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Proposing a Technique to Design a Boost Converter Based Charger and Analysis on the Power and Efficiency

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Abstract*:* This paper proposes a method to select the boost inductor and capacitor for effective battery charging. Mainly the boost inductor of the converter is designed, taking the charging current into account. Satisfactory results are seen and the inductor`s current is continuous as required by the converter. Finally, power and efficiency calculations are done to complete the research.

Keywords: Boost converter, battery charging, critical inductance, filter sizing, internal resistance.

I. INTRODUCTION

A dc to dc converter used to increase the magnitude of dc voltage is known as boost converter [1]. It is widely used in dc drives, dc power supplies, input power factor correction of rectifier and solar systems [2]. One of the major applications of this converter is to charge a battery that has a higher voltage level than the available voltage source. A wide range of research is recently done on boost converter to make the converter useful in the solar system, where battery charging is clearly noticed [3-4]. Moreover, in automobiles, battery charging is accomplished using the thermoelectric generation, which includes a boost converter [5]. Irrespective of the sources used, the converter requires a proper inductor which contributes to boost the voltage.

However, every battery has an ampere hour rating that effects the charging profile of the battery itself. In this research, a battery charging method considering the power rating of the converter and proper calculation sequence is presented to simplify the filter sizing phenomenon.

In the first section, the conventional method to design a boost converter is described. Next, some equations are represented to analyse the parameters that are considered to design the inductor and capacitor for the converter. Then, some useful modifications are added into the formulas and simulation is done to justify the charging procedure. Finally, different parameters such as, critical inductance, output voltage, output current, charging time and efficiency are analysed for different duty cycles.

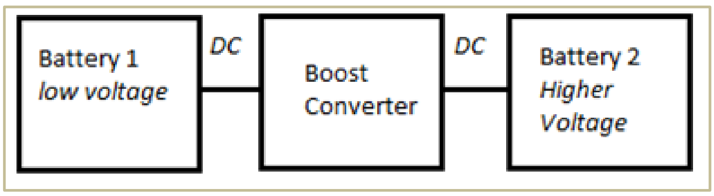
II. CONVENTIONAL METHOD TO DESIGN A FILTER

The Fig.1 shows the block diagram and a boost converter of a battery charging unit where the main power source is a low voltage battery. In this circuit, the connected load (parallel with capacitor) is a battery 'Vb' with its internal resistance 'R'. Diode is represented by 'D', capacitor which reduces the ripple in output voltage is denoted by 'C' and the boost inductor that is the main components of the boost action is indicated by 'L'. A switch is used to control the output voltage by PWM technique [6]. 'E' is the input voltage which is boosted at the output.

Before proceeding to the proposed method, it is important to recall some mathematical formulas related with the filter (L and C) for a boost converter [7].

$$Lc = \frac{D(1-D)R}{2f} \qquad (1)$$

$$Cc = \frac{DVo}{Rf\Delta Vo} \qquad (2)$$



(a)

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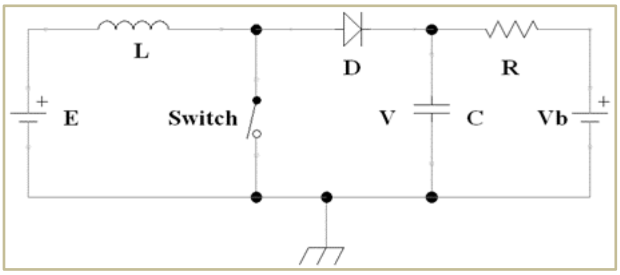

(b)

Fig 1. (a) Block diagram and (b) The circuit diagram of a boost converter based battery charging unit

To begin with, duty cycle 'D' is the variable of a boost converter that determines the degree of voltage increment. Then, the next step is to specify the converter`s power 'P' that ultimately helps to calculate the load resistance 'R'. Finally, selecting a switching frequency 'f', the filter containing inductor 'L' and capacitor 'C' is designed. Particularly, the inductance 'L' used in the circuit must be greater than the calculated critical inductance 'L_C' and the capacitance than the calculated capacitance 'C_C' to make the inductor current continuous that ensures the boost action of the converter. Another essential term in the equation (2) is the ripple factor ($\Delta Vo/Vo$) which is usually taken as small as possible to achieve smooth dc output.

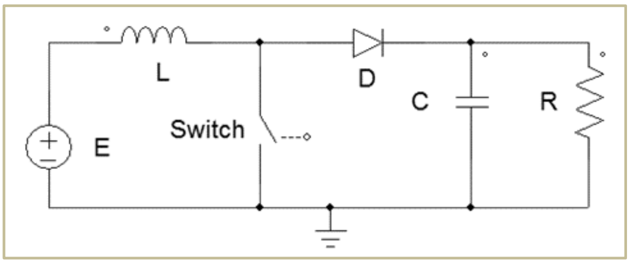

Fig 2. Boost converter

Fig. 2 shows the boost converter. However, the above-mentioned procedure is suitable for operating an electrical load but not for proper battery charging.

III. Proposed Technique For The Filter Design

The Fig. 1(b) connects a battery including its resistance with the boost converter and this is not a general loaded model as it shows a voltage source to represent a battery. In this situation, if the previously explained conventional technique is used to design the filter, then the output will not be perfect as that method only considers the loaded model where no other potential source is attached.

The 'R' in the equation (1) can simply be replaced by the voltage and current terms using Ohm`s law ($Vo=IR$),

$$Lc = \frac{D(1-D)\,Vo}{2fI} \qquad (3)$$

In equation (3), 'Vo' is the output voltage of the boost converter and 'I' is the output current. In addition, this equation does not directly reflect any presence of resistance that is generally seen in the equation (1). Interestingly, every parameter in equation (3) is selected, except the 'I' output current.

Higher output current selection is useful as it will reduce the charging time of the battery. Moreover, that high current will enhance the power of the converter.

Hence, to design a boost converter based battery charging system, the following steps are proposed.

(i) Duty cycle 'D': It is determined from the input and output voltage rating (E and Vo respectively) and using the formula below:

$$Vo = \frac{E}{1-D} \qquad (4)$$

However, the 'Vo' must be greater than the voltage rating of the battery, which is targeted for charging. Additionally, the 'D' must have a specific minimum value. The minimum value of the duty cycle can be achieved by Replacing 'Vo' by 'Vb' in (4),

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$$Dmin = 1 - \frac{E}{Vb} \qquad (5)$$

The duty cycle should be greater than 'D_{min}' to charge the battery.

(ii) <u>Output current 'I' rating selection:</u> It will vary depending on the internal resistance of the battery that is charged. For a particular voltage 'Vo', the current rating of the converter follows the formula given below.

$$I = \frac{Vo - Vb}{Rint} \qquad (6)$$

Here, 'Vb' and 'Rint' are the battery voltage and internal resistance respectively.

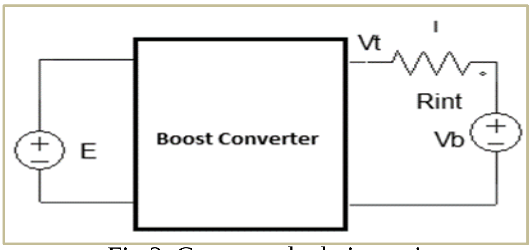

Fig 3. Current calculation unit

Fig.3 depicts the current calculation diagram of the above described fact. Here, 'Vt' is the output voltage (Vo) of the converter.

(iii) <u>Filter design:</u> This includes determining the size of the inductor and capacitor.
After following the step (i) and (ii), equation (3) for critical inductance calculation is used. In this equation, switching frequency 'f' is another parameter that should be selected arbitrarily but the inverse relation between the 'L_C' and 'f' suggests to choose higher switching frequency as for that frequency the 'L_C' becomes smaller. Hence, the following formulas are given to design the filter as the last step.

$$Lc = \frac{D(1 - D)\,Vo}{2fI} \qquad (3)$$

$$C = \frac{ID}{Vo\,f\,RF} \qquad (7)$$

In the equation (7), 'RF' is the ripple factor. Additionally, both of the capacitance and inductance used in the power circuit must be greater than the calculated values using (3) and (7).

IV. SIMULATION

Table I shows the parameters that are used in the boost converter charging circuit to justify the proposed methods. The parameters in the calculated section, are calculated using (5), (6), (3) and (7). This proposes sequence is obvious to design the filter.

TABLE I
PARAMETERS OF THE CHARGING CIRCUIT

Battery Parameters	
Input Battery, E	5V
Output Battery, Vb	12 V
Output battery`s Internal Resistance, Rint	2 Ω
Selected Parameters	
Terminal Voltage, Vt or Vo	14 V
Switching Frequency, f	2 KHz
Ripple Factor, RF	2%
Calculated Parameters	
Duty Cycle, D	64.3 %
Charging Current, I	1 A
Critical Inductance, Lc	0.803 mH
Calculated Capacitance, Cc	1148.2 uF
Circuit Inductance and Capacitance	
Circuit Inductor, L	0.1 mH
Circuit Capacitor, C	1420 uF

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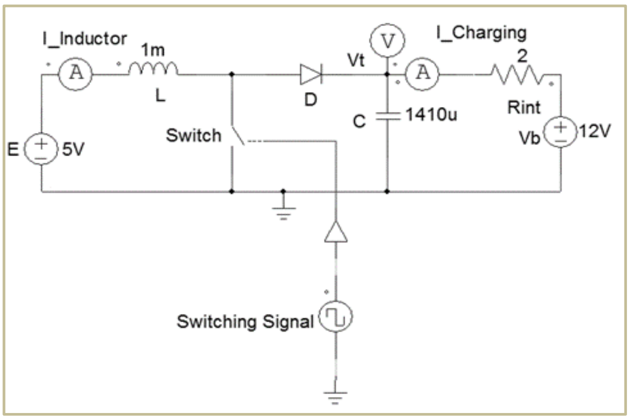

Fig 4. Circuit for simulation

Fig. 4 shows the circuit diagram for explaining the battery charging method. Here, the parameters are taken form the Table I. The output voltage 'Vt' will be taken across the capacitor. Additionally, the output and inductor current will be observed to verify the operation.

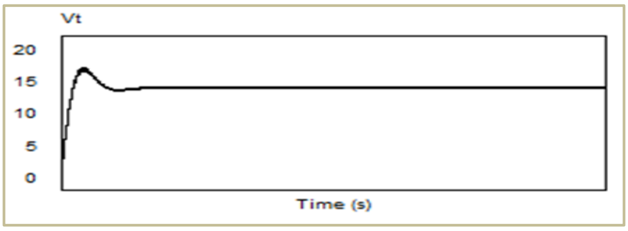

Fig 5. The simulated terminal voltage

Fig. 5 shows the terminal voltage of the boost converter, which is designed to charge a battery of 12 V. The output is 14 V and similar with the taken value in the Table I. The battery will be charged and the current will flow from the converter to the battery as the output voltage of the converter is greater than the battery voltage.

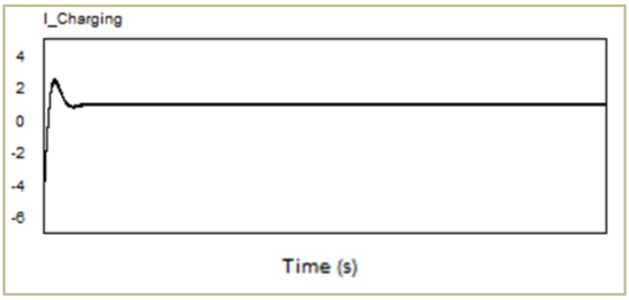

Fig 6. The simulated charging current

The charging current is shown in the Fig. 6 and around 1 A. This also matches with the values seen in the Table I. In addition, the waveform of the output current is same as the voltage as the internal resistance of the battery acts as a pure resistive load for the converter.

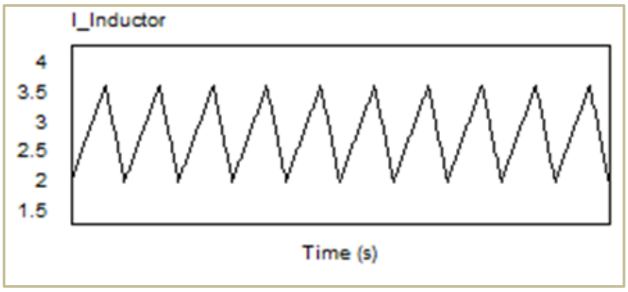

Fig 7. The simulated inductor current

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For proper operation of a boost converter, the inductor current must be continuous (i.e. no zero-crossing point of current waveform is seen). This continuity in current is clearly noticed in the Fig. 7. During the ON switch state of operation, the boost inductor stores energy, while the energy is decayed at the OFF mode of that switch. This mode of operation is termed as continuous conduction mode (CCM) [7-9].

Now some factors such as, critical inductance size, output voltage and current variation and power flow will be analysed for this particular charger circuit.

TABLE II
SEVERAL PARAMETERS OF THE CHARGING CIRCUIT FOR DIFFERENT DUTY CYCLES

D	Lc (H)	Vo (V)	Io (A)	Po (W)
0.6	0.003	12.5	0.25	3.125
0.65	0.000710937	14.29	1.14	16.33
0.7	0.000375	16.67	2.33	38.89
0.75	0.000234375	20	4	80
0.8	0.000153846	25	6.5	162.5
0.85	9.96094E-05	33.33	10.67	355.6
0.9	5.92105E-05	50	19	950
0.95	2.69886E-05	100	44	4400

Table II shows the variation of critical inductance, output voltage, output current and power with respect to different duty cycles. The minimum duty cycle taken as 60 % using (5).

TABLE III
CHARGING TIME AND POWER ANALYSIS FOR DIFFERENT DUTY CYCLES

D	Time (Hour)	P loss (W)	P effective (W)
0.6	240	0.125	3
0.65	52.5	2.612244898	13.71428571
0.7	25.71428571	10.88888889	28
0.75	15	32	48
0.8	9.230769231	84.5	78
0.85	5.625	227.5555556	128
0.9	3.157894737	722	228
0.95	1.363636364	3872	528

For the same duty cycle range, Table III shows the change in charging time, power loss and effective power for the charger. For further explanation, all curves will be examined. It is important to mention that; all the data are obtained from the simulation and given equations. The simulation is performed in PSIM.

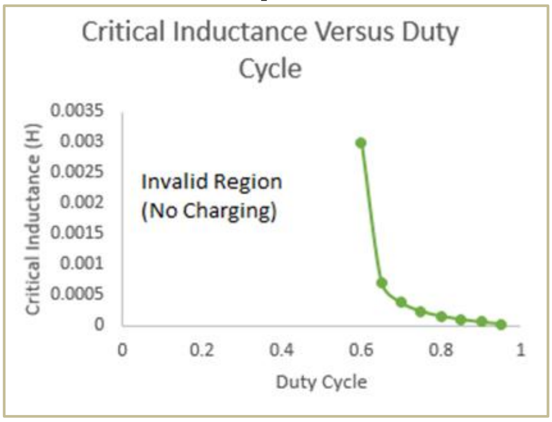

Fig 8. Critical inductance versus duty cycle

For different duty cycles the sizes of critical inductance are shown in Fig. 8. However, the minimum duty cycle for this charger is 0.6 and below that point power will flow in an opposite direction. From this characteristic it is seen that, there is an inverse relationship between the duty cycle and critical inductance. As a result, small inductor can be selected for higher duty cycle system. This reduces the size and cost of the converter.

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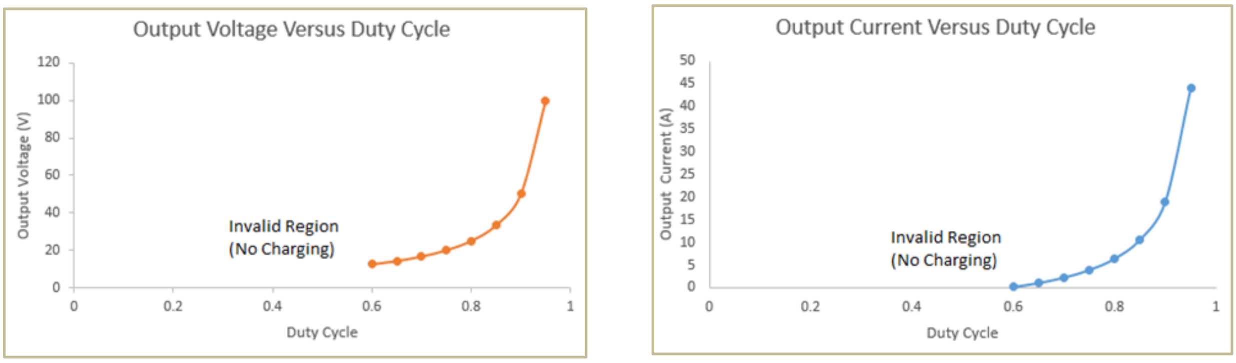

(a) (b)

Fig 9. (a) Output voltage and (b) Output current versus duty cycle

The output voltages and currents of the charger for different duty cycles are given in the Fig. 9. This feature shows the nonlinear characteristics of a boost converter.

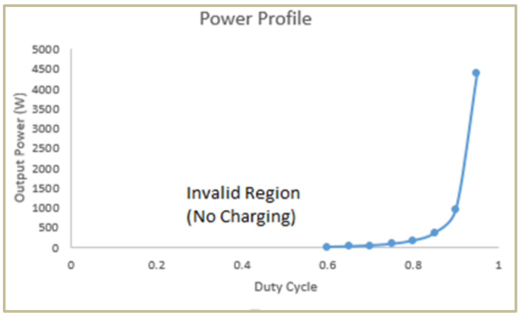

Fig 10. Output power for different duty cycles

For a particular system, the output power of a converter is dependent on the connected load. The battery and its internal resistance are the power consumers of the converter. The power profile is taken from the data shown in the Table II. The region becomes negative below 60% duty cycle. This negative region indicates a reverse power flow. Hence, that portion is not illustrated in the Fig. 10.

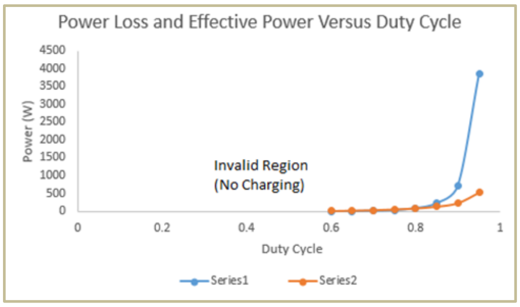

Fig 11. Power loss and effective power for different duty cycles

Fig. 11 shows the power loss (series 1) and charging power (Series 2). Charging at higher duty cycle is not effective as dramatic power loss is seen across the internal resistance of the battery. These data collected from the Table III.

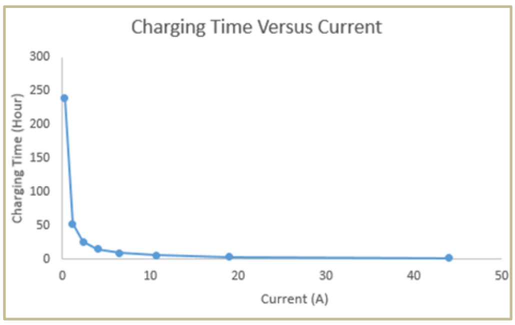

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Fig 12. Charging time and current

Fig. 12 shows the charging time for different charging current. These datas are calculated for a 60 Ah battery. It is clear from the figure that, charging at high current will reduce the charging time. In that sense, the converter should be operated at higher duty cycle.

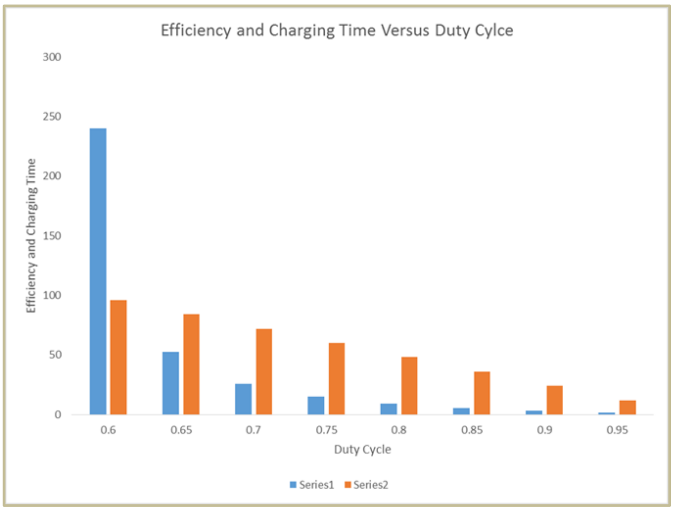

Fig 13. Efficiency and charging time for a boost charger (12 V and 60 Ah Battery)

TABLE IV EFFICIENCY CALCULATION

D	**Po (W)**	**P loss (W)**	**P effective (W)**	**Efficiency** $=\frac{P\ effective}{Po} * 100\%$
0.6	3.125	0.125	3	96
0.65	16.33	2.61	13.71	84
0.7	38.89	10.89	28	72
0.75	80	32	48	60
0.8	162.5	84.5	78	48
0.85	355.6	227.56	128	36
0.9	950	722	228	24
0.95	4400	3872	528	12

The efficiency of the system is calculated from the ratio of the effective power to total output power in the Table IV. Further explanation is given in the bar diagram of Fig. 13.

Fig. 13 reflects the efficiency (in percentage) and charging time (in hour) of the boost charger, which charges a 12 V and a 60 Ah battery. In this bar chart, series 1 indicates charging time in hour and series 2 shows the efficiency of the system in percentage. This result is very crucial as it shows an inverse trend between the efficiency and charging time. Both the efficiency and charging time have inverse relationship with the duty cycle. Hence, the efficiency will go down if a fast charging system is designed. Likewise, the inductor size will be reducing for a fast charging system. In contrast, higher efficient system slows the charging process. As a result, to select one feature, anther factors should be neglected based on the user`s requirement.

V. CONCLUSION

In this paper, a method based on some specific sequences is proposed to design a boost converter, which charges a battery. The procedure includes the sizing of boost inductor and filter capacitor. Finally, it shows the simulated charging current and terminal voltage. The output is satisfactory and battery is charged according to the expectation. However, compromise must be done between the charging speed and efficiency of the system. In near future, the hardware implementation will be done.

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