International Journal of Advanced Research in Engineering Technology & Science
ISSN: 2394-2819
Email: editor@ijarets.or Volume-4, Issue-10 October- 2017 www.ijarets.org

DESIGN AND IMPLEMENTATION OF HIGH FREQUENCY VARIABLE INPUTDC-DC BUCK CONVERTER APPLICABLE IN SPACE POWER APPLICATIONS

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ABSTRACT:
This paper introduces the design, simulation and implementation of variable input - constant output switching-mode high frequency dc-dc buck converter. It discusses the theoretical derivations and parameters equations with design and Simulation results for buck converter. The mathematical model for the buck converter is analyzed through the theoretical equation [1], simulated with Matlab program using Simulink, and implemented using the designed components. The output of the Buck converter depends on five aspects; selected frequency, inductor value, capacitor value, and type of MOSFET as well as diode, which are studied in the present work. The circuit is simulated in MATLAB SIMULINK and then the results are verified with hardware implementation. The Duty cycle that controls the output of the DC-DC converter was generated using the FPGA Kit. The main purpose of this design is to be applicable in space power application especially in MPPT photovoltaic control technique, battery charging/discharging control during daylight/eclipse and finally used for bus control to extract constant regulated output voltage.[2]

KEYWORDS: DC-DC Buck converter, Power Regulator, MPPT, Continuous Conduction Mode (CCM).

INTRODUCTION:

A lot of research has been done to improve the efficiency of the DC-DC converters, but all of these researches has been concentrated on the calculations of both critical inductanceand critical capacitance. The critical inductancesatisfies the CCM conditions, and reduces ripple current.The critical capacitancereduces the ripple voltage [3] [4].

The conversion of electric power from one form to another is necessary for the control of electric power, as it is the core of the nowadays technology. The widely usage of switching-mode dc–dc converters is due to providing smooth acceleration control, high efficiency, and fast dynamic response.The Dc–Dc convertersare used in many applications[5]:

- Convert a DC input voltage into a DC output voltage.
- Regulate the DC output voltage against load.
- Reduce the AC voltage ripple on the DC output voltage below the required level.
- Provide isolation between input source and load.
- Protect the supplied system and the input source from electromagnetic interference (EMI).

The DC–DC converters can be divided into two main types; linear power regulators, and switching power regulators. The linear power regulators, whose principle of operation is based on a voltage or current divider which are inefficient. The switching power regulators which use power electronic semiconductor switches in ON and OFF states. Since there is a small power loss in those states, switching regulators can achieve high energy conversion efficiencies [3][4].

The switching-mode DC–DC converters can be divided into two main types; Soft-switching converters (resonant converters), and Hard-switching pulse width modulated (PWM) converters. Soft-switching converters or resonant converters are used for resonant network dc-dc conversion, Compared to the PWM converters in the resonant converters the switching losses in the semiconductor device are avoided due to the fact that the current through or voltage across the switching device is at the switching point is equal to or near zero and also decrease the harmonic content in the converter voltage and current waveforms [2].Hard-switching or pulse width modulated (PWM) converters needs low component count, high efficiency, constant frequency operation, relatively simple control and commercial availability of integrated circuit controllers, and ability to achieve high conversion ratios for both step-down and step-up application. On the other hand, the PWM dc–dc converters due to the switching of semiconductor devices, aTurn-ON and Turn-OFF losses in semiconductor devices are occurred which limit practical operating frequencies to a megahertz range. There are three types of PWM switching regulators; Buck regulator (step down), Boost regulator (step up), and Buck-boost regulator (step up and step down) [4].

Most space applications in which switching-mode dc-dc power converters are included are related to power control/conditioning. Spacecraft power control/conditioning is classified into PV MPPT control, battery control andbus control. PV MPPT control, DC-DC converters are used as interface between PV and load to match the load resistance with the optimum resistance at which the maximum power is transferred. Battery control, DC-DC converters are used as battery charging/discharging control regulators .Bus control, the DC-DC converters are used to obtain constant output regulated voltage to feed the other spacecraft subsystems[6][7].

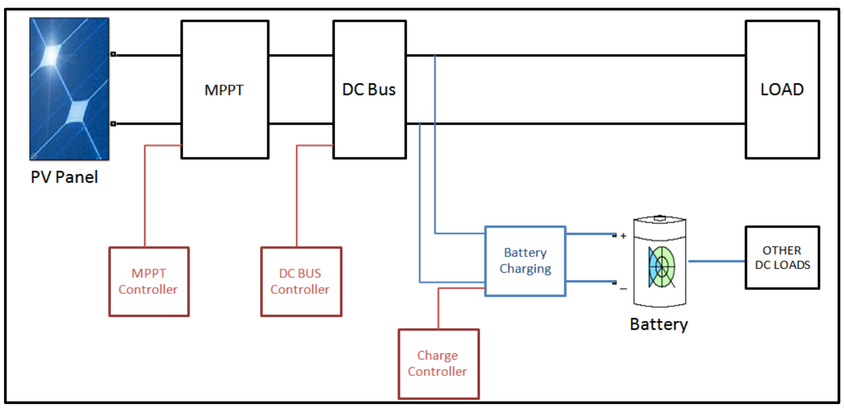


Fig. 1: Main structure of the spacecraft power System.

Figure 1 shows all necessary control function in which Dc-Dc converters are included. Some of them might be trimmed or merged with others in the implementation [8].

DC-DC BUCK CONVERTER

A buck converter, step-down converter consists of controlled switch(MOSFET transistor Q_1), uncontrolled switch (diode D_1), filter inductor(L_1), filter output capacitor (C_{out}),filter input capacitor(C_{in}) and load resistance (R_L). The input is exposed to the switch Q_1. An input capacitor C_{in} is required to filter the input current into the converter because the input current is a highly dynamic waveform. Fig. 2 presents the basic circuit of buck converter. The ratio between the output and the input voltages are known as the conversion ratio M(D) which is given by:$M(D) = \frac{V_O}{V_{in}}$ .For buck converter, M(D) is given by$M(D) = \frac{V_O}{V_{in}} = D$,where D is the Duty cycle[9].

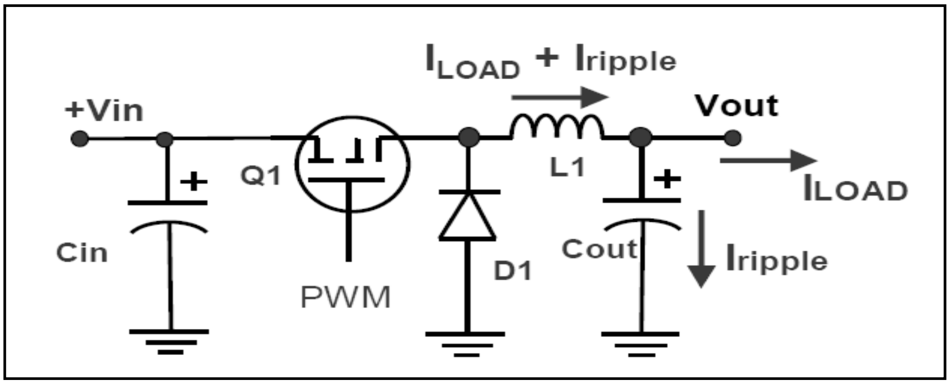


Fig. 2: Circuit diagram of Buck DC-DC converter.

The Dc-DC buck converter has two modes of conductions; Continuous Conduction Mode (CCM) where Inductor current remains positive throughout the switching period, and Discontinuous Conduction Mode (DCM) where Inductor current becomes zero for some time in the switching period. Fig. 3, shows different conduction modes [10].

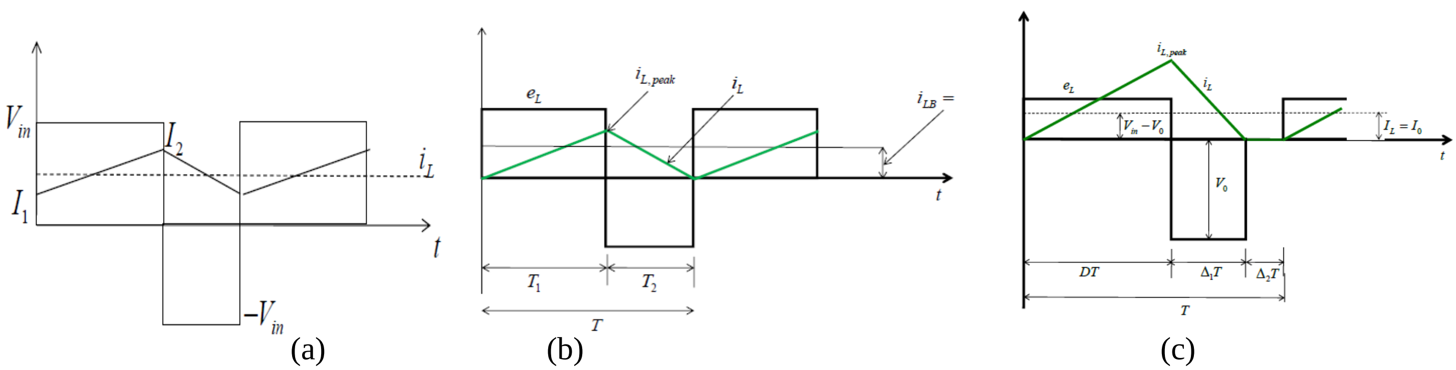


Fig. 3: Buck converter conduction modes (a) CCM, (b) Boundary between CCM and DCM, (c) DCM.

The dc- dc buck converter has two modes of operation related to the controlled switch Q1position [4];

1. *ON mode (Inductor charge mode):*When switching element Q_1 is ON (closed), current flows from V_{in} through the inductor L_1 linearly increasesand charges the output capacitor Cout, the voltage across the inductor is $V_L= V_i- V_o$. and the output current I_o is supplied. The current which flows into the coil L_1 at this time induces a magnetic field, and electric energy is transformed into magnetic energy and accumulated for storage. The diode doesn't allow current to flow through it, since it is reverse-biased by voltage as shown in Fig.4.
2. *OFF mode (Inductor discharging mode):*When switching element Q_1 is OFF (opened), free-wheeling diode D_1 turns ON (forward biased) and energy stored in L_1 is then released to the output side. The voltage across the inductor is $V_L= - V_o$. The inductor current now decreases until transistor Q_1 is switched on again in the next cycle as shown in Fig. 4.

Fig. 4, shows the waveforms for voltage and currents of the buck converter in continuous load current assuming that the current rises or falls linearly. In practical circuits, the switch has a finite, nonlinear resistance. Its effect can generally be negligible in the most applications depending on the switching frequency, filter inductance, and capacitance, the inductor current could be discontinuous.

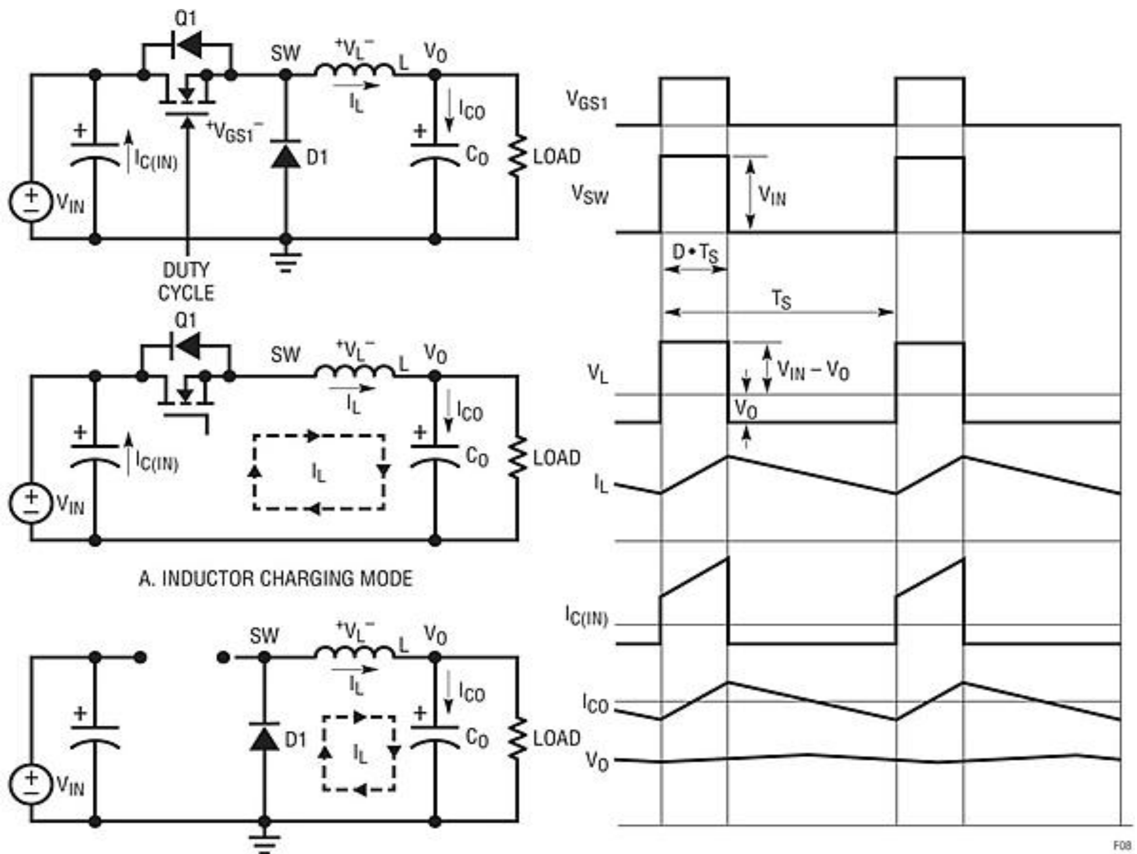


Fig. 4: Buck Converter Operation Modes and Typical Waveforms.

DESIGN METHODOLOGY OF BUCK CONVERTER:

The design of Dc-Dc converters requires proper selection of the values of its components like inductor, capacitor and switching frequency. Also proper calculation for rated current and voltage at which the switches (transistor, diode) will operate. This is important to decide the converter efficiency, performance and the behavior of the output. Those components should be discussed separately.

1. OPERATING FREQUENCY

It determines the performance of the switch. The higher is the switching frequency, the smaller the physical size and value of the capacitor and inductor. At higher frequencies the switching losses in the MOSFET increase, and therefore reduce the overall efficiency of the circuit so switching frequency selection is normally determined by efficiency requirements. On the other hand, the trade-off between size and efficiency has to be evaluated carefully [2][10].Another important point is the LC low-pass filter included in theconverter has a corner frequency f_C given by:

$$f_C = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

The corner frequency f_C is chosen to be sufficiently less than the switching frequency f_{sw}, so that the filter essentially passes only the dc component of v_O (t)[7].

2. INDUCTANCE SELECTION

It controls the percent of the ripple current that inversely proportional to the inductance and also determines whether or not the circuit is operating in CCM. The peak current through the inductor is used to determine the inductor's required saturation current rating, which in turn commands the approximate size of the inductor. A smaller inductor value enables a faster transient response; it also results in larger current ripple, which causes higher conductor losses in the switches, inductor, and parasitic resistances, but requires a larger filter capacitor to decrease the output voltage ripple. On the other hand, Critical inductance L_c is the minimum value of the inductor for a given D, f and R at which the converter is operating in CCM, lower than this value the converter operates in discontinuous conduction mode (DCM) which is no preferable[9][10].

For calculating the critical inductance value, $I_{L\text{-}min}$ is used. so some parameters should be defined and calculated, $D_{max}$is Calculated at Minimum Input Voltage,R_{max} is Calculated at Minimum Output Current,R_{max} = $V_o/I_{o\text{-}min}$, where $I_{o\text{-}min}$ is either given as percentage of load to maintain CCM, Or, $I_{o\text{-}min}$ is calculated as specified by maximum Δi_L which is the ripple current, such that $I_{o\text{-}min} = I_{L\text{-}avg} - \Delta i_L/2$. Switching frequency normally chosen by the designer, the higher the switching frequency, the smallerthe required critical inductance [12][13].

$$L = \frac{V_{in}\ D\ (1-D)}{F\ \Delta I} \tag{2}$$

$$I_{L-min} = I_L - \frac{\Delta I}{2} \tag{3}$$

$$\mathrm{I_{L-min}} = \mathrm{I_L} - \frac{\Delta \mathrm{I_L}}{2} = \mathrm{V_O}\left[\frac{1}{\mathrm{R_{max}}} - \frac{[1-\mathrm{D_{max}}]}{2\mathrm{LF}}\right] \tag{4}$$

Set $I_{Lmin} = 0$, then solve for $L = L_C$, then choose L_{opt}>>>> L_C

$$\mathrm{L_c} = \frac{(1-\mathrm{D_{max}})}{2\mathrm{F}}\mathrm{R_{max}} \tag{5}$$

Worst case maximum inductor current occurs at maximum load which causes Maximum output power rating per specified required output voltage.$I_{L\text{-}max}$ is used to determine the inductor peak current rating.

$$\mathrm{I_{L-max}} = \mathrm{I_L} + \frac{\Delta \mathrm{I}}{2} = \mathrm{V_O}\left[\frac{1}{\mathrm{R_{min}}} + \frac{[1-\mathrm{D_{min}}]}{2\mathrm{LF}}\right] \tag{6}$$

The chosen inductor is power through-hole toroid inductor, a coil is wire wounded on a toroid circular form {type number, DC Inductor (F107-2X1645 or 1625CS).electrical features, (220)µH, 12A with very low DC resistance}. In this type of inductor, Flux leakage is very low, the reliability is high and many mounting options available including open style vertical, open style flat.

3. CAPACITANCE SELECTION

The output filter capacitors are chosen to meet an output voltage ripple specifications, as well as the ability to handle the required ripple current stress. The primary criterion for selecting the output filter capacitor is its capacitance and equivalent series resistance (ESR). Since the capacitor's ESR affects the efficiency, low ESR capacitors will be used for best performance.

For reducing ESR, it is possible to connect capacitors in parallel[4]. The chosen capacitor is of type aluminum electrolytic capacitor {(1000µF), (ESR=0.034)}. The electrolytic capacitors are polarized capacitors. They can only be operated with DC voltage applied with the correct polarity. Operating the capacitor with wrong polarity or with AC voltage leads to short circuit and can destroy the component. Due to their very thin dielectric oxide layer and enlarged anode surface, electrolytic capacitors based on the volume, a much higher capacitance voltage product compare to ceramic capacitors or film capacitors but much smaller capacitance voltage value than super capacitors. The large capacitance of electrolytic capacitors make them suitable for passing or bypassing low frequency signals up to some mega-hertz and for storing large amount of energy. Due to their relatively high capacitance values, they have low impedance values even at lower frequencies. They are typically used in power supplies, switched-mode power supplies and DC-DC converters for smoothing and buffering rectified DC voltage in many electronic devices. They are widely used for decoupling or noise filtering in power supplies and DC link circuits for variable frequency devices [14]. The value of the critical capacitance which satisfies the required output ripple voltage ΔV_O.

$$C_c = \frac{V_O\ (1-D_{min})}{8*L*F^2*\Delta V_O} \tag{7}$$

Capacitor Voltage and the root mean square current should withstand with the maximum output voltage

$$i_{c-rms} = \frac{V_O\ (1-D_{min})}{2\sqrt{3}*L*F} \tag{8}$$

$$V_{C-max} = V_O + \frac{\Delta V_O}{2} \tag{9}$$

4. DIODE SELECTION

With ideal switch, the $V_{RRM} = V_{in\text{-}max}$, but for non-ideal diode, $V_{RRM} = V_{in\text{-}max} + V_{SW}$, where V_{SW} is the maximum forward drop across the switch (calculated at maximum load current) and V_{RRM} Known as Peak Inverse Voltage (PIV) or the maximum voltage across the diode.

$$I_F > I_{o-max} * (1 - D_{min}) \tag{10}$$

The selected diode is 20.0 AMP Schottky barrier rectifier, (type number EN220A). Electrical features, high voltage (V_{RRM} = 100V), low forward voltage drop (V_f = 0.85V), high current capability ($I_{f\text{-}max}$ = 20 A), high reliability, high surge current capability and steady operation even at high temperature [15].

5. MOSFET SELECTION

With ideal diode, the $V_{switch\text{-}max} = V_{in\text{-}max}$, but for non-ideal diode, $V_{switch\text{-}max} = V_{in\text{-}max} + V_F$ where V_F is the maximum forward drop across the diode (calculated at maximum load current).Switch current rating is calculated based on average value By KCL, Inductor Current = Switch Current + Diode Current. During t_{ON}, Inductor current equals switch current and during t_{OFF}, Inductor current equals diode current [15].

$$I_{sw-max} > I_{o-max} * D_{max} \tag{11}$$

The chosen switch is power MOSFET N-type (type number IRFP260N).electrical features, (V_{DSS} = 200V, $R_{ds\text{-}on}$ = 0.04Ω, I_D =50A, Total Gate Charge Q_g= 234nc, Turn-On Delay Time Td-on=17ns, Turn-Off Delay Time $T_{d\text{-}off}$ =55ns, Output Capacitance Coss=603pF).

6. BUCK CONVERTER EFFICIENCY

The efficiency determination is an important factor in the design of the DC-DC converter. The converter efficiency is defined as:

$$\eta = \frac{P_{out}}{P_{out} + P_{total\ -loss}} \tag{12}$$

The source of power losses is mainly due to the components of the converter and can be divided into [14]:

i. Inductor's copper loss, Due to the DC resistance of the inductor
ii. Capacitor's ESR loss, due to the effective series resistance (ESR).
iii. MOSFET losses can be divided into; Static losses, Switching losses and Gate Drive Losses. MOSFET Static losses, due to the current flowing through the ON resistance of MOSFET (R_{DS-ON}) when the switch is closed (The ON resistance mainly depends on the applied gate voltage and temperature of the MOSFET). MOSFET Switching losses, due to the power loss during the rise and fall times of the switch.
iv. Diode losses can be divided into; Static losses and Switching losses.

TABLE I. PARAMETERS OF DESIGNED BUCK CONVERTER

Parameters	Value - type
DC Input voltage range (V_{in})	7 to 45V
Output voltage (V_{out})	3.3 - 33V
Input ripple voltage (ΔV_{in})	0.3
Output ripple voltage (ΔVo)	1% of V_{out} (max 0.2V at V_{out} = 28V)
Max Output current (I_o)	12A
Inductor ripple current (ΔI_L)	10-30% of output rating current
Percent minimum load-CCM	10% of maximum power (1.2A)
Switching frequency (f_{SW})	100KHz
Load resistance (R_L)	2.333 to 23.333
Inductor(L)	220µH
Output capacitor(C_o)	1000µF
Input capacitor(C_{in})	1000µF
Transistor(controlled switch)	Power MOSFET (IRFP260N)
Diode (D) (uncontrolled switch)	EN220A

In the next section the selected parameters are presented in order to implement the required DC-DC buck converter, which its specification is shown in table 1. The selected parameters for the components that had been discussed in the previous section is shown in table 2. Those components are Inductor (L), Output capacitor (C_o), Input capacitor (C_{in}), Transistor (controlled switch), Diode (D) (uncontrolled switch), and Load resistance (R_L), Switching frequency.

SIMULATION RESULTS:

The simulation of the buck converter is accomplished using Matlab program using Simulink tool. The MATLAB program used to observe the inductor and output current and output voltage variation with duty cycle. Fig. 5, shows the designed DC-DC buck converter.

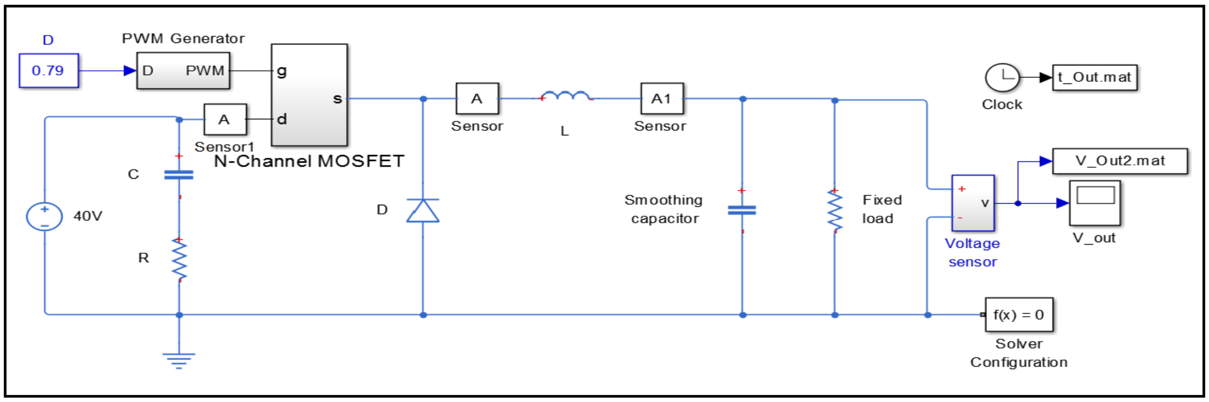
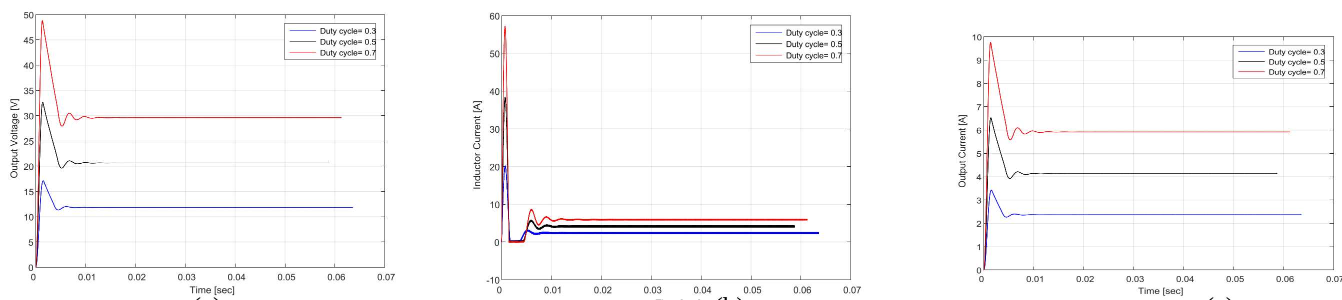


Fig5. Schematic Diagram of DC-DC converter designed using Simulink.

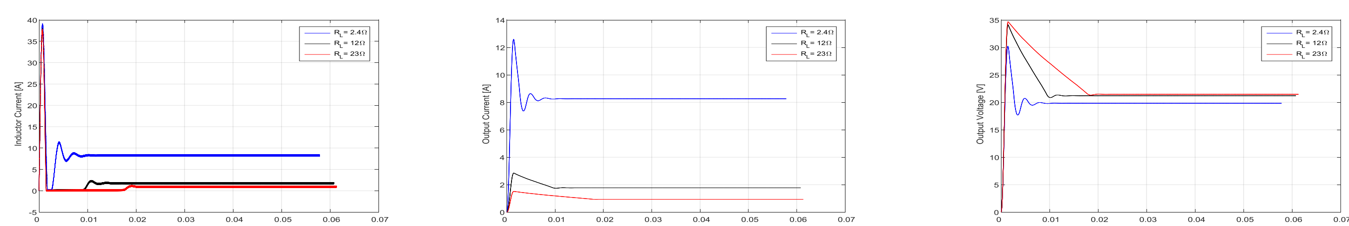
The simulation results are presented in this section and performed in two cases. Firstly, at constant load resistance (R_L= 5Ω) and three different values of duty cycle (0.3, 0.5, 0.7), an input voltage (40V). The output voltage, the inductor current and the load current are simulated in Fig.6.



(a) (b) (c)

Fig. 6 Output characteristics of designed buck converter at three different values of duty cycle and R_L= 5 Ω (a) Inductor current. (b) Output current. (c) Output voltage.

Secondly, at duty ratio (0.5) and three different values of load resistance (2.4Ω,12Ω, 23Ω), an input voltage (40V). The output voltage, the inductor current and the load current are simulated in Fig. 7.



(a) (b) (c)

Fig. 7 Output characteristics of designed buck converter at three different load values and duty cycle D= 0.5. (a) Inductor current. (b) Output current. (c) Output voltage

EXPERIMENTAL RESULTS:

The experimental results are performed for the designed DC-DC converter with the components mentioned above. They are commercial components that have been connected together on a white board to build the required specification of the DC-DC converter, and then are implemented using a PNC board and tested using a power supply to provide an input source, and the pulse width modulator signal is generated using the FPGA board by writing a VHDL code and simulated using Model-sim to insure that the designed code satisfies the customer specification, then is downloaded on Spartan-3 kit and tested using Oscilloscope. As the duty cycle value of the pulse width modulation (PWM) controls the output voltage value as introduced in the simulation results. The designed circuit for the DC-DC converter should be tested in different values of duty cycle.

To generate different values of duty cycles; FPGA program is executed and implemented on a xillinx Spartan-3 XC3S200 FPGA device. This kit contains 8 switches. Every switch generate a certain duty cycle (0.2, 0.3,0.4, 0.5, 0.6, 0.7, 0.8, and 0.9) respectively. Fig. 8, shows the Model-sim simulation results of the generated different pulse width modulation (PWM) ratio.

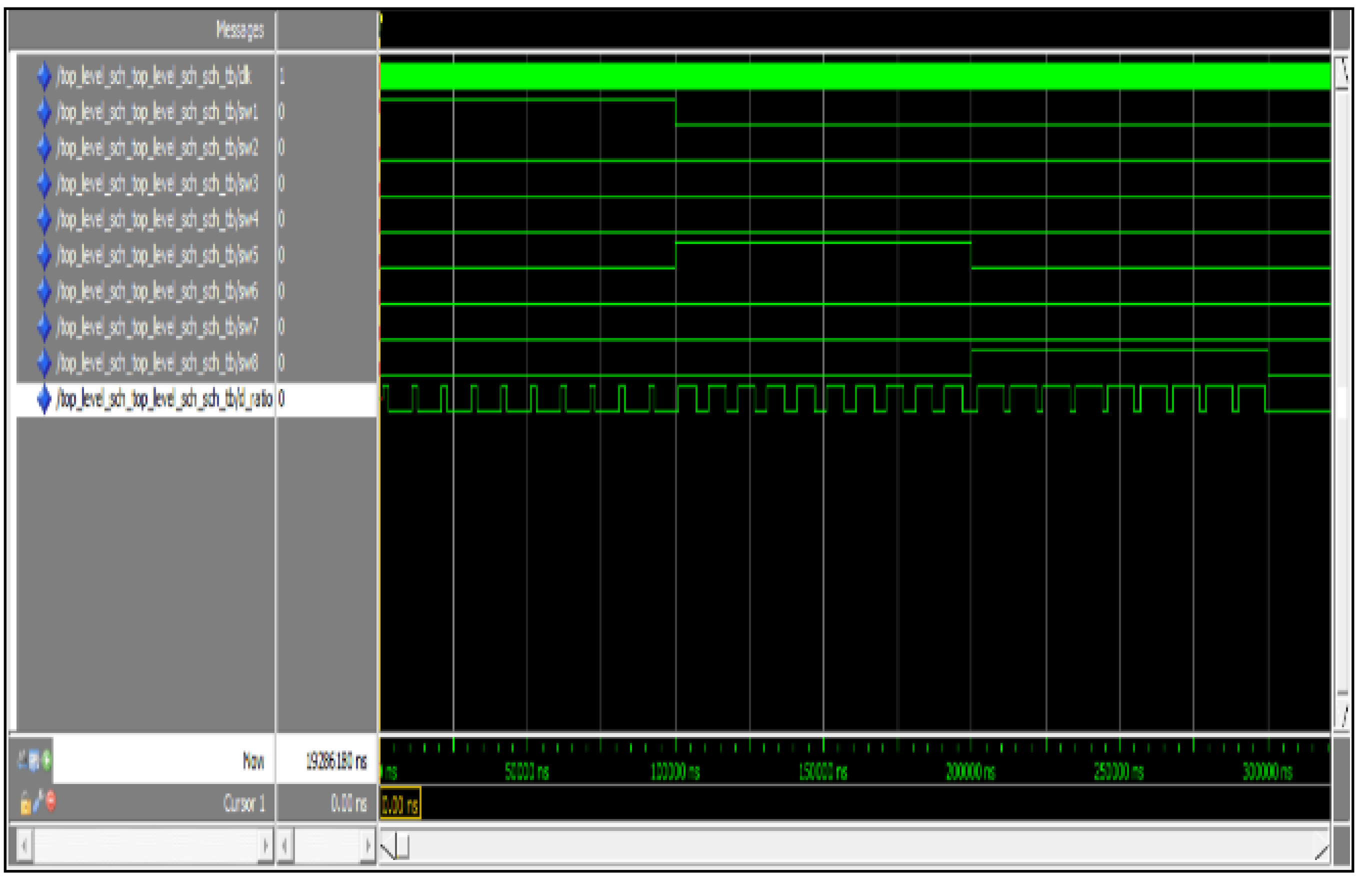


Fig.8Model-sim simulation results for generating different Duty cycle.

The experimental results of testing the DC-DC converter are listed in the table II.

TABLE II. DC-DC BUCK CONVERTER EXPERIMENTAL RESULS

Experiment No.	Input Voltage	Input current	output Voltage	output current	η
Experiment 1	28.0V	0.78A	12.02V	1.19A	65.0%
Experiment 2	15.0V	0.31A	3.30V	0.94A	66.7%
Experiment 3	12.0V	0.62A	5.00V	1.15A	77.28%
Experiment 4	20.0V	0.83A	12.0V	1.07A	77.35%
Experiment 5	25.0V	0.8A	12.0V	1.21A	72.6%

To verify the implemented theory a laboratory prototype DC-DC Buck converter is constructed. The prototype converter circuit parameter values are as listed in table I. The PWM is provided to the MOSFET by SPARTAN 3 FPGA Kit.

Experimental results are shown in table II, which explains the efficiency of the designed Buck converter at different values of input voltage and at different required output voltage(3.3V, 5V and 12V) at load resistance $2.3\Omega<RL>25\Omega$. In every experiment the designed DC-DC converter can reduce the input voltage to the required output voltage according to the adjusted duty cycle.

CONCLUSIONS:

In this paper a buck converter for converting DC voltage at different values to constant DC voltage is designed. The design analysis of Buck converter is presented. The most important feature of this Design is that it is very simple and easy to be implemented as it requires very less number of components, and cheap.

The Proposed system has been simulated in MATLAB SIMILINK environment. From the simulation results it is found that the desired output voltages can be obtained by proper selection of values of inductor, capacitor and switching frequency which is perfectly done by explaining the design equations and the trade-off between all parameters included in the Buck converter. According to the application in which the converter will be used, MPPT control algorithms and PID control can be used to control the output of the buck converter by controlling the duty cycle generated to control the MOSFET gate.

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