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A Theoretical Study of Performance and Design Constraints of Non-Isolated Dc-Dc Converters

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Abstract: This paper investigates the effect of the variation of duty ratio on the different performance parameters of the three non-isolated dc-dc converters namely buck, boost and buck-boost converter. Five important parameters dependent on the duty ratio have been identified namely output voltage, output current, effective impedance at the input, minimum inductance and minimum capacitance for continuous conduction mode (CCM). The effect of variation duty ratio on the performance of these parameters is investigated and reported.

Keywords: Duty ratio; performance parameters; dc-dc converter; continuous conduction mode.

I. INTRODUCTION

The world energy consumption is increasing while the fossil fuel energy reserve is on the verge of depletion. The future energy scenario will consist of a much needed dependence on the renewable energy sources like solar, wind, geothermal, biomass, etc. These new or alternate energy sources although being promising, their use and production of energy from them are still much more expensive than their relative counterparts of existing conventional sources of energy. Power electronics and power converters can play an important role by acting as an interface medium for the energy production by PV, wind turbines, etc. The converters can operate with high efficiency and thereby reduce the system losses and reduce the total loss of the systems connected with Power electronics converters. The semiconductor device and microprocessor technology has seen a rapid growth and development in the last three decades. New innovations and technological knowhow are increasing every day in this field. As such they provide a promising scope for use in renewable energy technologies. The ongoing research in the field of power electronics devices makes them a preferred choice in a number of applications like battery charging, as MPPT control interfaces in PV system applications, etc. This paper consists of an in-depth analysis and discussion on the theory of the three basic dc-dc converter topologies, their circuit analysis and working [1]. The paper is organised in the following manner. The introduction section I is followed by a brief discussion on the operation of DC-DC switched mode converters in section II. Section III covers the steady state analysis of the dc-dc converter topologies. Section IV reports on the design analysis of the converters with respect to the boundary filter inductance and capacitance. Section V draws conclusion to the work.

II. DC-DC SWITCHED MODE CONVERTERS

The purpose of any dc-dc switched mode converter is to convert an unregulated dc input to a regulated or controlled dc output at a desired voltage level. In a PV system, the dc-dc converter is used to act as MPPT interface between the source and the load. The converter works to adjust its duty cycle to match the requirements of the system.

The voltage transformation in a dc-dc converter (switched mode) is done by controlling the operation of the switches. This is achieved by controlling the operation period, i.e. the on time (t_{on}) and off time (t_{off}) of the switches by PWM (pulse width modulation) technique. The switching period $T_s=t_{on} + t_{off}$ is held constant while the ratio of the on time to the switching time (i.e. duty ratio) is varied. By using the switch mode control in the circuit, the output voltage V_o will be a constant pulse as shown in the figures below. Because of the inductive and capacitive circuit elements in the converter topologies the output voltage should be constant (given as the dashed line) V_o.The switch control signal is generated by comparing a control value (which mostly is a signal generated as an error signal) to a repetitive waveform V_{st}. The control value may be the difference between the actual and the desired output voltage V_o as seen by the figure 31 and figure 2. The effects of comparison are when V_{ctr} ($V_{control}$)> V_{st}, switch is on and vice versa.

Hence we can now define duty ratio (cycle) as

$$D=\frac{t_{on}}{T_s}=\frac{V_{ctr}}{V_{st}}$$

The frequency ($1/T_s$) can also be varied in a PWM switching mode. This method however might make it hard to filter the ripple components in the converter waveforms. The three basic dc-dc converters namely the buck, boost and the buck-boost converters along with their operation is discussed here below. The analysis is done with respect to their steady state operation, i.e. assuming that the switches are ideal and losses in the capacitor and inductor are neglected.

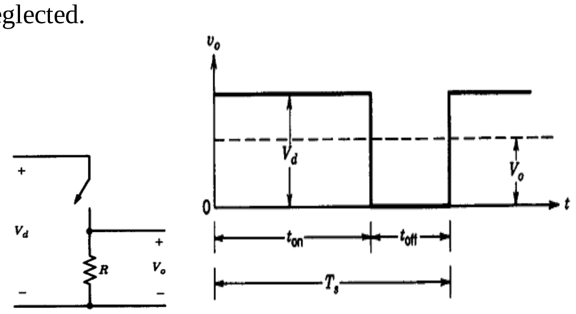

Fig 1: Switch mode operation of converters

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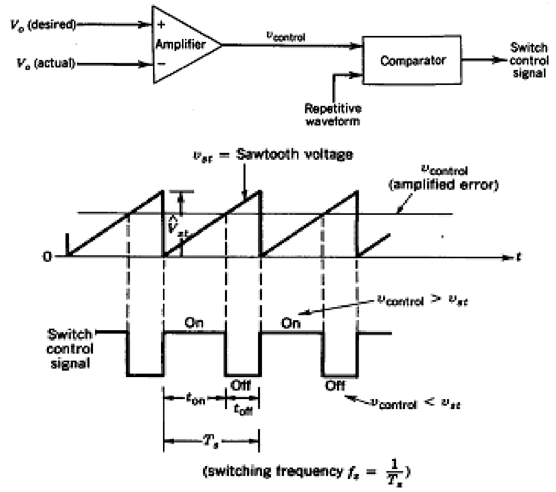

Fig 2: PWM block diagram and comparator signal

Moreover the switching time is assumed to be much shorter than the electric time constant of the circuit. Steady state implies that a constant duty cycle operation which means that the current starts from the same value at the beginning of each switching cycle. Due to the inductor the current will charge and discharge through one cycle and steady state conditions implies that $\Delta I_{on} = \Delta I_{off}$ .The change in the current is the only factor that decides if the system is in steady state or not. In a dc-dc converter with an optimal design it is assumed that the switching ripples are very small compared to the average values often less than 1% of the quantities. This is often referred to as the small or linear ripple approximation [2].

A BUCK CONVERTER

The buck converter is often referred to as a step down converter, and as the name implies, the converter produces a lower dc voltage output than the input. The circuit of the buck converter can be seen in figure 3.14 below. The buck converter will have different circuit schemes for each converter switch operation. To obtain the relation between the input and the output of the converter (and hence the duty ratio) the current through the inductor will be examined. Also the filter capacitor is assumed to be large so that v_o (t) =V_o which means that no current will flow through it.

Thus it can be concluded that the inductor current equals the output current for both switch positions. The earlier assumption about the system being in steady state implies that the voltage and current waveforms repeat themselves for each time period T_s. The equivalent circuits for this consideration are as shown in figure 3. When the switch is on the input voltage V_d leads to a linear increase in the inductor current. When the switch is turned off, the diode becomes forward biased and the stored energy in the inductor makes the current continue to flow. But as the energy is transferred from the inductor to the load, the current is decreasing again. The inductor voltage is given as:

$$v_L = L\frac{di_L}{dt} \qquad (1)$$

As the inductor voltage is repeating itself for each time period, the change for each period is zero:

$$(i_L)_{on} = (i_L)_{off}$$

$$\int_0^{Ts} v_L dt = 0,$$

i.e. the volt-sec product over time should be zero for steady state operation. On rearranging the expanded terms of the relationship between the input and output voltage we get

$$V_o = DV_{in} \qquad (2)$$

The buck converter is actually equivalent to a transformer where the turns ratio is changed by varying the duty cycle. The relation can be realized using the power input and power output equality criterion. (note that $V_{in} = V_d$)

$$V_{in}I_{in} = V_oI_o$$

$$\frac{V_o}{V_{in}} = D$$

$$\frac{I_o}{I_{in}} = \frac{1}{D}$$

$$\frac{V_o}{V_{in}} = D = \frac{I_o}{I_{in}} \qquad (3)$$

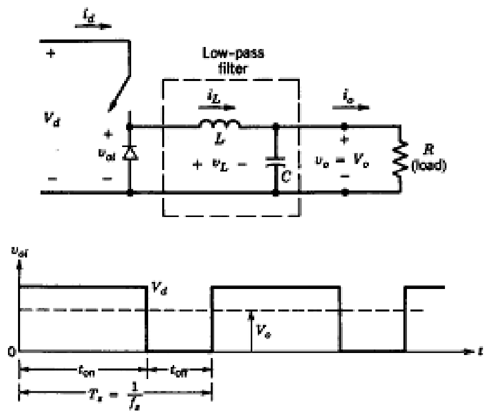

Fig 3: Buck Converter operation [3]

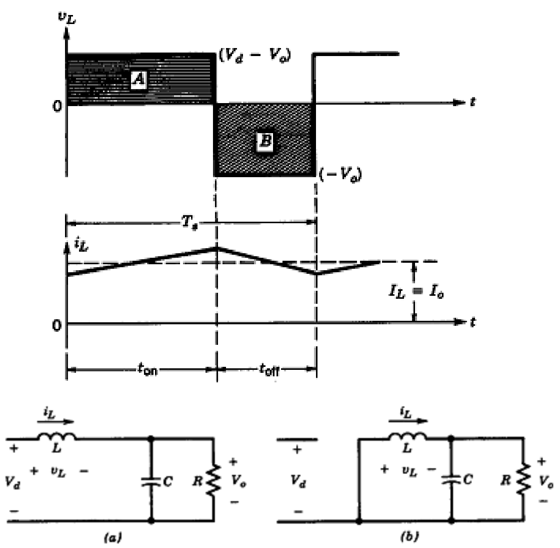

Fig 4: Buck converter circuits for t_{on} and t_{off}

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B. BOOST CONVERTER

As compared to the buck converter, the boost converter produces an output voltage which is higher than the input voltage. The circuit is according to figure 5 shown.

This topology also has different circuit schemes depending on the state of the switch as seen in figure 6. When the switch is on the output stage it is isolated from the input caused by the reverse biased diode. The input will supply the inductor with constant voltage and the inductor current will increase. When the switch is off the output will be supplied by both the input and the inductor, and the current through the inductor will decrease because of this energy transfer.

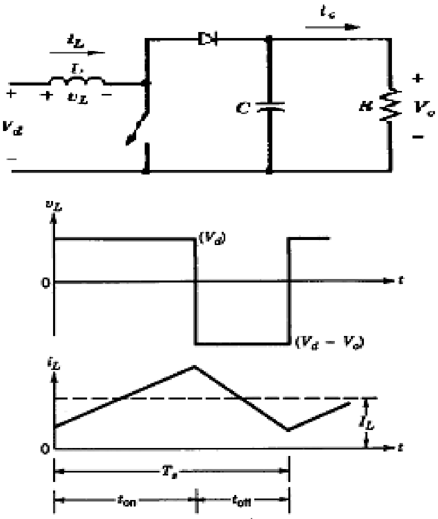

Fig 5: Boost converter operation[3]

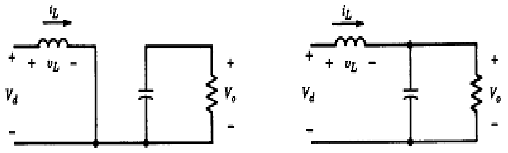

Fig 6: Boost converter circuits for t_{on} and t_{off} in CCM

The voltage and current graph of the inductor through one time period has been shown in figure 5 above along with the individual effective circuit for t_{on} and t_{off} in figure 6. The shapes are equal to those of the buck converter, but the voltage of the inductor is different due to the placement of the switch and the diode. Proceeding as before for the analysis of steady state performance for the buck converter, we have also for the boost converter,

$(i_L)_{on} = (i_L)_{off}$ and $\int_0^{Ts} v_L dt = 0$, which gives us

$$\frac{V_{in}}{V_o} = (1-D) = \frac{I_o}{I_{in}}. \quad (4)$$

C. Buck-Boost converter

The main application of a step down/step up buck boost converter is in regulated dc supplies where a negative polarity output may be required with respect to the common terminal of the input voltage, and the output may be either lower or higher than the input voltage as per requirement. The buck-boost converter can be obtained by the cascade connection of the two basic converters; the step down converter (buck) and the step up converter (boost). In steady state, the output to input voltage conversion ratio is the product of the conversion ratios of the two converters in cascade.

$$\frac{Vo}{Vin} = \frac{-D}{1-D} \quad (5)$$

The variation of the duty ratio will thus determine if the converter operates in the output mode as a boost or a buck converter. When the switch is closed the input provides the energy to the inductor and the diode is reverse biased. When the switch is opened the inductor will transfer the stored energy to the output.

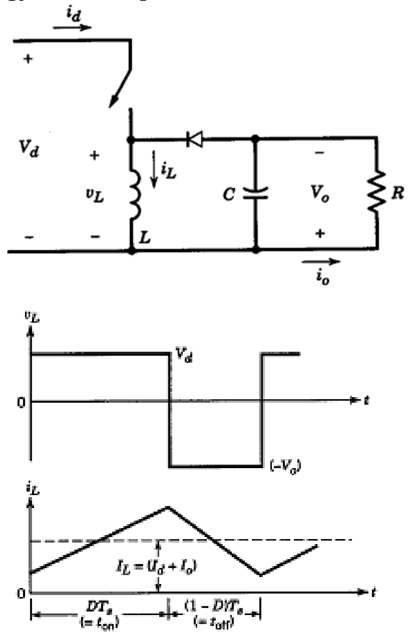

Fig 7 : Buck-Boost converter operation

For steady state analysis of the converter we have assumed that the value of the capacitor at the output is very large as a result of which v_o (t) $=V_o$. Figure 7shows the circuit layout of the buck-boost converter along with the voltage across the inductor and current through the inductor waveforms for one cycle operation of the converter. Figure 8 represents the circuits for the switch on and switch off instant of the converter.

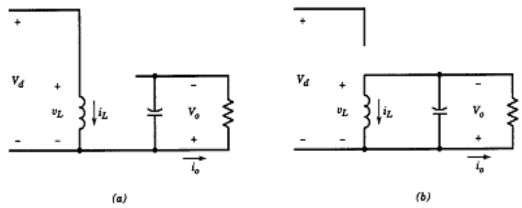

Fig 8: Buck-Boost converter operation (a) for switch on (b) for switch off

III. DC-DC CONVERTER STEADY STATE OPERATION ANALYSIS

The steady state analyses of converters are governed by two fundamental laws that dictate the operation of dc-dc converters. They are volt-second balance and the charge balance or ampere-second balance [2,4]:

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Volt-second balance

The inductor in the circuit will not support an average DC voltage across it. This implies that under steady state analysis

$$\int_0^T V_L dt = 0$$

Where V_L is the voltage across the inductor and T is the switching period. This means that the product of the voltage and time in one period must be zero under equilibrium conditions. This is called the volt-second balance for inductors.

Ampere-second balance or charge balance

The capacitor in the circuit will not allow an average DC current to pass through it. This implies that under steady state conditions,

$$\int_0^T i_C dt = 0$$

Where i_c is the current through the capacitor and T is the switching period. This means that the product of capacitor current and time should be zero under equilibrium condition. This is called ampere-second balance for capacitor. This indicates that under equilibrium condition there is no accumulation of charge on the capacitor. Based on the above two laws of volt-sec balance and ampere-sec balance, the input output relationship under steady state conditions can be obtained. However some assumptions are made for the analysis namely, switches used in the converters are lossless, i.e. there is no on-state and off-state loss in the circuit, winding resistance in the inductor is zero, the equivalent series resistance of the capacitor is zero and the converter is 100% efficient[2,4].

To analyse the behaviour of the three DC-DC converters with change of duty ratio(D) , we have taken five basic parameters, which have been found to be dependent on the duty ratio.

1. Voltage Gain (A_v)
2. Current Gain (A_i)
3. Input Impedance (R_i)
4. Boundary filter inductance (L_b)
5. Minimum filter capacitance (C_{min})

These parameters have been derived considering that the converters are in continuous conduction mode (CCM) of operation and work under 100% efficiency.

Table 1: Performance parameters for the Converters

Parameter	Buck	Boost	Buck-boost
Voltage gain (Av)	D	1/(1-D)	-D/(1-D)
Current gain (Ai)	1/D	1-D	-(1-D)/D
Input Impedance (R_i)	R_L/D^2	$R_L(1-D)^2$	$R_L(1-D)^2/D^2$
Boundary inductance (L_b)	$(1-D)R_L/2f$	$(1-D)^2 DR_L/2f$	$(1-D)^2 R_L/2f$
Minimum filter capacitance (C_{min})	$(1-D)V_o/(8V_rL_f)$	$V_oD/(V_rR_Lf)$	$V_oD/(V_rR_Lf)$

The variation of the first three basic parameters for different values of duty ratio have been plotted and studied in figures 9-11 along with their individual behaviour, and each section is followed by a explaination for each converter.The variation of the boundary filter inductance and capacitance for each of the converters is thereafter discussed for a resistive load of 20 Ω in subsequent sections.

A. Effect of duty ratio on A_v and A_i for different topologies of the DC-DC converters:

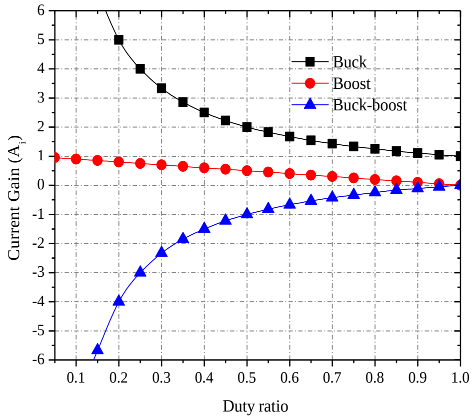

Fig 9: Effect of duty ratio on the current gain (A_i) of the converters

Explanation:

BUCK CONVERTER: with the increase of duty ratio from 0 to 1, the effective current gain of the converter decreases from a very high value (infinity) to unity at D=1. Thus for any operation taking place between 0 and 1, the current gain for a buck converter will be higher than unity, i.e. the current at the output will always be higher than the current at the input.

BOOST CONVERTER: with the increase in duty ratio from 0 to unity, the current gain decreases from one to zero. Thus for any operating duty period between 0 and 1, the current gain is always less than unity. The output current will always be less than the input current of the converter.

BUCK-BOOST CONVERTER: The gain of the converter is negative due to the relationship as tabulated above. So the gain value reaches from a negative maximum to unity as the duty ratio changes from 0 to 1 in a Buck-Boost converter.

B. Effect of Duty ratio on the voltage gain (A_v) of the three DC-DC converter topologies

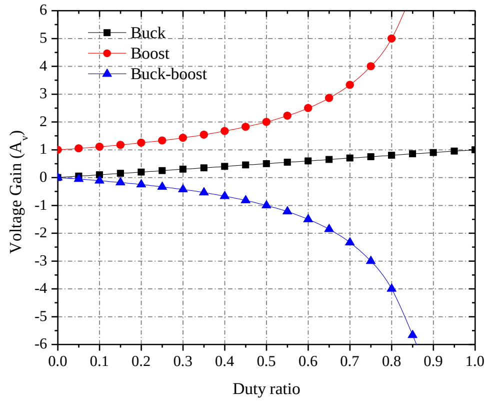

Fig 10: Effect of Duty ratio on the voltage gain (A_v) of the converters

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Explanation:
BUCK CONVERTER: with the increase of duty ratio from 0 to 1, the effective voltage gain of the converter increases linearly with duty ratio from a zero value (at D=0) to unity at D=1. Thus for any operation taking place between 0 and 1, the voltage gain for a boost converter will be less than unity, i.e. the current at the output will always be less than the current at the input.

BOOST CONVERTER: with the increase in duty ratio from 0 to unity, the voltage gain increases from one to a very high value (at D=1). Thus for any operating duty period between 0 and 1, the voltage gain is always greater than unity, indicating that the output current will always be more than the input current of the converter.

BUCK-BOOST CONVERTER: The voltage gain of the converter is negative due to the relationship as tabulated above. So the gain value reaches from zero to a negative high value as the duty ratio changes from 0 to 1 in a Buck-Boost converter.

C. Effect of Duty Ratio on R_i for different topologies of DC-DC converters:
Explanation: A resistive load of 10 Ω has been considered at the output of the converter. The behavior of the three converters for this load is explained here below.

BUCK CONVERTER: The resistance seen by the converter at its input (Input impedance R_i) is always higher than the load connected at the terminal of the converter. As a result of this the resistive gain of the converter is always higher than unity at any operating duty ratio, and equal to unity at D=1. As the duty ratio changes from 0 to 1, the gain of the converter decreases from a very high value to unity. Also at any value of duty ratio in between 0 and 1, the converter sees the output load decrease as the duty ratio increases. Therefore we can conclude that for optimal operating condition the BUCK converter is to be operated at a resistance higher than the load resistance to be matched.

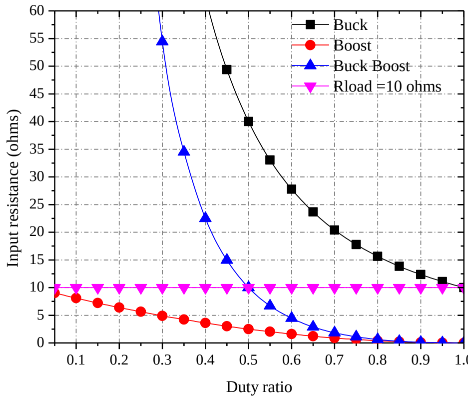

Fig 11: Effect of the duty ratio on the input impedance of the converters for 10 Ω

BOOST CONVERTER: From figure 11, it is clearly evident that the input impedance reflected at the input to the converter is less than the load resistance. It changes from the value of the load resistance to a value of zero as the duty ratio increases from 0 to 1. At any value of duty ratio in between 0 and 1, we see that the converter sees the resistance value less than that at the load terminals. So input impedance R_{in} in a boost converter is always less than the load resistance.

BUCK-BOOST CONVERTER: In case of the BUCK-BOOST converter, the resistance seen by the converter is high for duty ratio less than 0.5, and in between 0.5 and 1, the converter is seen to experience the effective resistance at the input less than the load resistance. Thus for the buck- boost converter it is evident that the operation of the converter for varying duty cycle covers values of resistance both higher and lower than the load resistance. So it is effective in covering all the range of values of resistance in the I-V curve of the PV module.

IV. DESIGN ANALYSIS

When there is a change in the atmospheric condition during a day, the MPP will change. The change in MPP will let the MPPT to adjust the duty ratio (D), in order to track the new MPP. So the corresponding values of L_{bmin} and C_{min} will change as a result of the new operating MPP and its relative new duty ratio. As a result, it may so happen that the converter may operate will a large value of ripple in the output parameters, which in turn affects the converter efficiency.

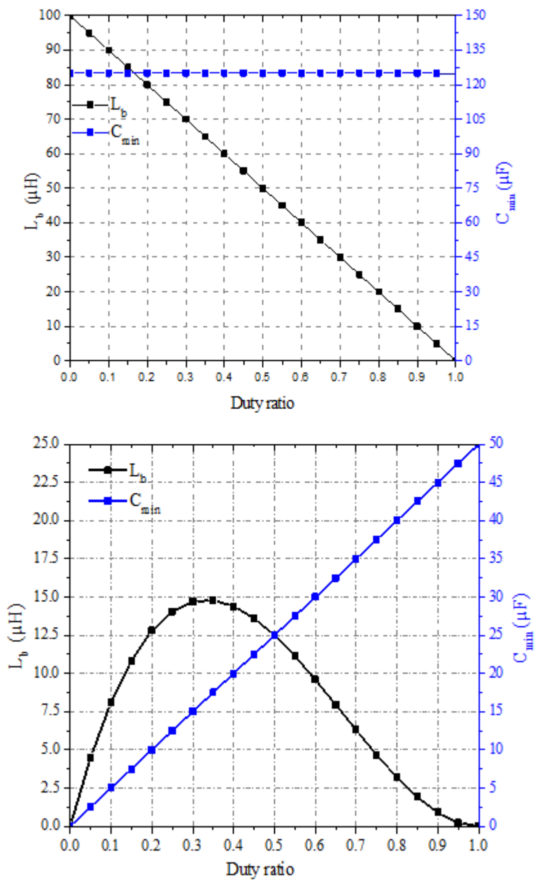

Fig 12: Effect of the duty cycle on the design of buck and boost converters for R_L= 20 Ω

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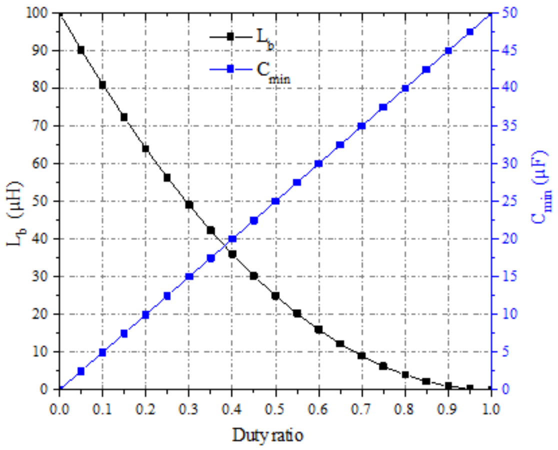

Fig 13. Effect of the duty cycle on the design of buck-boost converter for R_L =20 Ω

To avoid this problem, it is imperative to have knowledge of these boundary values which change according to atmospheric conditions. From the relationship developed in table 1, and assuming that

1. A frequency of operation is 100 kHz.
2. A common load resistance for the converters
3. A percentage ripple of 1% in the converter output.

We have studied the effect of the change of duty ratio (D) as a result of the changing atmospheric conditions on the design of different topologies of DC-DC converter in the following subsections. The value of resistance such that R_L= 20 Ohms has been considered for investigation. Here $R_{mpp(min)}$ <R_L<$R_{mpp(max)}$ and is useful for making a comparison of the boundaries of design parameters for different topologies. It is also evident that it serves as a case of non-optimal loading for the buck and boost converters.

The buck converter has the capacitance value dependent on the minimum boundary value of filter inductor as seen in the table 1. The boundary inductance is seen to decrease with for increase in the duty ratio, and the filter capacitance value remains the same. For a boost converter, the filter capacitance value increases linearly with the increase in duty ratio. However the boundary inductance curve follows a hill curve with its peak at a duty ratio of 0.33 and values decreasing to zero value as duty ratio reach unity. For a buck boost converter the filter capacitance increases linearly while the boundary inductor value decreases as an inverse square law graph with the increase in duty ratio from zero to unity.

V. CONCLUSIONS

The three topologies of non-isolated dc-dc converters each have dependence on their performance constraints. Considering the impedance reflected at the input side of the converter, it is seen that for a connected load Rl, the buck converter will have values of Ri>=Rl for the duty ratio in the range [0,1]. For a boost converter, the condition is Ri<=Rl for the duty ratio in the range [0,1]. For the buck-boost converter it is seen that for the range of operation of the converter subject to variation of duty ratio from 0 to 1, the input impedance is seen to vary from a very high value of resistance (such that Ri>Rl for $D\in[0,0.5]$) to Ri=Rl at duty ratio =0.5 and subsequently have values of Ri<Rl to reach zero at D=1.

For a particular value of duty ratio it is seen that for the design constraints it is observed that the largest value of inductance follows the relationship Buck>Buck-Boost>Boost and the value of capacitance is observed to have higher values for the buck-boost and boost converter compared to its corresponding value in case of buck converter.

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