Technical Article **Duty Cycle Calculation in WEBENCH® Power Designer**

TEXAS INSTRUMENTS

Pavani Jella

The duty cycle of a switching regulator is often thought of as being simply proportional to the input and output voltages. But when we look into the details of the calculations, we see that it also reflects circuit losses. Selecting components that give more losses, such as an inductor with a higher DCR, can cause the duty cycle to increase (for a buck converter), potentially resulting in additional efficiency loss from other components. When creating a power supply design with TI's WEBENCH® Power Designer, the model calculations do not rely on basic ideal equations, but instead use detailed calculations that show you the interaction between component losses via small changes in duty cycle. To explore this, let's look at an example of a buck converter as shown in Figure 1.



Figure 1. Asynchronous Buck Converter.

In a buck converter duty cycle D is defined as, D = Ton/Ts

Where Ts = 1/switching frequency

Ton = switch on-time

When the high-side power switch is turned on, current drawn from the input flows through the inductor. When the high-side switch is turned off, the diode (or low-side NMOS switch in this case of a synchronous converter) is turned on and current circulates through the diode (or low-side NMOS switch) since the inductor current cannot instantaneously stop. During the steady-state operation, the on and off times of the switch are balanced to maintain the desired output voltage. Figure 2 illustrates that during on-time of the switch, inductor current and the current through the high-side MOSFET ramps up, whereas, during the off-time of the switch, the diode and inductor currents ramp down.

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Figure 2. Buck Converter Waveforms.

Through substitution, we can get an equation for duty cycle that appears dependent on input voltage, output voltage, and the FET and diode voltage drops. If the FET and diode voltage drops are small compared to the input and output voltage, the duty cycle equation further reduces to the ratio of Vout to Vin.

$$D = \frac{V_{OUT} + V_D}{V_{IN} - V_{Q1(ON)} + V_D}$$

$$\simeq \frac{V_{OUT}}{V_{IN}}$$



For an ideal synchronous buck converter, where there are no voltage drops across the switches or other losses, duty cycle is exactly the ratio of output voltage to input voltage.

$$D = \frac{V_{OUT}}{V_{IN}}$$

However, realistic calculation of duty cycle in a synchronous buck converter involves voltages across the high-side and low-side components. Thus, we have to return to the non-ideal case and include all the original terms:

$$D = \frac{V_{OUT} + V_{LS(ON)}}{V_{IN} - V_{HS(ON)} + V_{LS(ON)}}$$

The voltage terms in the above equation are proportional to the output load current, lout.

$$D = \frac{V_{out} + I_{out} \left(R_{DS}^{LS} + R_{DCR} \right)}{V_{in} - I_{out} \left(R_{DS}^{HS} - R_{DS}^{LS} \right)}$$

 R_{DS}^{L} = low-side FET Rdson R_{DS}^{H} = high-side FET Rdson R_{DCR} = Inductor DCR

From the above equation observe that:



WEBENCH Power Designer calculations are based on these realistic loss terms. To study the effect of Vin, lout and DCR on the inductor during duty cycle, a design using TI's TPS54325-Q1 4.5V to 18V input, 3A synchronous step-down converter was created with Vin=11.5-12.5 V and Vout=3.3 V Vout @ 3A output current (see Figure 3).





Figure 3. TPS54325-Q1 Synchronous Step-down Converter Vin=11.5-12.5V and Vout of 3.3V @ 3A lout Load



Figure 4. Notice That the Inductor Selected Is a TDK SPM6530T-2R2M with 2.2 uH Inductance and 19 mOhm DCR



| | | | 0 | PERATING VALUES | | | |
|-----------------------|---------------|--------------------------------------|-----------------------|-----------------|---|--|--|
| Optimizatio | on Tuning | Modify Operating Point | | | | | |
| Lowest BOM Cost | • | Vin: 12.5 Iout: 3.0 Recalculate Expo | rt to: 🔀 Excel Export | | | | |
| Smallest | Highest | Name | Value | Category | Description | | |
| | 5 Enciency | VIN_OP | 12.55V | Op_Point | Vin operating point | | |
| | | Vout OP | 3.3V | Op_Point | Operational Output Voltage | | |
| Footprint BOM Co | st Efficiency | IOUT_OP | 3A | Op_Point | lout operating point | | |
| 196 \$2.81 | 8 | Cin IRMS | 1.363A | Current | Input capacitor RMS ripple current | | |
| | | Cin Pd | 3.696mW | Power | Input capacitor power dissipation | | |
| Change Dec | ian Innute | Cout IRM S | 0.514A | Current | Output capacitor RMS ripple current | | |
| change bes | igniniputa | Cout Pd | 454uW | Power | Output capacitor power dissipation | | |
| Advanced | Options | Duty Cycle | 28.84% | Op_Point | Duty cycle | | |
| Soft Start Time (ms): | | Efficiency | 86.37% | Op_Point | Steady state efficiency | | |
| 1ms< 1 ms | < 10ms | Frequency | 676kHz | General | Switching frequency | | |
| Mode of Operation: | | IC Tj | 105degC | Op_Point | IC junction temperature | | |
| VSOURCE ENABL | E OFF | ICThetaJA | 55.65degC/W | Op_Point | IC junction-to-ambient thermal resistance | | |
| | | L Ipp | 1.786A | Current | Peak-to-peak inductor ripple current | | |
| opu | are - | L Pd | 0.220W | Power | Inductor power dissipation | | |
| Current Des | ian: #6505 | IC Pd | 1.349W | Power | IC power dissipation | | |
| Current Des | TDS64326-04 | Pout | 9.9W | General | Total output power | | |
| VinMin | 11 5 V | a lin Avg | 0.917A | Current | Average input current | | |
| VinMax | 12.5 V | IC lpk | 3.896A | Current | Peak switch current in IC | | |
| ROUTCR | DC. | Mode | CCM | General | Conduction Mode | | |
| Vout | 33.1/ | Vout p-p | 8.771mV | Op_Point | Peak-to-peak output ripple voltage | | |
| lout | 3.6 | IC lq Pd | 0.013W | Power | IC lq Pd | | |
| ta | 30 deaC | FootPrint | 196mm2 | General | Total Foot Print Area of BOM components | | |
| ta | oo acyc | Total BOM | 2.815\$ | General | Total BOM Cost | | |
| | | Total Pd | 1.574W | Power | Total Power Dissipation | | |
| | | BOM Count | 12 | General | Total Design BOM count | | |
| | | | | | | | |

Figure 5. Calculated Operating Values of This Design, Including Duty Cycle of 28.8%, Efficiency of 86.3% and Inductor Power Dissipation L Pd of 0.22 W



Figure 6. WEBENCH® Power Designer Charts That Confirm That:

Vin \uparrow , D \downarrow and as lout \uparrow , D \uparrow

To study the impact of DCR on duty cycle and efficiency let's choose a Coilcraft inductor XAL4020-222MB with the same inductance of 2.2 uH and an increased DCR of 35 mOhm(Figure 7). View the design here.

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| _ | Alternate Parts - Charts | | | | | | Summary | information for sele | cted Component S | ummary informat | tion for selected C | mponent L1: | | | - |
| Filter by M | anufacturer: Select All | Manuf | Part Number | L | DCR | IDC | Pi | rice Qty Avail | Foot Print | Height | Power Diss | | Top View | | |
| Updat | te X Axis Update Y Axis | | | (H) | (Ohm) | (A) | | | | | | | | | |
| Power D | iss (₩) ▼ Footprint (mm2) ▼ [| TDK | SPM6530T-2R2 | 1 2.2u | 0.019 | 8.4 | \$ | 0.56 > 10 | 77 | 3 | 0.220 | | | | |
| 900 - | 0 | LIMITS | | | | | | | | | | | L (H |) DCR (Ohm) | IDC (A) |
| | õ | Upperbound | Upperbound | | | | | | | | | 3.3u | 0.055 | 108.2 | |
| | | Lowerbound | | | | | | | | | | | 2.2u | 100u | 5.412 |
| 800 - | | Target | | | | | | | | | | | 2.2u | 5.5m | 5.412 |
| | | _ | Select an alternate part for Component L1: show More Columns | | | | | | | | | | | | |
| | | Edit | Manuf P | art Number | L (H) | DCR (Ohm) | IDC (A) | Price | Qty Avail | Foot Print | Height | Power Diss | Foot Prin | nt | |
| 700 - | | | TDK S | PM6530T-2R21 | 2.2u | 0.019 | 8.4 | \$0.56 | > 10 | 77 | 3 | 0.220 | | | ÷ |
| | | Select | Bourns | RN8040-3R3Y | 3.3u | 0.021 | 5.5 | \$0.22 | > 10 | 100 | 4 | 0.243 | 8 | | 1 |
| 600 - | | Select | Bourns S | RN8040-2R2Y | 2.2u | 0.013 | 6.3 | \$0.22 | > 10 | 100 | 4 | 0.151 | 8 | | |
| | | Select | ток у | LP8040T-2R2N | 2.2u | 0.015 | 6.7 | \$0.22 | > 10 | 113 | 4 | 0.174 | | | |
| | | Select | Colleraft X | AL4020-222ME | 2.2u | 0.035 | 5.5 | \$0.60 | > 10 | 25 | 2.1 | 0.408 | | | |
| F 600 | | Select | Bourns § | DR http://www | .coilcraft.com/p | dfs/xal4000.pdf | 5.5 | \$0.26 | > 10 | 176 | 5 | 0.139 | 0 | 1 | |
| (mm) | 00 | Select | Collcraft x | AL4030-332ME | 3.3u | 0.026 | 5.5 | \$0.62 | > 10 | 25 | 3.1 | 0.301 | | | |
| 400 - | 0 0 | Select | ток с | LF7045T-2R2N | 2.2u | 0.02 | 5.5 | \$0.42 | > 10 | 86 | 4.8 | 0.232 | Ō | | |
| | 90. 88 | Select | Bourns s | RU1048-3R0Y | 3u | 7.2m | 6 | \$0.33 | > 10 | 144 | 4.8 | 0.083 | | | |

Figure 7. Selection of Coilcraft Inductor XAL4020-222MB with the Same Inductance of 2.2 uH and an Increased DCR of 35 mOhm

With increase in DCR the duty cycle is now 29.2% and efficiency dropped to 84.9% as seen in Figure 8.

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|-------------------------------|---|-------------------------------|---|---|--|--|
| | Back New Solutions Visualizer | BOM Charts Schematic Optimize | dV dt V Op Vals Sim Thermal Build-It Lite Edit Export | Print Share Design Assistant | | |
| | | | OPERATING VALUES | | | |
| Optimization Tuning | Modify Operating Point | | | | | |
| Lowest BOM Cost | Vin: 12.5 lout: 3.0 Recalculate Export to | | | | | |
| Smallest Highest | Name | Value | Category | Description | | |
| | VIN_OP | 12.5V | Op_Point | Vin operating point | | |
| | Vout OP | 3.3V | Op_Point | Operational Output Voltage | | |
| Footprint BOM Cost Efficiency | IOUT_OP | 3A | Op_Point | lout operating point | | |
| 143 \$2.84 85 | Cin IRMS | 1.36A | Current | Input capacitor RMS ripple current | | |
| | Cin Pd | 3.72mW | Power | Input capacitor power dissipation | | |
| Change Design Inputs | Cout IRMS | 0.52A | Current | Output capacitor RMS ripple current | | |
| | Cout Pd | 474uW | Power | Output capacitor power dissipation | | |
| Advanced Options | Duty Cycle | 29.2% | Op_Point | Duty cycle | | |
| Soft Start Time (ms): | Efficiency | 84.9% | Op_Point | Steady state efficiency | | |
| 1ms < 1 ms < 10ms | Frequency | 6/1KH2 | General | Switching frequency | | |
| Mode of Operation: | IC Tj | 105degC | Op_Point | IC junction temperature | | |
| VSOURCE ENABLE OFF | ICThetaJA | 55.6degC/W | Op_Point | IC junction-to-ambient thermal resistance | | |
| lindate | L lpp | 1.82A | Current | Peak-to-peak inductor ripple current | | |
| opdate | L Pd | 0.40W | Power | Inductor power dissipation | | |
| Current Design: #6582 | IC Pd | 1.34W | Power | IC power dissipation | | |
| IC TP\$54325.01 | Pout | 9.9W | General | Total output power | | |
| VinMin 11.5 V | lin Avg | 0.93A | Current | Average input current | | |
| VinMax 12.5 V | IC lpk | 3.91A | Current | Peak switch current in IC | | |
| source DC | Mode | CCM | General | Conduction Mode | | |
| Vout 33V | Vout p-p | 9.07mV | Op_Point | Peak-to-peak output ripple voltage | | |
| lout 3 A | IC lq Pd | 0.01W | Power | IC lq Pd | | |
| ta 30 degC | Total Pd | 1.76W | Power | Total Power Dissipation | | |
| in oo dego | FootPrint | 143mm2 | General | Total Foot Print Area of BOM components | | |
| | Total BOM | 2.85\$ | | Total BOM Cost | | |
| | BOM Count | 12 | | Total Design BOM count | | |
| | | | | | | |

Figure 8. OpVals with Inductor with 35mOhm DCR.

To see a more significant change, a CUSTOM inductor with higher DCR of 0.5 W and with same inductance is selected (Figure 9). See the design here.



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| Filter by M | anufacturer: Select All 🛛 🗸 🗸 | Manuf | Part Number | L | DCR | IDC | Price | Qty | Avail | Foot Print | Hei | ght | Power Diss | | Top View | | |
| Updat | le X Axis Update Y Axis | | | (H) | (Ohm) | (A) | | | | | | | | | | | |
| Power D | iss (W) 🛛 🔻 Footprint (mm2) 🖉 | Coilcraft | XAL4020-2228 | E 2.2u | 0.035 | 5.5 | \$0.60 | | 10 | 25 | 2. | .1 | 0.405 | | | | |
| 900 - | | LIMTS | | | | | | | | | _ | | | | L | H) DCR (Ohm | IDC (A |
| | 0 I | Upperbound | Boorhound | | | | | | | | | | | | 3.3u | 0.055 | 108.2 |
| | | Lowerbound | 1 | | | | | | | | | | | | 2.20 | 100u | 5.412 |
| | | Taroet | | | | Enter Cust | Enter Custom Part Information X | | | | × | | | | 2.20 | 5.5m | 5.412 |
| | | | | | | | | | | lore Columns | | | | | | | |
| | | Edit | Manuf P | art Number | L (H) | D | Part Number | imber | | | | nt l | Height | Power Diss | rer Diss Foot Print | | |
| 700 | | | Colleraft | (AL4020-22211) | 2.2u | М | anufacturer | | CUSTOM |] | | | 2.1 | 0.405 | | | |
| | | Select | Bourns | SRN8040-3R3Y | 3.3u | Budget Price | | 0.10 | s | | | 4 | 0.243 | <u></u> | 8 | | |
| | | Select | Bourns | SRN8040-2R2Y | 2.2u | quanti | ty in parallel | arallel DCR 1.0E-4 <= | 1 | Ohm <= 0 | | | 4 | 0.151 | | ·) | |
| 600 | | _ | Terr | | | | DCR 1. | | 0.5 | | 0.055 | | | 0.674 | | | |
| | | Select | 100 | /LP80401-2K2N | 2.23 | · · | Default Disty | | Coilcraft | | | | | 9.174 | | | |
| - | | Select | Bourns | SDR1005-2R5M | 2.5a | | IDC 5 | 5.412 <- | 5.5 | A < | 108.2 | | 5 | 0.139 | 1 | 8 | |
| 1 | | Select | Coilcraft) | KAL4030-332ME | 3.3u | | IDC_Max | 2F.6 <= | 0.0 | A H 4 | 136.6 | | 3.1 | 0.301 | | | |
| ĵ. | 00 | Select | TDK (| CLF7045T-2R2N | 2.2u | | Material | | Shielded | | | | 4.8 | 0.232 | 0 | | |
| 400 | 0 0 | Select | Bourns | SRU1048-3R0Y | 3u | | Tolerance | | 20.0 | % | | | 4.8 | 0.083 | | | |
| | 800 BB | Scient | Bourns | SRU1038.285Y | 2.5a | | Dimension X | | 4.0 | mm | | | 3.8 | 0.145 | | | |
| 300 | 0 00 | | | | | | Dimension Y | | 4.0 | mm | | | | | | | |
| | 000 | Select | Bourns | SRP5030T-2R28 | 2.2u | | Dimension Z | | 2.1 | mm | | | 3 | 0.405 | | | |
| | and the second s | Select | Vishay-Dale J | HLP2020CZER2 | 2.2u | | Save ch | hanges | Cancel | 1 | | | 3 | 0.290 | | | |

Figure 9. Setting of CUSTOM Inductor with 0.50hm DCR and Same Inductance 22uH

Note that now there is a significant jump in duty cycle to 40.4% and efficiency has dropped drastically to 57%. The drop in efficiency is due to a significant rise in inductor loss to 6.08 W. Figure 10 shows the steep increase in duty cycle and sharp drop in efficiency reiterating the same.



Figure 10. Efficiency and Duty Cycle Charts Showing the Effect of CUSTOM Inductor with High DCR of 0.50hm

Figure 11 and Figure 12 summarize the three DCR cases of 19 mW, 35 mW and 0.5 W of a 2.2 uH inductor, and its impact on duty cycle, efficiency and inductor power dissipation.

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| | | | (| OPERATING VALUES | | | | | | |
| Optimization Tuning | Modify Operating Point | | | | | | | | | |
| Lowest BOM Cost | Vin: 12.5 lout 3.0 Recalculate Expor | | | | | | | | | |
| Smallest Highest | Name | Value Value | Value | Category | Description | | | | | |
| | VIN_OP | 12.5V 12.5V | 12.5V | Op_Point | Vin operating point | | | | | |
| | Vout OP | 3.3V 3.3V | 3.3V | Op_Point | Operational Output Voltage | | | | | |
| Footprint BOM Cost Efficience | IOUT_OP | 3A 3A | 3A | Op_Point | lout operating point | | | | | |
| 196 \$2.81 86 | Cin IRMS | 1.36A 1.36A | 1.47A | Current | Input capacitor RMS ripple current | | | | | |
| | Cin Pd | 3.69mW 3.72m | W 4.34mW | Power | Input capacitor power dissipation | | | | | |
| Change Design Inputs | Cout IRMS | 0.51A 0.52A | 0.85A | Current | Output capacitor RMS ripple current | | | | | |
| onango ocorgii inputo | Cout Pd | 454uW 474uW | 1.25mW | Power | Output capacitor power dissipation | | | | | |
| Advanced Options | Duty Cycle | 28.8% 29.2% | 40.4% | Op_Point | Duty cycle | | | | | |
| Soft Start Time (ms): | Efficiency | 86.3% 84.9% | 57.0% | Op_Point | Steady state efficiency | | | | | |
| 1ms< 1 ms<10ms | Frequency | 676kHz 671kH | z 572kHz | General | Switching frequency | | | | | |
| Mode of Operation: | IC Tj | 105degC 105de | gC 107degC | Op_Point | IC junction temperature | | | | | |
| VSOURCE ENABLE OFF | ICThetaJA | 55.6degC/W 55.6de | gC/W 55.6degC/W | Op_Point | IC junction-to-ambient thermal resistance | | | | | |
| lindate | L Ipp | 1.78A 1.82A | 2.96A | Current | Peak-to-peak inductor ripple current | | | | | |
| opdate | L Pd | 0.22W 0.40W | 6.08W | Power | Inductor power dissipation | | | | | |
| Current Design: #6592 | IC Pd | 1.34W 1.34W | 1.38W | Power | IC power dissipation | | | | | |
| Current Design. #0582 | Pout | 9.9W 9.9W | 9.9W | General | Total output power | | | | | |
| IC 1P554325-Q1 | lin Avg | 0.91A 0.93A | 1.39A | Current | Average input current | | | | | |
| Vinitin 11.5 V | IC lpk | 3.89A 3.91A | 4.48A | Current | Peak switch current in IC | | | | | |
| VIIIMAX 12.5 V | Mode | CCM CCM | CCM | General | Conduction Mode | | | | | |
| source DC | Vout p-p | 8.77mV 9.07m | V 0.01V | Op_Point | Peak-to-peak output ripple voltage | | | | | |
| Vout 3.5 V | C lq Pd | 0.01W 0.01W | 0.01W | Power | IC lq Pd | | | | | |
| to 10 do | FootPrint | 196mm2 1.76W | 7.46W | General | Total Foot Print Area of BOM components | | | | | |
| ta 30 degc | U Total BOM | 2.81\$ 143mr | m2 143mm2 | General | Total BOM Cost | | | | | |
| | Total Pd | 1.57W 2.85\$ | 2.35\$ | Power | Total Power Dissipation | | | | | |
| | BOM Count | 12 12 | 12 | General | Total Design BOM count | | | | | |
| | | | | | | | | | | |

Figure 11. Comparison of OpVals for Three Cases of DCR





In conclusion, the switching regulator has to work extra hard to maintain the output voltage at the desired level with increase in DCR, which results in higher power dissipation losses. It's thus important to choose an appropriate inductor with minimal DCR to maximize the efficiency of a switching regulator with an optimal duty cycle.

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