POWER ELECTRONICS AND MOTOR DRIVE

BOOST CONVERTER DESIGN

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AIM

- Design, simulate and implement a boost converter which operates on the Continuous Conduction Mode (CCM).

OBJECTIVES

- Do proper calculations to select suitable components for the boost converter.
- Design the boost converter to give stable required output.
- Compare the theoretical values and experimental values.

THEORY

Non isolated switching DC to DC power converter is very important in power electronics. There are many converters named Buck, Boost, Buck-Boost, Cuk converters. Out of those converters to step up the DC voltage of a given input DC voltage; Boost converter is used. In 1960s, these converters got developed highly with the availability of the semiconductor switches. The Boost converter is constructed using an inductor (L), diode (D), capacitor (C) and a switching device (S).

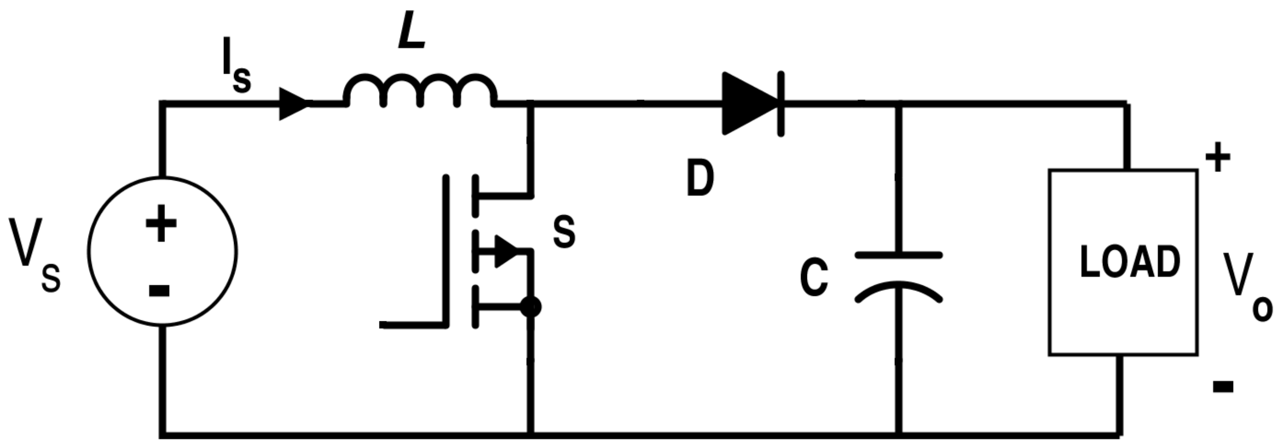

Figure 01: Boost Converter Circuit

In this design of boost converter, we have used Continuous Conduction Mode (CCM) as the operating mode. So that the current through the inductor (I_L) never falls to zero. A higher efficiency can be achieved in CCM compare to Discrete Conduction Mode (DCM). The voltage gain is not dependent of the load, the input current is continuous and not pulsating, the ripple component of the inductor current is lower than the average component are some properties of CCM. In the steady state, the average DC voltage across the inductor must be zero. So that after each cycle the inductor returns the same state, because voltage across the inductor is proportional to rate of change of current through it.

APPARATUS USED

- Input DC voltage source
- Inductor (L)
- Switching device (s) (MOSFET Switch)
- Diode (D)
- Capacitor (C)
- Load Resistor (R)
- Pulse generator
- Scope to view graphs
- Display to view values
- Voltage, Current measurement equipment
- MATLAB Simulink for simulation

DESIGN THE BOOST CONVERTER

First link the inductor, MOSFET switch and pulse generator with DC input voltage source as given below.

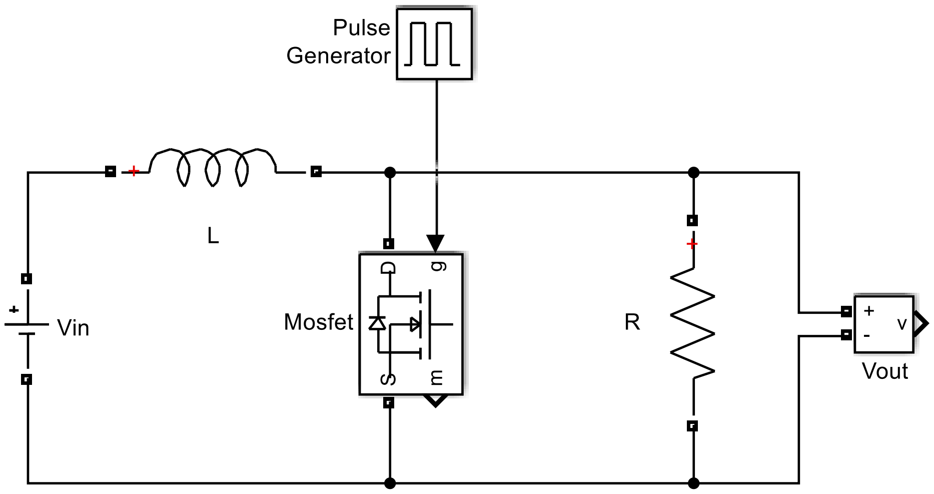

Figure 02: Inductor connect to the booster converter circuit

The pulse generator inputs ON and OFF signal pulses to the MOSFET switch. When the switch turns to ON position (switch closed), circuit get short from switch. Then the current starts to move through the inductor and generate a magnetic field. Then that magnetic field starts to store as energy in the inductor. Storage of energy increases proportional to the switch ON time and the inductor capacity.

Again, when the pulse generator input OFF signal, then the switch turns to open position. As the inductor does not like to change the current through itself, it also starts to act like a battery using its stored energy. So, the current (I_L) starts to move through the load resistor constantly. Then the output voltage (V_{OUT}) will increase with the addition of both input voltage (V_{IN}) and inductor voltage (V_L).

$$V_{OUT} = V_{IN} + V_L$$

But with the time the magnetic field starts to drop down and the stored energy get dissipated. So the I_L current get reduced and as a result of it V_L also get reduced.

So, the same procedure can be repeated by turning ON and OFF the switch. Then the energy get store and increase the V_{OUT} for some time and it get reduced when the switch turned OFF. To maintain the V_{OUT} we must store the dissipating V_L voltage. For that we use a capacitor for this boost converter circuit.

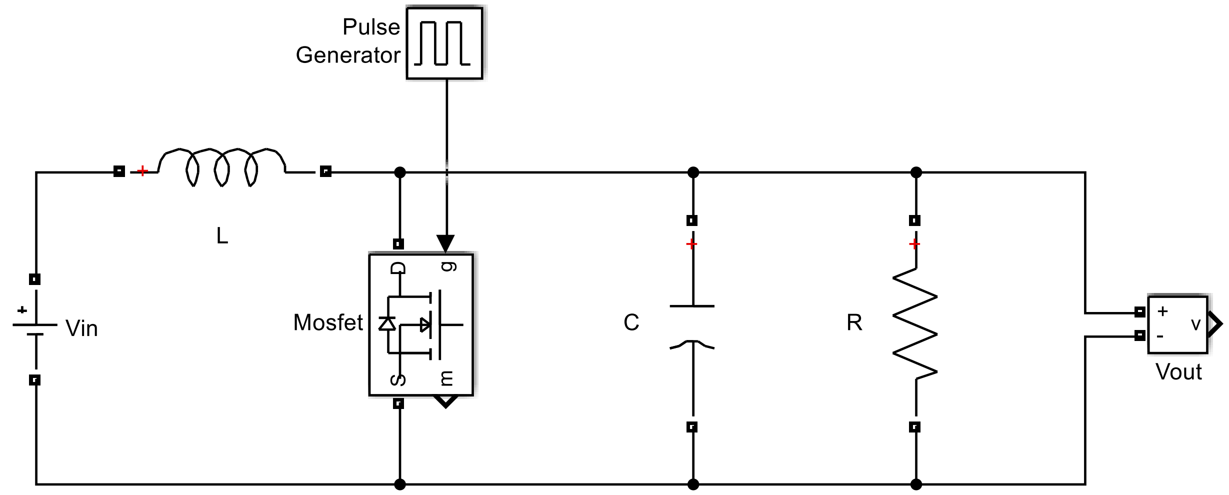

Figure 03: Capacitor connect to the booster converter circuit

Now, when the switch turned ON, circuit get short from switch and as like before magnetic field is generated and then energy get stored in the inductor. After the switch turned OFF circuit get open from switch and store the V_L voltage in the capacitor. Then the capacitor voltage (V_C) will be as below.

$$V_C = V_{IN} + V_L$$

But due to getting short circuit of the capacitor, it gets discharge and the stored V_L get reduced with the time. So, to get the proper functioning of the capacitor we must add a diode to the boost converter system.

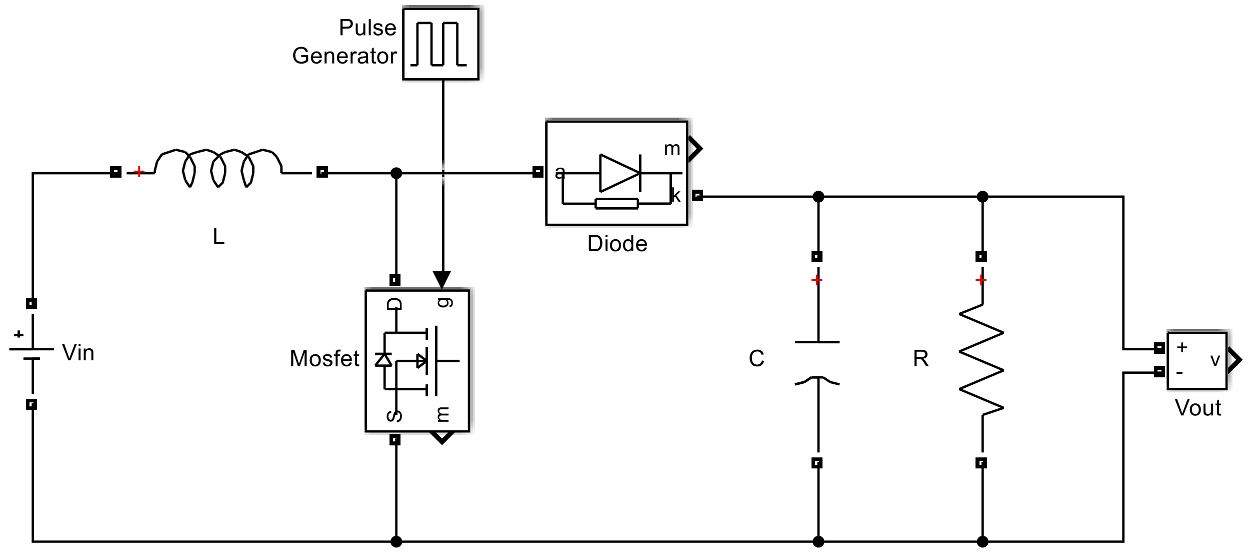

Figure 04: Diode connect to the booster converter circuit

After adding the diode, the circuit will complete. Now, when the switch turned ON, the circuit get shorted from switch and store energy in the inductor. Then after the switch is turned OFF, then the circuit get shorted from the capacitor. As earlier, inductor current (I_L) moves through the capacitor and store the inductor energy in the capacitor. As the inductor energy dissipated, capacitor cannot discharge by giving energy back to the inductor because diode block the reverse current coming from the capacitor. Therefore, the V_{OUT} remains constant.

Inductor voltage (V_L) is the key component that effect on the output voltage (V_{OUT}). The V_L value can be adjust by considering the storage capacity of the inductor. So, we must calculate the value of the inductor and the capacitor to full fill the requirements of the application.

IMPLEMENTATION OF EQUATIONS

To find out the required measurements of the components used for the boost converter circuit, we need to do some calculations. For that we need to implement some equations. There are some assumptions to be made for implementation. They are,

1. Assume that the boost converter is operating under Steady State conditions.
   - Average inductor voltage (V_L) = 0
   - Average capacitor current (I_C) = 0
   - Inductor current should be equal in the both beginning and end of the period [$I_L(T) = I_L(0)$]
   - Capacitor voltage should be equal in the both beginning and end of the period [$V_C(T) = V_C(0)$]
2. Assume that the boost converter is operating under Continuous Conduction Mode (CCM).
   - $I_{MIN}>0$
3. Assume output capacitor (C) is very large.
   - Can neglect the ripple of the output voltage.
   - Instantaneous value and the average value of the output voltage are equal [$V_{OUT}(t) = V_{OUT}$].
4. Assume all the components are ideal, so it has 100% efficiency. (negligible internal resistances)
5. Assume switching transients are neglected.

Switching Equations

For this boost converter circuit, we can use any semiconductor non isolated switches like MOSFET, Ideal Switch, IGBT etc. For this moment I have used a MOSFET switch because it has very low drain source on state voltage drop and lower input power loss. There are mainly two modes of switching statuses. They are,

$$\text{Switching status} = \begin{cases} \text{Mode I} - \text{ON}\,;\; 0 < t < dT \\ \text{Mode II} - \text{OFF}\,;\; dT < t < T \end{cases}$$

Here, d – Duty cycle and T – Switching period

Let's consider the Mode I (ON),

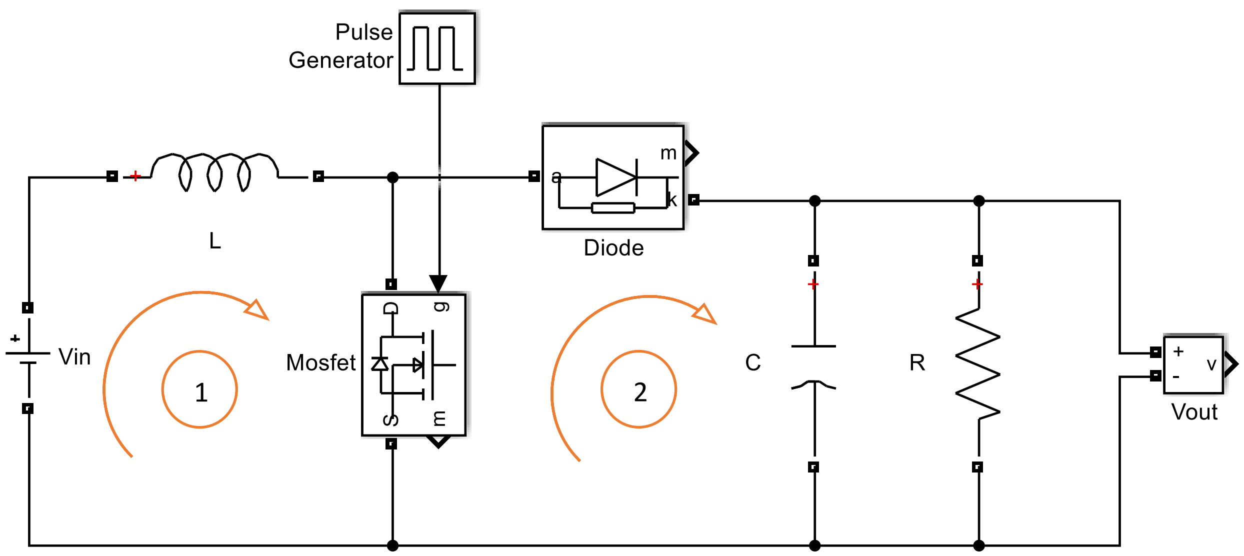

Figure 05: Boost Converter circuit in ON switch mode

Here, the voltage across the diode is turned to negative, that means diode is off and reversed biased. So, it acts like an open circuit. Let's apply KVL to the above circuit to build equations.

By applying KVL around 1,

$$V_D = -V_{OUT}$$

By applying KVL around 2,

$$V_L = V_{IN}$$
$$V_L = L\frac{dI_L}{dt}$$
$$I_L(t) = I_{MIN} + \frac{V_{IN}}{L}t$$

Therefore,

$$I_{MAX} = I_L(dT) = I_{MIN} + \frac{V_{IN}}{L}dT \quad ------------------------(1)$$

$$\Delta I_L = I_{MAX} - I_{MIN} = \frac{V_{IN}}{L}dT \quad ------------------------(2)$$

Let's consider the Mode II (OFF),

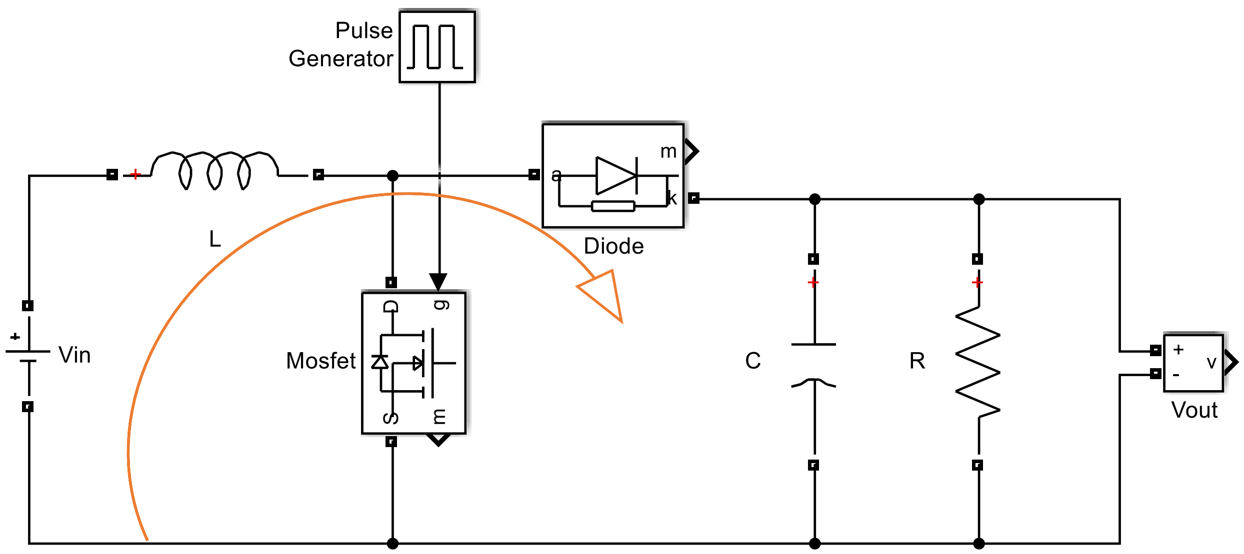

Figure 06: Boost Converter circuit in OFF switch mode

Here, the inductor forces the diode to turn on because the inductor current (I_L) doesn't like to become zero.

By applying KVL for All,

$$V_L = V_{IN} - V_{OUT} \qquad ; V_L < 0$$
$$V_L = L\frac{dI_L}{dt}$$
$$I_L(t) = I_{MAX} + \frac{V_{IN} - V_{OUT}}{L}(t - dT)$$

Therefore,

$$I_{MIN} = I_L(T) = I_{MAX} + \frac{V_{IN} - V_{OUT}}{L}(T - dT) \quad --------------------(3)$$

$$\Delta I_L = I_{MAX} - I_{MIN} = -\frac{V_{IN} - V_{OUT}}{L}(T - dT) \quad --------------------(4)$$

By considering equation (2) and (4),

$$\frac{V_{IN}}{L}dT = -\frac{V_{IN} - V_{OUT}}{L}(T - dT)$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1-d} \quad ---------------------------------(5)$$

Let's find average inductor current,

$$< I_L > = \frac{I_{MIN} - I_{MAX}}{2} \qquad ;V_{OUT} = \frac{V_{IN}}{1-d}$$

$$I_{MAX} + I_{MIN} = \frac{V_{OUT}}{(1-d)R} = \frac{2V_{IN}}{(1-d)^2R} \quad --------------------------(6)$$

By adding equations (6)+(2),

$$I_{MAX} = \frac{V_{IN}}{(1-d)^2R} + \frac{V_{IN}}{2L}dT \quad ------------------------------(7)$$

By subtracting equations (6)-(2),

$$I_{MIN} = \frac{V_{IN}}{(1-d)^2R} - \frac{V_{IN}}{2L}dT \quad ------------------------------(8)$$

By considering the 5th assumption (assuming the ideal condition),

$$P_{IN} = P_{OUT}$$
$$V_{IN} * < I_L > = \frac{V_{OUT}^2}{R} \qquad ;V_{OUT} = \frac{V_{IN}}{1-d}$$

$$< I_L > = \frac{V_{IN}}{(1-d)^2R}$$

Inductor Equations

Let's consider the 2nd assumption (assume that the boost converter is operating under Continuous Conduction Mode). This assumption states that the minimum inductor current is greater than zero.

$$I_{MIN} > 0$$

From the equation (8),

$$\frac{V_{IN}}{(1-d)^2R} - \frac{V_{IN}}{2L}dT > 0$$

$$L > \frac{d(1-d)^2RT}{2} \qquad ;T = \frac{1}{f}$$

$$L > \frac{d(1-d)^2R}{2f}$$

Considering the load resistance, $R_{MIN} < R < R_{MAX}$

$$L > \frac{d(1-d)^2R_{MAX}}{2f}$$; the inductance will reduce when increasing the switching frequency

Capacitor Equations

By applying KCL to the junction connecting diode, capacitor and the resistor we get the following equation.

$$I_D = I_C + I_R$$
$$I_C = I_D - I_R$$
$$I_C = I_D - < I_D >$$

By considering the graph I_C vs time and using the capacitor charge formula,

$$q = C * V$$
$$\Delta q = C * \Delta V$$; ΔV is the peak to peak ripple of the output voltage.
$$\frac{V_{OUT}}{R} dT = C * \Delta V_{OUT}$$

$$\frac{\Delta V_{OUT}}{V_{OUT}} = \frac{d}{RCf}$$

$$C > \frac{d}{Rf\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right)}$$

CALCULATIONS AND OBSERVATIONS

For the calculations there are some usable data given in the question.

$$V_{IN} = 10V \pm 15\%$$; $\therefore V_{IN} = 8.5V, 10V, 11.5V$
$$V_{OUT} = 30V$$
$$R_{MAX} = 20\Omega$$

To continue the calculations, switching frequency (f) and $(\frac{\Delta V_{OUT}}{V_{OUT}})$ must be assumed. So, let's assume,

$$f = 100KHz$$
$$\frac{\Delta V_{OUT}}{V_{OUT}} = 0.01$$

So, we can calculate switching period (T) as below,

$$T = \frac{1}{f} = \frac{1}{100K} = 1x10^{-5}s$$

Let's find suitable values for inductor, capacitor and component currents when $V_{IN} = 8.5V$

Duty cycle,

$$d = 1 - \frac{V_{IN}}{V_{OUT}} = 1 - \frac{8.5V}{30V} = 0.7167$$

Inductor,

$$L > \frac{d(1-d)^2 R_{MAX}}{2f}$$
$$L > \frac{0.7167(1-0.7167)^2 * 20}{2 * 100K}$$
$$L > 5.75\mu H$$

Selectable inductor should be nearly more than 5.75µH.

Capacitor,

$$C > \frac{d}{Rf\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right)}$$

$$C > \frac{0.7167}{20*100K*0.01}$$

$$C > 35.83\mu F$$

Selectable capacitor should be nearly more than 35.83µF.

Ripple in inductor current,

$$\Delta I_L = \frac{V_{IN}}{L} dT = \frac{8.5}{5.75\mu} * 0.7167 * 1x10^{-5} = 10.594A$$

Average input and inductor current,

$$I_L = \frac{V_{IN}}{(1-d)^2 R} = \frac{8.5}{(1-0.7167)^2 * 20} = 5.295A$$

Ripple output voltage,

$$\Delta V_{OUT} = \frac{dV_{OUT}}{RCf} = \frac{0.7167*30}{20*35.83\mu*100K} = 0.3V$$

Output current,

$$I_{OUT} = \frac{V_{OUT}}{R_{MAX}} = \frac{30}{20} = 1.5A$$

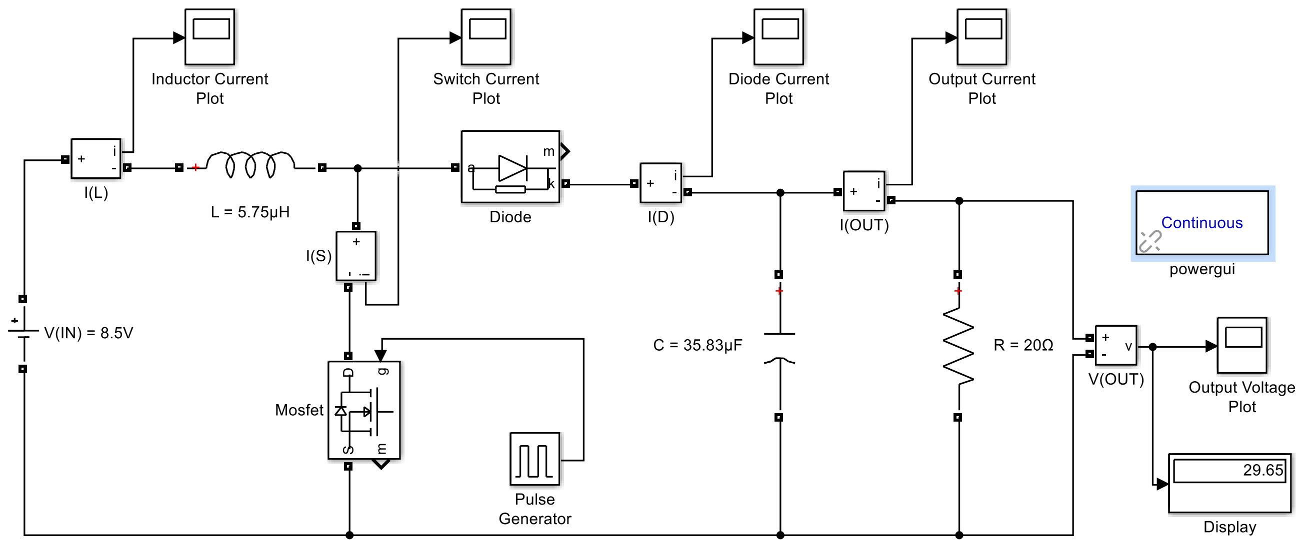

Figure 07: Boost converter circuit output 29.65V for given input 8.5V

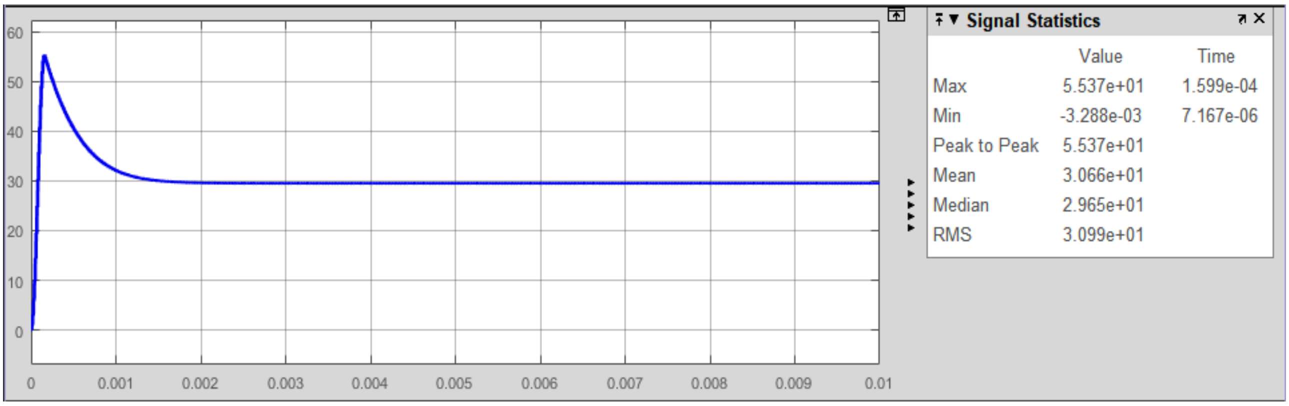

Figure 08: Output voltage (V_{OUT}) plot

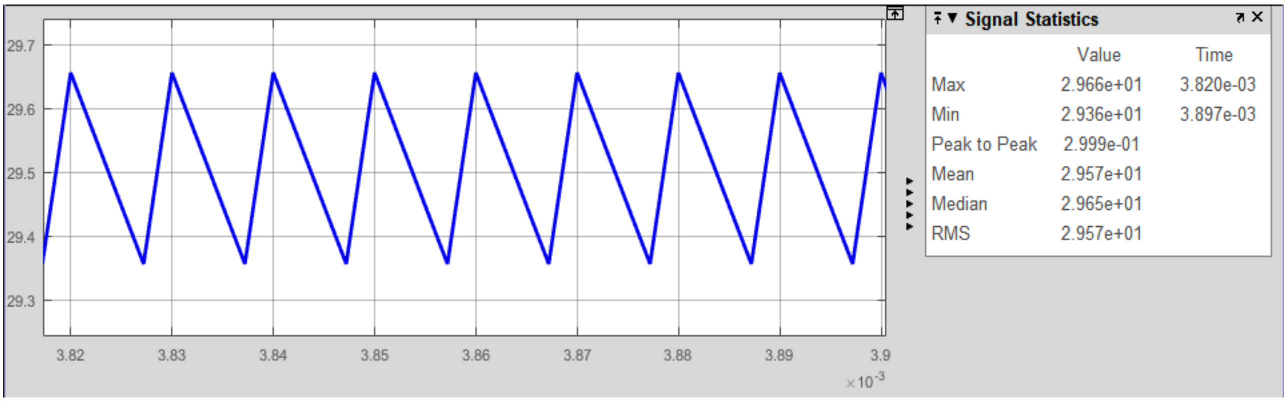

Figure 09: Peak to peak output voltage (V_{OUT}) plot

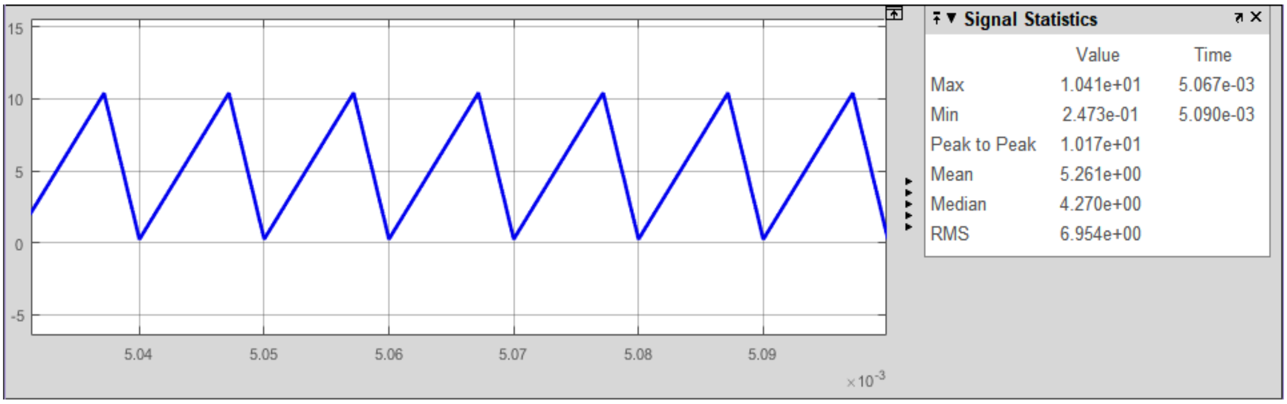

Figure 10: Inductor current (I_L) plot

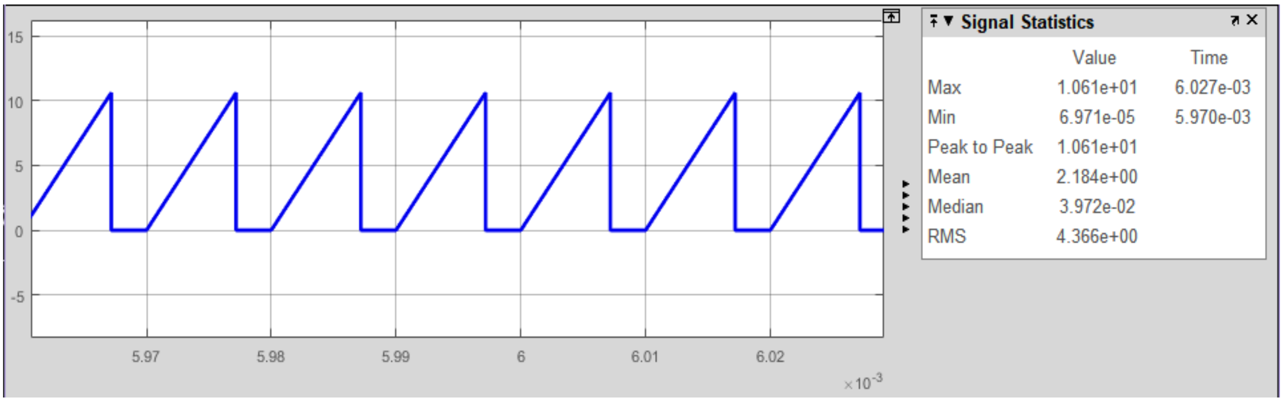

Figure 11: Switch current (I_S) plot

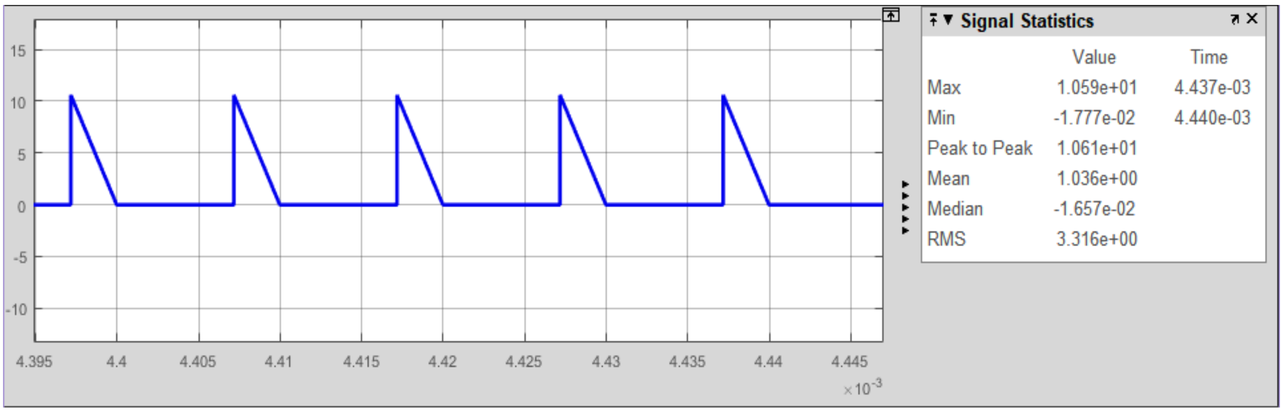

Figure 12: Diode current (I_D) plot

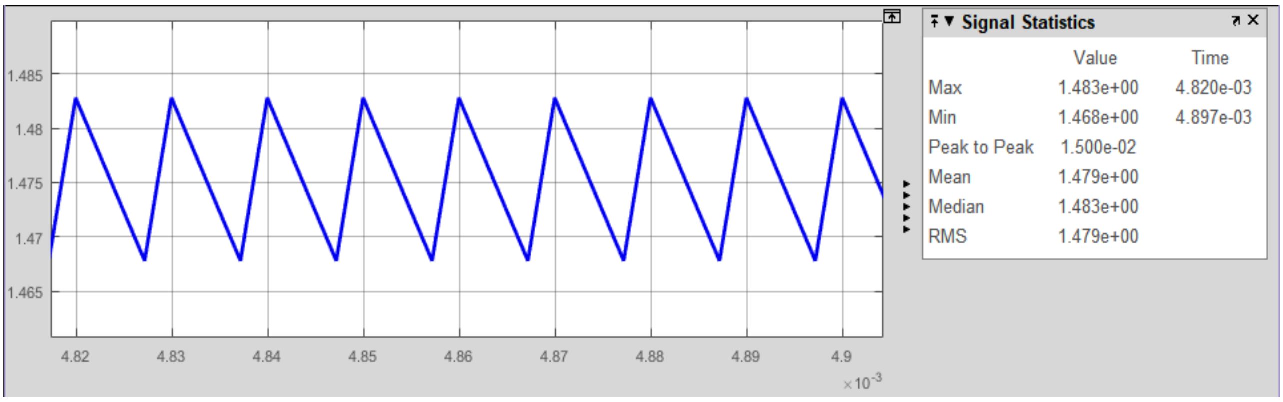

Figure 13: Output current (I_{OUT}) plot

<u>Let's find suitable values for inductor, capacitor and component currents when $V_{IN} = 10V$</u>

Duty cycle,

$$d = 1 - \frac{V_{IN}}{V_{OUT}} = 1 - \frac{10V}{30V} = 0.667$$

Inductor,

$$L > \frac{d(1-d)^2 R_{MAX}}{2f}$$

$$L > \frac{0.667(1-0.667)^2 * 20}{2 * 100K}$$

$$L > 7.39\mu H$$

Selectable inductor should be nearly more than 7.39µH.

Capacitor,

$$C > \frac{d}{Rf\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right)}$$

$$C > \frac{0.667}{20 * 100K * 0.01}$$

$$C > 33.35\mu F$$

Selectable capacitor should be nearly more than 33.35µF.

Ripple in inductor current,

$$\Delta I_L = \frac{V_{IN}}{L} dT = \frac{10}{7.39\mu} * 0.667 * 1x10^{-5} = 9.025A$$

Average input and inductor current,

$$I_L = \frac{V_{IN}}{(1-d)^2 R} = \frac{10}{(1-0.667)^2 * 20} = 4.509A$$

Ripple output voltage,

$$\Delta V_{OUT} = \frac{dV_{OUT}}{RCf} = \frac{0.667 * 30}{20 * 33.35\mu * 100K} = 0.3V$$

Output current,

$$I_{OUT} = \frac{V_{OUT}}{R_{MAX}} = \frac{30}{20} = 1.5A$$

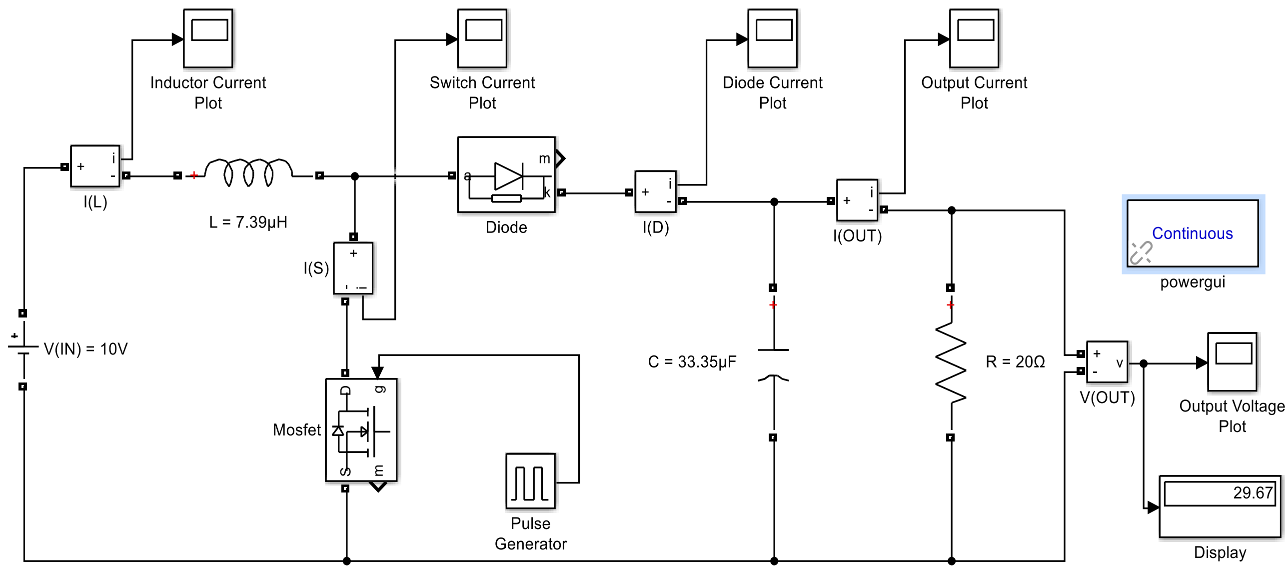

Figure 14: Boost converter circuit output 29.67V for given input 10V

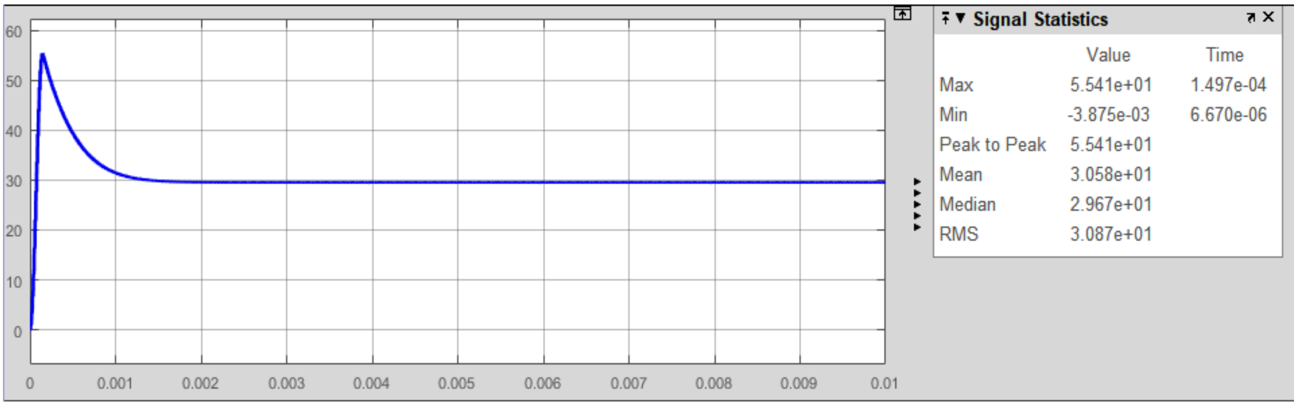

Figure 15: Output voltage (V_{OUT}) plot

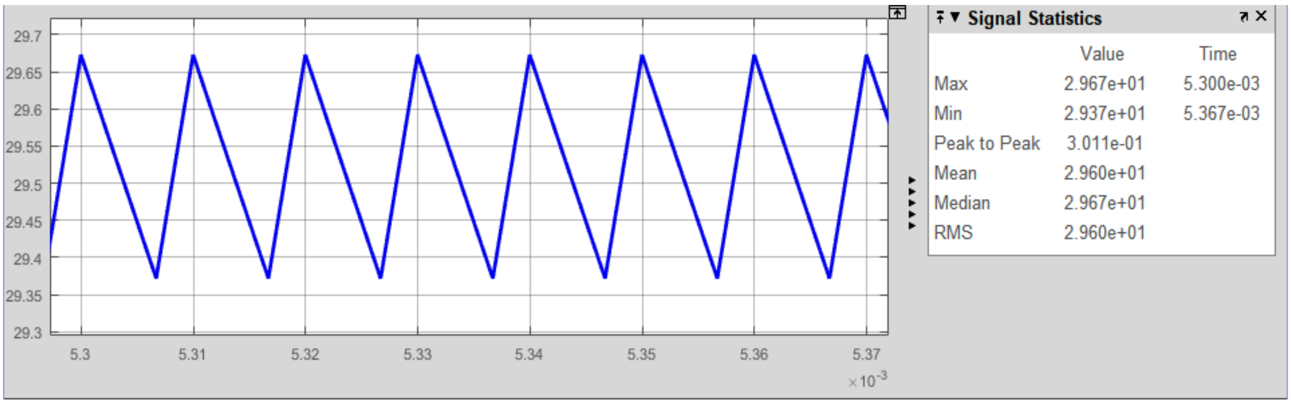

Figure 16: Peak to peak output voltage (V_{OUT}) plot

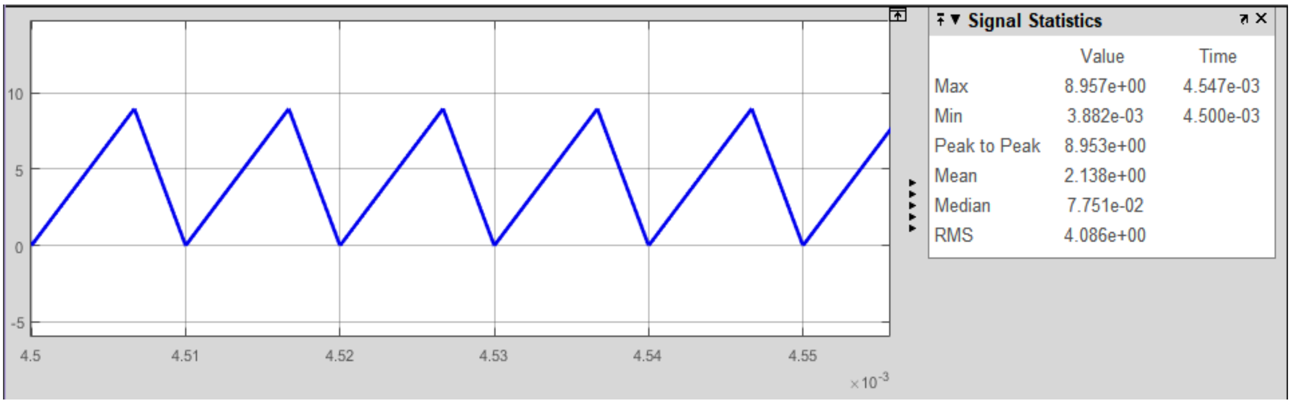

Figure 17: Inductor current (I_L) plot

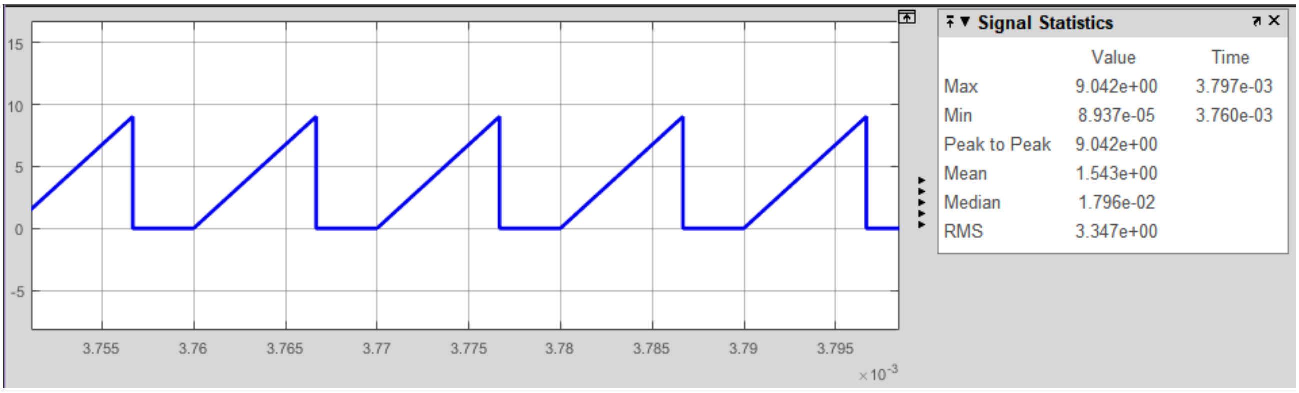

Figure 18: Switch current (I_S) plot

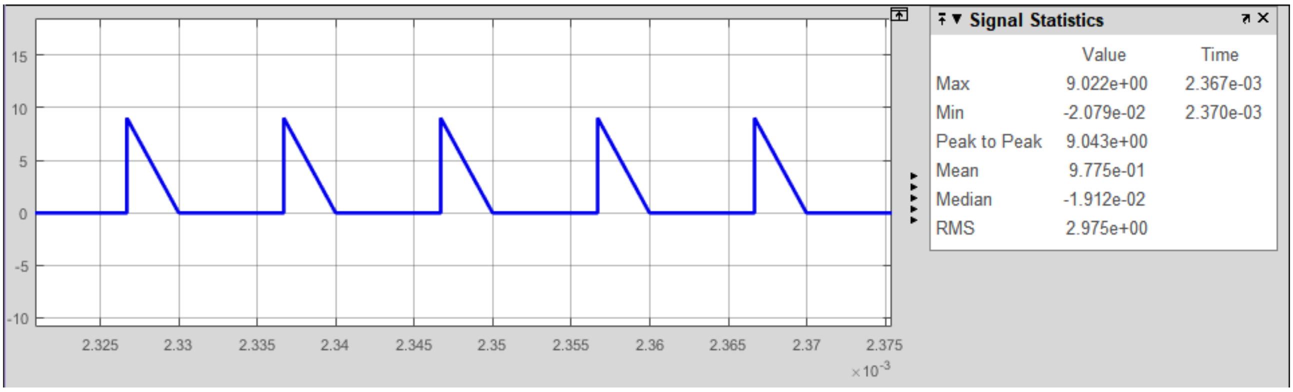

Figure 19: Diode current (I_D) plot

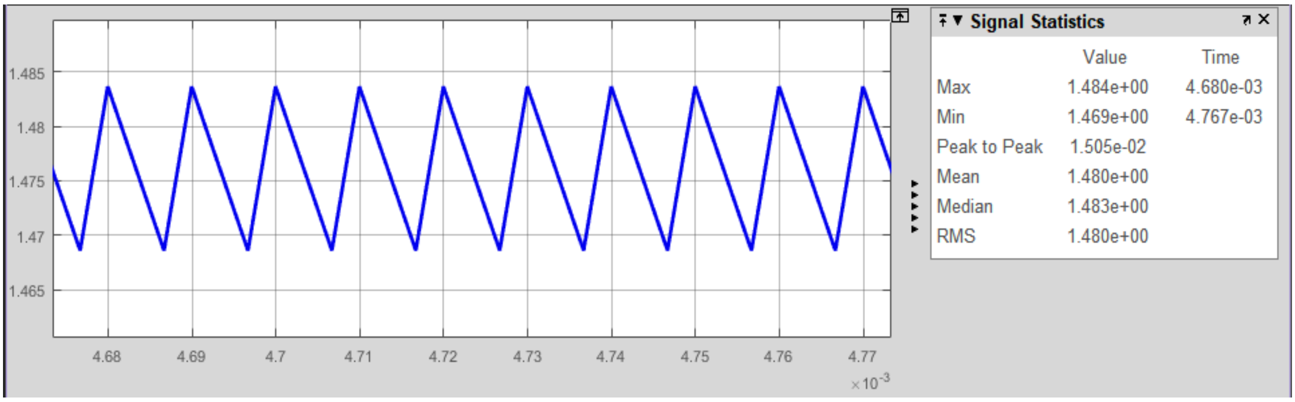

Figure 20: Output current (I_{OUT}) plot

Let's find suitable values for inductor, capacitor and component currents when $V_{IN} = 11.5V$

Duty cycle,

$$d = 1 - \frac{V_{IN}}{V_{OUT}} = 1 - \frac{11.5V}{30V} = 0.6167$$

Inductor,

$$L > \frac{d(1-d)^2 R_{MAX}}{2f}$$

$$L > \frac{0.6167(1-0.6167)^2 * 20}{2 * 100K}$$

$$L > 9.06\mu H$$

Selectable inductor should be nearly more than 9.06µH.

Capacitor,

$$C > \frac{d}{Rf\left(\frac{\Delta V_{OUT}}{V_{OUT}}\right)}$$

$$C > \frac{0.6167}{20 * 100K * 0.01}$$

$$C > 30.83\mu F$$

Selectable capacitor should be nearly more than 30.83µF.

Ripple in inductor current,

$$\Delta I_L = \frac{V_{IN}}{L} dT = \frac{11.5}{9.06\mu} * 0.6167 * 1x10^{-5} = 7.827A$$

Average input and inductor current,

$$I_L = \frac{V_{IN}}{(1-d)^2 R} = \frac{11.5}{(1-0.6167)^2 * 20} = 3.913A$$

Ripple output voltage,

$$\Delta V_{OUT} = \frac{dV_{OUT}}{RCf} = \frac{0.6167 * 30}{20 * 14.15\mu * 100K} = 0.3V$$

Output current,

$$I_{OUT} = \frac{V_{OUT}}{R_{MAX}} = \frac{30}{20} = 1.5A$$

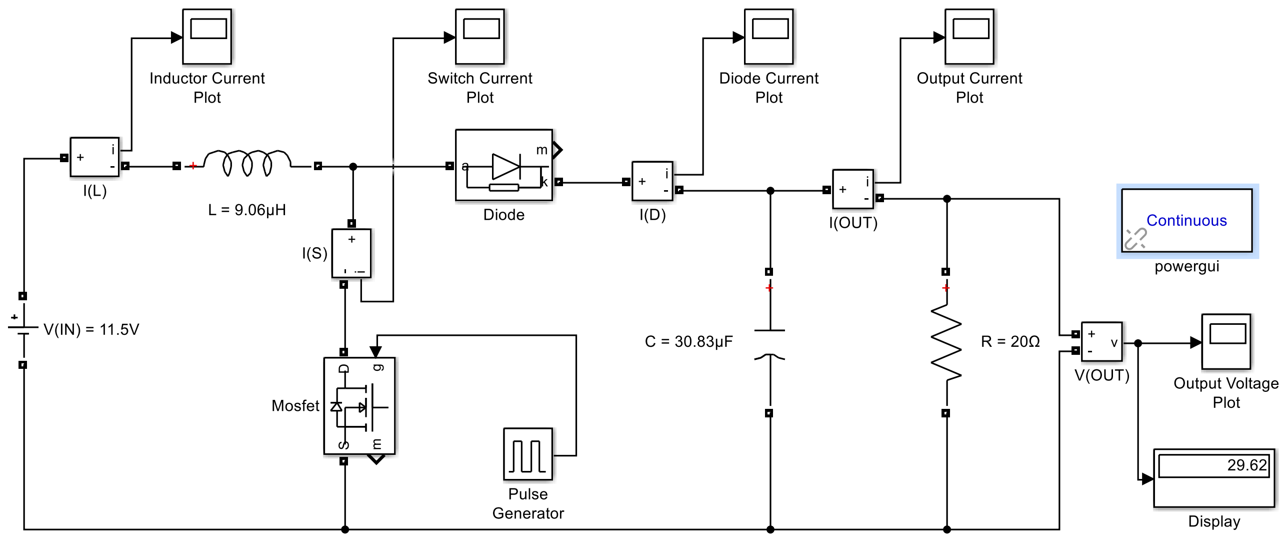

Figure 21: Boost converter circuit output 29.62V for given input 11.5V

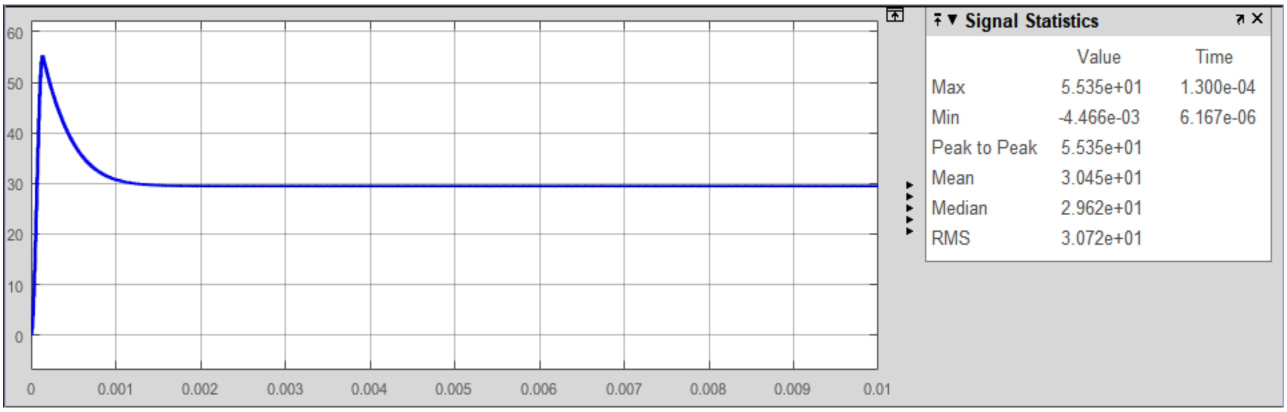

Figure 22: Output voltage (V_{OUT}) plot

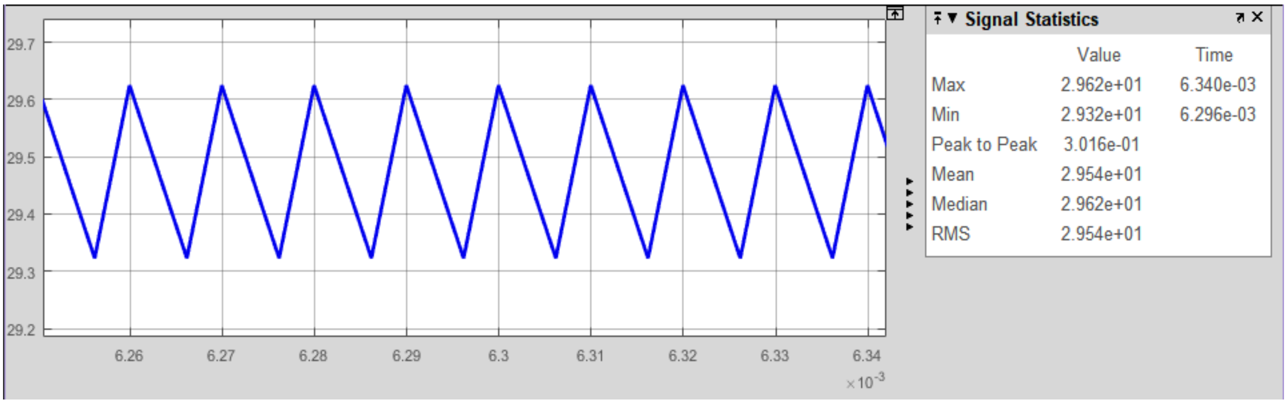

Figure 23: Peak to peak output voltage (V_{OUT}) plot

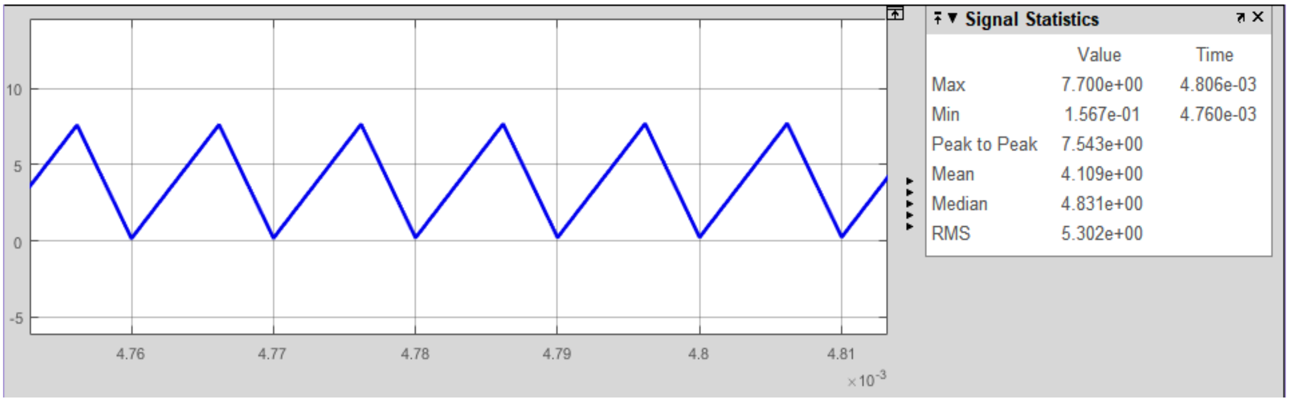

Figure 24: Inductor current (I_L) plot

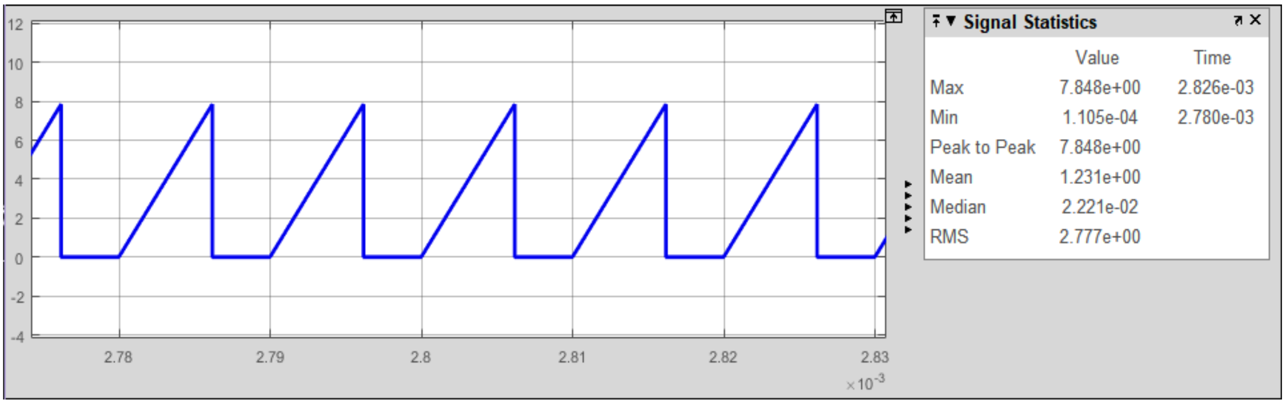

Figure 25: Switch current (I_S) plot

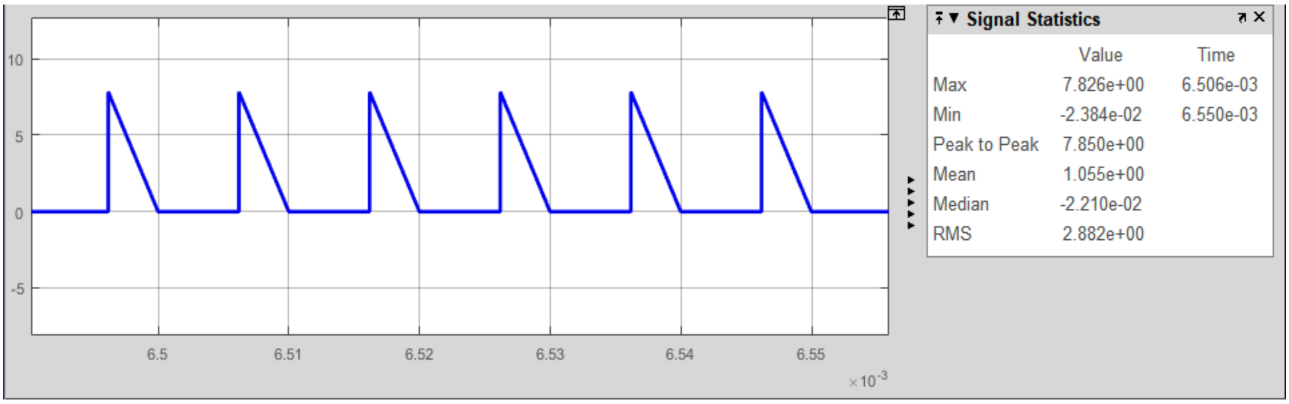

Figure 26: Diode current (I_D) plot

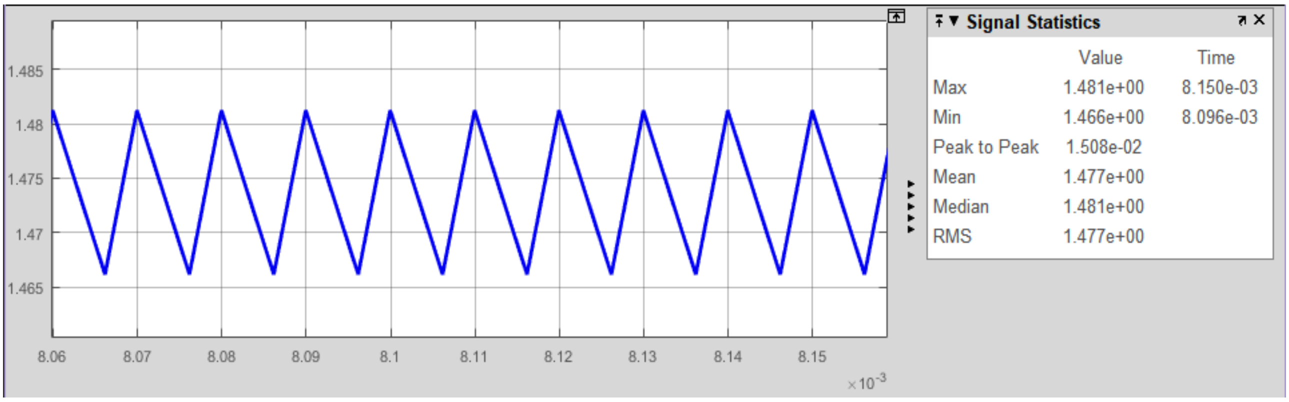

Figure 27: Output current (I_{OUT}) plot

EXPERIMENTAL RESULTS

Experimental results for the circuit with 8.5V input voltage,

$$V_{OUT} = 29.57V$$
$$\Delta V_{OUT} = 0.299V$$
$$\Delta I_L = 10.17A$$
$$I_L = 5.26A$$
$$I_S = 2.18A$$
$$I_D = 1.036A$$
$$I_{OUT} = 1.48A$$
$$\eta = 98.5\%$$

Experimental results for the circuit with 10V input voltage,

$$V_{OUT} = 29.6V$$
$$\Delta V_{OUT} = 3.01V$$
$$\Delta I_L = 8.95A$$
$$I_L = 2.14A$$
$$I_S = 1.54A$$
$$I_D = 0.97A$$
$$I_{OUT} = 1.48A$$
$$\eta = 98.56\%$$

Experimental results for the circuit with 11.5V input voltage,

$$\begin{aligned} V_{OUT} &= 29.54A \\ \Delta V_{OUT} &= 3.02A \\ \Delta I_L &= 7.54A \\ I_L &= 4.11A \\ I_S &= 1.23A \\ I_D &= 1.05A \\ I_{OUT} &= 1.47A \\ \eta &= 98.45\% \end{aligned}$$

CONCLUSION

From the calculations I have got the boundary values for inductor and capacitor. Here it is used as it is for this simulation to operate in continuous conduction mode. If the circuit runs in CCM, the I_{MIN} should be greater than zero. In this simulation that condition can be clearly observe from the experimental results. But if we are doing this in physical, we must select the proper inductor and capacitor because there are not any such components to select for these calculated values. So, considering the standard values for inductors and capacitors, must select one which is nearly equal to around 25% more than the calculated value.

According to the range of the given DC input voltage, it varies in between 8.5V to 11.5V. with the change of this input voltage, it effects to the duty cycle. The duty cycle increases when the input voltage is decreasing. So, for the simulation we must calculate each duty cycle and its corresponding inductor and capacitor values.

The circuit does not give exact required output voltage of 30V. Therefore, we can supply a closed loop feedback for this circuit to maintain exact 30V output.

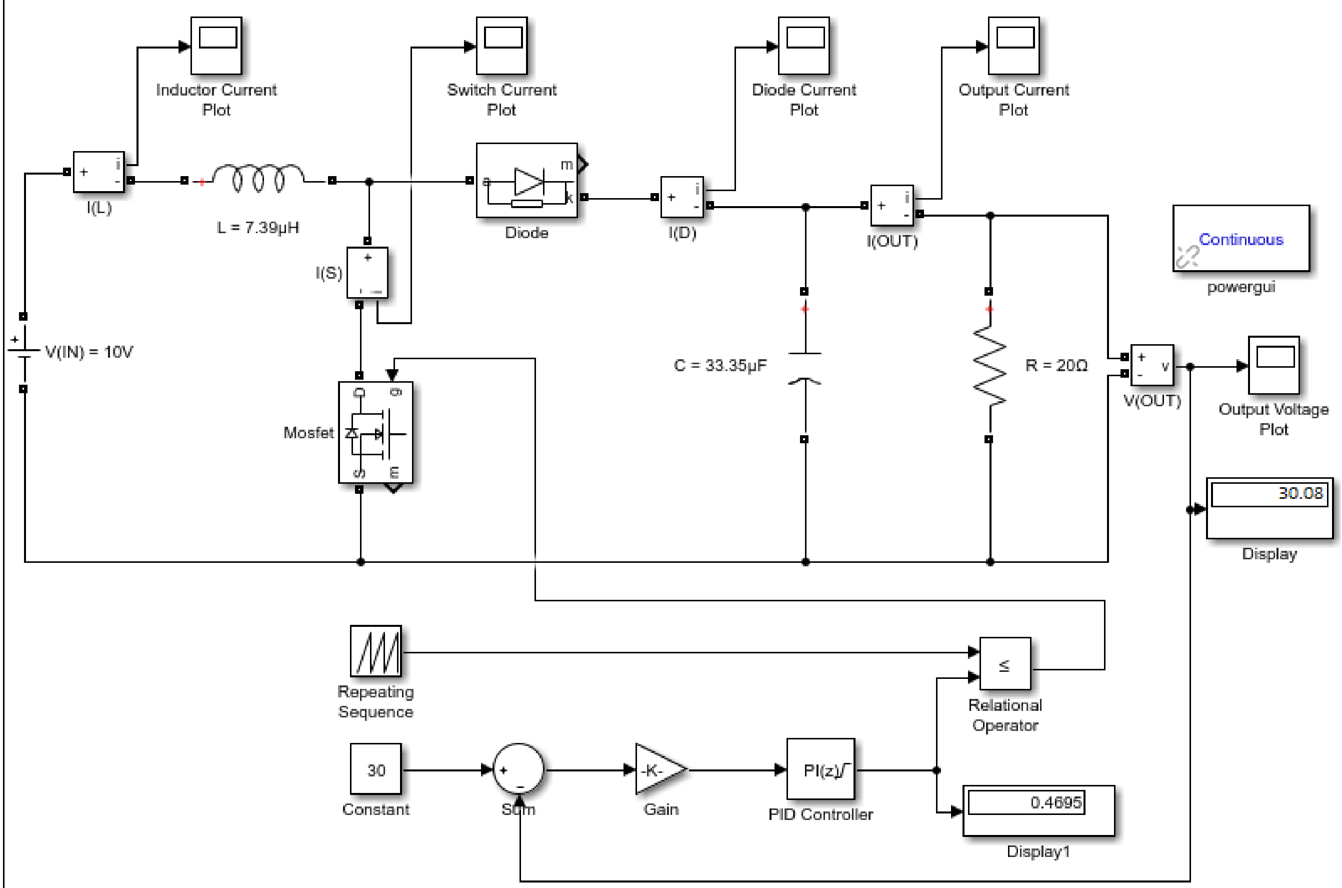

Figure 28: Closed loop boost converter controlled by PID

The feedback is controlled by a PID. We must tune the PID and insert P, I, D values for it. Then the circuit give an output voltage around exact 30V. The control system adjusts the missing voltage to complete 30V. Each 3 circuits give an efficiency only around 98.5% in the beginning, even though we have assumed that each component is ideal (100% efficiency). It happens because of the added voltage, current measurement devices, internal resistances and other energy dissipations. After this PID modification we may able to get a 100% efficiency from the circuit.

Switching device is very important for this circuit. We can use any switching transistor as the switching device. MOSFET is commonly used in many applications these days, since they are very efficient, but there may be situations where a normal bipolar transistor may suffice because of simplicity. Considering the type of the application, must pick a transistor with a breakdown voltage higher than the maximum output voltage of the application. And the diode selection also very important because the choice of diode plays a large role in efficiency.

In output voltage graph, can observe a sudden increase of voltage before it gets stable. That happened because of the internal inductance at the beginning of the circuit. With the time, the generated inductor energy transfer to capacitor and make the system stable. Then only a peak to peak steady graph flow can be observed.

The values obtained from the simulation experiment are very nearly equal to its calculated values. Measures are little bit differ due to its internal resistances.

As I mentioned earlier, the suitable inductor and capacitor values for physical experiment of boost converter should be about 25% more than the calculated value. Then have to select the device considering the available values in the market. It should be near to the new calculated value.

Boost converters are used to increase the voltage and reduce the number of cells. That means battery power systems stack cells in series to achieve higher voltage, but cell stacking is not possible in high voltage application as there is no space. To overcome from that boost converters are used. Boost converters are attached to two battery powered applications like hybrid electric vehicles (HEV) and lighting systems for boosting purposes. By using boost converters, Toyota Prius HEV car reduced their 417 cells in previous version to 168 cells in new version. So, to maintain the voltage they have boost the 202V to 500V. So, DC to DC boost converters are very important to have in power electronics applications to make them simple.