Technical Article

Duty Cycle Calculation in WEBENCH® Power Designer

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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.

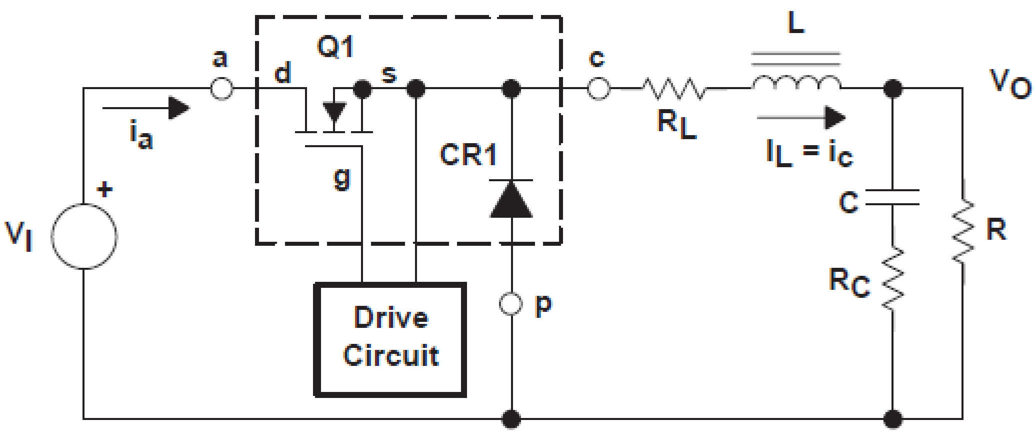


Figure 1. Asynchronous Buck Converter.

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.

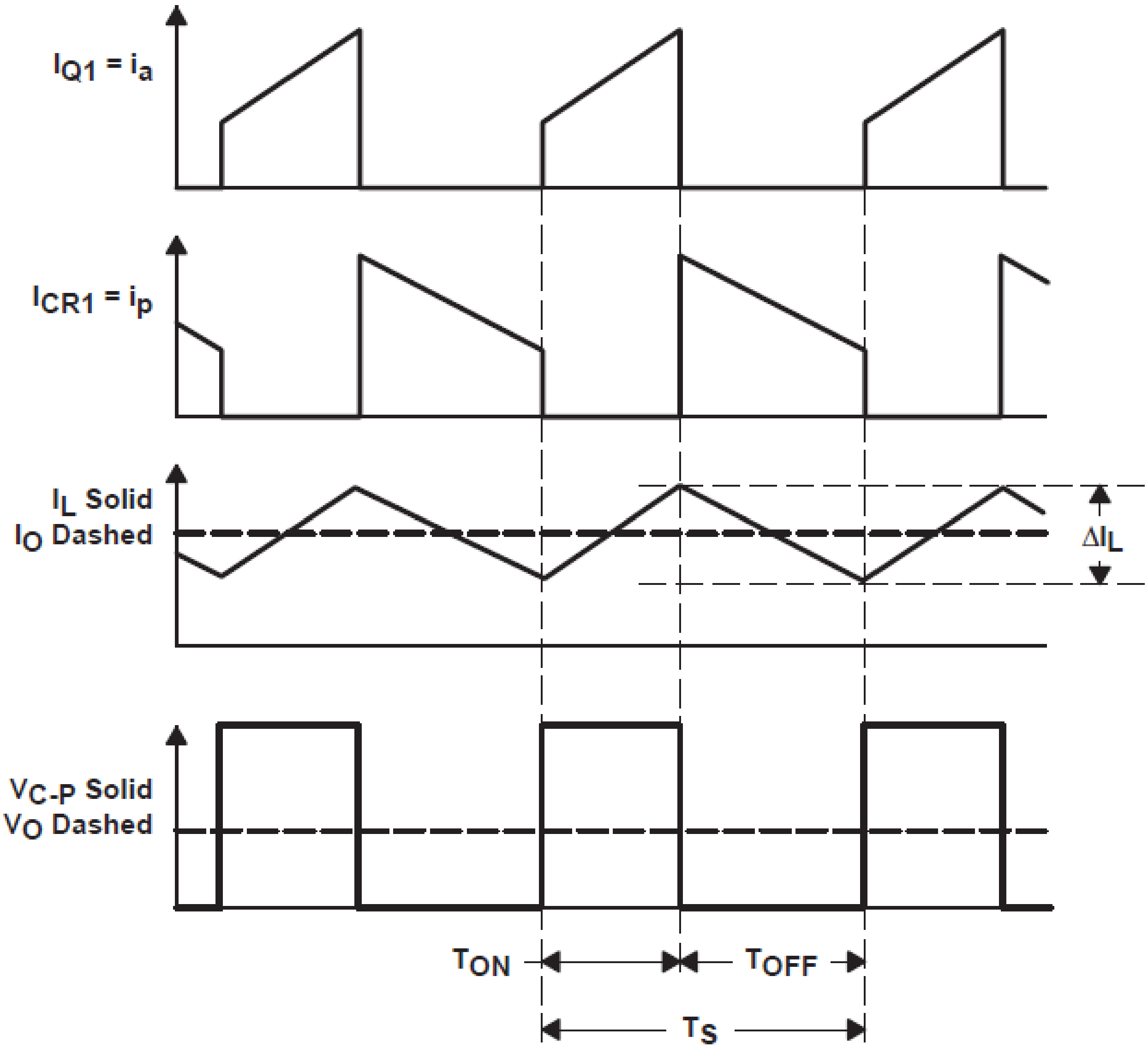


Figure 2. Buck Converter Waveforms.

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.

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

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

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, Iout.

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

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

From the above equation observe that:

- as Vin ↑, D ↓
- as Iout ↑ , D ↑
- as R_{DCR} ↑ , D ↑

WEBENCH Power Designer calculations are based on these realistic loss terms. To study the effect of Vin, Iout 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).

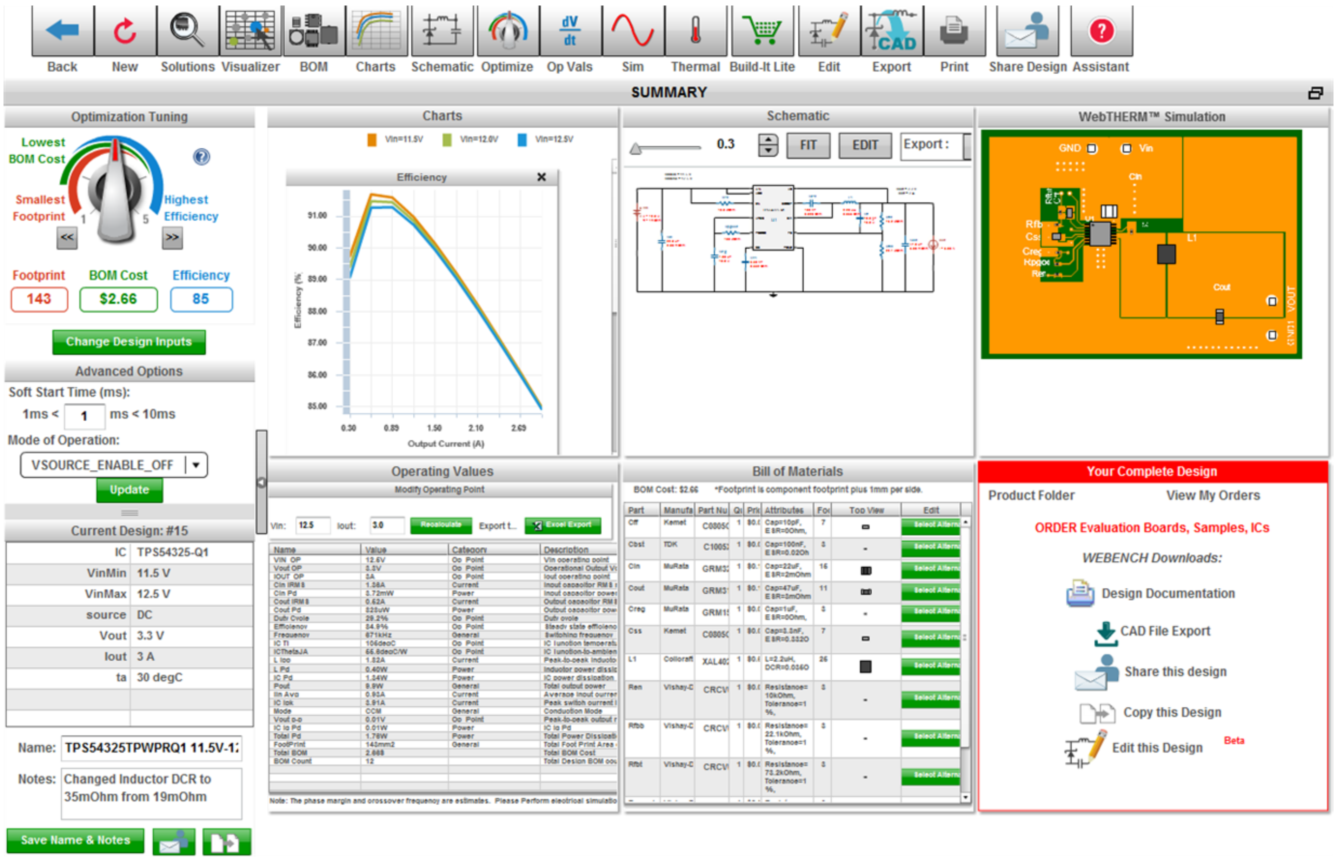


Figure 3. TPS54325-Q1 Synchronous Step-down Converter Vin=11.5-12.5V and Vout of 3.3V @ 3A Iout Load

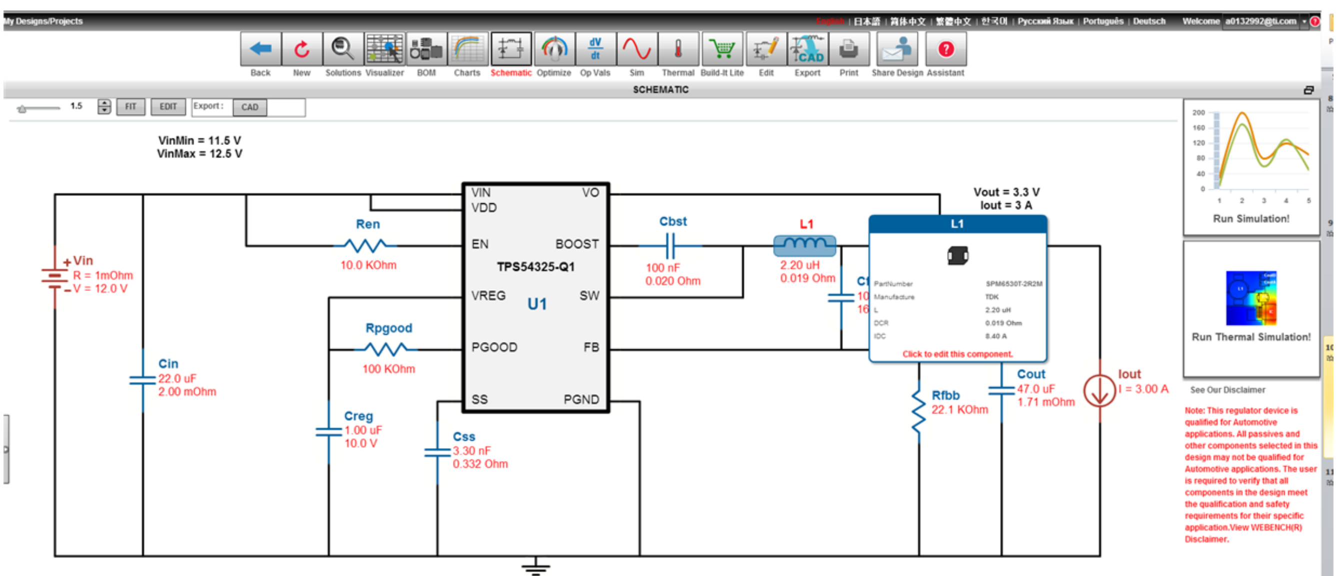
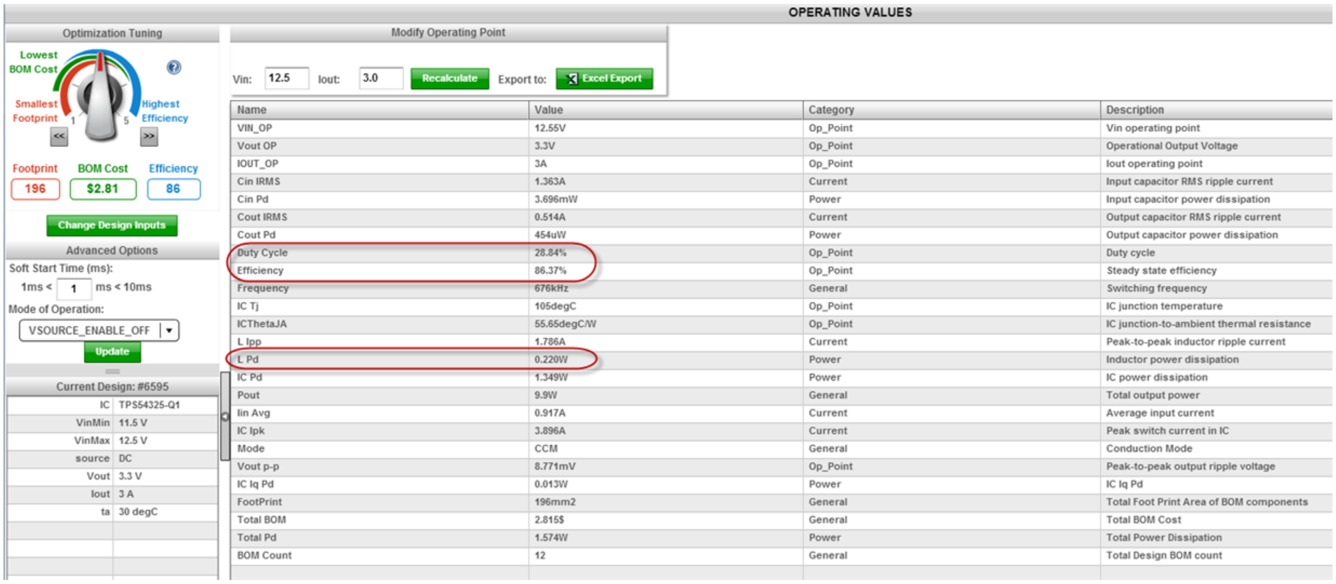


Figure 4. Notice That the Inductor Selected Is a TDK SPM6530T-2R2M with 2.2 uH Inductance and 19 mOhm DCR



Name	Value	Category	Description
VIN_OP	12.55V	Op_Point	Vin operating point
Vout OP	3.3V	Op_Point	Operational Output Voltage
IOUT_OP	3A	Op_Point	Iout operating point
Cin IRMS	1.363A	Current	Input capacitor RMS ripple current
Cin Pd	3.696mW	Power	Input capacitor power dissipation
Cout IRMS	0.514A	Current	Output capacitor RMS ripple current
Cout Pd	454uW	Power	Output capacitor power dissipation
Duty Cycle	28.84%	Op_Point	Duty cycle
Efficiency	86.37%	Op_Point	Steady state efficiency
Frequency	676kHz	General	Switching frequency
IC Tj	105degC	Op_Point	IC junction temperature
ICThetaJA	55.65degC/W	Op_Point	IC junction-to-ambient thermal resistance
L Ipp	1.786A	Current	Peak-to-peak inductor ripple current
L Pd	0.220W	Power	Inductor power dissipation
IC Pd	1.349W	Power	IC power dissipation
Pout	9.9W	General	Total output power
Iin Avg	0.917A	Current	Average input current
IC Ipk	3.896A	Current	Peak switch current in IC
Mode	CCM	General	Conduction Mode
Vout p-p	8.771mV	Op_Point	Peak-to-peak output ripple voltage
IC Iq Pd	0.013W	Power	IC Iq Pd
FootPrint	196mm2	General	Total Foot Print Area of BOM components
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

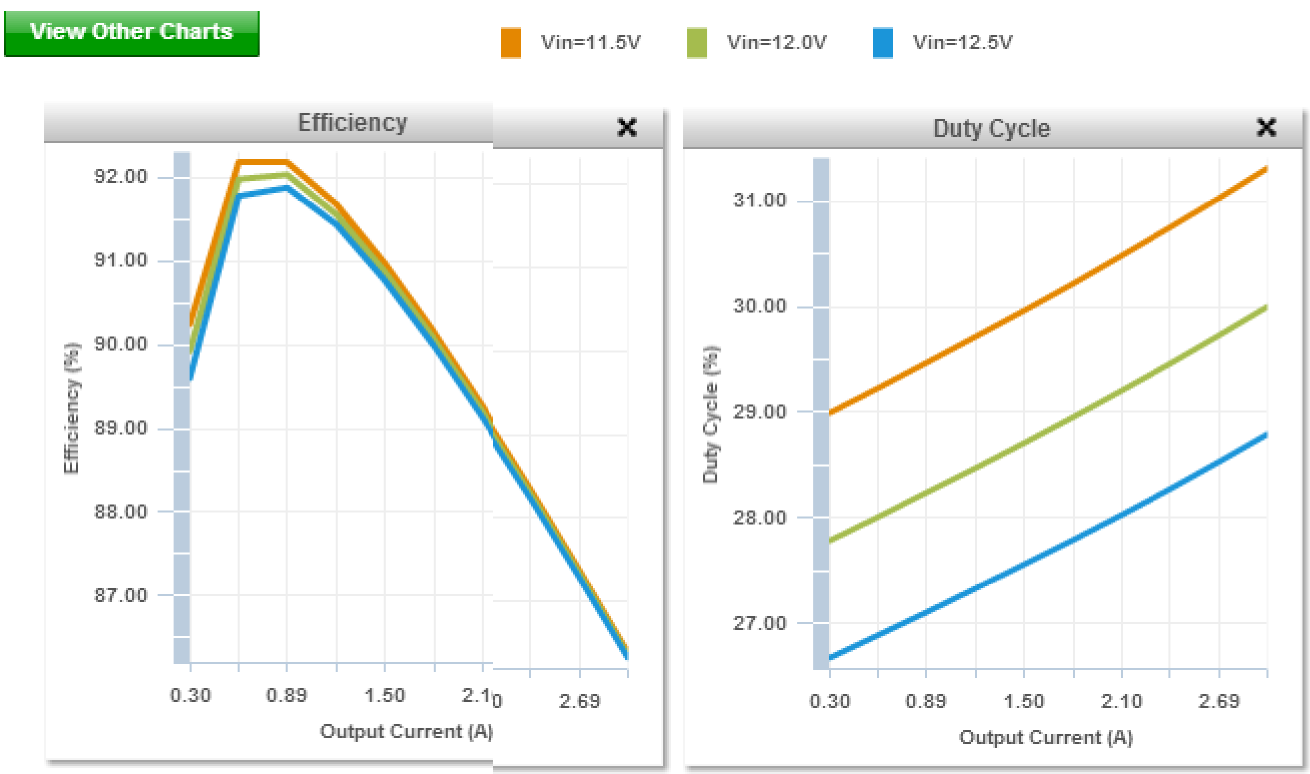


Figure 6. WEBENCH® Power Designer Charts That Confirm That:

Vin ↑, D ↓ and as Iout ↑ , D ↑

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.

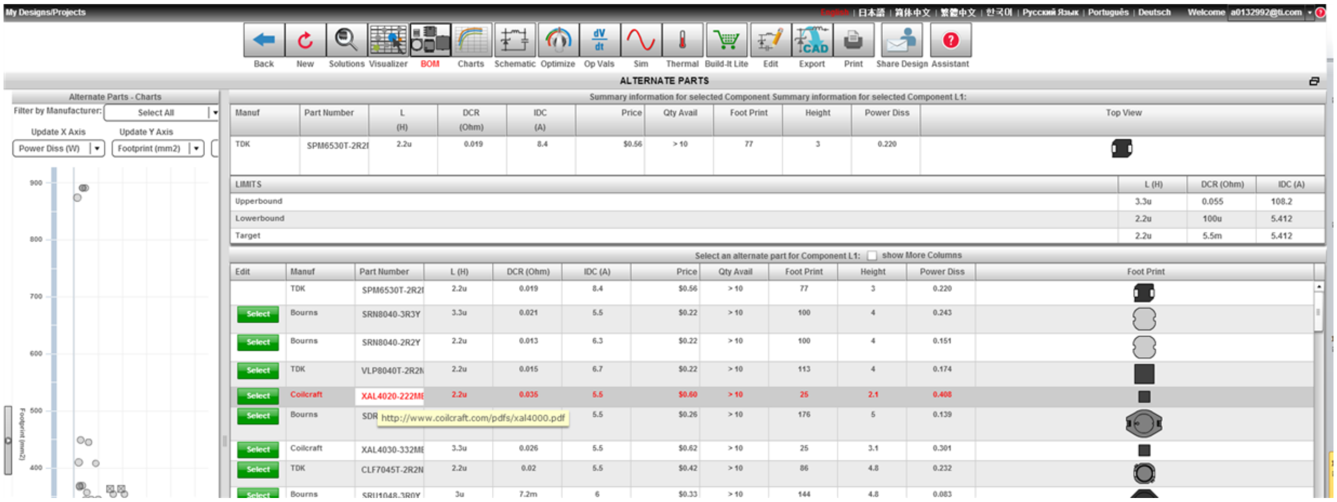


Figure 7. Selection of Coilcraft Inductor XAL4020-222MB with the Same Inductance of 2.2 uH and an Increased DCR of 35 mOhm

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

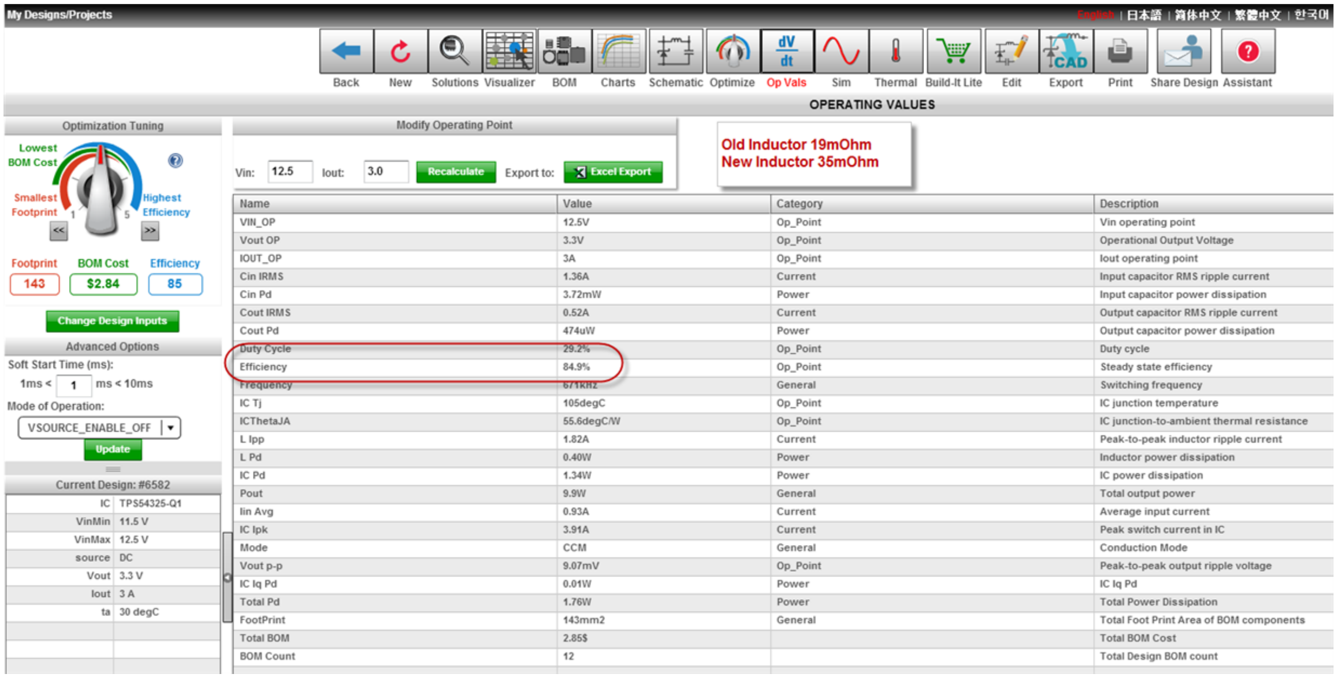


Figure 8. OpVals with Inductor with 35mOhm DCR.

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.

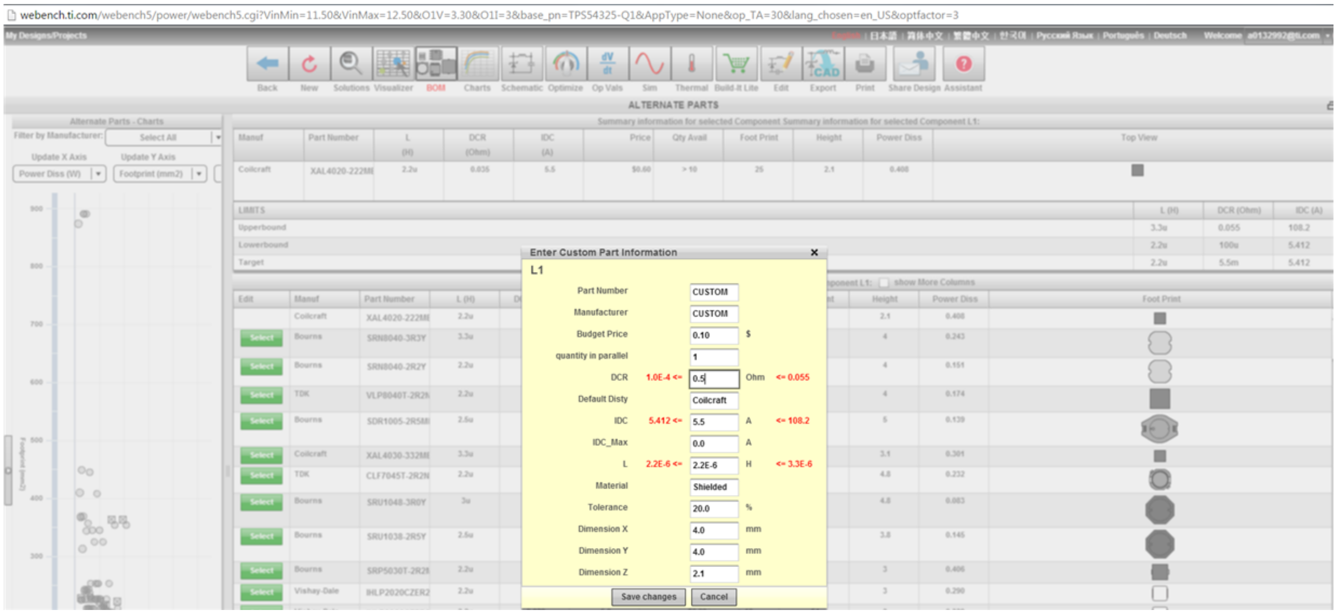


Figure 9. Setting of CUSTOM Inductor with 0.5Ohm DCR and Same Inductance 22uH

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.

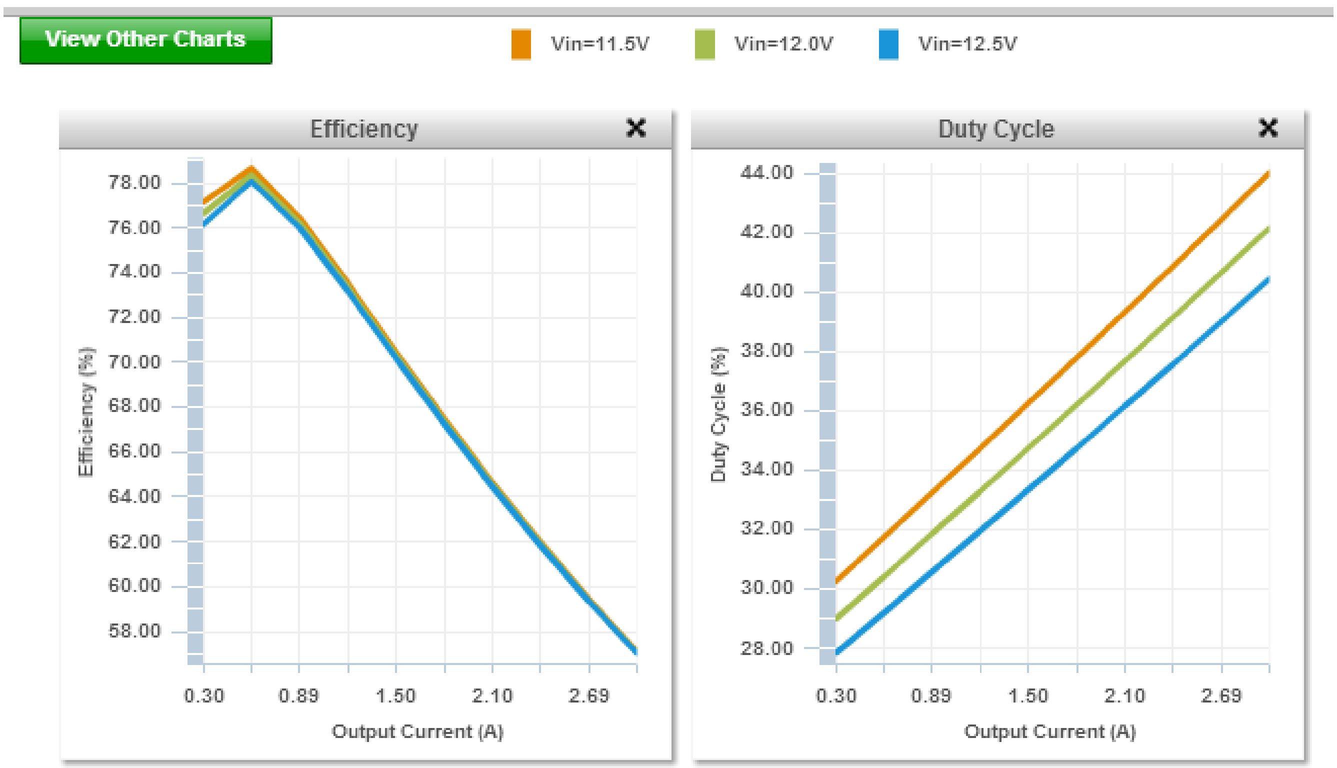


Figure 10. Efficiency and Duty Cycle Charts Showing the Effect of CUSTOM Inductor with High DCR of 0.5Ohm

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.

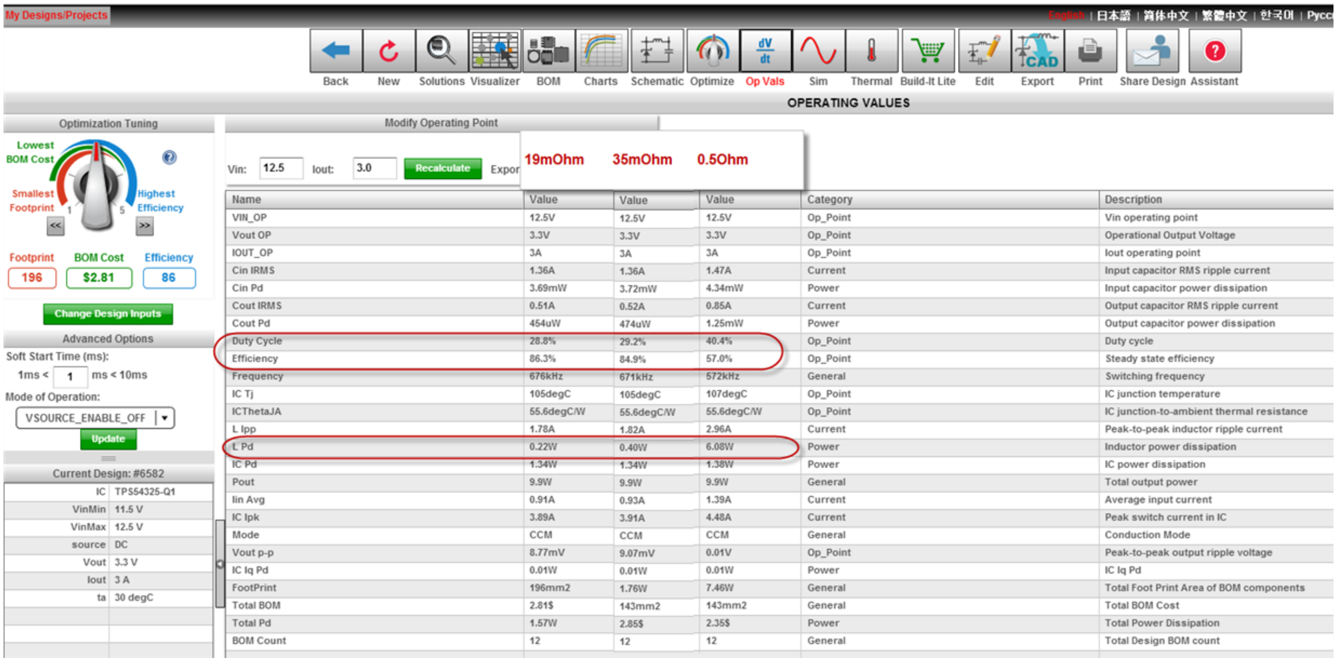


Figure 11. Comparison of OpVals for Three Cases of DCR

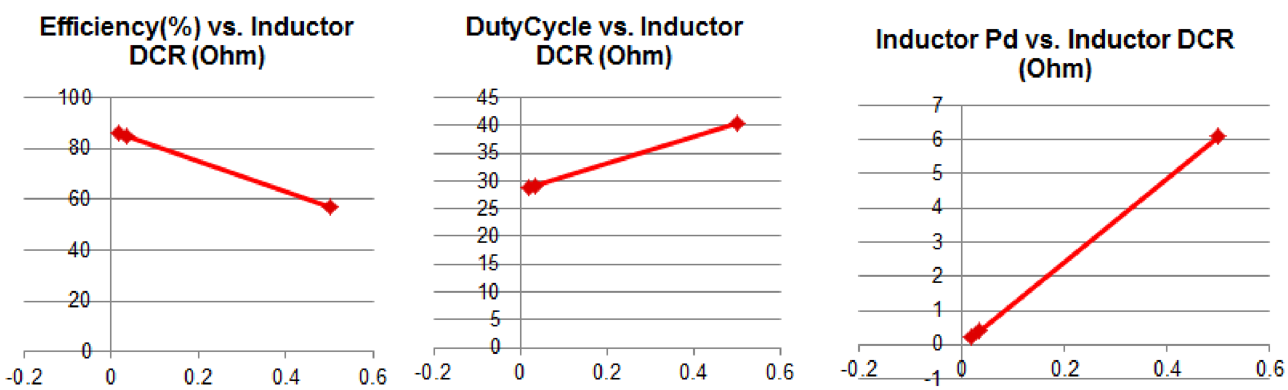


Figure 12. Summary of Charts for Efficiency, DutyCycle and L Pd

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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