BUCK CONVERTER DESIGN
(DATASHEET REFERENCED)

Design Parameters

$V_{(IN)}$ = 5-28V

$V_{(OUT)}$ = 3.3V

$I_{(OUT)}$= 3A

Efficieny = %90+

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*** The *TPS54331* IC meeting these criteria was selected for use in the design.**

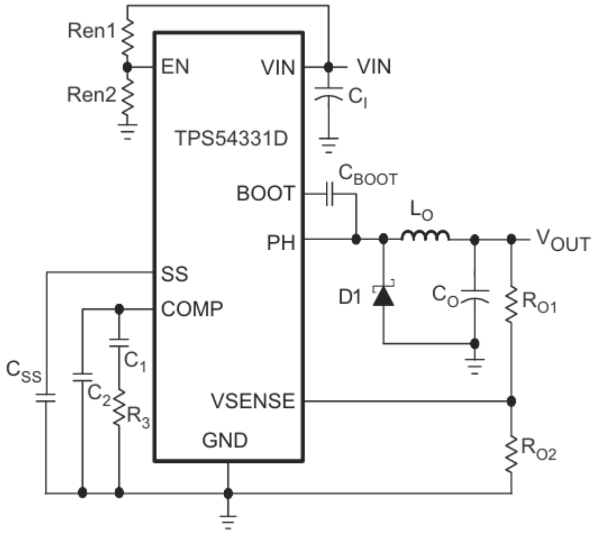

Figure 1. Simplified Schematic

Design Steps

1- Feedback Resistors

- Determine the $R_{(O1)}$ & $R_{(O2)}$ by using $V_{(OUT)}$ = 3.3V, $V_{(REF)}$ = 0.8V and Equation 1.

$$V_{OUT} = V_{\mathrm{REF}}.\left(\frac{R_{O1}}{R_{O2}} + 1\right) \qquad \text{Equation 1}$$

<u>$R_{(O1)}$ = 10kΩ and $R_{(O2)}$ = 3.2kΩ</u>

2- Input Capacitors

- Determine the $C_{(IN)}$ by using ΔV_{IN} = 0.15mV, $ESR_{(MAX)}$=2mΩ and Equation 2.

$$\Delta \mathrm{V_{IN}} = \frac{\mathrm{I_{OUT(MAX)}} \times 0.25}{\mathrm{C_{BULK}} \times \mathrm{F_{SW}}} + (\mathrm{I_{OUT(MAX)}} \times \mathrm{ESR_{(MAX)}}) \qquad \text{Equation 2}$$

<u>C_{BULK}= 9.14 µF, so input capacitor can be divided into two separated capacitors by 4.7 µF.</u>

3- Inductor

- K_{IND} is a coefficient that represents the amount of inductor ripple current relative to the maximum output current can be selected by using Equation 3.

- In general, this value is at the discretion of the designer; however, the following guidelines may be used. For designs using low-ESR output capacitors, such as ceramics, a value as high as K_{IND} = 0.3 can be used. When using higher ESR output capacitors, K_{IND} = 0.2 yields better results. For this design example, use K_{IND} = 0.3 and the minimum inductor value is calculated as 5.7 µH. For this design, a large value was selected: 10 µH.

$$L_{MIN} = \frac{V_{OUT(MAX)} \times (V_{IN(MAX)} - V_{OUT})}{V_{IN(MAX)} \times K_{IND} \times I_{OUT} \times F_{SW}} \qquad \text{Equation 3}$$

L = 10 µH

- For the output filter inductor, do not exceed the RMS current and saturation current ratings. These calculations can made with Equation 4, Equation 5 and Equation 6.

$$IL_{PP} = \frac{V_{OUT} \times (V_{IN(MAX)} - V_{OUT})}{V_{IN(MAX)} \times L_{OUT} \times F_{SW} \times 0.8} \qquad \text{Equation 4}$$

$$I_{LRMS} = \sqrt{I^2_{OUT(MAX)} + \frac{1}{12} \times IL^2_{PP}} \qquad \text{Equation 5}$$

$$I_{LPK} = I_{OUT(MAX)} + \frac{IL_{PP}}{2} \qquad \text{Equation 6}$$

I_{LPP} = 580mA, I_{LRMS} = 3A, I_{LPK} = 3.29A

4- Output Capacitors

- There are some critical parameters such as DC voltage rating, ripple current rating, and equivalent series resistance (ESR). Minimum capacitor value can be calculated by using Equation 7.

- Consider the relationship between the desired closed-loop crossover frequency of the design and LC corner frequency of the output filter.

- In general, keeping the closed-loop **crossover frequency** at **less than 1/5 of the switching frequency** is desired. With high switching frequencies such as the 570-kHz frequency of this design, internal circuit limitations of the TPS54331 device limit the practical maximum crossover frequency to approximately **25 kHz.** In general, the closed-loop crossover frequency must be higher than the corner frequency determined by the load impedance and the output capacitor.

$$C_{OMIN} = \frac{1}{2\times\pi\times R_O \times F_{CO(MAX)}}, \text{ where } R_O = \frac{V_O}{I_O} \qquad \text{Equation 7}$$

R_O=1.1Ω, C_{OMIN} = 5.8 μH

- This value may not satisfy the output ripple voltage requirement. The output ripple voltage consists of two components: the voltage change because of the charge and discharge of the output filter capacitance and the voltage change because the ripple current times the ESR of the output filter capacitor. These can be calculated by using Equation 8.,Equation 9 and Equation 10.

$$V_{OPP} = IL_{PP} \times \left(\frac{D-0.5}{4\times F_{SW}\times C_O} + R_{ESR}\right) \qquad \text{Equation 8}$$

$$ESR_{MAX} = \frac{V_{OPP(MAX)}}{IL_{PP}} - \frac{D-0.5}{4\cdot F_{SW}\cdot C_O} \qquad \text{Equation 9}$$

$$I_{COUTRMS} = \sqrt{\frac{1}{12}\times\frac{V_{OUT}\cdot(V_{IN(MAX)}-V_{OUT})}{V_{IN(MAX)}\cdot L_{OUT}\cdot F_{SW}\cdot N_C}} \qquad \text{Equation 10}$$

C_O = 5.8μF	**V_{IN} = 5V**	**V_{IN} = 28V**
V_{OPP} (mV)	8	17.9
ESR_{MAX} (mΩ)	1.7	-15*
$I_{COUTRMS}$ (mA)	206	206

Table 1. Used minimum capacitor value

* Obtained negative resistor. This means the minimum capacitor value is not enough. So bulkier capacitor must be used.

To overcome the problem, it is decided to use 2x47uF capacitor. In addition, the equivalent ESR (equivalent series resistance) value of the capacitors has been halved.

Co = 94µF	**Vin = 5V**	**Vin = 28V**
V_{OPP} (mV)	1.59	2.19
ESR_{MAX} (mΩ)	1.99	1.99
$I_{COUTRMS}$ (mA)	145.88	145.88

Table 2. Modified capacitor value

5- Compensation Design

- First, The P_L (Phase Loss) must be calculated. PL means the lost phase value when filtering output of the circuit by using inductors and capacitors (LC Filter). This can be calculating with using Equation 11.

$$P_L = \frac{\pi}{180} \times (\arctan(2\pi \cdot F_{CO} \cdot R_{ESR} \cdot C_O) - \arctan(2\pi \cdot F_{CO} \cdot R_O \cdot C_O)) \qquad \text{Equation 11}$$

Let F_{CO}=25kHz, R_{ESR} = 2mΩ/2=1mΩ (parallel capacitors' resistance), C_O = 54µF (DC bias)

P_L=-1.456 rad/s = -83.42°

- Phase Boost (P_B) is the additional phase angle that the compensation network must add to the system at the crossover frequency. In other words, it is added to compensate for the negative phase loss caused by the buck converter's output filter and modulator's phase loss (P_L). **Phase margin is selected generally 60-70°.** P_B is calculated by using Equation 12.

$$P_B = P_M - 90^\circ - P_L \qquad \text{Equation 12}$$

P_B=63.5°

- Zero (F_{Z1}): The point that increases the phase positively as frequency increases (before the crossover).
  Pole (F_{P1}): The point that decreases the phase as frequency increases (after the crossover).
  The zero and pole are placed symmetrically around the crossover frequency. The coefficient (k) that determines this symmetry can be found using Equation 15. The zero and pole values of the circuit are found using Equation 14 and Equation 13, respectively.

$$k = \tan\left(\frac{P_B}{2} + 45°\right) \qquad \text{Equation 13}$$

$$F_{Z1} = \frac{F_{CO}}{k} \qquad \text{Equation 14}$$

$$F_{P1} = F_{CO} \times k \qquad \text{Equation 15}$$

<u>k = 4.25, F_{Z1} = 5.95kHz, F_{P1} = 105kHz</u>

- To obtain R_Z, CZ and C_P; Equation 16, Equation 17, and Equation 18 can be used respectively.

$$R_Z = \frac{2 \cdot \pi \cdot F_{CO} \cdot V_O \cdot C_O \cdot R_{OA}}{G_{MCOMP} \cdot V_{GGM} \cdot V_{REF}} \qquad \text{Equation 16}$$

$$C_Z = \frac{1}{2 \cdot \pi \cdot F_{Z1} \cdot R_Z} \qquad \text{Equation 17}$$

$$C_P = \frac{1}{2 \cdot \pi \cdot F_{P1} \cdot R_Z} \qquad \text{Equation 18}$$

R_Z = 29.157kΩ, C_Z = 917.4pF, C_P = 51.99pF so,

<u>R_Z = 33kΩ, C_Z = 1000pF, C_P 47pF</u>

6- Bootstrap Capacitor

- Bootstrap capacitor is selected 0.1μF for necessary. The bootstrap capacitor must be a high-quality ceramic type with X7R or X5R grade dielectric for temperature stability.

7- Catch Diode

- In buck converters, when the high-side MOSFET is turned off, current must continue to flow through the inductor. The diode that guides this current is called a catch diode. In other words, when the MOSFET is off, the inductor current flows through this diode. This ensures that the inductor's energy is conserved and the output operates properly.

- The selected diode must meet the absolute maximum ratings for the application. In a circuit switching at high frequencies, diodes with short reverse recovery times, that is, diodes that do not store charge in reverse voltage, should be preferred. Furthermore, for low power consumption, it is preferable to select diodes with low forward voltage drop. Schottky diodes are ideal for this purpose. There are important criteria for diode selection.

  - Reverse Voltage - It is the maximum voltage that the diode can withstand in reverse bias. This can be calculated by using Equation 19.

$$V_R > V_{PH(MAX)} = V_{IN(MAX)} + 0.5 \qquad \text{Equation 19}$$

V_R = 28.5V

  - Peak Current - It is the maximum current that the diode can carry. This can be calculated by using Equation 20.

$$I_{peak} > I_{OUT(MAX)} + \frac{I_{LPP}}{2} \qquad \text{Equation 20}$$

I_{PEAK} = 3.29A

B340A was selected, with a reverse voltage of 40 V, forward current of 3 A, and a forward-voltage drop of 0.5 V.

8- Slow-Start Capacitors

- Programming the slow-start time externally is highly recommended because no slow-start time is implemented internally. The TPS54331 device effectively uses the lower voltage of the internal voltage reference or the SS pin voltage as the reference voltage of the power supply that is fed into the error amplifier and regulates the output accordingly. A capacitor (C_{SS}) on the SS pin to ground implements a slow-start time. The TPS54331 device has an internal pullup current-source of 2 μA that charges the external slow-start capacitor.

- The slow-start time must be set between 1 ms to 10 ms to ensure good start-up behavior. The value of the slow-start capacitor must not exceed 27 nF. For this reason slow-start capacitor value is selected as 10nF. V_{REF} is 0.8 V and I_{SS} is 2 μA.

$$TSS_{ms} = \frac{C_{SS(nF)} * V_{REF(V)}}{I_{SS(\mu A)}} \qquad \text{Equation 21}$$

- **$C_{SS(nF)}$ = 10nF, TSS_{ms}= 4ms**

9- Enable Resistors

- Additionally, the maximum voltage rating of the TPS54331 IC's Enable pin must be adjusted to avoid violating the maximum voltage rating limits. The maximum voltage is clearly stated as 6V in the datasheet. Because high V_{IN} voltages can exceed the maximum rating limit via the voltage divider circuit, a 5.1V zener diode has been added between this pin and ground for safety. The BZX84C5V1 zener diode was selected with a 5.1V zener voltage and a power rating of 350mW.

$$V_{OUT} = V_{IN} \cdot \frac{R_2}{R_1+R_2} \quad \text{Equation 22}$$

R_{en1} = 100kΩ, R_{en2} = 47kΩ

10- Power Consumption

- The following equations show how to estimate the device power dissipation under continuous-conduction mode (CCM) operations. These formulas must not be used if the device is working in the discontinuous-conduction mode (DCM) or pulse-skipping Eco-mode.

$$P_{con} = I_{OUT}^2 \cdot R_{DS(on)} \cdot \frac{V_{OUT}}{V_{IN}} \quad \text{Equation 23}$$

$$P_{sw} = 0.5 \times 10^{-9} \cdot V_{IN}^2 \cdot I_{OUT} \cdot f_{SW} \quad \text{Equation 24}$$

$$P_{gc} = 22.8 \times 10^{-9} \cdot f_{SW} \quad \text{Equation 25}$$

$$P_q = 0.11 \times 10^{-3} \cdot V_{IN} \quad \text{Equation 26}$$

$$P_{tot} = P_{con} + P_{sw} + P_{gc} + P_q \quad \text{Equation 27}$$

VIN (V)	*5*	*12*	*20*	*28*
P_{con}(W)	*0.475*	*0.198*	*0.119*	*0.085*
P_{sw}(W)	*0.021*	*0.123*	*0.342*	*0.670*
Pgc(W)	*0.013*	*0.013*	*0.013*	*0.013*
P_q (W)	*0.0006*	*0.0013*	*0.0022*	*0.0031*
P_{tot}(W)	*0.510*	*0.355*	*0.476*	*0.771*

Table.3 Power Dissipation due to V_{IN}