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Design of DC-DC Buck Converter for Airborne Radar Applications

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Abstract:

Switching mode DC/DC converters are critical building blocks in portable devices and hence their power efficiency, accuracy and cost are a major issue. The primary focus of this thesis is to address these critical issues. Power supply gives the system life by providing consistent and repeatable power to its circuits. DC-DC converter is used in most of the airborne systems like, Radar seeker, Missile computer, Sensor interfaces, telemetry system etc. Using DC converters in power management, electronic system becomes smaller in size, low loss of power, EMI/EMC compatible and highly efficient (up to 95%). The switching regulator converting a DC input voltage to DC output voltage. It has conversion efficiency up to 95%, it also does efficient voltage regulation, and pulse width modulation is used for controlling the on-off time of the transistor and holds the output voltage constant under varying line or load conditions. To analyze the real time feasibility the system is simulated using LTSpice an Electronic Design Automation Tool.

Keywords:
Buck Converter; Compensation Network; Current Mode Controller (CMC); DC-DC Converter; Equivalent Series Resistance (ESR); Pulse Width Modulation (PWM); SMPS.

I.INTRODUCTION:

Applications of DC-DC Converters have been increased significantly due to the rapid growth of power electronics techniques. This paper deals with study of different methods of DC-DC Converters having different regulating DC voltages and a DC-DC Buck converter for ultra low power applications is implemented in Current Mode Controller (CMC) technology with different switching frequency [1].

The main objective of this paper is to first study about the switching mode power supplies (SMPS) and different controlling methods which are used nowadays in the circuit of SMPS then implement a buck converter and try to enhance the buck converter's efficiency [2]. Scaling down the passive components like inductor's size without sacrificing the systems overall performance is another purpose of this thesis.

II.DC-DC CONVERTERS:

SMPS and linear regulators are two main methods which are employed to convert an unregulated DC voltage to a regulated DC level, regardless of changes in load current and input voltage [3]. Linear regulator is a type of power supply which instead of using switches, employs voltage divider network for adjusting output voltage. Unlike the switching mode power supply, the linear regulator operates continuously, thus its efficiency is less than switching regulator and it produces much more heat comparison to SMPS.

Switching-mode power supply which is also called as switching-mode DC to DC converter is a type of power supply which uses switches (usually in the form of transistor) and low loss components such as inductors, capacitors and transformers for regulating output voltage. The circuit of SMPS consists of two main parts: power stage and control part [4]. Nowadays most of the work is done on control part for better regulation of output voltage, whereas the power part has not undergone many changes.The following reasons vividly demonstrate why the switching regulator is the only reasonable choice compared with a linear regulator:

A.High power efficiency:

Linear regulator uses voltage drop across series passive element to regulate output voltage.

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Therefore excess power is dissipated in the form of heat which requires a large volume heat-sink to reduce the circuit's temperature; whereas SMPS uses switching technique to suppress the extra power. Since the switches are not continuously conducted (depends on the switching duty cycle), it losses much less power comparison to linear regulator. The Power efficiency in both SMPS and linear regulator is expressed in equation (1):

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out}.I_{out}}{V_{in}.I_{in}}\ \% \qquad (1)$$

Where Pout is the output power, Pin is the input power, Vout is the output voltage, Iout is the load current, Vin is the input voltage and Iin is the input current. Since in the linear regulators input current and output current have the same value (Iout = Iin) therefore "Equation (1)" can be simplified to "Eq.(2)" for a linear regulator.

$$\eta = \frac{V_{out}}{V_{in}}\ \% \qquad (2)$$

Based on "Equation (2)", we can easily find that the efficiency of a linear regulator is directly related to the power drop across its variable resistance. Therefore whenever the difference between input and output voltage is high the efficiency of linear regulators can be significantly reduced which means reduction in battery life for any application.

B.Versatility:

The energy stored by the output inductor of a SMPS can be transformed to output voltage, which can be greater than input voltage (stepped-up), or lower than input voltage (stepped-down) or even converted to a negative voltage; however the linear regulator is only able to step-down the dc voltage level.

C.SMPS drawbacks:

Of course, SMPS is not without its drawbacks; although the size and weight of the switching-mode power supply is smaller than linear regulator but it requires a more complicated feedback control loop compared to linear regulator for energy management. This causes increase in overall cost of the power supply and makes it more expensive than linear one.

The main concern in the switching-mode power supply is Electromagnetic Interference (EMI) noise caused by the fast transitions of current and voltage due to high frequency switching. Rapid voltage changes at the inductor node leads to radiated electric fields, while fast-changing inductor current produces magnetic fields. Output voltage ripples at the switching frequency is another issue which is needed to be filtered out with an extra LC filter.

III.BUCK CONVERTER:

Buck converter is a type of switching-mode power supply which is used for stepping-down DC voltage level [5]. Switch controller block and power block are two main parts of buck converter's circuit. "It can operate in Continuous Conduction Mode (CCM) or in Discontinuous Conduction Mode (DCM), depending on the waveform of the inductor current". Voltage Mode Control (VMC) and Current Mode Control (CMC) are two main methods to control switching.

Both of these two methods can be applied with either PWM (Pulse width modulation) or PFM (pulse frequency modulation) techniques [6]. The PFM is more efficient when the load current is too low. Figure (1) depicts the DC/DC buck converter circuit. As can be seen it is included a switch controller block, high side power switch, low side power switch, inductor L, output capacitor C, and load resistance.

The diode (which is used in conventional buck converters) is usually replaced by an n-channel MOSFET (NMOS) as a low side switch to improve power efficiency of converter. Since voltage drop in conducted MOSFET is very low comparison to conducted diode (even from Schottky diode which has low forward voltage drop), the total power loss in DC/DC converter will be significantly reduced by this replacement.

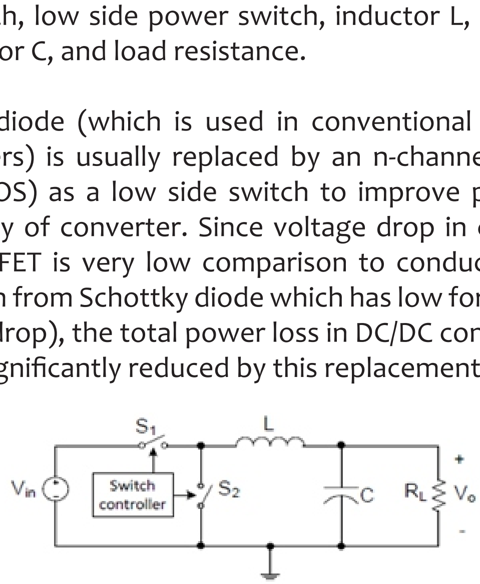

Figure (1). Buck Converter.

Figure (2) illustrates the schematic model of a generic buck converter.

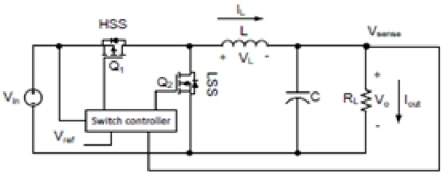

Figure (2). Buck Converter Schematic.

IV. PRINCIPLEOPERATION OF BUCK CONVERTER:

When high side switch Q1 is on, a path will be provided for the DC input voltage to charge the inductor and supplies the load current [7]. Charging will continue till the output voltage reaches to reference voltage, then the control part turns off the high side switch to keep the output voltage close to Vref. Therefore there is no path to charge inductor, and then inductor changes its polarity and the current flows in the same direction through the low side switch which is turned on by switch controller part.

Discharging will continue until the output voltage reaches below of the reference voltage, then control part again turns on the high side MOSFET to compensate the output voltage drop and this cycle continues until complete regulation of output voltage [8]. This process is accomplished by sensing the output voltage of the circuit by means of a negative feedback loop which adjusts the duty cycle "Equation (3)" to control on and off state of the MOSFET switches under specified frequency.

$$D = \frac{t_{on}}{T} = \frac{t_{on}}{t_{on}+t_{off}} = f_{sw} \cdot t_{on} \qquad (3)$$

Where ton is the time interval that power MOSFET Q1 conducts (on state), toff is the time interval that Q1 is open (off-state), T is the period and fsw is the switching frequency.

DESIGN OF DC-DC BUCK CONVERTER:

The Buck converter is designed for N-Channel designed controller. The design of Buck Converter using LTSpice an Electronic Design Automation Tool is done using various switching frequencies for output voltage 1V, 3.3V, and 5V. The input voltage range is 28-60V. Some of the important circuit parameters considered are as follows:

MOSFET	: MTOP- RJK0651DPB
	MBOTTOM-BSC028N06LS3
Scott key Diode	: MBRS360
INTVCC	: 4.7μF
VIN	: 22μF; 4.7μF
Power Good	: 100K
Track/SS	: 0.01μF
Iripple	: 30%
Vripple	: for (5V-20mV; 3.3V-10 mV; 1V-5mV)

A.For output voltage -1volt:

For the given
Input voltage VIN =28V;
switching frequency is taken, f =144.7 KHz;
to obtain the output voltage, VOUT =1V;
with a ripple current, Iripple =30%;
and ripple voltage, Vripple =5mV;

To obtain the values of duty cycle, feedback resistance, equivalent series resistance, inductance, capacitance and voltage ripple the following calculations are as follows:
The on time is calculated by,

$$T_{ON} = \frac{V_{OUT}}{V_{IN}} \times \frac{1}{f} = \frac{1}{28} \times \frac{1}{144.7\times10^3} = 246.81\, ns$$

$$T = \frac{1}{f} = \frac{1}{144.7\times10^3} = 6910.8\, ns$$

Duty cycle,

$$D = \frac{T_{ON}}{T} = \frac{246.81}{6910.8} = 0.0357$$

$$\text{Now, } V_{OUT} = 0.8\left(1 + \frac{R_{bottom}}{R_{top}}\right)$$

Let $R_{top} = 7.5K\Omega$ then R_{bottom} will be,

$$R_{bottom} = \left(\frac{V_{OUT}}{0.8} - 1\right) \times R_{top} = 30K\Omega$$

The inductor value will be calculated by,

$$L = \frac{V_{OUT}}{f \times \Delta I} = \frac{1}{144.7\times10^3 \times \left(30\times\frac{5}{100}\right)} = 4.7\mu H$$

The Equivalent Series Resistance is,

$$ESR \le \frac{\Delta V}{\Delta I} \le 5mV$$

$$\text{The } R_{sense} = \frac{V_{sense\,(max)}}{I_{max}+\frac{\Delta I}{2}} = 8m\Omega$$

$$\text{The } C_{OUT} \ge \frac{L(\Delta I)^2}{2\times0.1\times V_{OUT}\times V_{OUT}} \ge 585.5\mu F$$

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B.For output voltage- 3.3v:

For the given
Input voltage VIN =28V;
switching frequency is taken, f =535 KHz;
to obtain the output voltage, VOUT =3.3V;
with a ripple current, Iripple =30%;
and ripple voltage, Vripple =10mV;

To obtain the values of duty cycle, feedback resistance, equivalent series resistance, inductance, capacitance and voltage ripple the following calculations are as follows:
The ON time is calculated by,

$$T_{ON} = \frac{V_{OUT}}{V_{IN}} \times \frac{1}{f} = \frac{1}{28} \times \frac{1}{535 \times 10^3} = 66.75\ ns$$

$$T = \frac{1}{f} = \frac{1}{535 \times 10^3} = 1869.15\ ns$$

Duty cycle,

$$D = \frac{T_{ON}}{T} = \frac{66.75}{1869.15} = 0.0357$$

Now, $V_{OUT} = 0.8\left(1 + \frac{R_{bottom}}{R_{top}}\right)$

Let $R_{top} = 47K\Omega$ then R_{bottom} will be,

$$R_{bottom} = \left(\frac{V_{OUT}}{0.8} - 1\right) \times R_{top} = 15K\Omega$$

The inductor value will be calculated by,

$$L = \frac{V_{OUT}}{f \times \Delta I} = \frac{3.3}{535 \times 10^3 \times \left(30 \times \frac{5}{100}\right)} = 3.9\mu H$$

The Equivalent Series Resistance is,

$$ESR \leq \frac{\Delta V}{\Delta I} \leq 10mV$$

$$\text{The } R_{sense} = \frac{V_{sense(max)}}{I_{max} + \frac{\Delta I}{2}} = 8m\Omega$$

$$\text{The } C_{OUT} \geq \frac{L(\Delta I)^2}{2 \times 0.1 \times V_{OUT} \times V_{OUT}} \geq 350\mu F$$

C.For output voltage- 5V:

For the given
Input voltage VIN =28V;
switching frequency is taken, f =535 KHz;
to obtain the output voltage, VOUT =5V;
with a ripple current, Iripple =30%;
and ripple voltage, Vripple =20mV;

To obtain the values of duty cycle, feedback resistance, equivalent series resistance, inductance, capacitance and voltage ripple the following calculations are as follows:
The ON time is calculated by,

$$T_{ON} = \frac{V_{OUT}}{V_{IN}} \times \frac{1}{f} = \frac{1}{28} \times \frac{1}{535 \times 10^3} = 66.75\ ns$$

$$T = \frac{1}{f} = \frac{1}{535 \times 10^3} = 1869.15\ ns$$

Duty cycle,

$$D = \frac{T_{ON}}{T} = \frac{66.75}{1869.15} = 0.0357$$

Now, $V_{OUT} = 0.8\left(1 + \frac{R_{bottom}}{R_{top}}\right)$

Let $R_{top} = 36K\Omega$ then R_{bottom} will be,

$$R_{bottom} = \left(\frac{V_{OUT}}{0.8} - 1\right) \times R_{top} = 6.8K\Omega$$

The inductor value will be calculated by,

$$L = \frac{V_{OUT}}{f \times \Delta I} = \frac{5}{535 \times 10^3 \times \left(30 \times \frac{5}{100}\right)} = 6\mu H$$

The Equivalent Series Resistance is,

$$ESR \leq \frac{\Delta V}{\Delta I} \leq 20mV$$

$$\text{The } R_{sense} = \frac{V_{sense(max)}}{I_{max} + \frac{\Delta I}{2}} = 8m\Omega$$

$$\text{The } C_{OUT} \geq \frac{L(\Delta I)^2}{2 \times 0.1 \times V_{OUT} \times V_{OUT}} \geq 300\mu F$$

The following shows the respective values of the different output voltages.

TABLE I

Values	For output voltages		
Votages	1V	3.3V	5V
Feedback resistance	R_{top} =7.5KΩ R_{bottom} =30KΩ	R_{top} =47KΩ R_{bottom} =15KΩ	R_{top} =36KΩ R_{bottom} =6.8KΩ
Inductor	$4.7\mu H$	$3.9\mu H$	$6\mu H$
Output capacitor	$585.7\mu F$	$350\mu F$	$300\mu F$
ESR	5mV	10mV	20mV
Compensation components	C1=27000pF R1= 15KΩ C2=18pF	C1=220pF R1=47KΩ C2=18pF	C1=2200pF R1= 47KΩ C2=18pF
Voltage ripple	0.1162	0.0842	0.0957

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VI.ANALYSIS OF BUCK CONVERTER IN LTSPICE:

The DC-DC buck converter schematic circuit diagram is done in LTSpice using LTC3891 is shown in the following figures below.The following schematic diagram of LTC3891 is as shown in figure (3). The LTC3891 is a high performance step-down switching regulator DC/DC controller that drives an all N-channel synchronous power MOSFET stage [9].

Constant frequency current mode architecture allows a phase lockable frequency of up to 750Kz. The LTC3891 features a precision 0.8V reference and power good output indicator. A wide 4V to 60V input supply range encompasses a wide range of intermediate bus voltages and battery chemistries. The output voltage of the LTC3891 can be programmed between 0.8V to 24V.

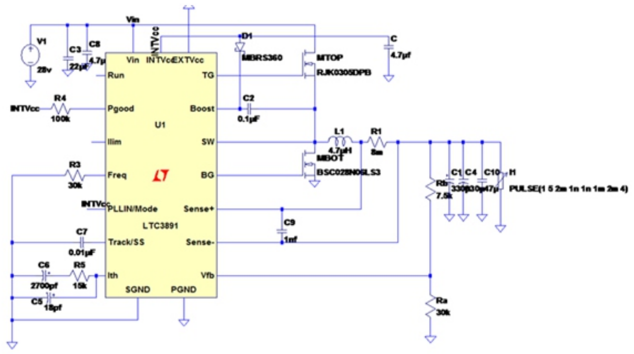

Figure (3): Schematic diagram of LTC3891

VII.SIMULATION RESULTS:

The simulation results of the various output voltages are shown in figures below:

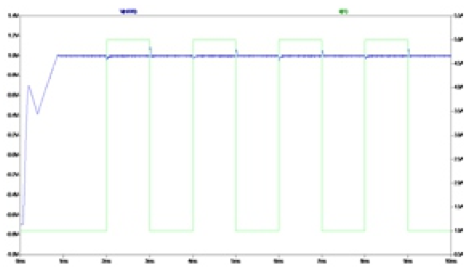

Figure 4(a): Output Voltage plot for 1 Volt.

Figure 4(b): Output Voltage ripple

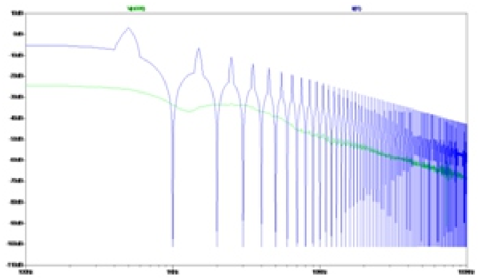

Figure 4(c): FFT plot for 1 VoltNow for the output voltage 3.3 volts the graph is as shown below:

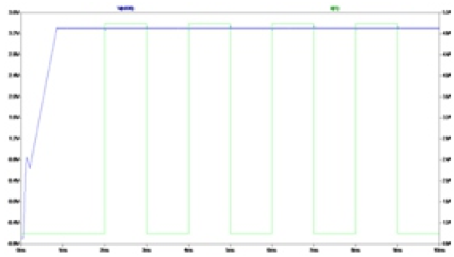

Figure 5(a): Output voltage plot for 3.3 Volt

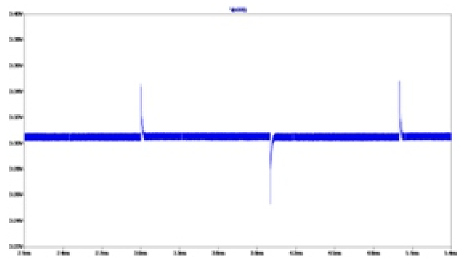

Figure 5(b): Output Voltage ripple

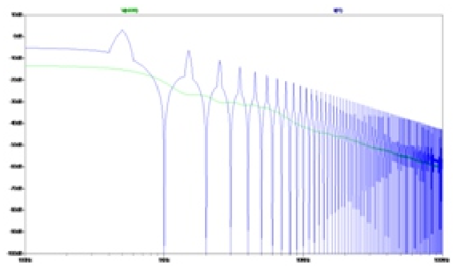

Figure 5(c): FFT plot for 3.3 Volts Now for the output voltage 5 Volts the graphs are as shown below:

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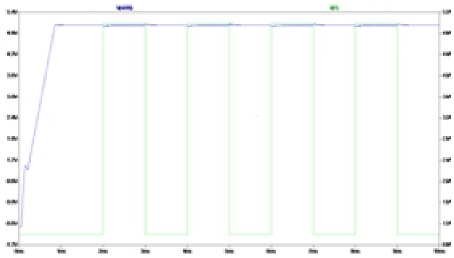

Figure 6(a): Output Voltage plot for 5 Volts

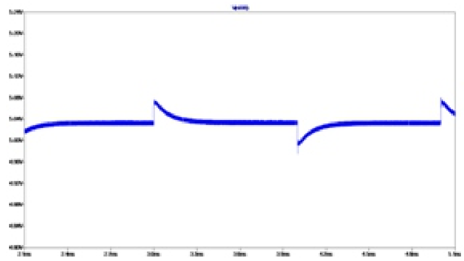

Figure 6(b): Output Voltage ripple

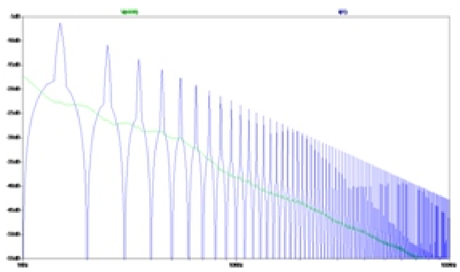

Figure 6(c): FFT plot for 5 Volts

VIII.CONCLUSION:

Thus applying a short dead time can guarantee that both the power MOSFETs will not conduct at the same time for any period of time. Another recommendation for future work is designing the converter for air borne radar applications to determine the full chip area. Also more study can be done about other modern control techniques to find a proper feedback control method which can enhance the power efficiency of this buck converter.

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