Power efficiency of the LLC

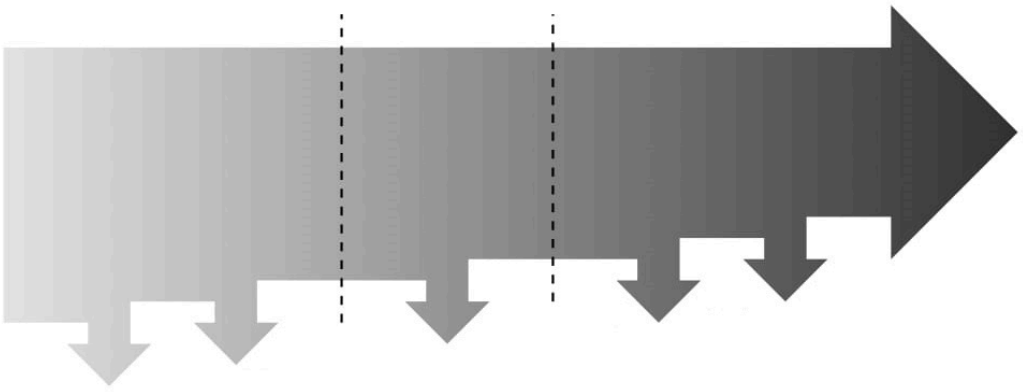


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Introdution

Measuring the efficiency of a power electronic converter is challenging due to the sensitivity to measurement accuracy. For instance, a 1% overestimation on the primary-side measurement combined with a 1% underestimation on the secondary side results in a 2% reduction in calculated efficiency, decreasing it from 96% to 94%.
The opposite is also true:minor measurement errors can similarly lead to an overestimation of efficiency.

For this test, shunt resistors will be employed to measure current using a millivoltmeter, while a voltmeter is used to measure voltage.

To minimize measurement errors, the same instruments are used for both primary and secondary voltage measurements (and similarly for current). This methodology requires waiting for the power transfer to stabilize before taking readings.

Test setup

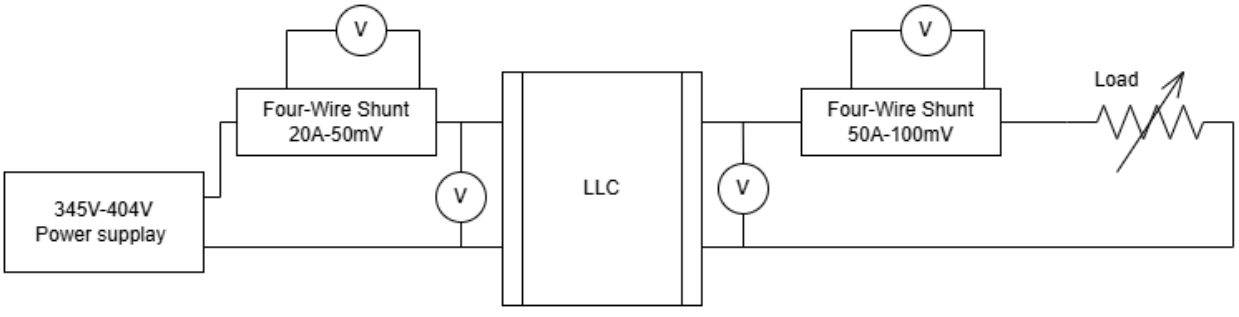


Figure 1: Setup schematic



Figure 2: Shunt 50A 100mV

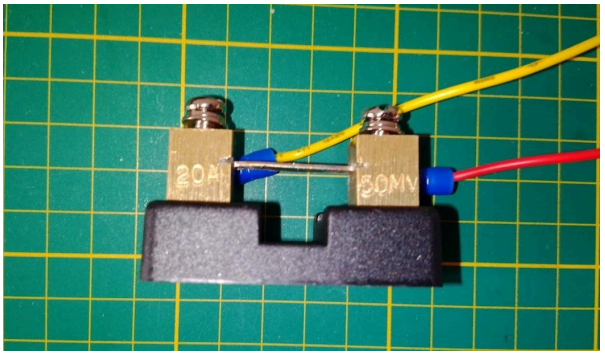


Figure 3: Shunt 20A 50mV

The detailed measurement methodology is provided in the introduction section.

Efficiency

Measurements

```
# Pv_w=  40.647 w
```

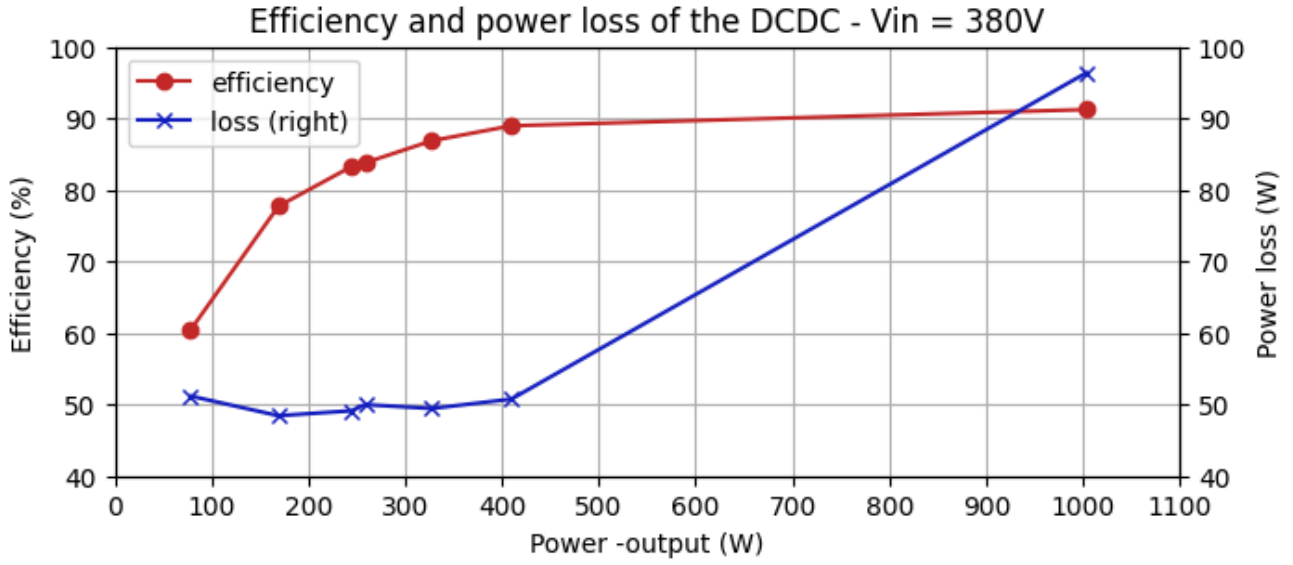
	Vin_v	V_shunt_inp_mV	Vout_v	V_shunt_out_mV
0	380.2	0.85	45.53	3.43
1	380.2	1.43	44.66	7.57
2	380.1	1.93	44.34	11.02
3	380.1	2.03	44.29	11.68
4	380.0	2.48	44.11	14.85
5	379.9	3.03	43.91	18.66
6	379.4	7.25	42.25	47.52

Efficiency calculations

```
(0.002, 0.0025)
```

	Vin_v	V_shunt_inp_mV	Vout_v	V_shunt_out_mV	I_inp	I_out	Pin	Pout	eff	loss	R_
0	380.2	0.85	45.53	3.43	0.34	1.72	129.27	78.08	60.40	51.18	
1	380.2	1.43	44.66	7.57	0.57	3.78	217.47	169.04	77.73	48.44	
2	380.1	1.93	44.34	11.02	0.77	5.51	293.44	244.31	83.26	49.12	
3	380.1	2.03	44.29	11.68	0.81	5.84	308.64	258.65	83.80	49.99	
4	380.0	2.48	44.11	14.85	0.99	7.42	376.96	327.52	86.88	49.44	
5	379.9	3.03	43.91	18.66	1.21	9.33	460.44	409.68	88.98	50.76	
6	379.4	7.25	42.25	47.52	2.90	23.76	1100.26	1003.86	91.24	96.40	

```
Text(0.5, 1.0, 'Efficiency and power loss of the DCDC - Vin = 380V')
```



Areas for Improvement

Transformer loss

Transformer losses represent a major contributor to the reduction of the overall power-transfer efficiency of the DC-DC converter.

Below, a simplified estimation of the peak magnetic flux density in the transformer core is presented:

The magnetic core characteristics are specified in the ELP core datasheet [2].

$$\mathrm{Vin} = 380 \ \ (\mathrm{V})$$

$$\mathrm{Freq} = 100 \ \ (\mathrm{kHz})$$

$$N = 4 \ \ (\mathrm{turns})$$

$$A_{mm2} = 534.200 \ \ (\mathrm{mm2 \text{ - see datasheet}})$$

$$A = A_{mm2} \cdot 1 \times 10^{-6} = 534.200 \cdot 1 \times 10^{-6} = 0.001 \ \ (\mathrm{m2})$$

$$T = \frac{1}{\mathrm{Freq} \cdot 1 \times 10^{3}} = \frac{1}{100 \cdot 1 \times 10^{3}} = 0.000$$

$$\mathrm{Li} = \left(\frac{\mathrm{Vin}}{2}\right) \cdot \frac{T}{2} = \left(\frac{380}{2}\right) \cdot \frac{0.000}{2} = 0.001 \ \ (\mathrm{v{=}L.di/dt})$$

$$\mathrm{Flux} = \frac{\mathrm{Li}}{N} = \frac{0.001}{4} = 0.000$$

$$\mathrm{deltaB} = \frac{\mathrm{Flux}}{A} = \frac{0.000}{0.001} = 0.445$$

$$\mathrm{Bpeak} = \frac{\mathrm{deltaB}}{2} = \frac{0.445}{2} = 0.222 \ \ (\mathrm{T})$$

$$\mathrm{Bpeak}_{mT} = \mathrm{Bpeak} \cdot 1 \times 10^{3} = 0.222 \cdot 1 \times 10^{3} = 222.295 \ \ (\mathrm{mT})$$

The TDK documentation [1] provides data on the relative core losses associated with the N97 magnetic material.

For a peak flux density of B_peak = 220 mT, the average volumetric core loss density (Pv), estimated between the 20°C and 100°C characteristic curves, is approximately 700 kW/m³.

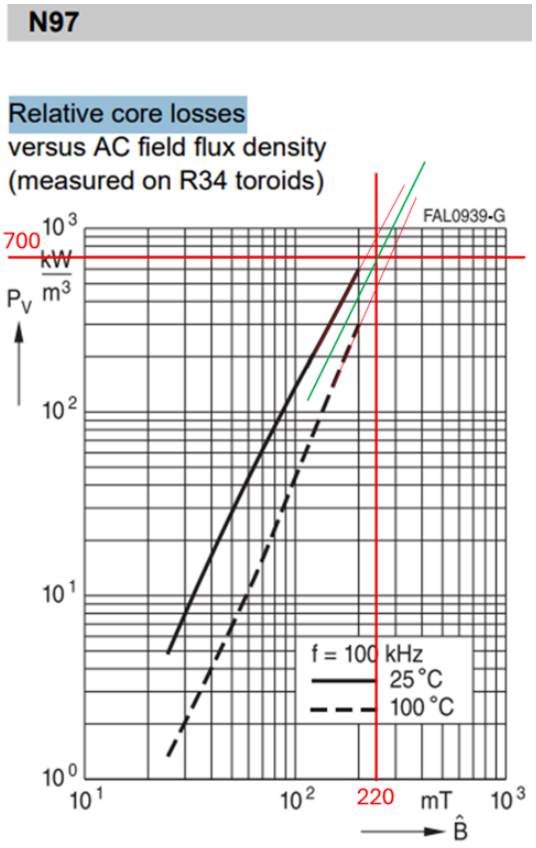


Figure 4: Core loss of the transformer

Based on the ELP core datasheet [2]. the core loss can be estimated as follows.

$$\begin{aligned}
\mathrm{Pv}_{kW} &= 700 \ \ (\mathrm{kW/m3}) \\
P_{nominal} &= 1200 \ \ (\mathrm{w}) \\
\mathrm{Pv} = \mathrm{Pv}_{kW} \cdot 1000 = 700 \cdot 1000 &= 700000 \ \ (\mathrm{W/m3}) \\
\mathrm{Ve}_{mm3} &= 67745 \ \ (\mathrm{mm3 \text{ - see datasheet}}) \\
\mathrm{Ve} = \mathrm{Ve}_{mm3} \cdot 1 \times 10^{-9} = 67745 \cdot 1 \times 10^{-9} &= 0.000 \\
P_{loss} = \mathrm{Pv} \cdot \mathrm{Ve} = 700000 \cdot 0.000 &= 47.422 \ \ (\mathrm{W}) \\
P_{lossRelative} = 100 \cdot \frac{P_{loss}}{P_{nominal}} = 100 \cdot \frac{47.422}{1200} &= 3.952 \ \ (\%)
\end{aligned}$$

The estimated core loss is approximately 47.5 W. This value is reasonably accurate, as a consistent power loss of around 50 W is observed between 0 and 400 W, largely independent of the transmitted power(see the efficiency loss curve above).

This core loss is relatively significant for a 1200 W DC-DC converter. Considering this loss alone, the corresponding efficiency reduction is already around **4%**.

Magnetizing Current

Due to the relatively low magnetizing inductance (83 µH), a significant peak current flows even under zero power transfer conditions. This results in increased Joule losses in both the copper and the primary-side MOSFETs.

Below a quick estimation of the peak magnetizing current:

$$\begin{aligned}
\mathrm{Li} &= 0.001 \ \ (\text{see formulas above}) \\
\mathrm{Lm}_{uH} &= 83 \ \ (\mu\mathrm{H}) \\
\mathrm{Lm} &= 1 \times 10^{-6} \cdot \mathrm{Lm}_{uH} = 1 \times 10^{-6} \cdot 83 && = 0.000 \\
I_{peak} &= \frac{\mathrm{Li}}{\mathrm{Lm}} = \frac{0.001}{0.000} && = 11.446 \ \ (\mathrm{A})
\end{aligned}$$

Assuming a total series resistance of approximately 100 mΩ for the PCB traces (primary side), MOSFETs, ..., and considering the primary current as a pure sinusoidal waveform, the estimated copper loss in the primary side is:

$$\begin{aligned}
I_{rms} &= \frac{I_{peak}}{\sqrt{2}} = \frac{11.446}{\sqrt{2}} && = 8.093 \\
R_{primaryLoop} &= 0.100 \ \ (\Omega) \\
P_{CopperPrimary} &= R_{primaryLoop} \cdot (I_{rms})^2 = 0.100 \cdot (8.093)^2 && = 6.550 \ \ (\mathrm{W}) \\
P_{CopperPrimaryRelative} &= 100 \cdot \frac{P_{CopperPrimary}}{P_{nominal}} = 100 \cdot \frac{6.550}{1200} && = 0.546 \ \ (\backslash\%)
\end{aligned}$$

An additional 0.6% efficiency loss occurs.

Output synchronous rectifier (SR)

As shown below, the turn-on time of the secondary MOSFET is dependent on the output current. Even at 250 W, the turn-on interval remains short, leading to extended conduction through the intrinsic body diode. This increased diode conduction significantly degrades the overall conversion efficiency.

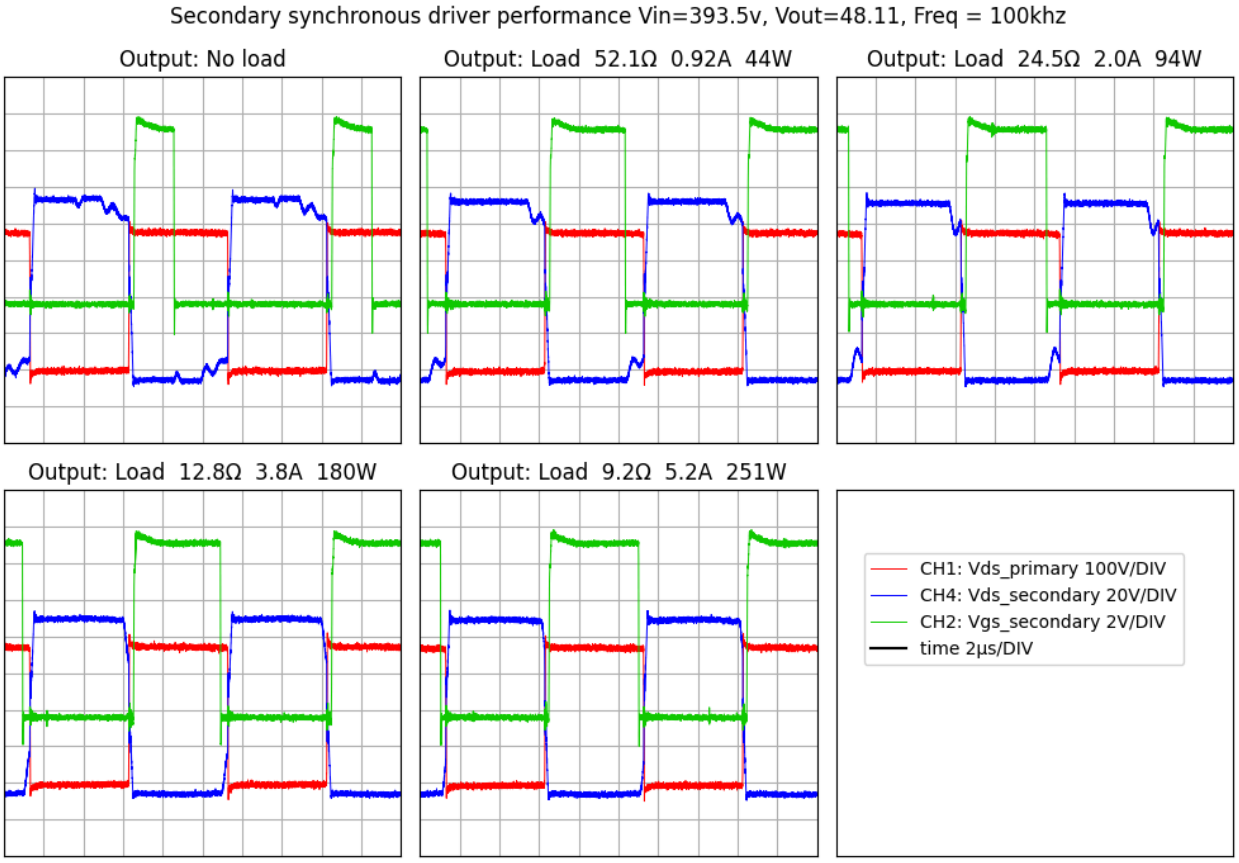


Figure 5: Secondary synchronous driver waveforms

To understand this problem, I propose the simplified calculation below of the dead-time impact in a MOSFET power module.

$$\begin{aligned}
\text{DeadTime} &= 0.050 \ \ (1 \ \% \text{ of the perdiode}) \\
T_{us} &= 10 \\
T &= 1 \times 10^{-6} \cdot T_{us} = 1 \times 10^{-6} \cdot 10 && = 0.00 \\
\text{Vf} &= 1 \\
\text{Vds}_{on} &= 0.300 \\
I &= 30
\end{aligned}$$

$$\begin{aligned}
E_{conductionDiode} &= 1 \times 10^{6} \cdot 2 \cdot \text{DeadTime} \cdot \text{Vf} \cdot I \cdot T \\
&= 1 \times 10^{6} \cdot 2 \cdot 0.050 \cdot 1 \cdot 30 \cdot 0.000 \\
&= 30.000
\end{aligned}$$

$$\begin{aligned}
E_{conductionMos} &= 1 \times 10^{6} \cdot (1 - 2 \cdot \text{DeadTime}) \cdot \text{Vds}_{on} \cdot I \cdot T \\
&= 1 \times 10^{6} \cdot (1 - 2 \cdot 0.050) \cdot 0.300 \cdot 30 \cdot 0.000 \\
&= 81.000
\end{aligned}$$

$$P_{conductionTotal} = 1 \times 10^{-6} \cdot \frac{E_{conductionDiode} + E_{conductionMos}}{T} = 1 \times 10^{-6} \cdot \frac{30.000 + 81.000}{0.000} \quad = 11.100 \ \ (\text{W}$$

The calculation is repeated below for a range of dead-time values:

	DeadTime %	E_conductionDiode µJ	E_conductionMos µJ	P_conductionTotal W
0	0.00	0.0	90.0	9.0
1	0.01	7.8	88.2	9.6
2	0.02	15.6	86.4	10.2
3	0.05	39.0	81.0	12.0
4	0.10	78.0	72.0	15.0
5	0.20	156.0	54.0	21.0

Under simplified assumptions, it can be observed that a dead time of 2% increases the MOSFET conduction loss by approximately 50%, while a 20% dead time triples the loss.

References

[1] TDK, Ferrites and accessories, SIFERRIT material N97

[2] TDK, ELP 102/20/38 with I 102/7/38 Datasheet