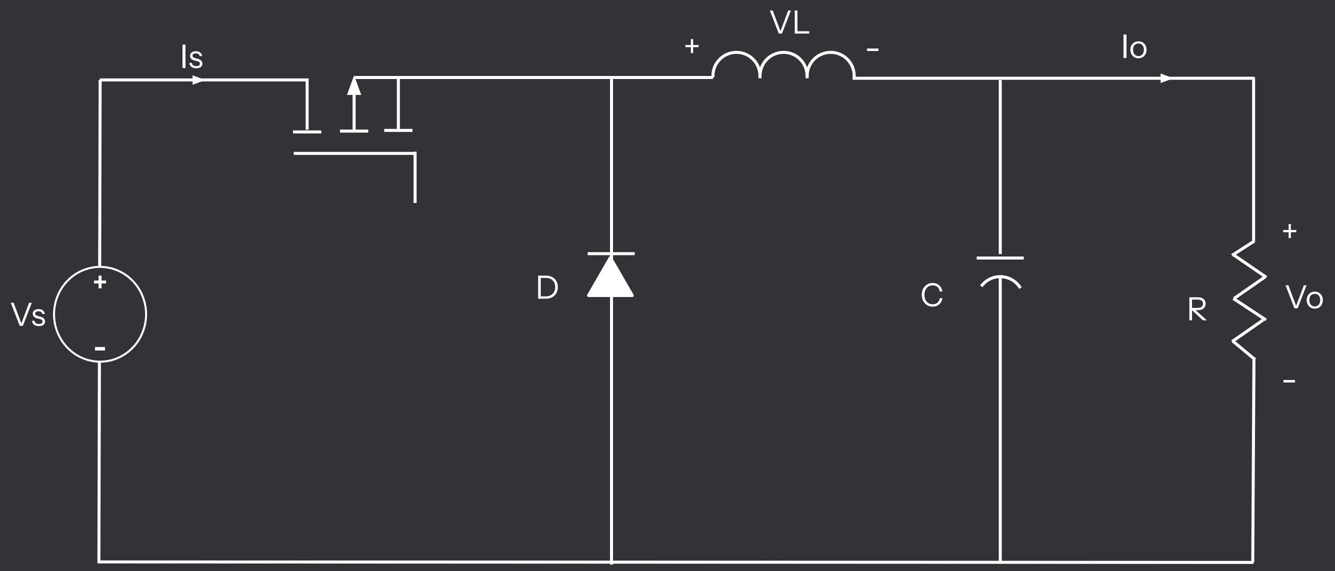
BUCK CONVERTER

01 BUCK CONVERTER

- A Dc-Dc converter which **steps down** voltage.
- Main circuit includes a switch (IGBT or MOSFET), a diode, and an LC Filter.
- PWM controls the timing of the switch in a buck converter, crucial for regulating output voltage and minimizing ripples.
- In Mode I, the switch is on and the diode is off, vice versa for Mode II, each mode essential for continuous current flow through the load.
- Analysis of the buck converter in steady state demonstrates that the inductor current remains constant overall, ensuring a stable output.

02 CIRCUIT DIAGRAM



03 COMPONENTS

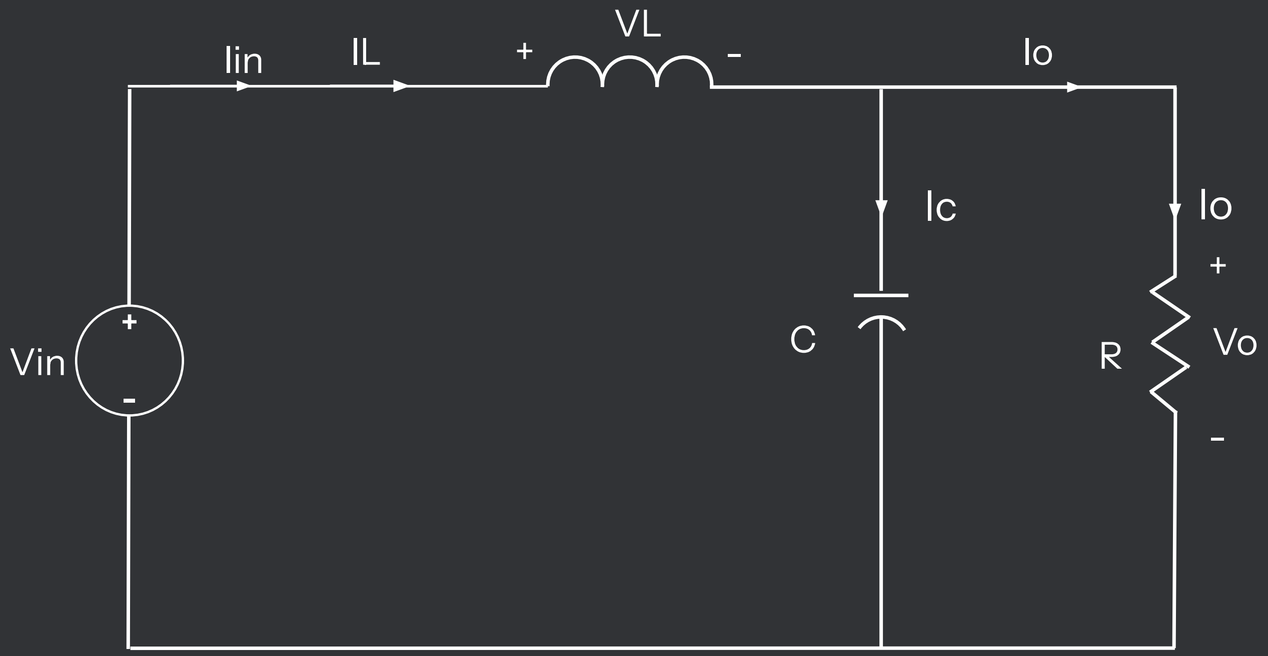
Switch (S): Typically a power MOSFET or transistor, rapidly turned ON and OFF by a control circuit using Pulse Width Modulation (PWM).

Diode (D): Often called a freewheeling diode (or sometimes replaced by a second MOSFET in a synchronous buck converter for higher efficiency). It provides a path for the inductor current when the main switch is off.

Inductor (L): The key energy storage component. It stores energy in its magnetic field when the switch is ON and releases it to the load when the switch is OFF, smoothing the current.

Capacitor (C): Placed at the output to filter the voltage, smoothing the ripple and maintaining a steady DC output voltage to the load.

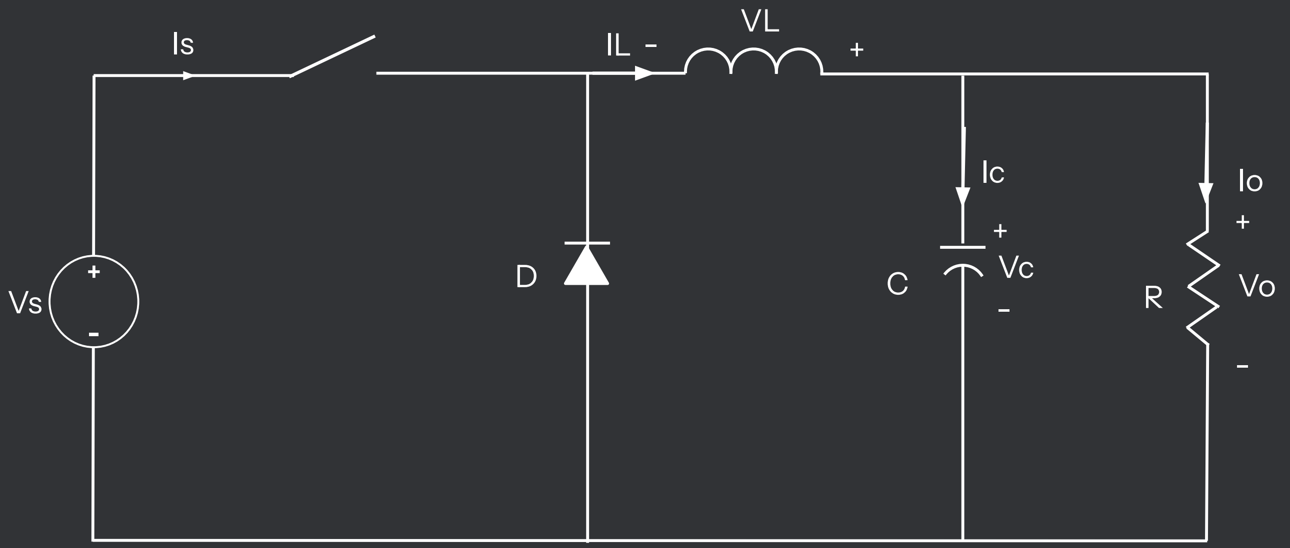
04 MODE-1: SWITCH ON



04 MODE-1: SWITCH ON

Diode	Reverse Biased
Inductor Voltage (VL)	The input voltage is directly connected to L-C load network. VL = Vin - Vout
Inductor current (iL)	Since Vin > Vout, the voltage across inductor is positive. This causes the current in inductor to **ramp up** linearly. The inductor is storing energy in its magnetic field. $\frac{di_L}{L} = \frac{V_{in} - V_{out}}{L}$
Capacitor/Load	The output capacitor and load resistance are both supplied by input source and remaining charge on C itself.

05 MODE-2: SWITCH OFF



05 MODE-2: SWITCH OFF

Diode	Forward Biased
Inductor Voltage (VL)	The inductor resists the change in current by suddenly reversing its voltage polarity (self-inductance). This negative voltage forward-biases the diode. VL = -Vout
Inductor current (iL)	Since the voltage across the inductor is now negative, the inductor current decreases (ramps down) linearly. The inductor is releasing the energy stored during the ON state to the capacitor and the load. $\frac{di_L}{dt} = \frac{-V_{out}}{L}$
Capacitor/Load	e load is now solely supplied by the energy released from the inductor L and the output capacitor. The inductor current continues to flow in the same direction, but its magnitude is decreasing.

06 MODES OF OPERATION

	Continuous conduction mode	Discontinuous conduction Mode
Inductor current	Never drops to 0	Drops to 0, resulting in 3rd state (idle time)
Load Condition	Occurs at moderate to heavy loads	Occurs at light loads
RMS/Peak currents	Lower RMS and lower peak currents in the switch and diode.	Higher RMS and higher peak currents for the same output power, leading to higher conduction losses.
Control & Stability	Easier to compensate (simpler control-to-output transfer function).	More difficult to compensate due to load-dependent gain.
Switching Losses	Diode has Reverse-Recovery Loss (or synchronous FET body diode loss) when switching from ON to OFF.	Zero Current Switching (ZCS) occurs when the inductor current reaches zero, eliminating diode reverse-recovery loss and offering potentially higher efficiency at light load
EMI / Noise	Generally lower EMI as the inductor current waveform is smoother	Higher EMI due to the rapid change in voltage/current when the current rings (LC resonance between L and parasitic capacitances) during the idle (zero-current) period.

07 DESIGN FORMULAS

$$D = \frac{V_{in}}{V_{out}}$$

$$L = \frac{V_{in} - V_{out} \cdot D}{f_s \cdot \Delta I_L}$$

$$I_{L(peak)} = I_{out(max)} + \frac{\Delta I_L}{2}$$

$$C_{out} = \frac{\Delta I_L}{8 \cdot f_S \cdot \Delta V_{out}}$$

08 ASYNCHRONOUS BUCK CONVERTER DESIGN

Parameter	Value
Input Voltage (Vin)	12V
Output Voltage (Vout)	5V
Maximum output current (Iout(max))	1A
Switching Frequency	500kHz
Output Voltage (ΔVout)	50mV
Inductor current Ripple (ΔIL)	30 % Io(max) = 0.3A

09 INITIAL CALCULATIONS

Parameter	Calculations	Value
T	1 / 0.5M	2us
D	5 / 12	0.417
Ton	D * T	0.83us
L	(12 - 0.417 * 5) / (500k * 0.3)	19.44uH
IL(peak)	1 + 0.3 / 2	1.15A
Cout	(0.3) / (8*0.5M*50m)	1.5uF
RL	Vout / Io(max) = 5 / 1	5Ω

10 INDUCTOR SELECTION

Parameter	Criterion	Selected Value
Value	Closest to calculated value	20uH
Peak current	20-30% more than IL(peak): 1.3 * 1.15 = 1.5A	2
Series Resistance	Low as possible to reduce conduction loss.	0.029
Material / Frequency	High-frequency power inductor is essential to minimize core loss.	N.A in LTSPICE

11

CAPACITOR SELECTION

Parameter	Criterion	Selected Value
Value	Closes to calculate value.	1.5uF
Equivalent Resistance	$R_{ser} < \Delta V_{out} / \Delta I_L = 50 / 0.3 = 167m\Omega$	0.0063Ω
Temperature / Voltage Stability	**X7R** is the standard recommendation for decoupling and filtering in power supplies	X7R
Voltage rating	$2 * V_{out} = 2 * 5 = 10V$	10V
Equivalent series inductance	ESL causes high-frequency ringing and is minimized by using small case sizes (e.g., 0805 or 0603) and good PCB layout	N.A in LTSPICE

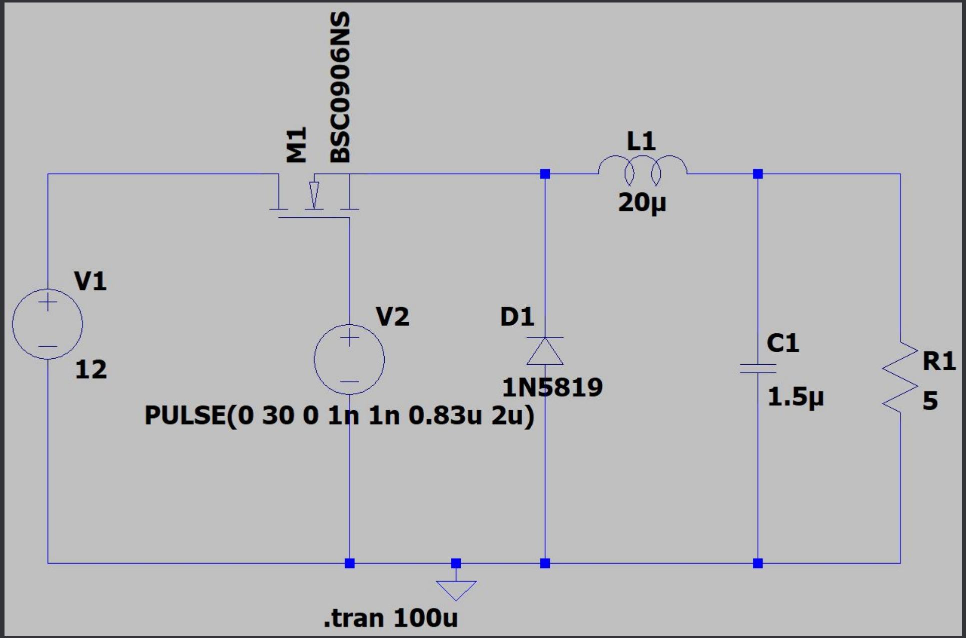
12 DIODE SELECTION

Parameter	Criterion	Selected Value
Type	Schottky Power Diodes are preferred due to low conduction loss and faster switching (preferred 1N58xx series)	1N5819
Breakdown Voltage (Vbkdn)	1.2 * Vin(max) = 14.4V (>)	40
Average Current (Iave)	1.2 * (1 - D) * Vout = 0.7A (>)	1
Saturation current (Is)	10^-9 to 10^-6 A (preferred high)	31.7uA
Emission Coefficient (N)	1.0 to 1.7 (preferred low)	1.373
Series Resistance (Rs)	10 mΩ to 100 mΩ (preferred low)	51mΩ

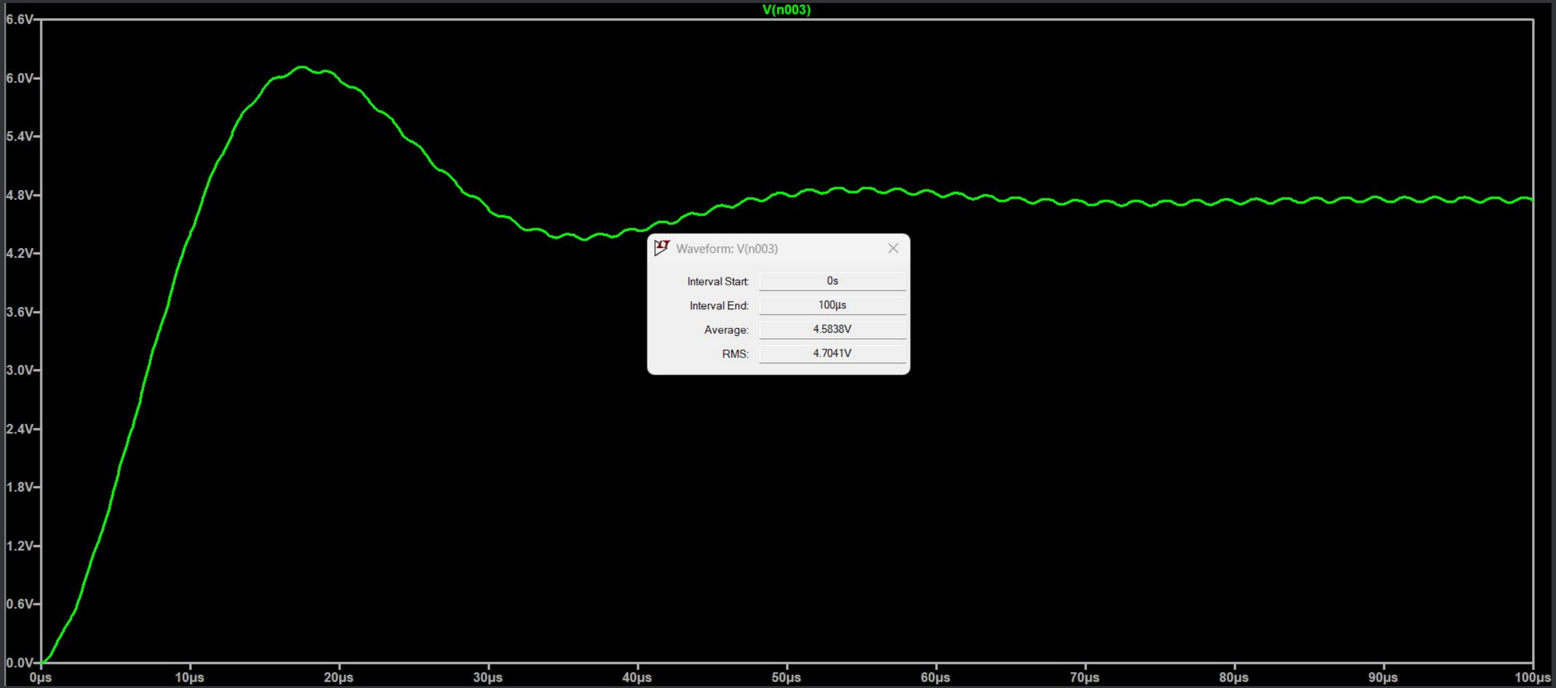
12 MOSFET SELECTION

Parameter	Criterion	Selected Value
Type	N-channel FETs have lower resistance and are standard for the low-side switch (BSC, Si series)	N - channel
Drain source voltage (Vds)	The MOSFET must block the full input voltage: Vds > 1.2 * Vin(max) = 14.4V	30V
Max Current (Id)	The MOSFET handles the full inductor current: > 1.5*IL(peak) = 1.7A	-
Gate-Source Voltage (Vgs)	Vgs (<2V), Must be a Logic-Level FET if driven by a standard 5V or 3.3V PWM signal.	-
On resistance Rds(on)	As low as possible (< 50 mΩ), (Dominant factor for efficiency.)	-
Gate source capacitance (Cgs) & Gate drain miller capacitance (Cgd)	As low as possible	0.82nF & 0.38nF

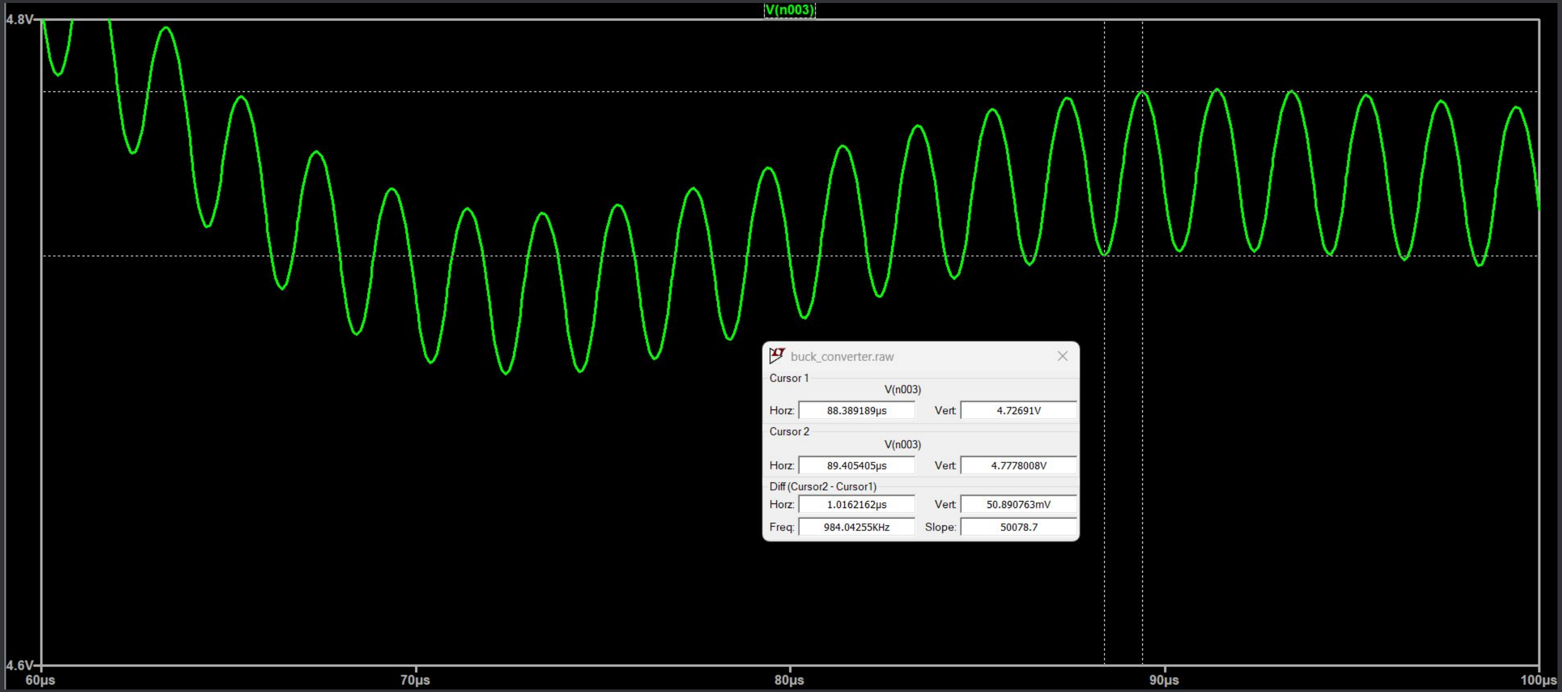
13 SIMULATION-CIRCUIT



13 SIMULATION-PLOT (STEADY STATE)



13 SIMULATION-PLOT (RIPPLE)



13 AVERAGE POWER SPICE DIRECTIVES

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* Transient Simulation setup (Example: 50uS startup, 100uS total time)
.tran 0 100u 50u 0

* Power Measurements (Pin and Pout use the AVG function over the simulation period 50u to 100u)
.meas tran Pin avg -V(In)*I(V1)
.meas tran Pout avg V(Out)*I(R1)

* Component Loss Measurements
.meas tran PM1 avg V(In, n001)*Id(M1)
.meas tran PD1 avg -V(n001)*I(D1)
.meas tran PL1 avg V(n001, out)*I(L1)
.meas tran PC1 avg V(out)*I(C1)
.meas tran Pdriver avg -V(G)*I(V2)

* Efficiency
.meas tran Eff param Pout/Pin*100

*Power Balance verifictation
.meas tran diff param Pin-Pout-PM1-PD1-PL1-PC1-Pdriver
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13 AVERAGE POWER OBSERVATION

Power Component	Formula	Value
P(in)	V(in) * I(in)	4.7946W
P(out)	V(out) * I(out)	4.5391W
P(mosfet)	[Vd - Vs] * Id + [Vg - Vs] * Ig	0.3246W
P(diode)	Vd*Id	0.2290W
P(inductor)	V(L) * I(L)	0.0121W
P(capacitor)	V(out)* I(C)	0.0085W
Efficiency	P(out) / P(in) * 100	94.67%
Power balance	Pin-Pout-PM1-PD1-PL1-PC1-Pdriver ~ 0	-0.0037

14 MODIFYING DUTY CYCLE

$$D_{new} = D_{old} \times \frac{V_{out,expected}}{V_{out,simulated}}$$

Component	New	Old	Change
D	0.46	0.417	10.71%
Ton	0.92u	0.83u	10.84%
Efficiency	95.43	94.67	0.80%