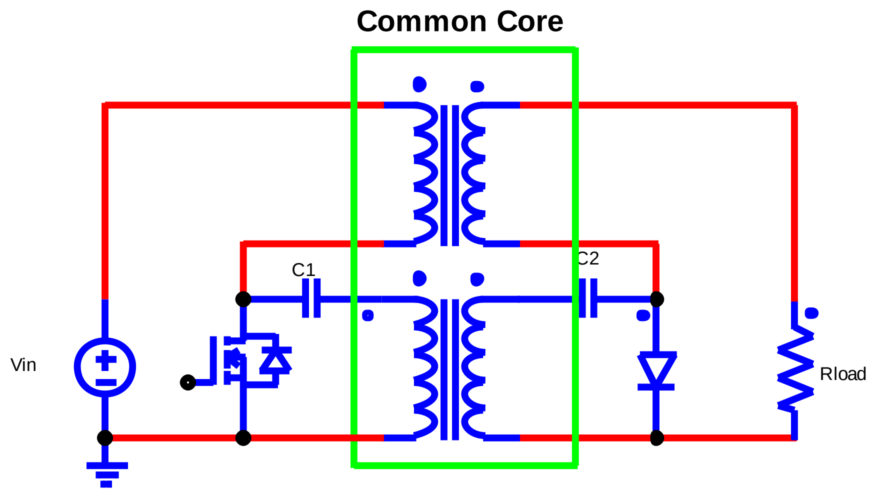
Ćuk Integrated Magnetics Converter With Current Ripple Cancellation: The Optimal Power Conversion Topology?*

by Isaac Cohen, Huntington Station, NY



The integrated magnetics Ćuk topology narrative is been it is superior to other topologies (operating at same frequency) because it has:

- Zero (very low) current ripple at both input and output yielding very low DM EMI and low output voltage ripple.
- Capacitive energy storage in place of inductive energy storage providing lower cost and smaller volume.
- Dc current in the inductor, which eliminates ac copper loss.
- Higher efficiency.

Some publications supporting the narrative include:

- "A New Optimum Topology Switching Dc-to-Dc Converter“ by Slobodan Ćuk and R. D. Middlebrook, IEEE Power Electronics Specialists Conference, 1977 Record, pp. 160-179 (IEEE Publication 77CH 1213-8 AES)

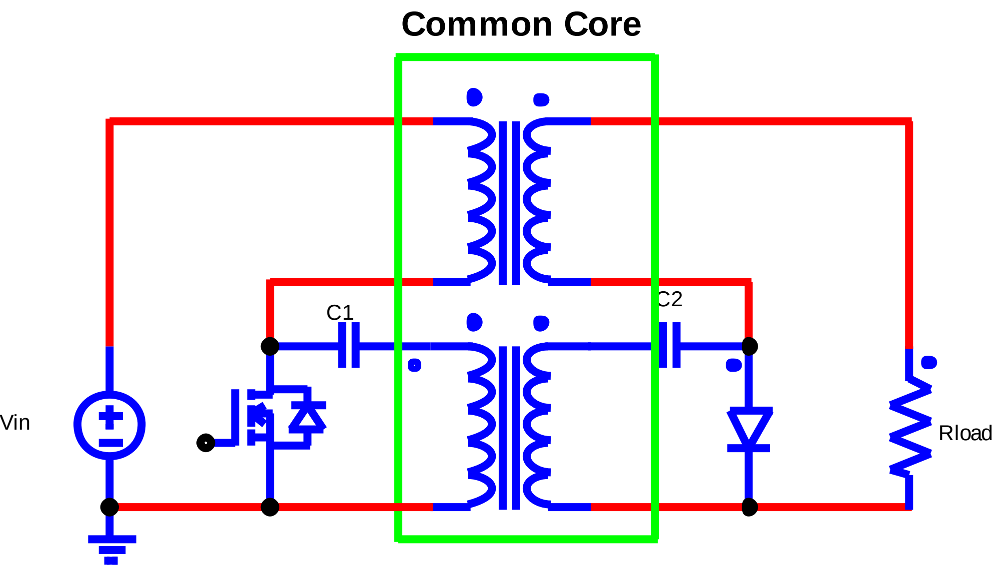
- US Patents 4,274,133 and 4,184,197.

- “Isolation And Multiple Output Extensions Of A New Optimum Topology Switching DC-To-DC Converter” by R. D. Middlebrook and Slobodan Ćuk.

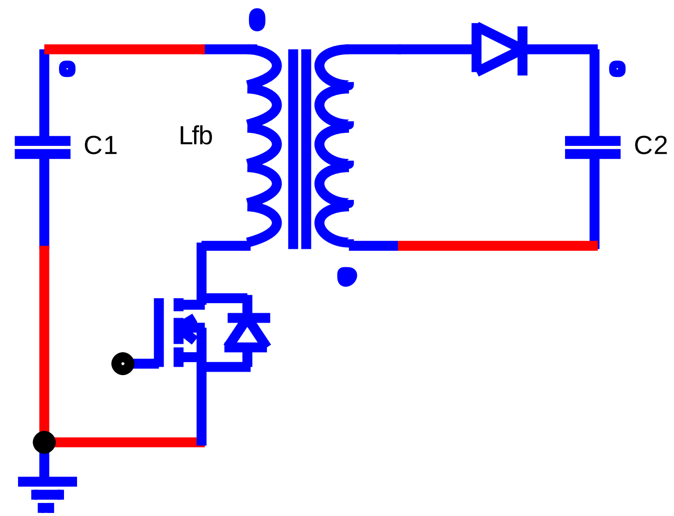
- “Rediscovering The Integrated-Magnetics Isolated Ćuk Topology” by Dennis Feucht, How2Power Today, July 2010.

However, no rigorous quantitative comparison was ever done (at least that I am aware of) to validate the narrative and quantify the advantage in power density and efficiency.

The purpose of this presentation is to test the veracity of the Ćuk narrative by comparing the performance of the Ćuk converter to that of an equivalent flyback converter (both are buck-boost).



Isolated Ćuk converter topology with integrated inductors and transformer



Isolated flyback

Isaac Cohen, The Ćuk Integrated Magnetics Converter

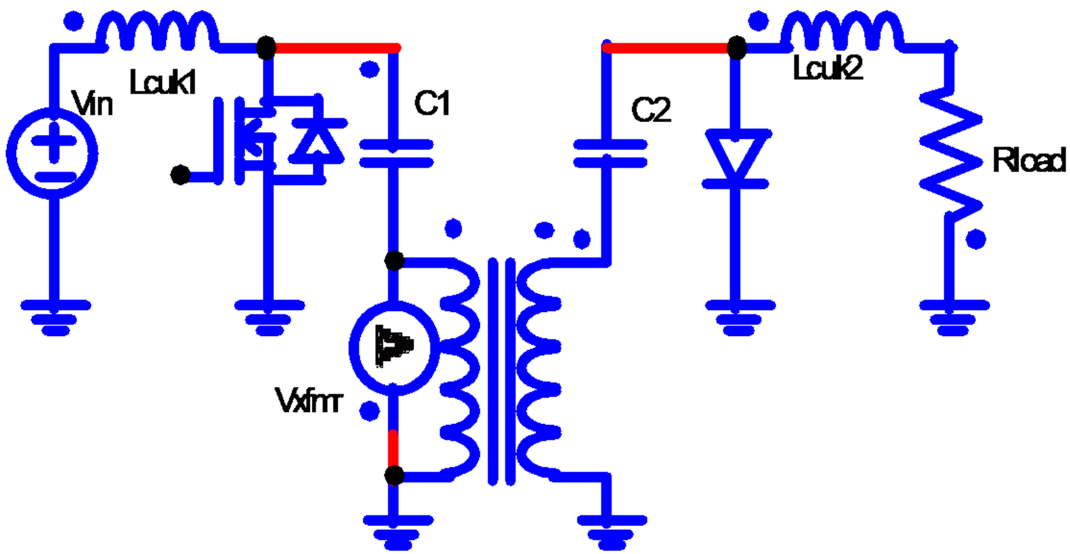
This analysis consists of the following steps:

- Create a model of the ideal Ćuk converter with integrated magnetics; explain operation and demonstrate model validity.
- Create a model of an equivalent ideal flyback (FB) converter.
- Simulate both models under identical operating conditions and compare performance.

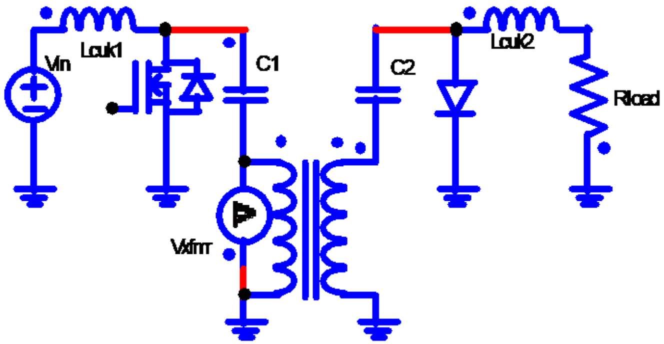
To simplify the analysis, we'll make the following assumptions:

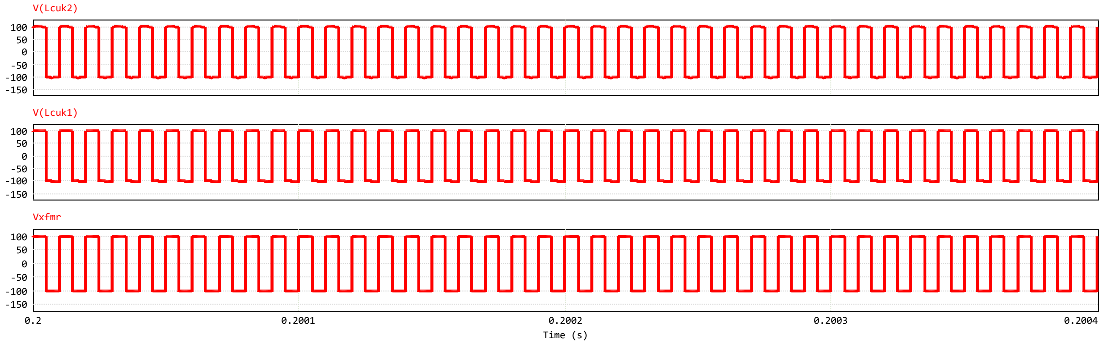
- Circuits have ideal switches.
- All windings have an equal number of turns (all turns ratios equal unity).
- Coupling capacitors have **infinite capacitance**, and zero ESR and ESL.
- All coupled windings have perfect coupling (K = 1), unless deliberately modified.
- Cores have infinite permeability; magnetizing inductances set by gapping.

Consider the ideal isolated Ćuk converter with discrete inductors and transformer.



Ideal isolated Ćuk converter with discrete inductors and isolation transformer.



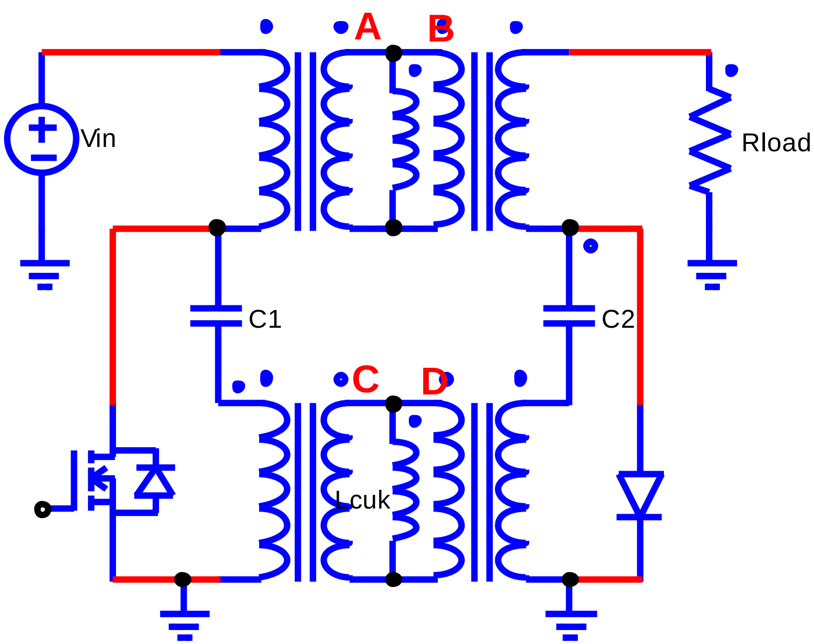


V(C1)=Vin and V(C2)=Vout

Therefore the AC voltages applied to the Ćuk inductors and the isolation transformer windings are equal.

Consquently, all the windings can be wound on a common core.

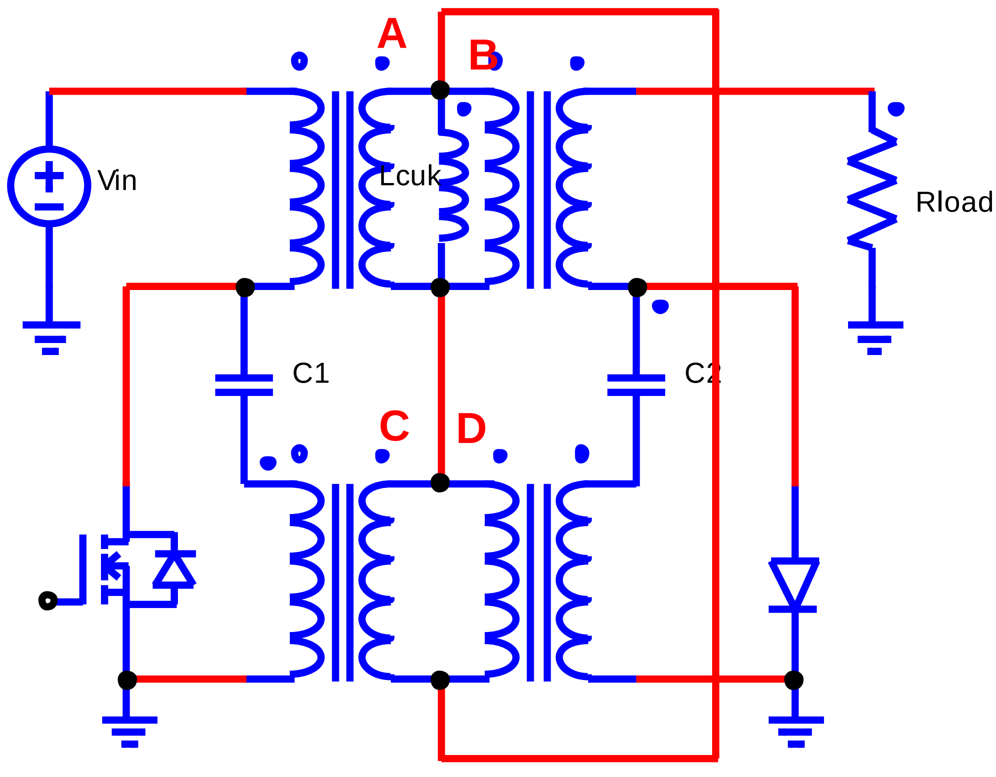
Ćuk converter with integrated inductors and transformer model.



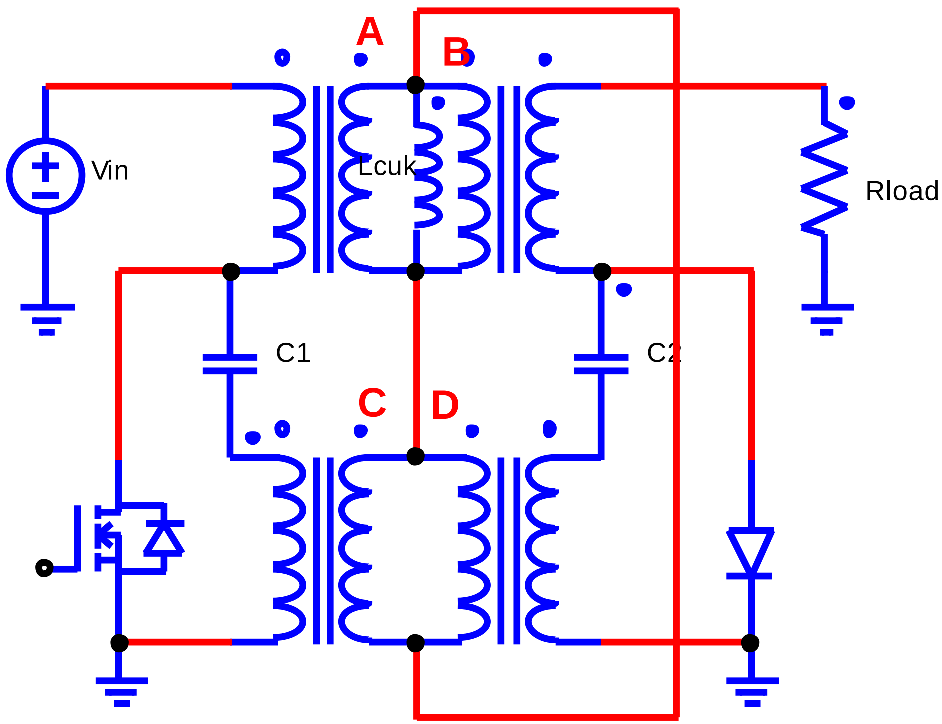
The coupled Ćuk inductor is modelled as two unity turns ratio transformers with a common magnetizing inductance equal to the Ćuk inductance connected to the paralleled A, B primaries.

The transformer is modelled as two unity turns ratio transformers with infinite magnetizing inductances and paralleled C,D primaries.

We can now place all the magnetics windings of the isolated Ćuk converter on a common core by connecting all the primaries in parallel:



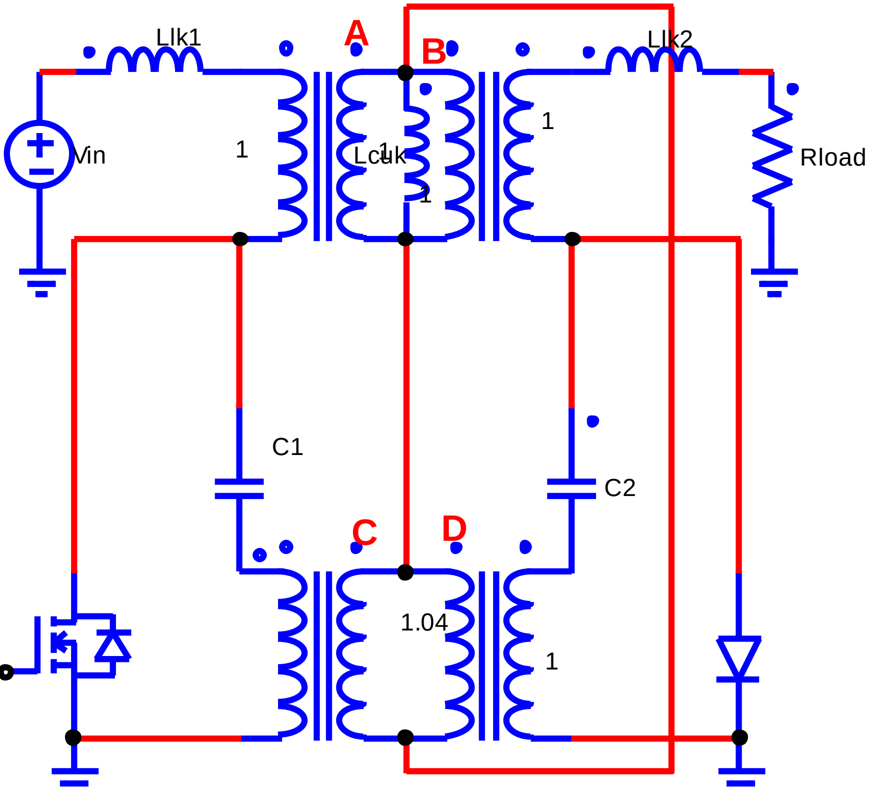
Where is the ripple with ideal windings and all K‘s=1?

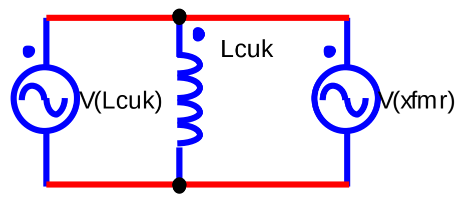


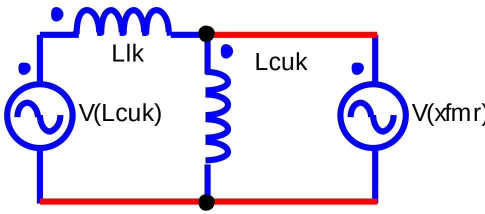
Both the transformer and the inductor share the core and are connected to equal ac voltage sources.

- **The magnetizing current (= ripple) may flow in the transformer or the Ćuk inductor primaries or both.**

How the current ripple at ports is “cancelled”:



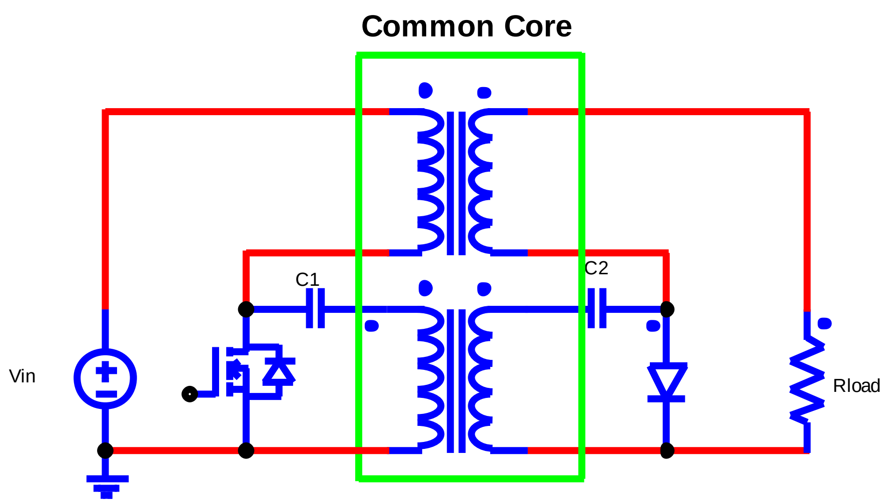


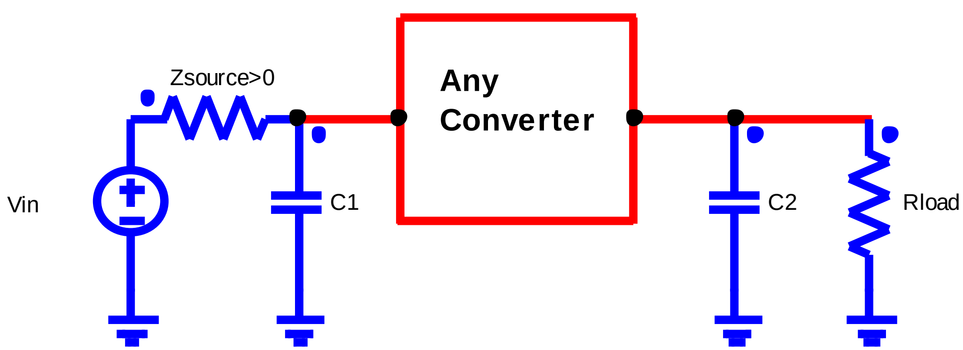


If leakage inductances (any value > 0) is added to the Ćuk inductor windings all the magnetizing current is forced to the transformer windings.

No AC current present at either IN or OUT: RIPPLE is CANCELLED!

The Ćuk capacitive hocus pocus



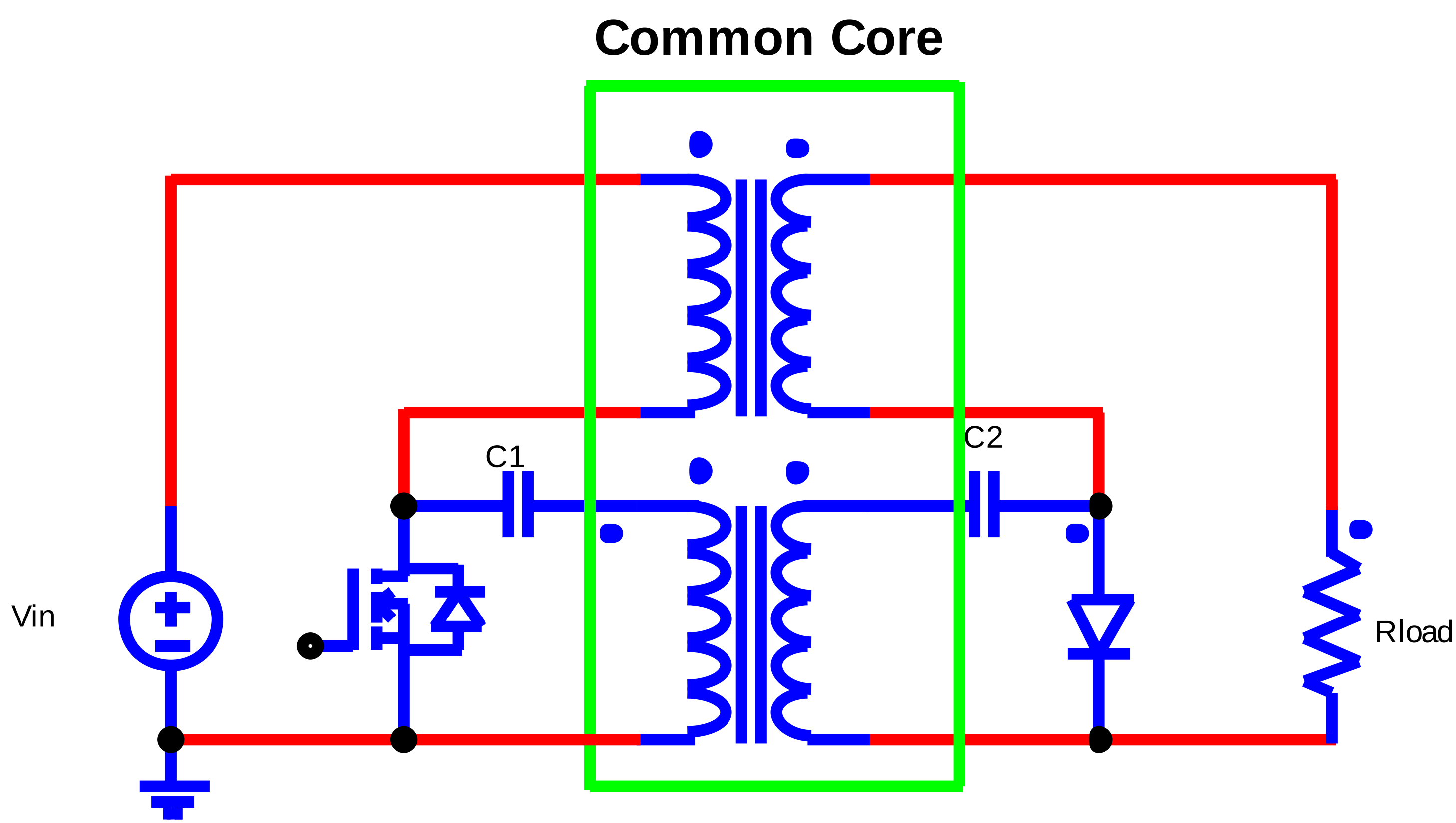


- **The Ćuk topology needs 2 infinite capacitors** to nullify the ripples.
- **If two infinite capacitors are available, connecting one across the input and the other across the output of any converter will nullify the ripples at both ports.**
- **The Ćuk topology is no different from any other topology!**

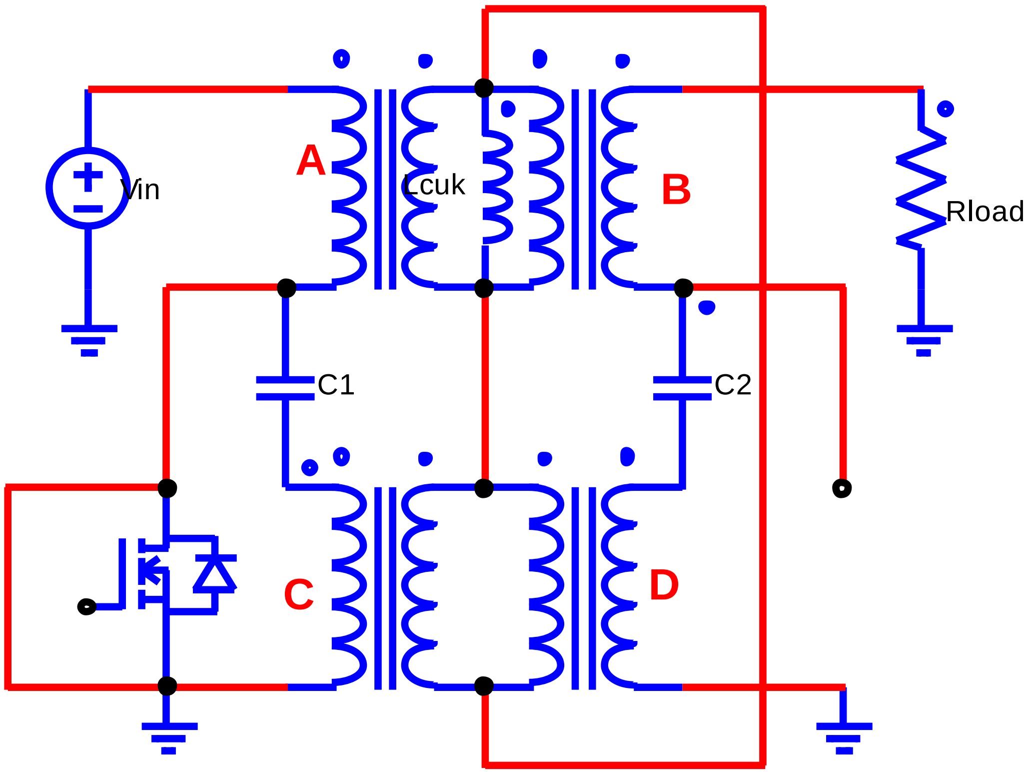
Comments on the proposed model of the ideal integrated Ćuk converter.

- The proposed model is simple and useful for the topology analysis and simulation, but has no physical embodiment.
- Ripple cancelling magnetic structures for practical use are proposed in the literature.
    - Complicated, and as we will see, generally irrelevant.

To understand ripple cancellation using the ideal model, let’s start with a qualitative explanation.

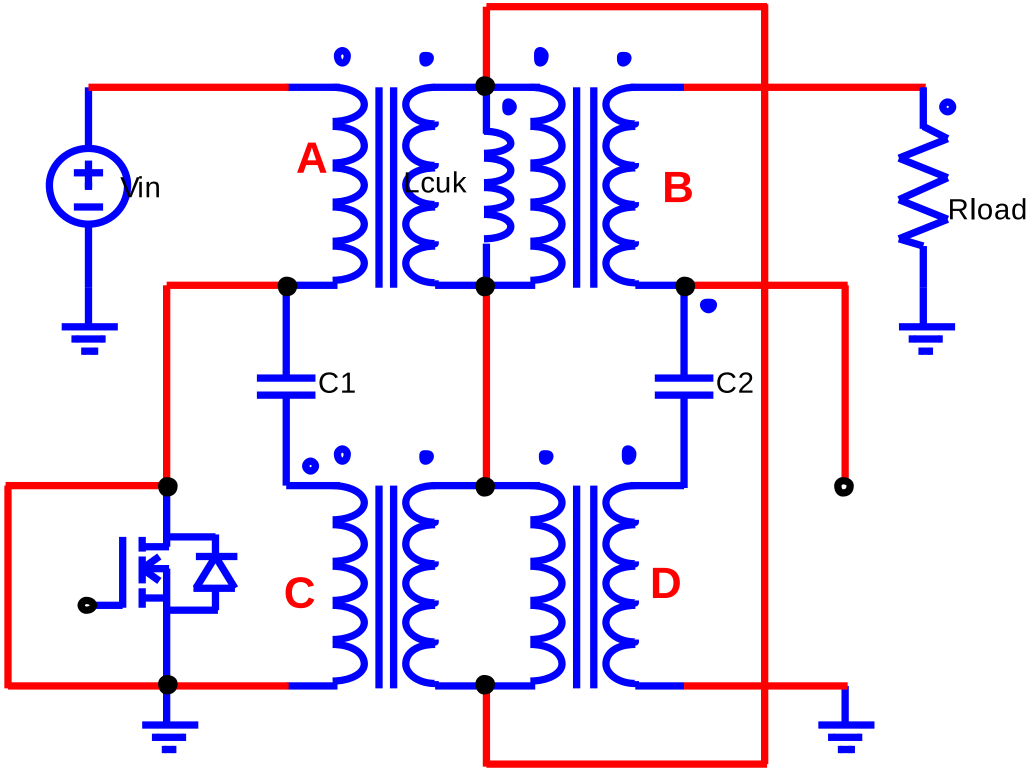


The no-ripples qualitative explanation with CCM and switch on:



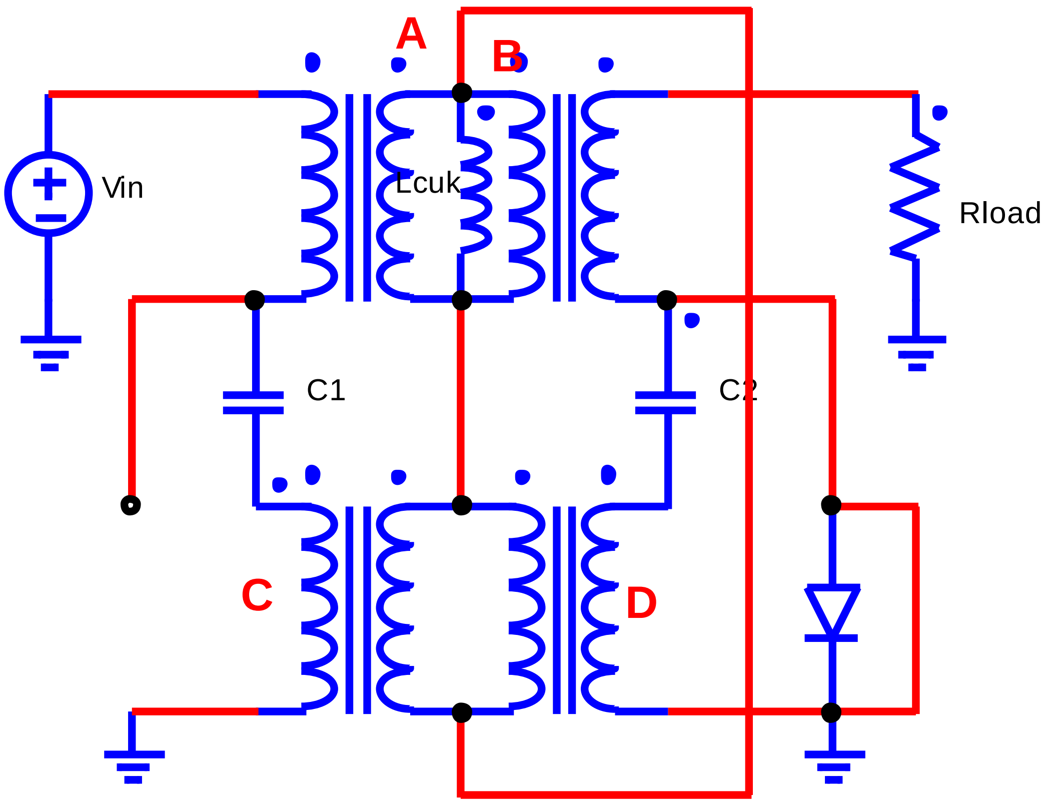
Vin is applied across winding C and propagates to all other windings; the voltages on the inductor and transformer windings A&C and B&D cancel so cap C1 is connected across the input and cap C2 across the output.

The no-ripples qualitative explanation with CCM and switch on:



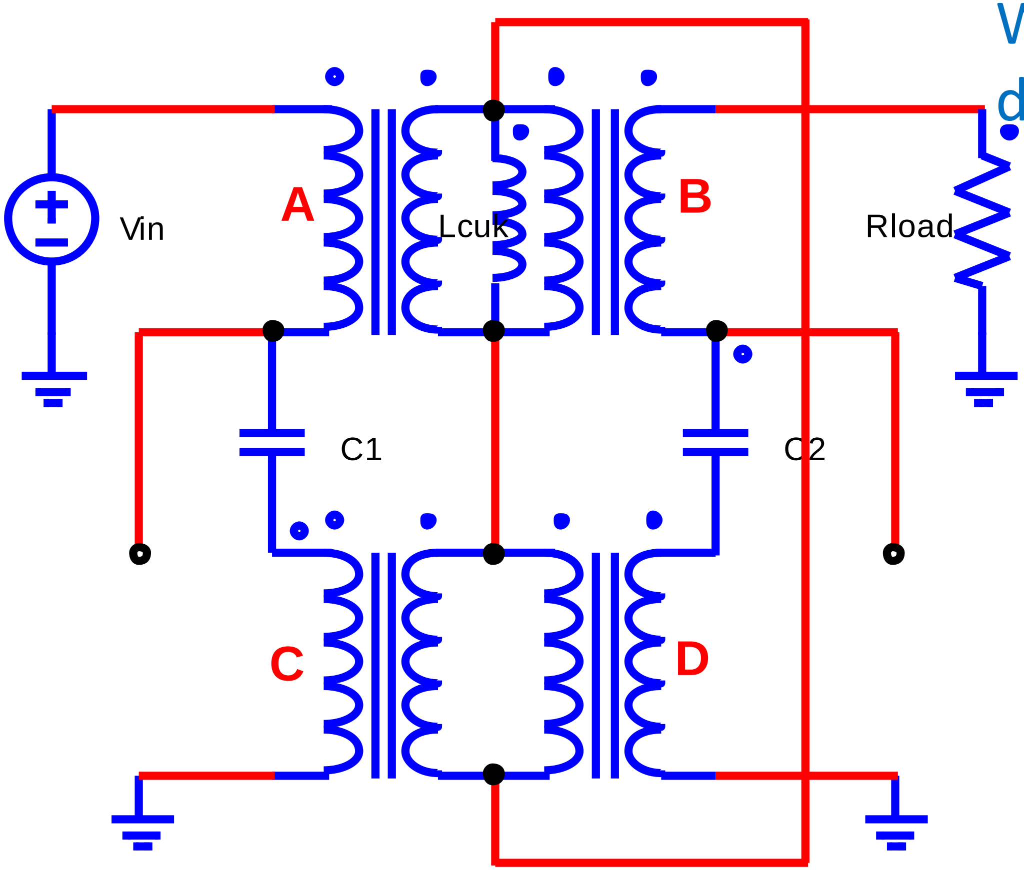
C1 and C2 are effectively the input and output caps of the converter – their voltages are constant dc, so no ripple (voltage or current!) is present at either port.

The no-ripples qualitative explanation with CCM and diode on:



Cap C2 (charged to Vout) is applied across winding D and the Vout voltage propagates to all other windings, voltages on the inductor and transformer windings A&C and B&D cancel, so again V(C1) appears across the input V(C2) appears across the output.
Thus, no ripples are present at either port.

The no-ripples qualitative explanation with DCM and both switch and diode off:



With both the switch and the diode off:

- Output: The voltage on all windings is zero , so V(C2) appears at the output and V(C1) at the input
- Again, no voltage/current ripple at either port!

What about quantitative analysis comparison?

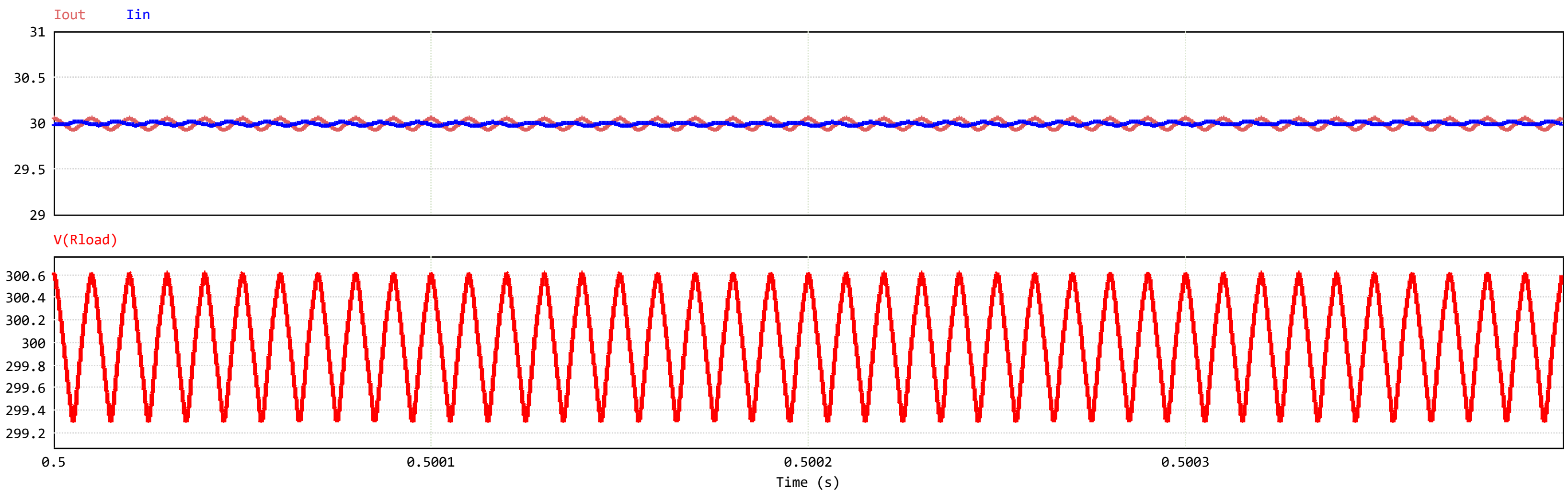
- The above explanations are qualitative and provide insight into the physics of the converter.
- Validation of the model and quantification of the converter variables by symbolic solution of the circuit equations will make for an impressive and authoritative presentation, but the process is very tedious and unnecessary for practical purposes.
- Instead, we will just simulate the model with some arbitrary parameters.
  - No infinite component values allowed!

Is simulation a valid substitute for symbolic solution of the circuit equations?

- The simulator generates the correct circuits equations and solutions.
- The simulated circuits are linear, so the results for an arbitrary set of circuit parameters scale to any other set.

Simulation results are valid as general proof!

Ideal integrated Ćuk converter. Duty cycle D = 0.5 and operating mode = CCM.

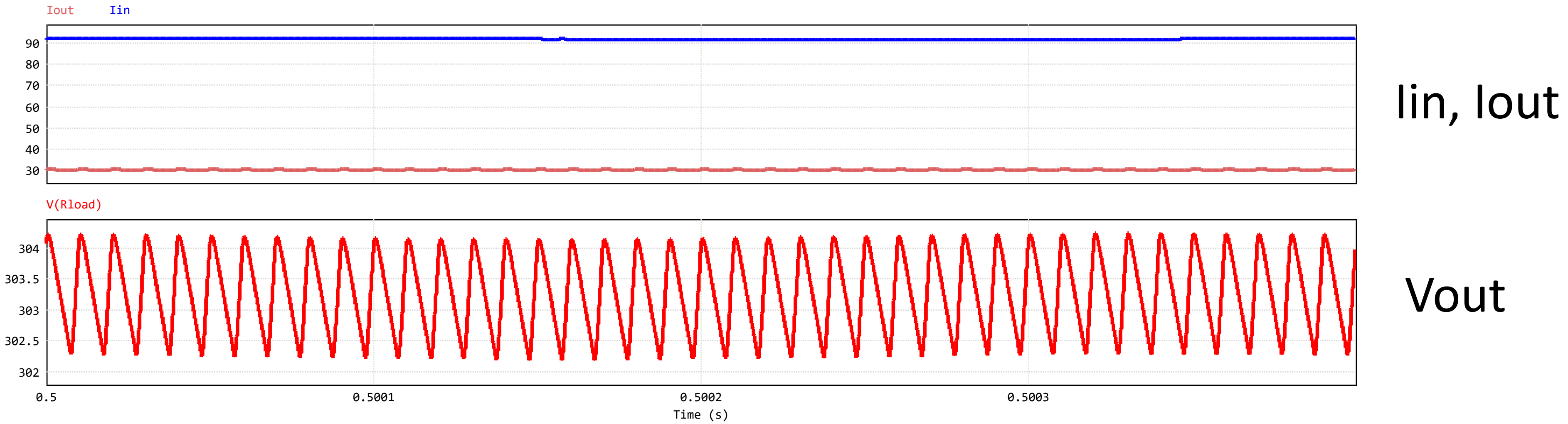


Iin, Iout

Vout

As the coupling caps C1 and C2 have large but finite values, small residual current ripples are still present at the ports.

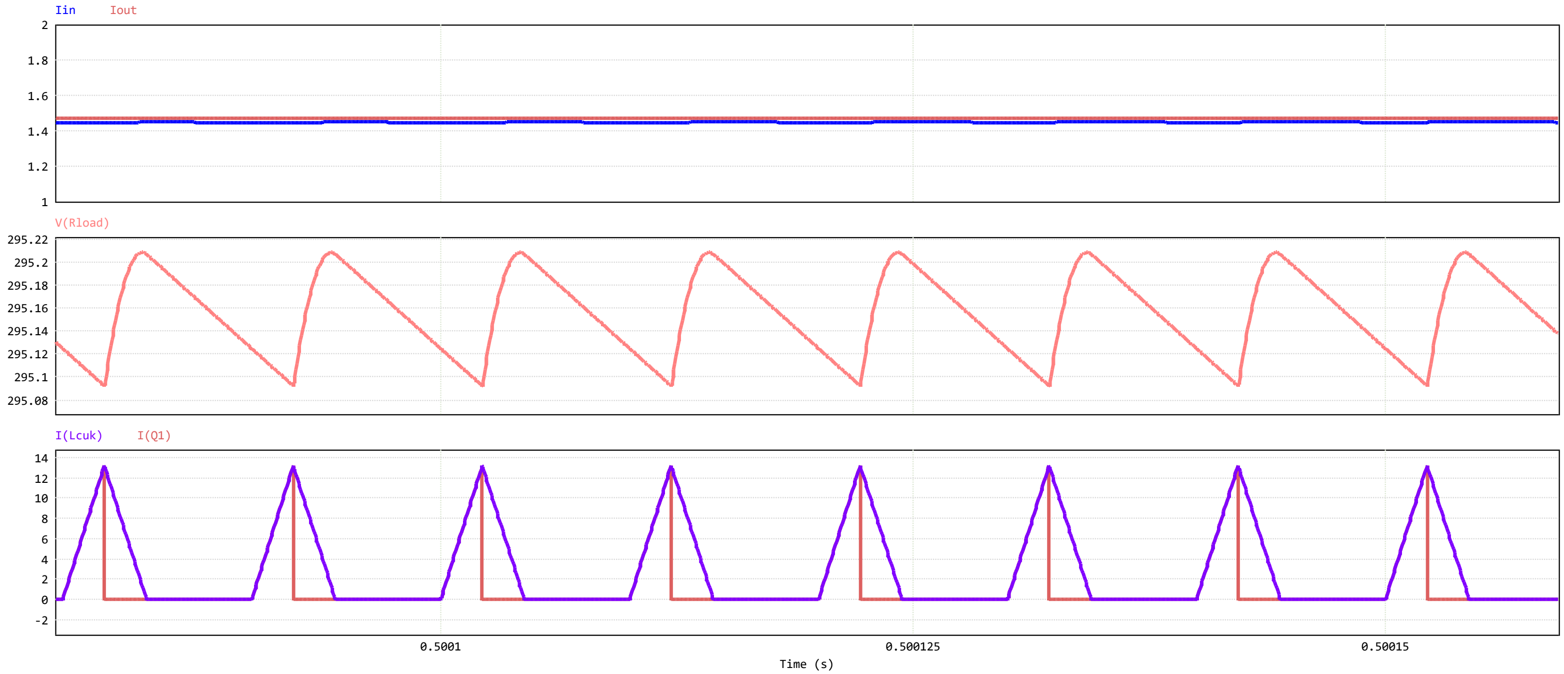
Ideal integrated Ćuk converter - duty cycle changed to D = 0.752 (still in CCM):



Cancellation still effective!

Ideal integrated Ćuk converter: Duty cycle is changed to D = 0.22 and operating mode = DCM:

:



Iin, Iout

Vout

I(Q), I(LĆuk)

Cancellation is still effective!

What are our conclusions so far about the ideal integrated Ćuk converter model?

- The proposed model is more transparent (physics of the circuit easier to understand) and easier to analyze than the models found in the literature.
- The model is based on ideal transformers and very easy to simulate.
- It has been shown (and confirmed by simulation) the model exhibits ripple cancellation as expected.

What else can we say about the ideal integrated Ćuk's model ripple cancellation?

- The cancellation is maintained in DCM and at any duty cycle.
- The clamp capacitors C1 and C2 are effectively the input and respectively the output caps of the Ćuk converter.
  - Consequently, ripple voltages generated by the ac currents flowing in the clamping caps appear as voltage ripple at output port and DM EMI at the input port.
- *The capacitors are connected to the ports via windings of the magnetics.*
  - The (unavoidable in real life) winding resistances add to the caps' ESR, which will increase the Ćuk output ripple and DM EMI.

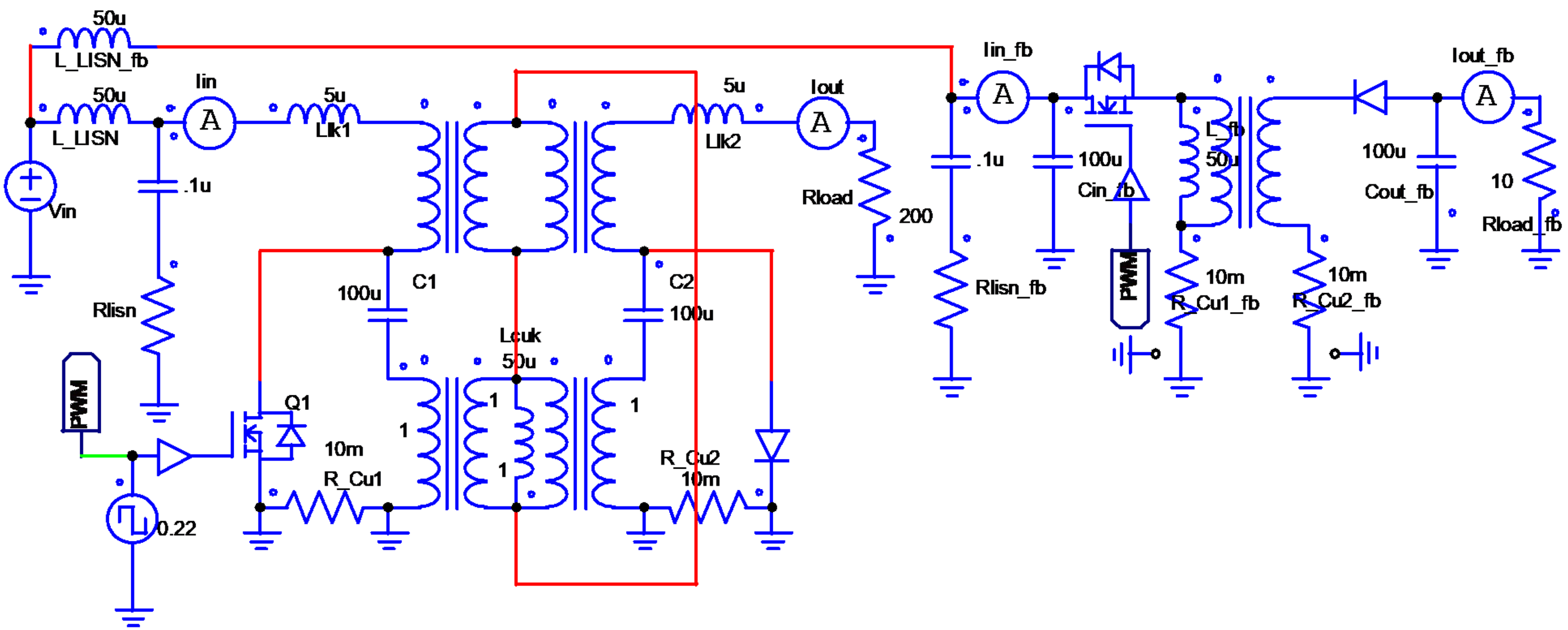
Now let's compare the ideal integrated Ćuk to an equivalent flyback using the following steps:

- Create an ideal flyback model **using the Ćuk components**.
  - Eliminate the leakages added for ripple steering.
  - Form the FB transformer by connecting the Cuk inductor and transformer windings in parallel (current in the FB windings are equal to the sum of the currents in Ćuk inductors and transformer windings).
    - In practice, the two-winding FB cost will be lower than the four-winding Ćuk.
  - Use the coupling caps C1 and C2 as the input and respectively the output caps of the flyback (see appendix).
  - Same switches are used – the voltage and current stresses are identical.

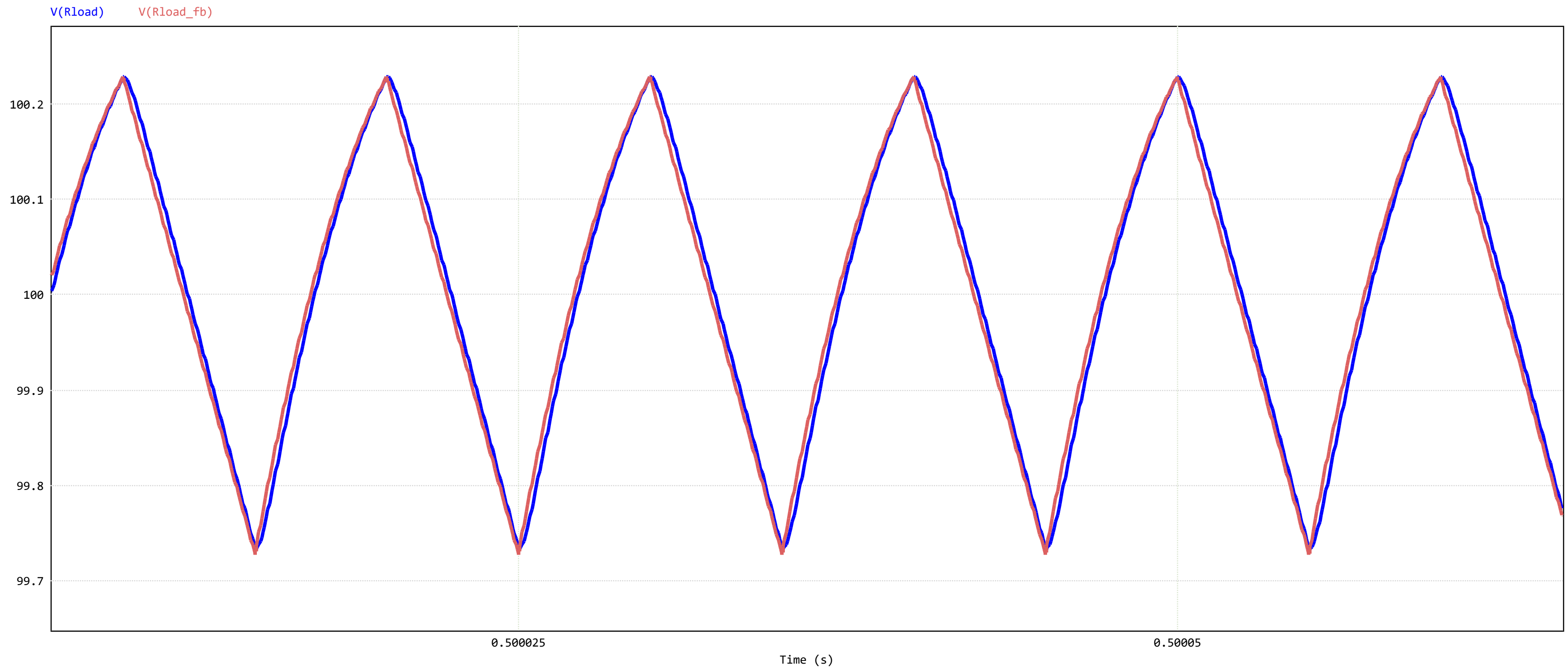
Now let's compare the ideal model of the integrated Ćuk to the equivalent flyback:

- **Simulate (PSIM)** the Ćuk and flyback models under identical operating conditions and compare performance.

These are the simulated (PSIM) Ćuk and flyback converters (*Note the LISN model used for DM EMI measurement):*

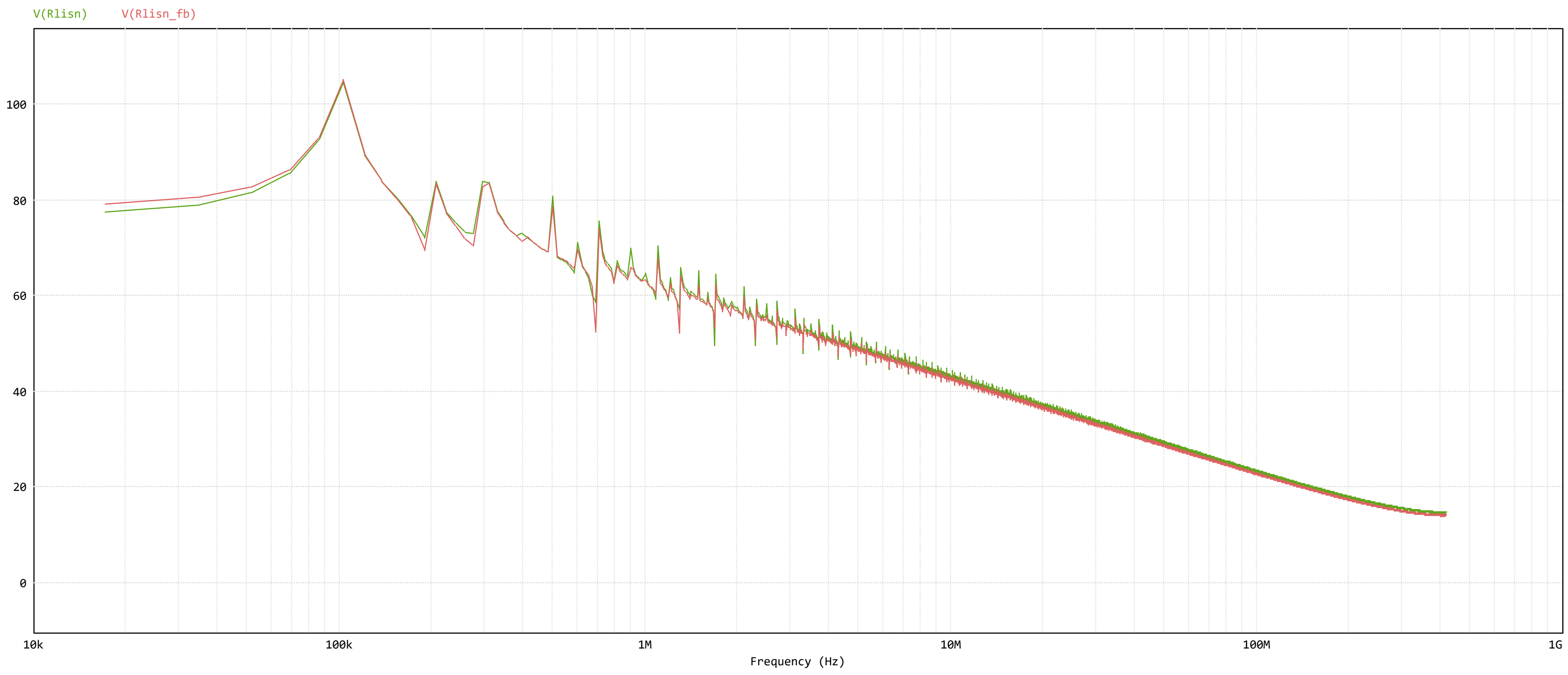


Ćuk vs. flyback: output ripple, measured open loop, D = 0.5.



The output voltage ripples of the converters are identical!

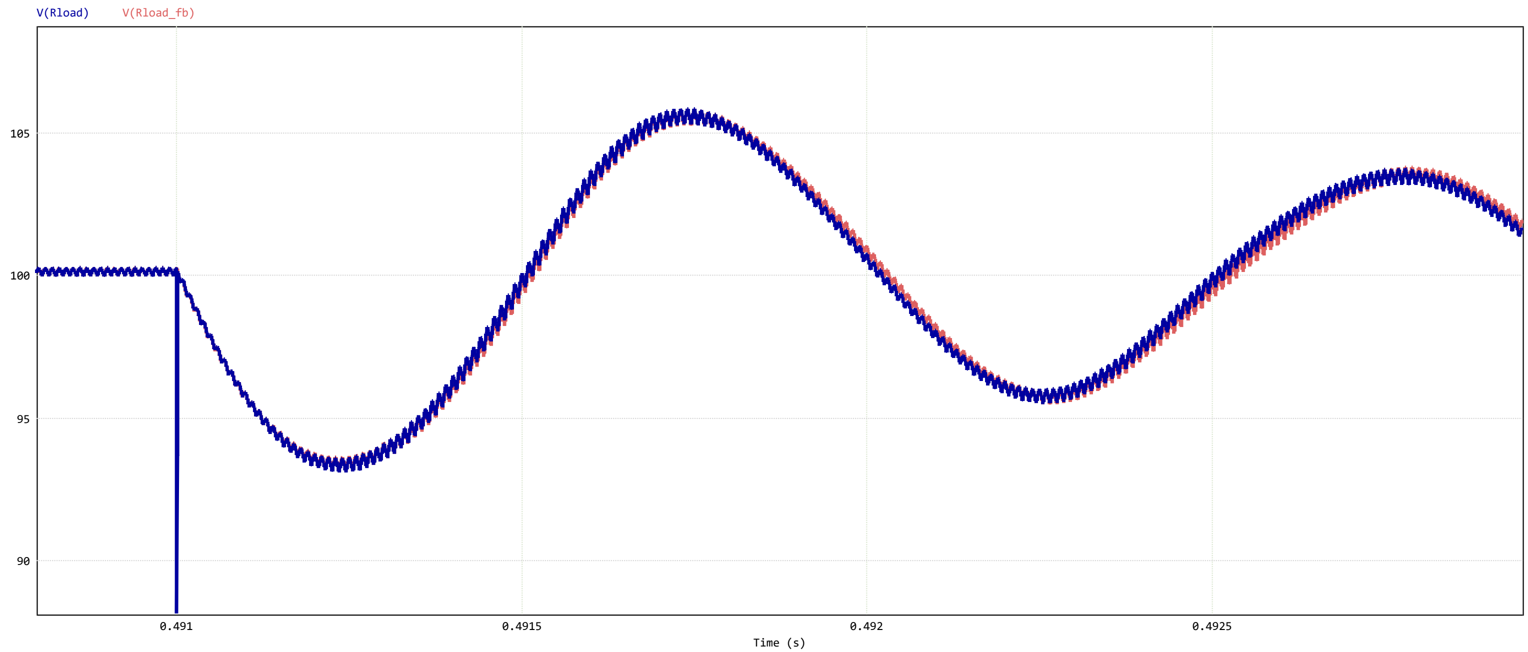
Ćuk vs. flyback: Differential-mode EMI,* D = 0.5.



The DM EMI is also identical.

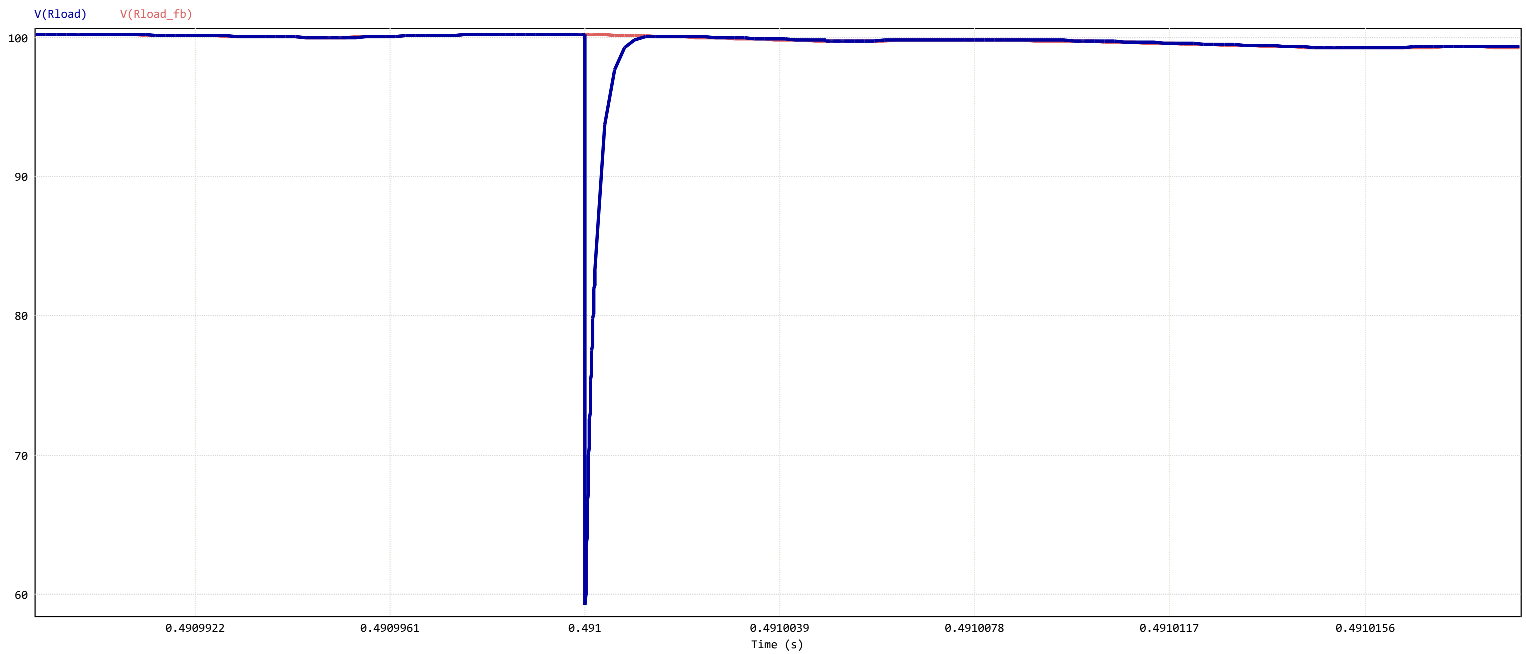
***Measured on LISN**

Ćuk vs. flyback: Vout under step 50% load transient, open loop.



The dynamics of the equivalent Ćuk and flyback converters are essentially identical, so control-to-output transfer functions will also be identical!

Ćuk vs. flyback: Vout under step load transient, open loop (detail).



ΔV = 40%Vout! *(Ćuk only)*

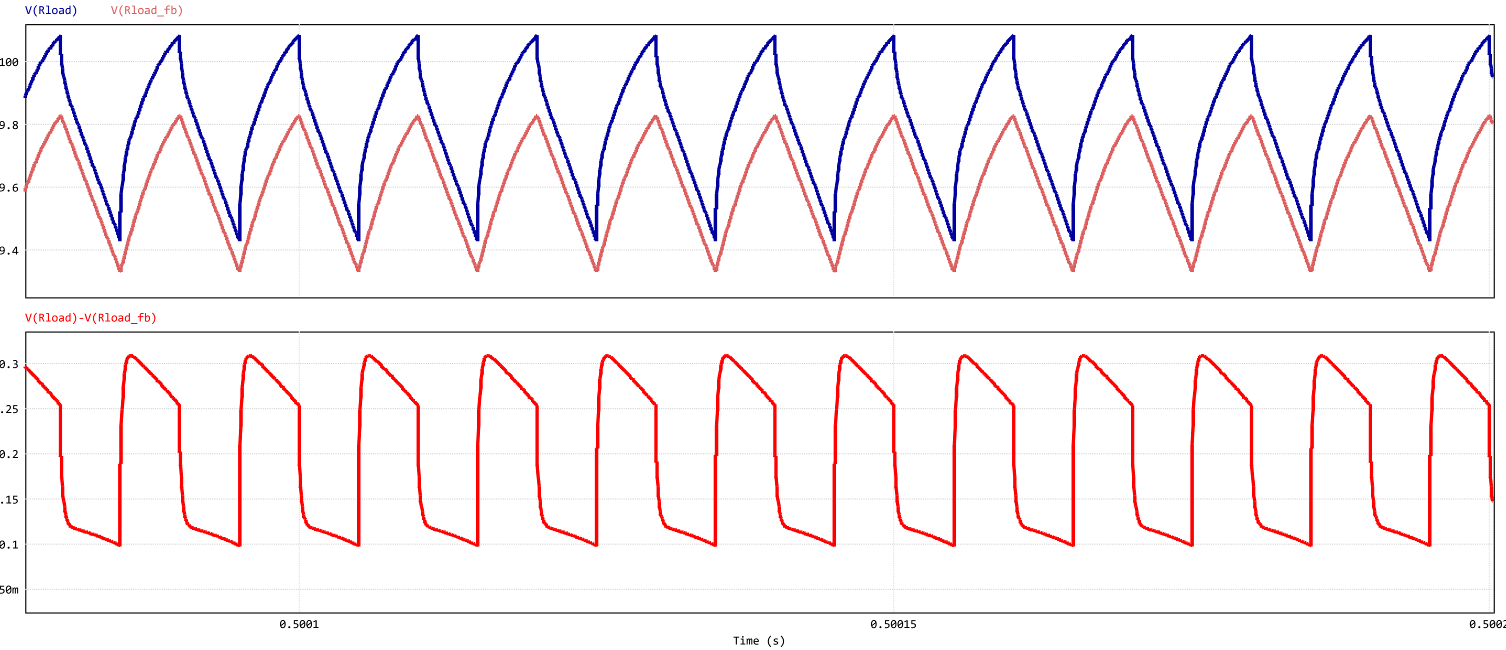
The large voltage drop spike in the Ćuk output voltage (too fast to be attenuated by the control loop) ***is caused by the leakage inductance needed to steer the ripple current from the inductors to the transformer.***

Question to the audience: Why doesn't the leakage affect the voltage ripples?

Another issue: high-frequency ripple and DM EMI of the Ćuk.

- In the flyback converter *the input and output caps are connected directly* across the converter's input and output ports, so they are very effective in bypassing high-frequency currents.
- This not the case with the Ćuk converter: *the coupling caps are effectively connected across the converter's ports via transformer/inductor windings*
- The dc resistance and leakage inductance of the transformer windings add to the ESL/ESR of the capacitors
- The output voltage ripple, DM EMI and load transient response substantially worse than those of the flyback converter.

Ćuk vs. flyback: adding dc resistance of windings–effect on output ripple. (**10 mΩ added to the windings (both converters).**

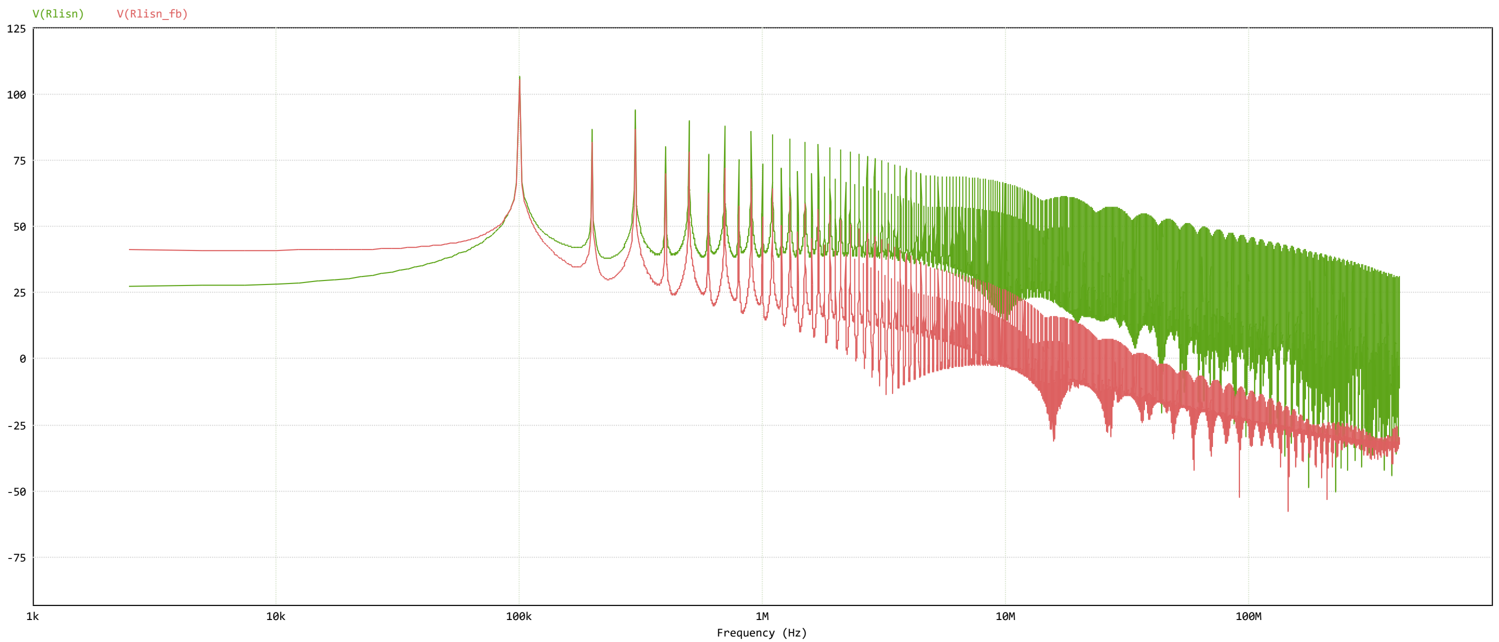


Output voltages
Red: FB
Blue: Ćuk

Output ripples difference:
Vout (Ćuk)-Vout (FB)

- **For the Ćuk, including the winding resistance effectively increases the ESR of the input and output capacitances. Ripple and EMI are substantially** worse than the equivalent flyback.
- For the flyback, including the winding resistance only causes a small dc drop.

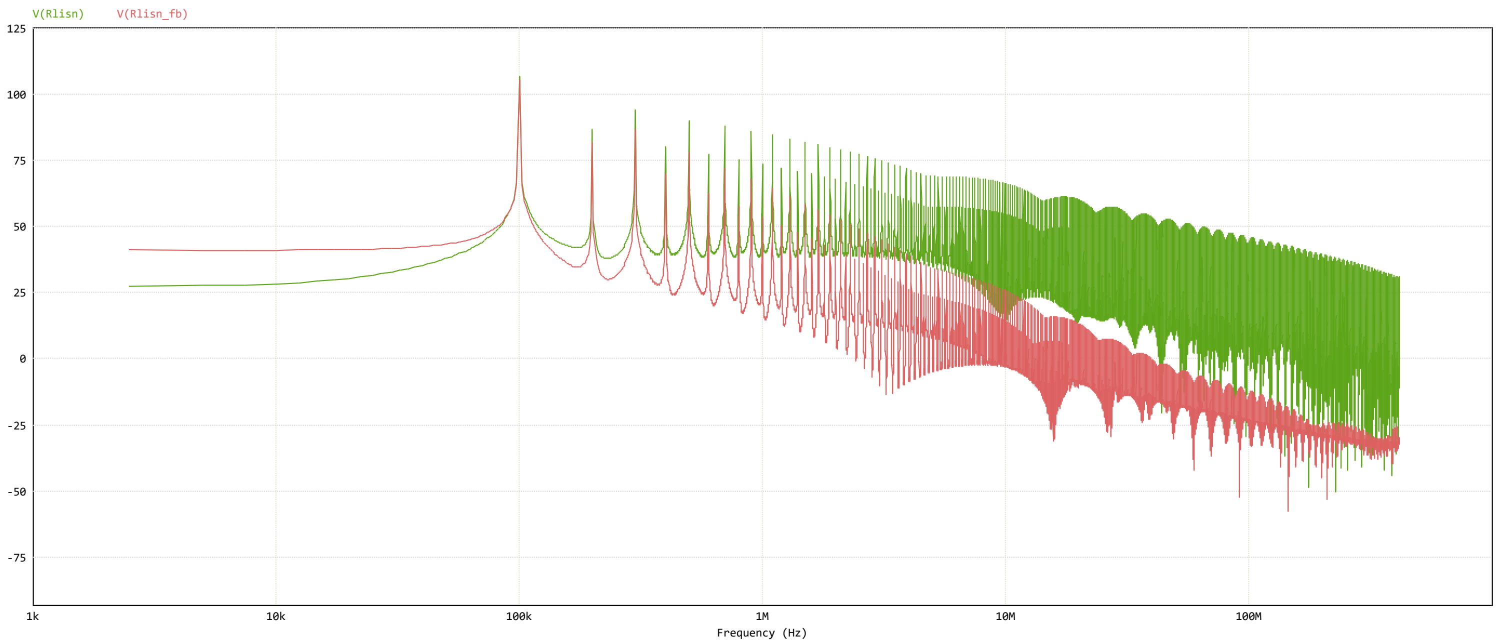
Ćuk vs. flyback: Adding dc resistance of windings–effect on DM EMI.



Green: Ćuk
Red: Flyback

Adding 10-mΩ dc resistance to the windings of the transformers (both converters) has massive impact on the Ćuk DM EMI, none on the flyback!

Ćuk vs. flyback: Adding dc resistance of windings–effect on DM EMI.

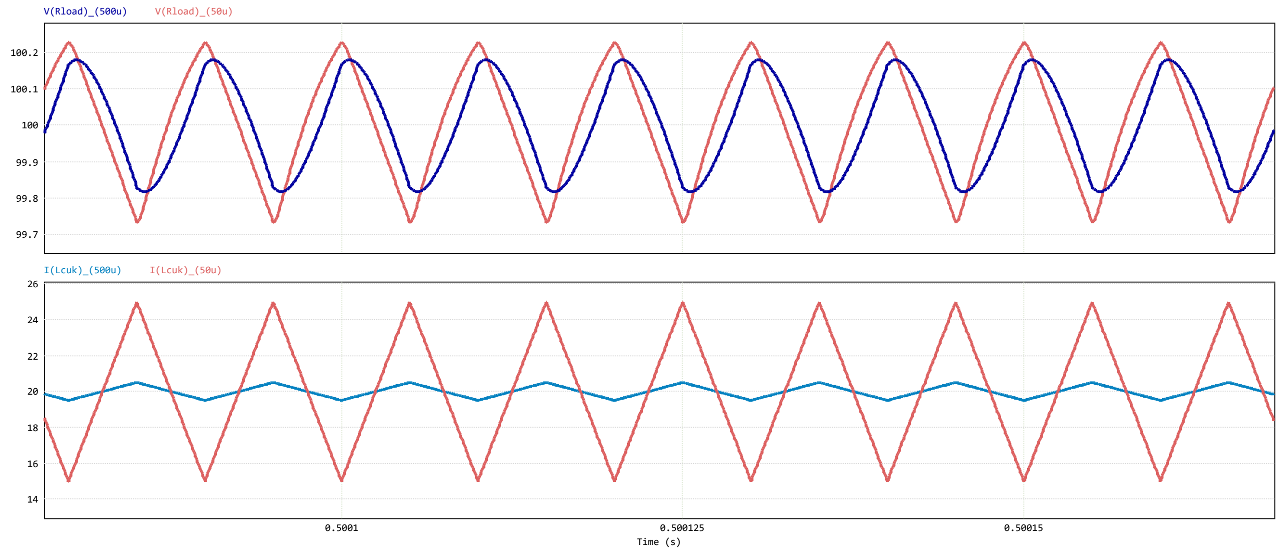


Green: Ćuk
Red: Flyback

The impact is small at low frequency, but large at high frequency. ***(Question to Audience: Why?)***

Further proof the integrated Ćuk converter is just a (bad) flyback in disguise!

- Increase Ćuk inductance by a factor of 10.



Output ripple
Red: LĆuk = L

Blue: LĆuk = 10L

Inductor current
Red: LĆuk = L

Blue: LĆuk = 10L

- **Di**screte Ćuk topology (cascaded boost and buck!): increasing inductances reduces both input and output current ripple proportionally
- **Integrated** Ćuk: **Insignificant ripple attenuation - the integration annihilates the inductors filtering functionality – the Ćuk topology degenerates to a (bad) flyback.**

Summary and conclusions.

- A simple, easy-to-simulate model for the integrated magnetics Ćuk converter has been developed and a simple explanation of the converter operation provided.
- The integrated Ćuk converter has been compared to an equivalent flyback converter (*built from the Ćuk components*) and *found to be inferior to the flyback*:
  - The output ripple performance and DM EMI are worse.
  - Load transient response is worse.
  - *Cost is higher (four-windings transformer, coupling coefficients adjustments costs).*

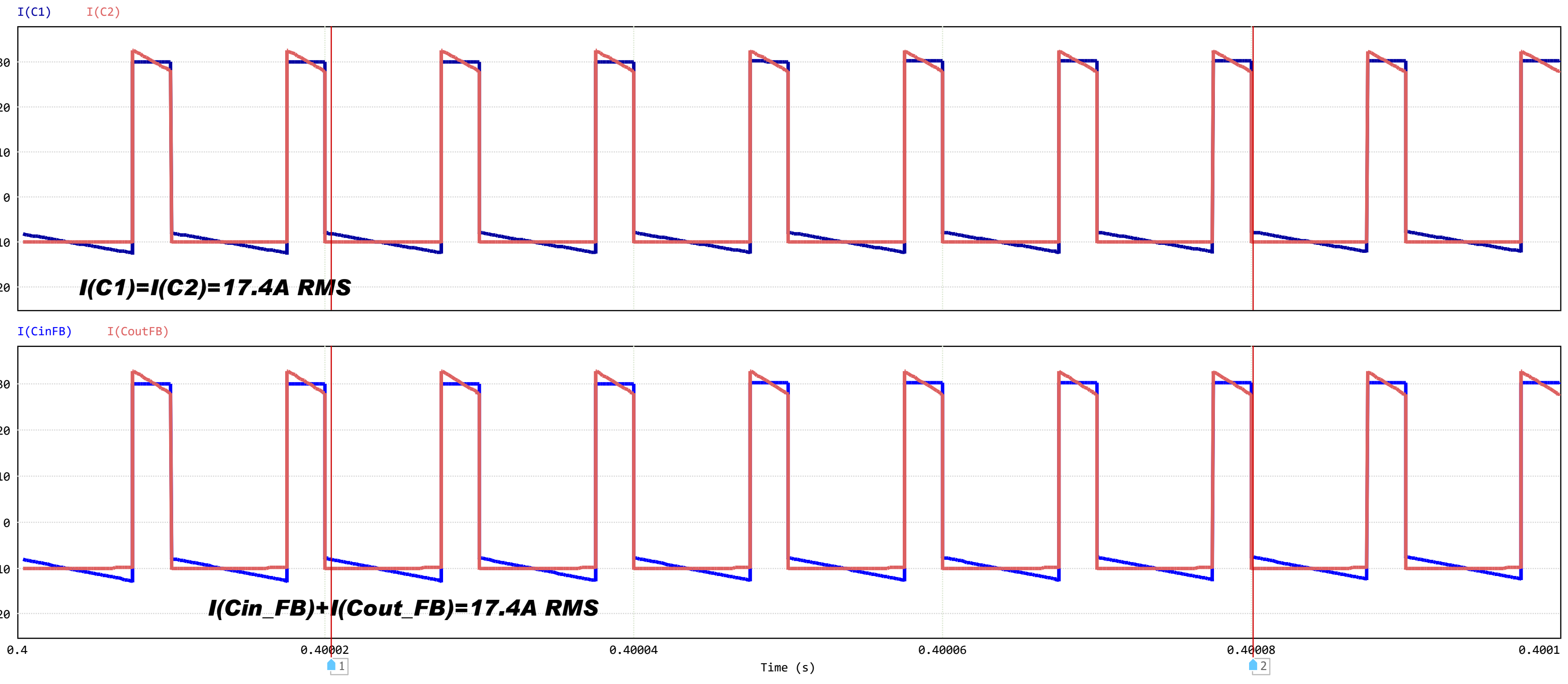
Summary and conclusions (continued).

- The transfer functions of the converters are identical.
- The power densities are equal.
- No reason can be identified for higher Ćuk efficiency.
- **Bottom line: The "Optimal Topology" narrative is an illusion.**
- **The Ćuk "Optimal" converter is good teaching tool, but has no real practical value.**

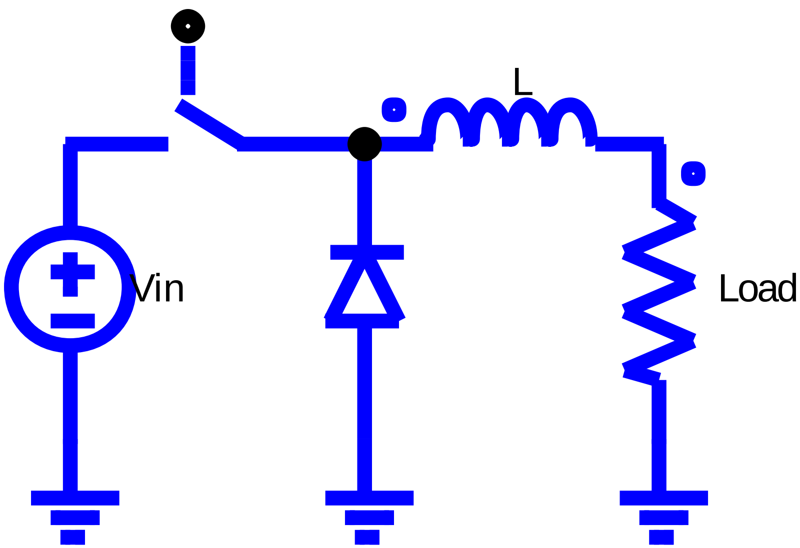
Challenges to my conclusions are welcome!

APPENDIX

Capacitors currents are are identicalfor both converters.

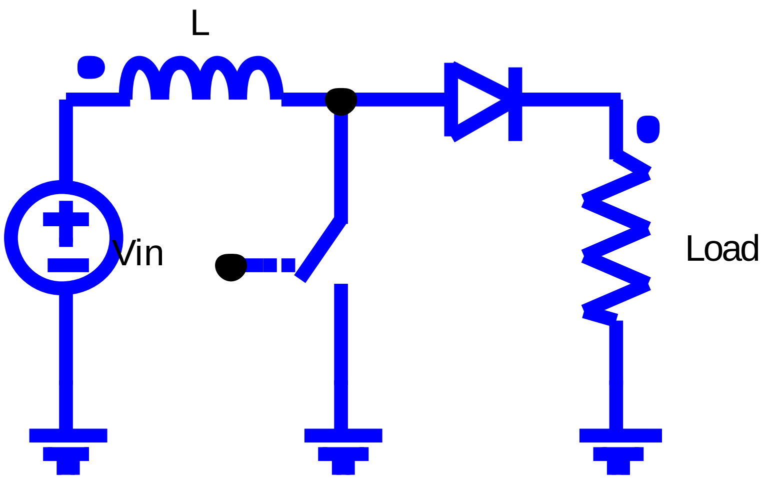


Review of buck converter characteristics in deep CCM:



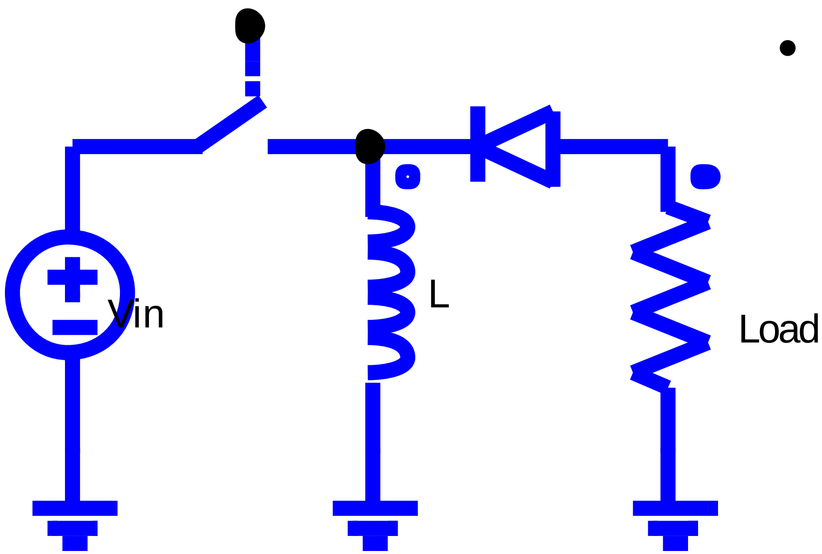
- Input ac current ripple is a square wave.
- Output ac current ripple is triangular.
  - *The inductor filters the output current.*
    - A test that proves this: Increasing the inductance proportionally reduces the amplitude of output ripple.
  - There is no input current filtration.

Review of boost converter characteristics in deep CCM:



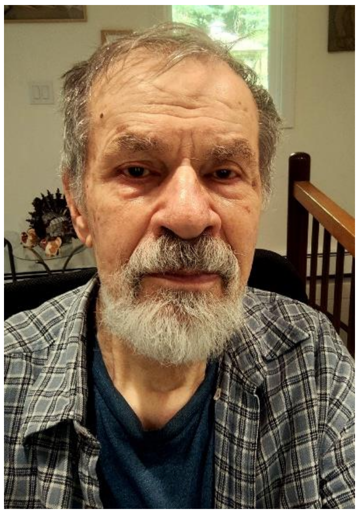
- Output current ac ripple is a square wave.
- Input ac current ripple is triangular.
  - *The inductor filters the input current.*
    - A test that proves this: Increasing the inductance proportionally reduces the amplitude of input ripple.
  - There is no output current filtration.

Review of buck-boost converter characteristics in deep CCM:



- Both input and output ac current ripples are square waves.
  - There is no input or output filtering as the inductor has (almost) no filtering functionality!
    - Increasing the inductance has virtually no impact on amplitude of either current ripple!

About The Author



Isaac Cohen retired after a 50-year career and now considers power electronics a hobby. He is a senior member of the IEEE, Texas Instruments technical staff (emeritus) and holder of numerous power electronics patents.