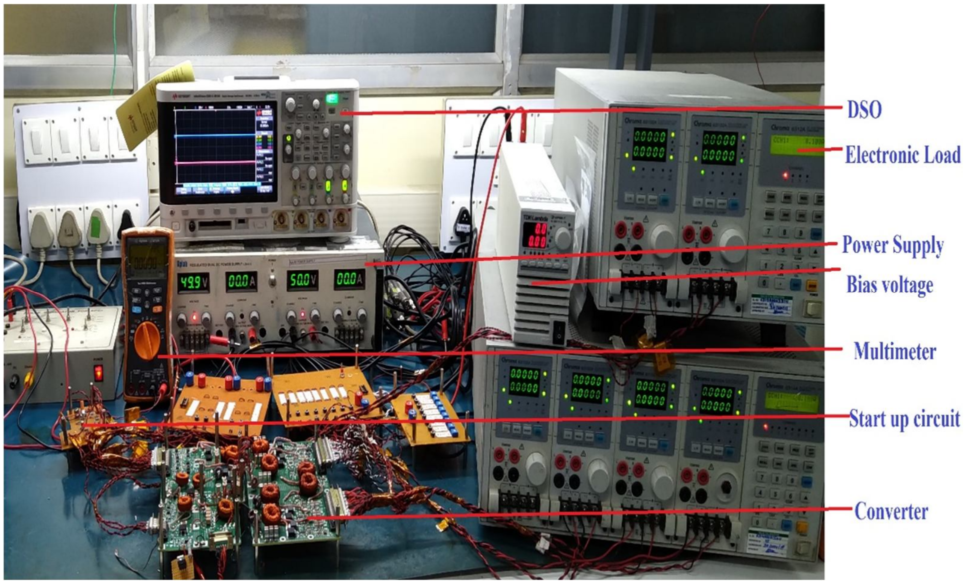

Fig 3: Hardware lab setup

It consists of converter board, start-up circuit, power supplies, electronic loads, digital oscilloscopes and multimeter. The electronic load equipped to load converter for different load conditions. It is also used for dynamic loading of the converter board; which means changing load instantaneously to check stability of the multistage converter. The start-up circuit generates firing pulses to trigger the converter stages. The various waveforms are observed and captured through Digital Storage Oscilloscope.

The supply is turned on and bias voltage is applied. After tuning reference voltage to the desired value and maintaining load in different conditions, various parameters such as output voltage, ripple voltage, transient voltage and turn on timings are noted. The process is repeated for different input voltage settings, load and reference voltages. Further these values are used to compute efficiency and compared with desired efficiency. The feedback circuit is tuned such that loop response, maximum transient voltage and ripple voltage are well within the range. A well settled and stabilized converter is implemented after several iterations of tuning 'trial and error'.

V. Results and Waveforms

The results obtained through hardware experiments are tabulated and analyzed against desired specifications.

A. *Efficiency*

The converter efficiency is calculated using equation (5) for entire system which need to be above 92%.

$$\eta = \frac{Vout*Iout}{Vin*Iin} * 100 \qquad (5)$$

Maximum load condition: -
1.TC_Vdd=5V
Nominal input=100V and maximum load=3.9A.
The below Table 2 illustrates efficiency calculation at maximum load and TC_Vdd=5V.

TABLE II: Efficiency calculation at maximum load and TC_Vdd=5V

Parameters	Sync 1[1]	Sync 2	Sync 3	Sync 4	Sync 5	Sync 6	Sync 7	Sync 8
Input current(A)	6.68							
V_{out}(V)	20.13	20.14	20.23	20.15	20.07	20.16	20.17	20.12
Input Power(W)	668							
Total Output Power (W)	628.563							
Efficiency(%)	**94.09**							

2.TC_Vdd=1.5V
Nominal input=100V and maximum load=3.2A.
The below Table 3 illustrates efficiency calculation at maximum load and TC_Vdd=1.5V.

TABLE III: EFFICIENCY CALCULATION AT MAXIMUM LOAD AND TC_VDD=1.5V

Parameters	Sync 1	Sync 2	Sync 3	Sync 4	Sync 5	Sync 6	Sync 7	Sync 8
Input current(A)	4.04							
V_{out}(V)	14.92	14.93	15.01	14.92	14.87	14.94	14.93	14.89
Input Power(W)	404							
Total Output Power (W)	382.112							
Efficiency(%)	**94.58**							

90% load condition: -
1.TC_Vdd=5V
Nominal input=100V and 90% load=3.51A.
The below Table 4 illustrates efficiency calculation at 90% load and TC_Vdd=5V.

TABLE IV: EFFICIENCY CALCULATION AT 90% LOAD AND TC_VDD=5V

Parameters	Sync 1	Sync 2	Sync 3	Sync 4	Sync 5	Sync 6	Sync 7	Sync 8
Input current(A)	5.82							
V_{out}(V)	20.13	20.15	20.23	20.15	20.08	20.11	20.17	20.16
Input Power(W)	582							
Total Output Power (W)	565.7418							
Efficiency(%)	**97.2**							

2. TC_Vdd=1.5V
Nominal input=100V and 90% load=2.88A.
The below Table 5 illustrates efficiency calculation at 90% load and TC_Vdd=1.5V.

TABLE V: EFFICIENCY CALCULATION AT 90% LOAD AND TC_VDD=1.5V

Parameters	Sync 1	Sync 2	Sync 3	Sync 4	Sync 5	Sync 6	Sync 7	Sync 8
Input current(A)	3.52							
V_{out}(V)	14.92	14.93	15.0	15.0	14.95	14.88	14.94	14.94
Input Power(W)	352							
Total Output Power (W)	344.3328							
Efficiency(%)	**97.82**							

The test results of efficiency for the converter system at maximum load condition and 90% load condition is above 92% which satisfies the expected values. Main objective of this work is high efficiency which is achieved as per design.

B. Output Ripple Voltage and Maximum Transient Voltage

The undesirable AC components in the DC output voltage is termed as ripple. To limit its influence on performance of converter, suitable capacitor filters are needed. The voltage shoot occurs during a sudden transmission from minimum load to maximum load or vice versa which is termed as transient voltage.
Maximum load condition: -
TC_VDD=5V, Vin=100V, Vout=20V and Iout=3.9A.
The below Table 6 illustrates ripple voltage and maximum transient voltage.

TABLE VI: RIPPLE VOLTAGE AND MAXIMUM TRANSIENT VOLTAGE

Parameters	Sync 1	Sync 2	Sync 3	Sync 4	Sync 5	Sync 6	Sync 7	Sync 8
Ripple voltage(<300mV)	153	153	129	121	133	161	173	141
Max transient voltage(1000mV)	560	510	540	590	520	570	600	530

The desired specifications of the ripple voltage and transient voltage are 300mv and 1000mV respectively. The tabular column presents, both parameters are well within the range.

C. Hardware Waveforms

The output ripple voltage and maximum transient voltage waveforms are observed and captured using DSO. 4 stage output voltage ripple is illustrated in Fig 4.

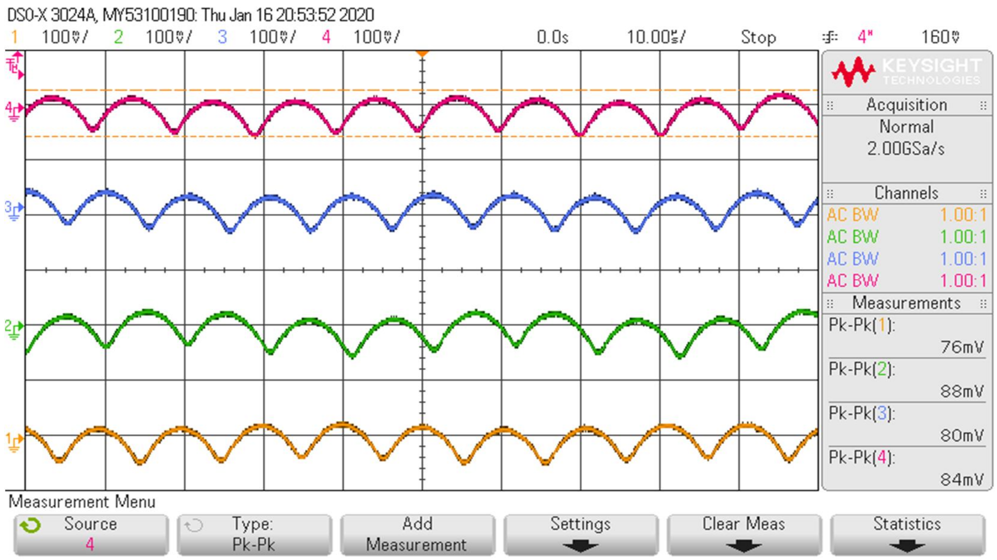

Fig 4: 4-stage sync buck converter output ripple voltage

The following Fig 5 illustrates maximum transient voltage for 4-stage synchronous buck converter.

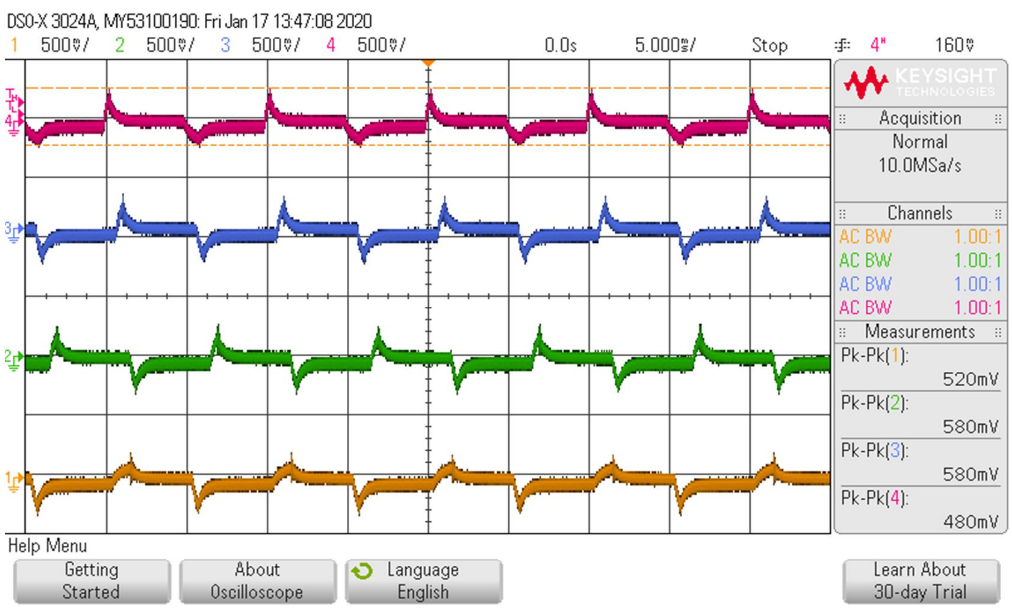

Fig 5: 4-stage sync buck converter maximum transient voltage response

VI. CONCLUSION

The efficiency of the complete Multistage Synchronous Buck converter system is above 93% which is a primary objective of this work is successfully achieved. All stages of synchronous buck converter met specifications without any issues after integration. System can sustain for long duration of time with all stages in running state by producing very low amount of heat. Also this Multistage Converter System will sustain extreme environmental conditions and effectively can be employed for aerospace and satellite applications.

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