Simplified Analysis and Design of Series-resonant LLC Half-bridge Converters

MLD GROUP

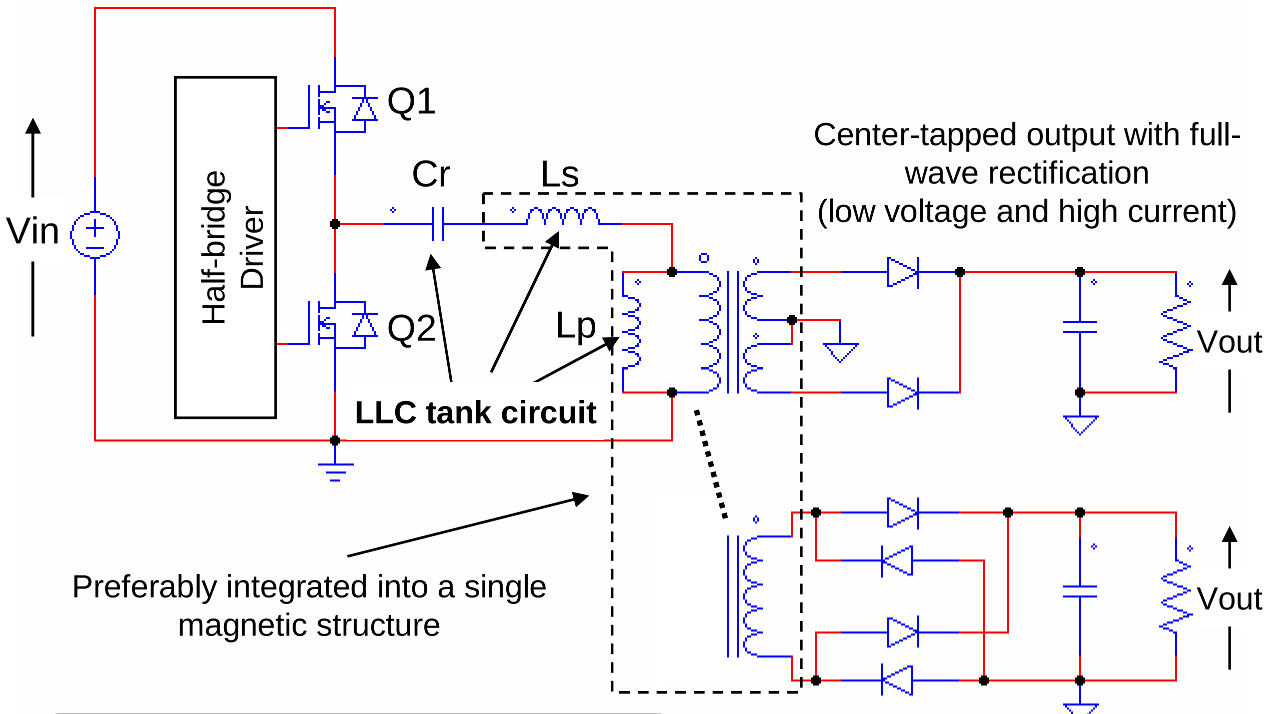
INDUSTRIAL & POWER CONVERSION DIVISION

Off-line SMPS BU Application Lab

Presentation Outline

- LLC series-resonant Half-bridge: operation and significant waveforms
- Simplified model (FHA approach)
- 300W design example

Series-resonant LLC Half-Bridge Topology and features



Center-tapped output with full-wave rectification (low voltage and high current)

LLC tank circuit

Preferably integrated into a single magnetic structure

Single-ended output with bridge rectifiication (high voltage and low current)

3 reactive elements, 2 resonant frequencies

$$f_{r1} = \frac{1}{2\cdot\pi\cdot\sqrt{Ls\cdot Cr}}$$

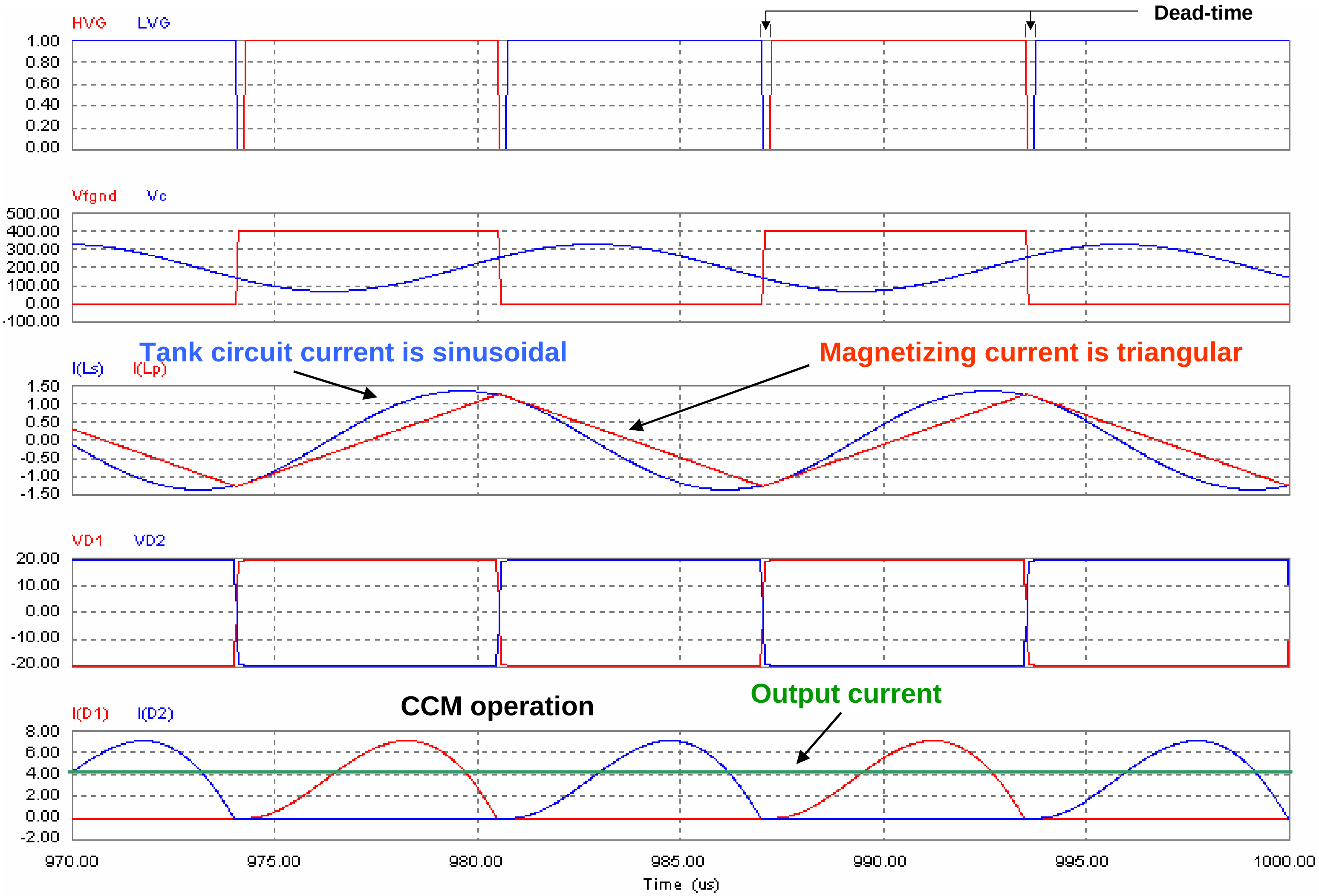
$$f_{r1} > f_{r2}$$

$$f_{r2} = \frac{1}{2\cdot\pi\cdot\sqrt{(Ls + Lp)\cdot Cr}}$$

- Multi-resonant LLC tank circuit
- Variable frequency control
- Fixed 50% duty cycle for Q1 & Q2
- Dead-time between LG and HG to allow MOSFET's ZVS @ turn-on
- fsw ≈ fr, sinusoidal waveforms: low turn-off losses, low EMI
- Equal voltage & current stress for secondary rectifiers; ZCS, then no recovery losses
- No output choke; cost saving
- Integrated magnetics: both L's can be realized with the transformer.
- High efficiency: >96% achievable

LLC Resonant Half-bridge

Waveforms at resonance ($f_{sw} = f_{r1}$)



Dead-time

Gate-drive signals

HB mid-point Voltage

Resonant cap voltage

Tank circuit current is sinusoidal

Magnetizing current is triangular

Transformer currents

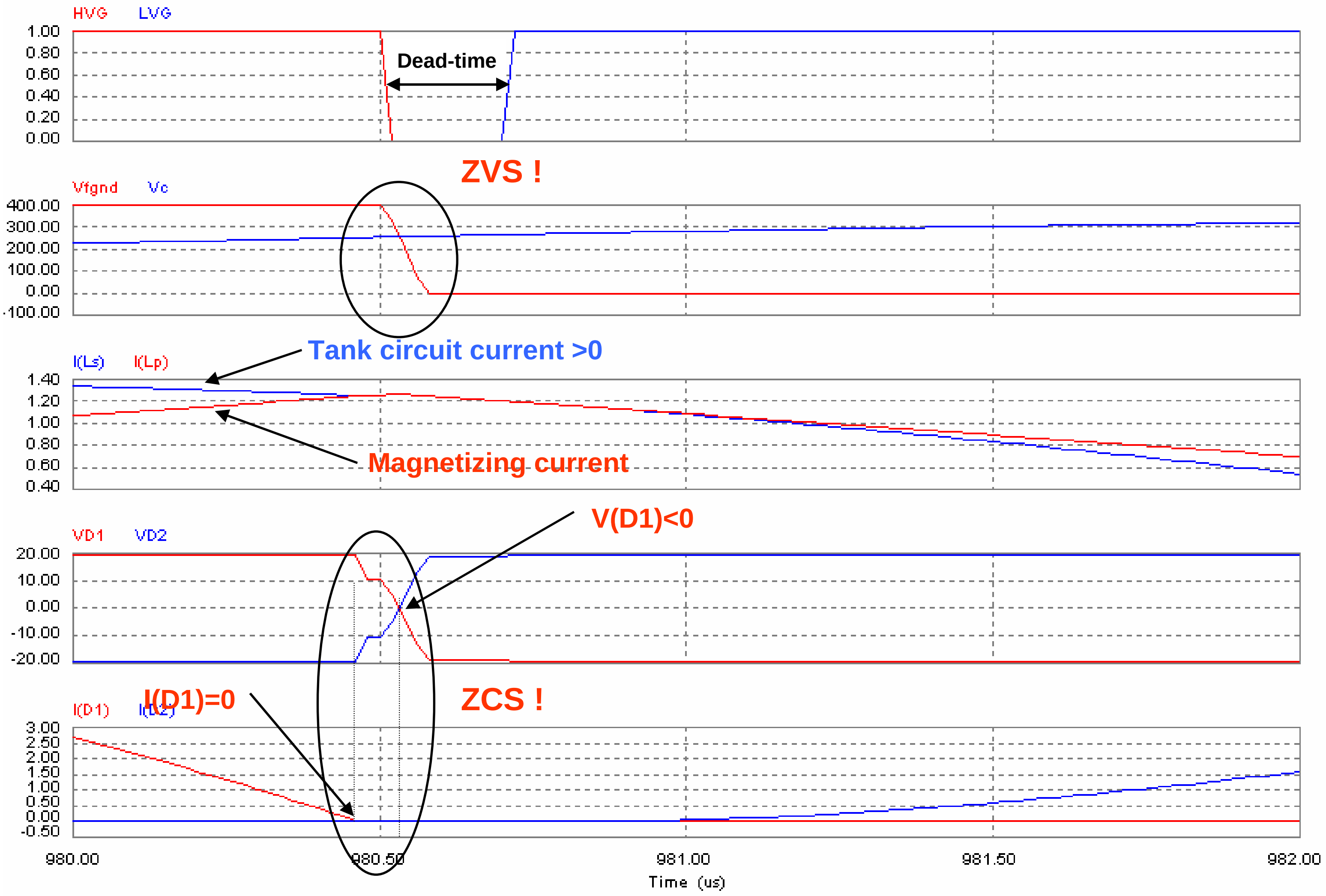
Diode voltages

CCM operation

Output current

Diode currents

LLC Resonant Half-bridge
Switching details at resonance ($f_{sw} = f_{r1}$)



Dead-time

ZVS !

Tank circuit current >0

Magnetizing current

V(D1)<0

I(D1)=0

ZCS !

Gate-drive signals

HB mid-point Voltage

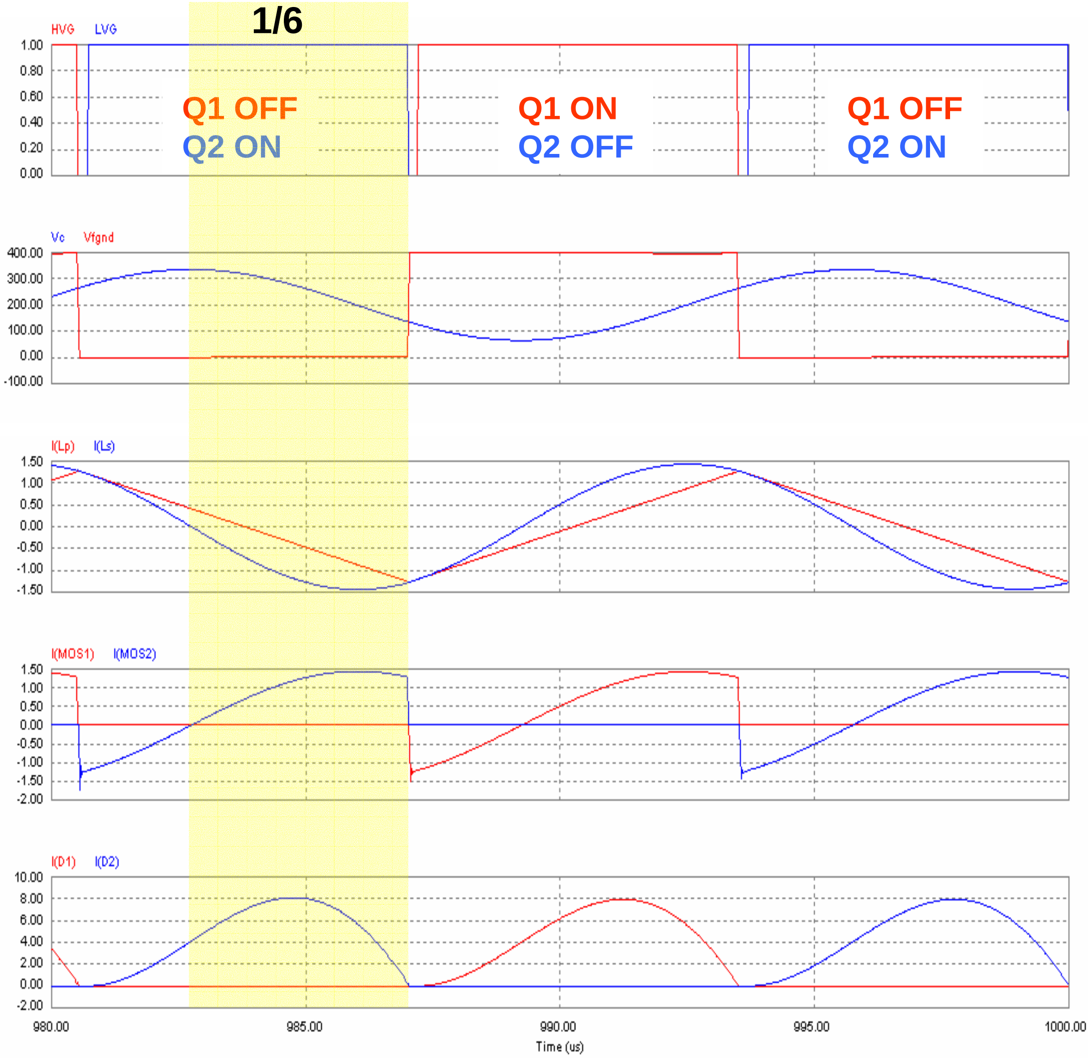
Resonant cap voltage

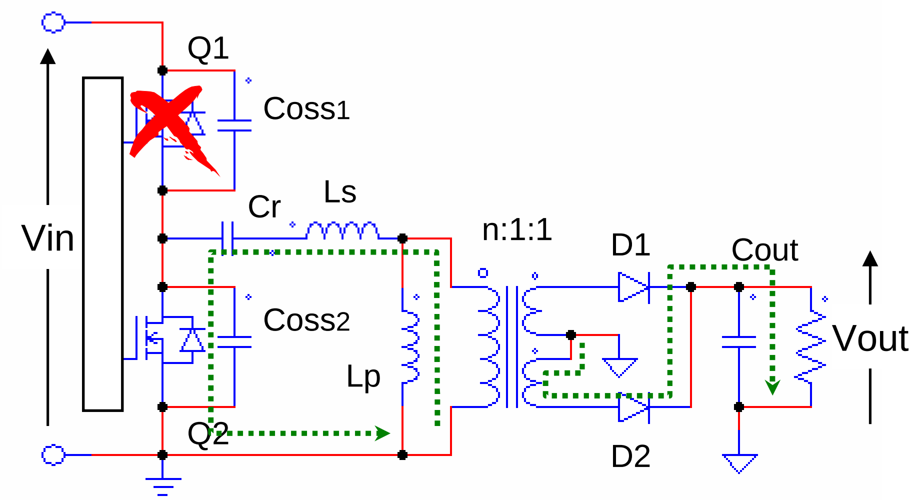
Transformer currents

Diode voltages

Diode currents

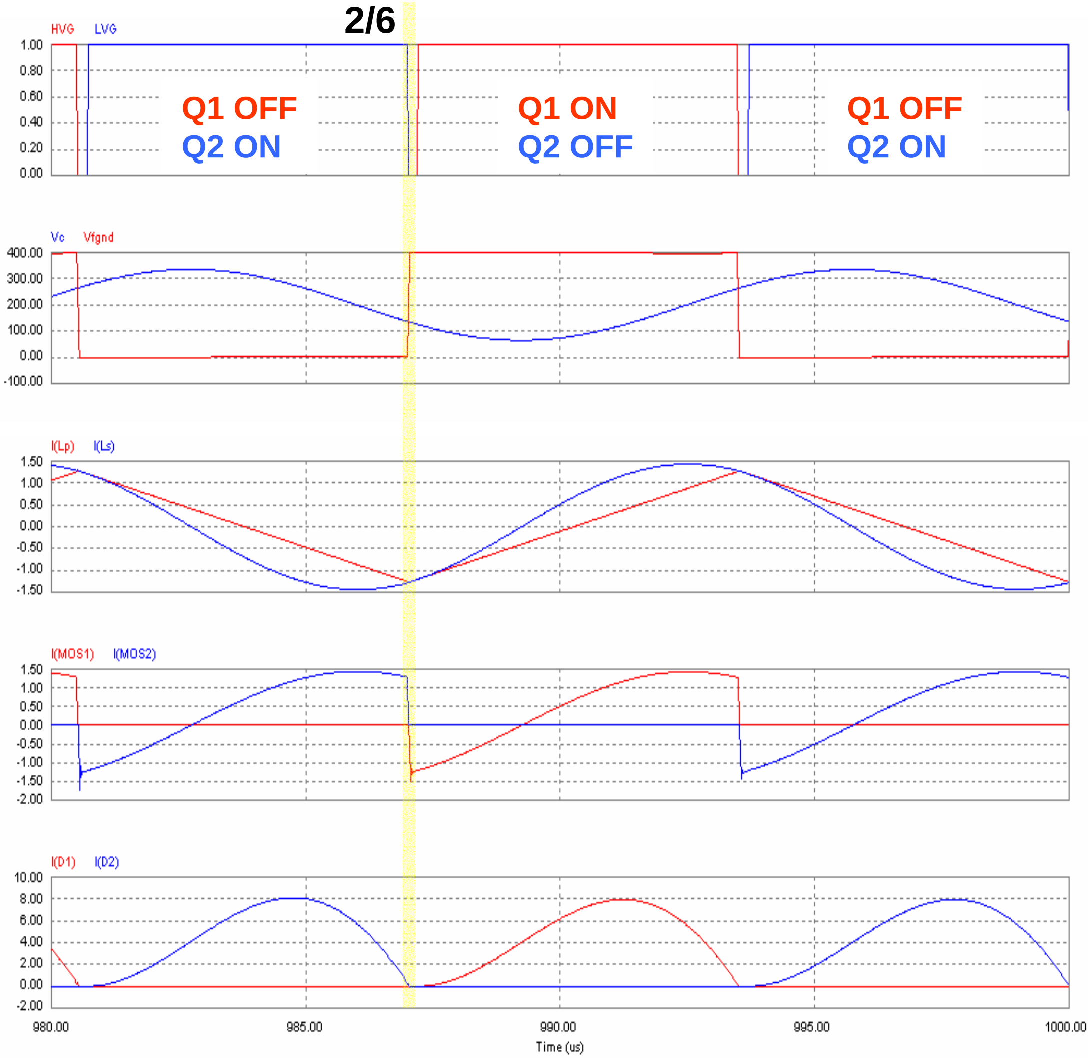
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 1/6)

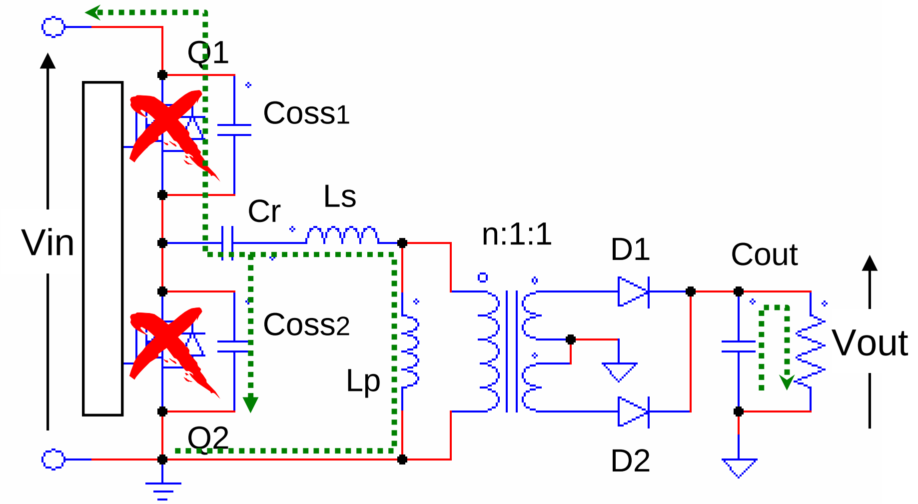




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when Q2 is switched off

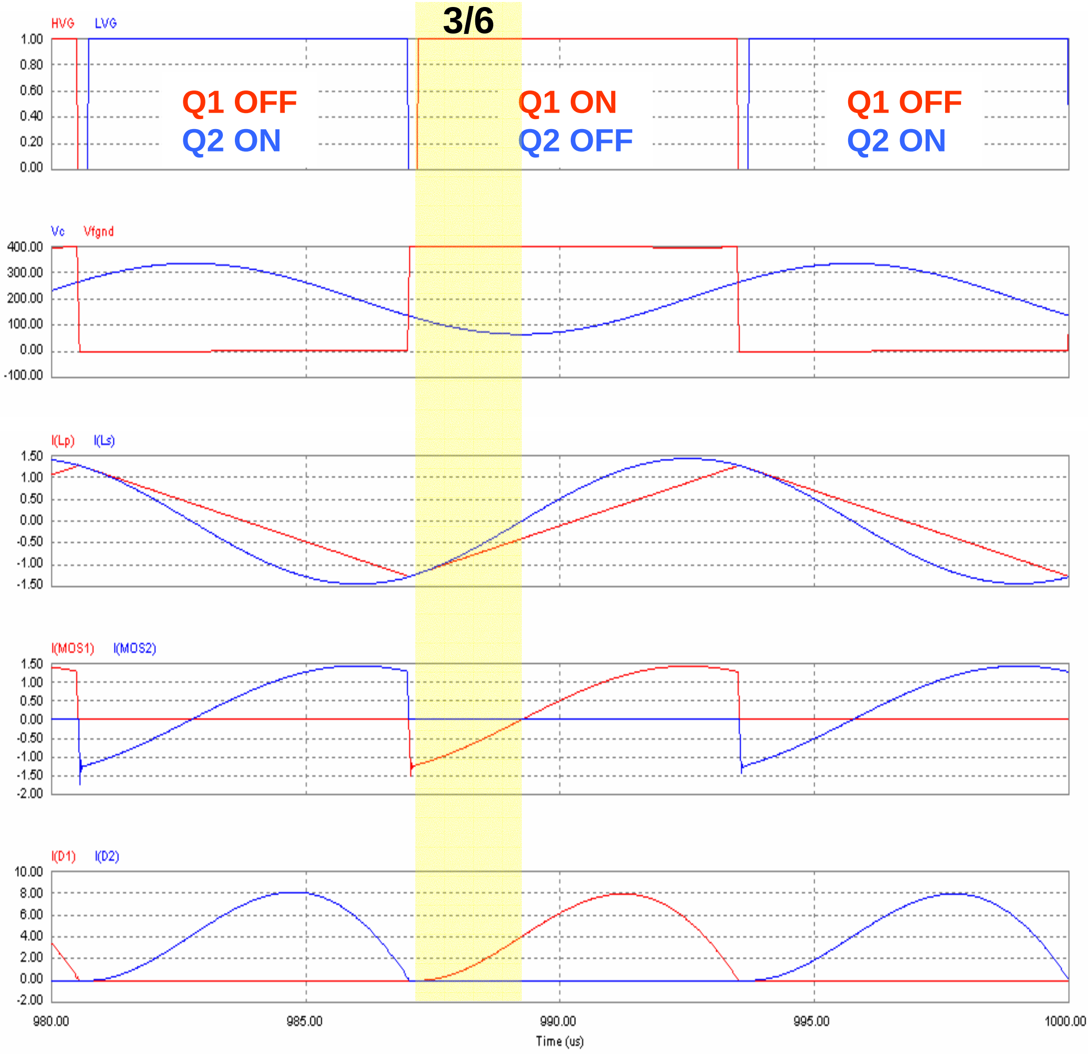
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 2/6)

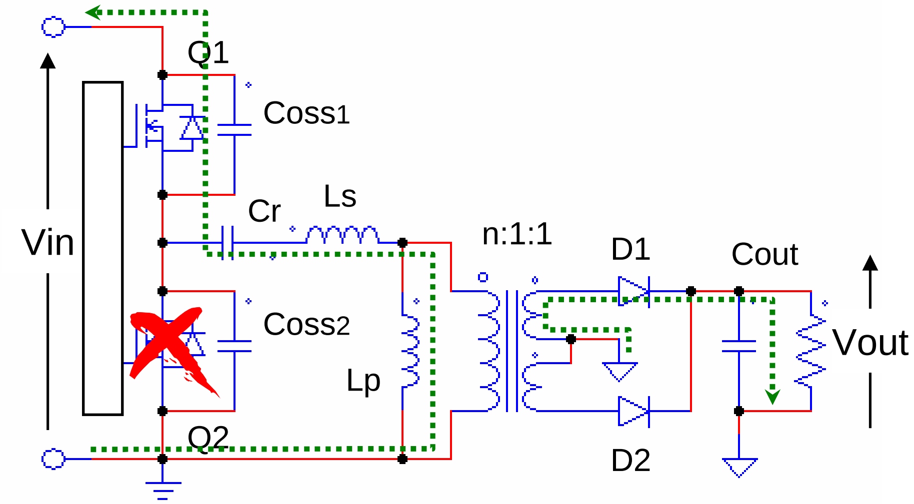




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharges C_{OSS1}, until V(C_{OSS2})=Vin; Q1's body diode starts conducting, energy goes back to Vin
- I(D2) is exactly zero at Q2 switch off
- Phase ends when Q1 is switched on

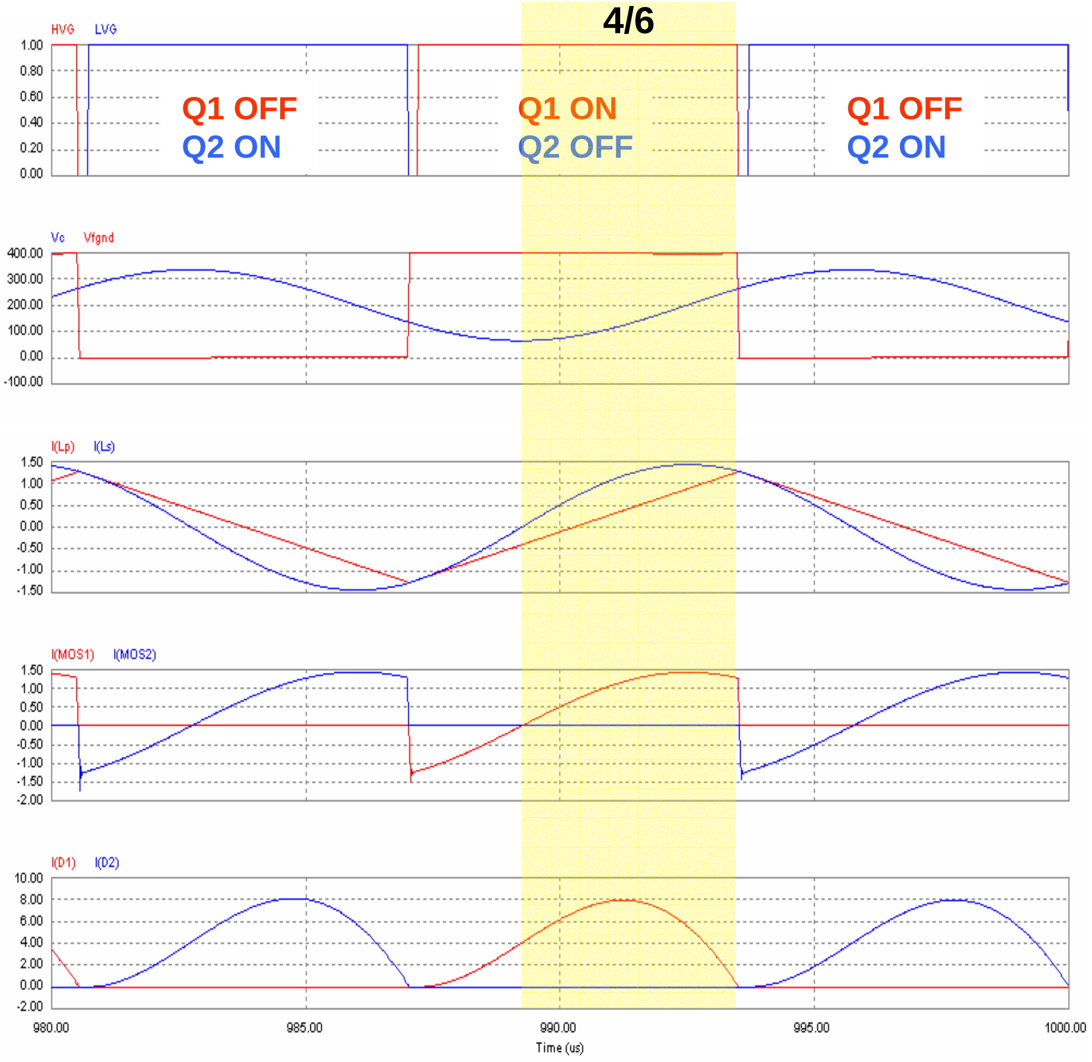
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 3/6)

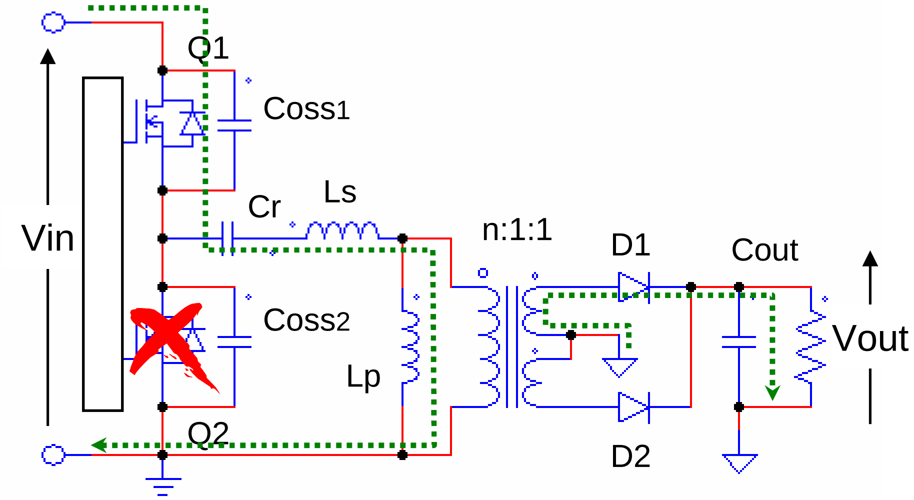




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back to Vin (Q1 is working in the 3^{rd} quadrant)
- Phase ends when I(Ls)=0

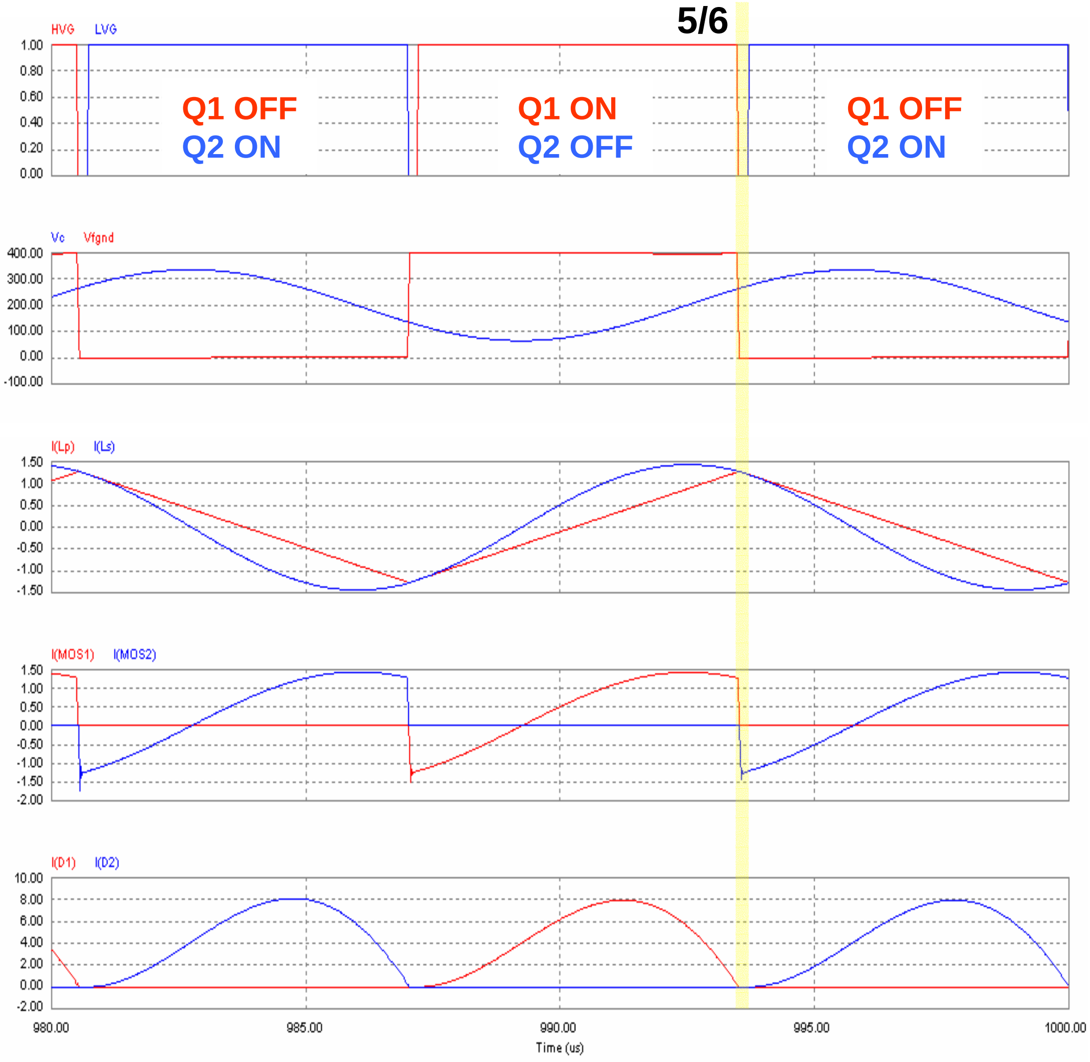
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 4/6)

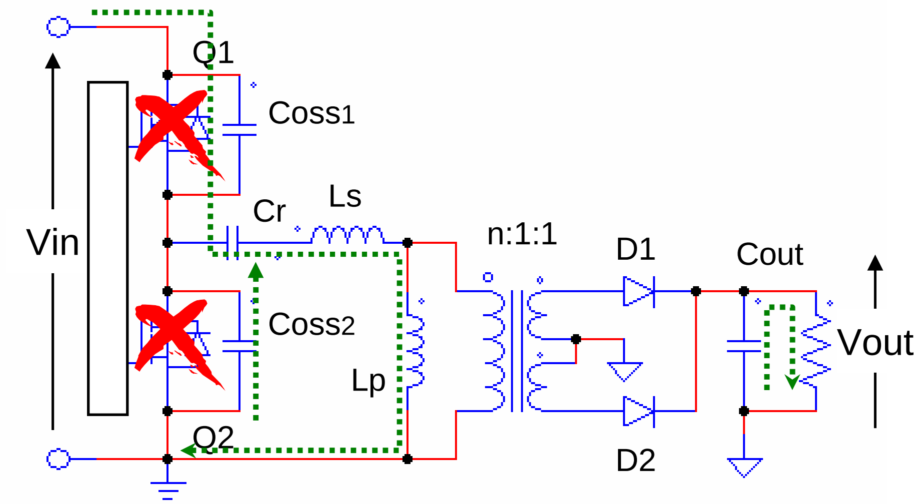




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from Vin to ground
- Energy is taken from Vin and goes to Vout
- Phase ends when Q1 is switched off

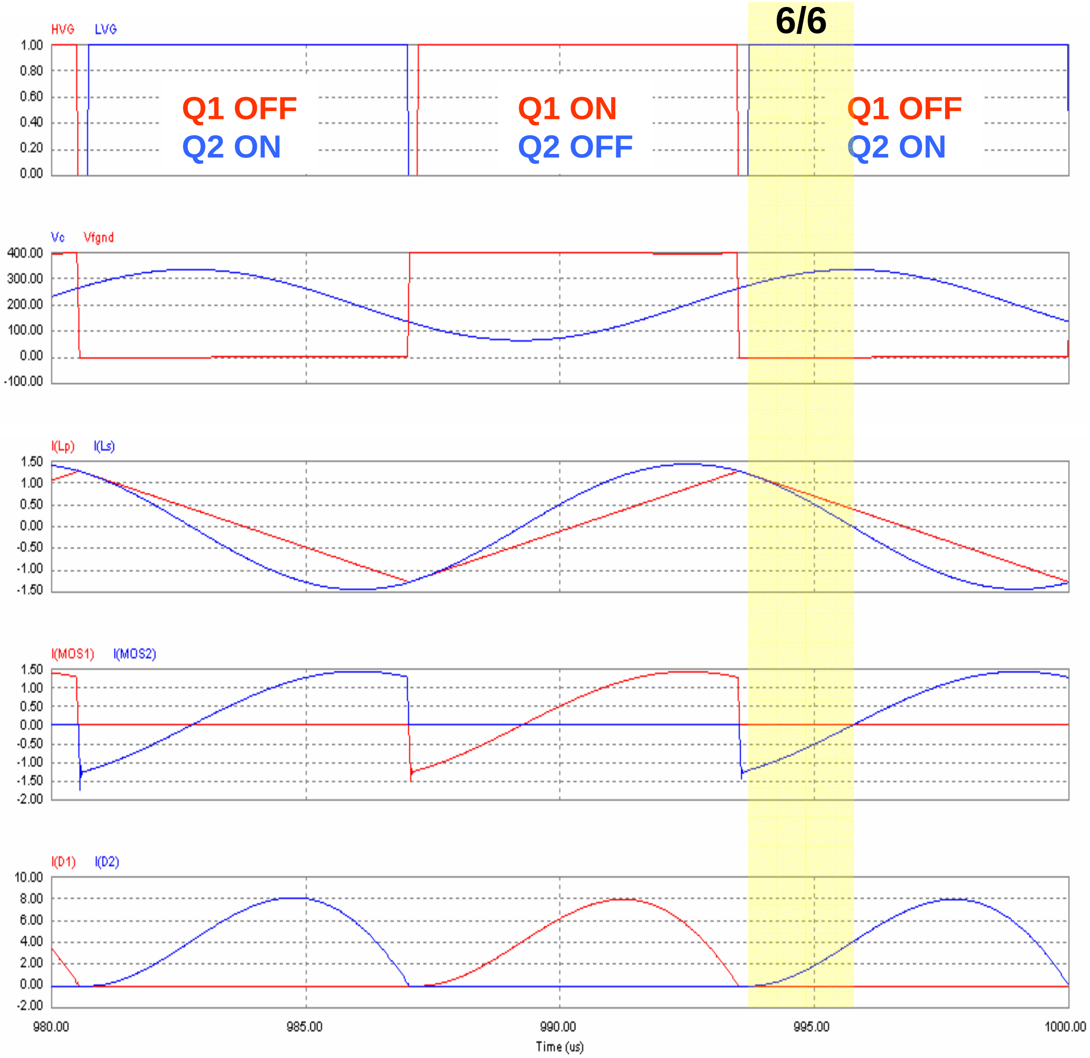
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 5/6)

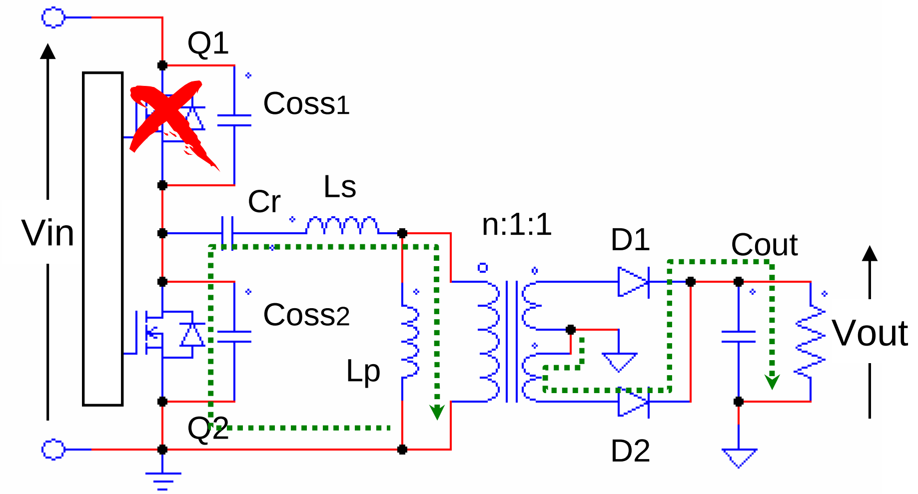




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharges C_{OSS2}, until V(C_{OSS2})=0; Q2's body diode starts conducting
- I(D1) is exactly zero at Q1 switch off
- Phase ends when Q2 is switched on

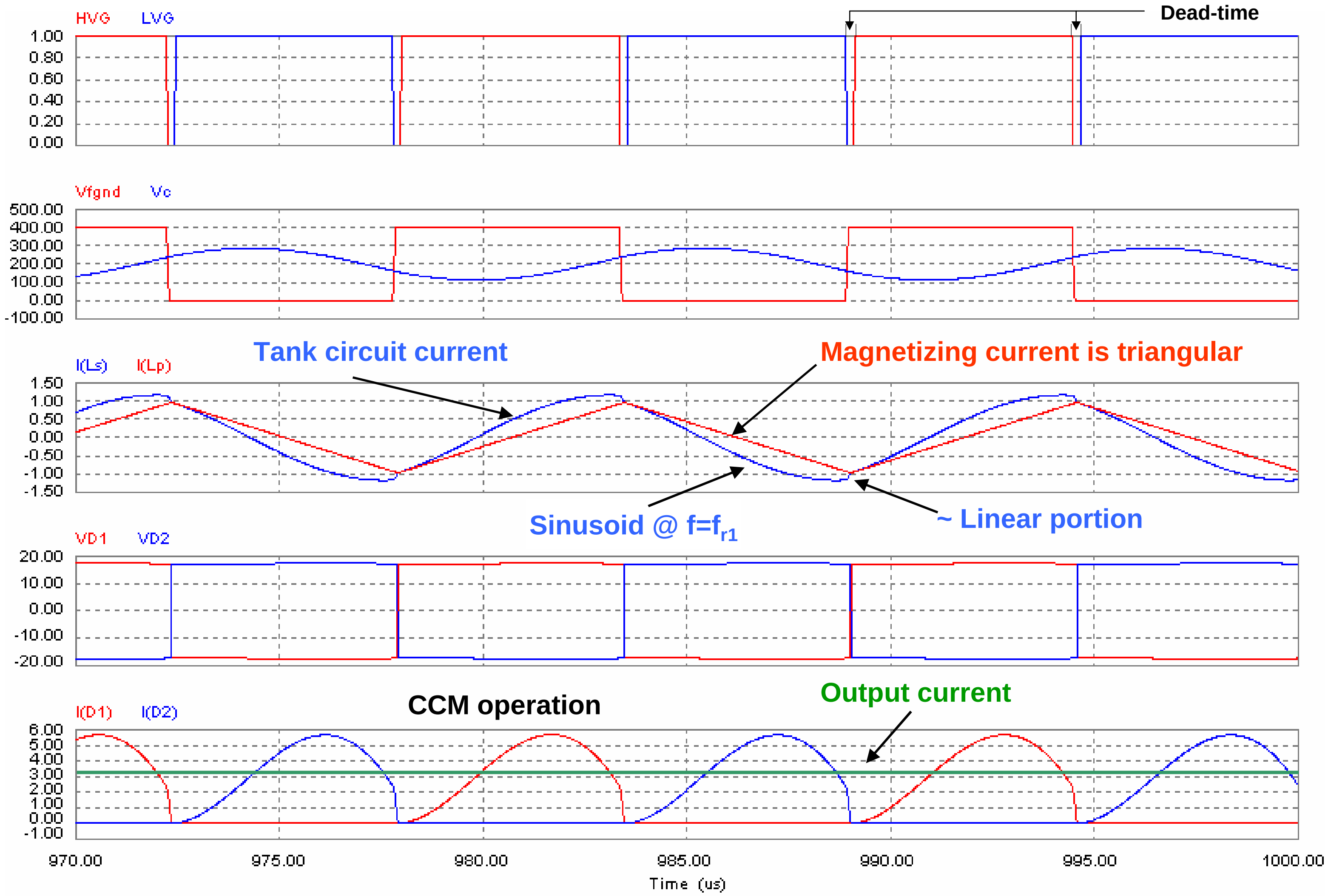
LLC Resonant Half-bridge
Operating Sequence at resonance (Phase 6/6)





- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, fr1 appears
- I(Ls) flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from Cr and Ls
- Phase ends when I(Ls)=0, Phase 1 starts

LLC Resonant Half-bridge
Waveforms above resonance ($f_{sw} > f_{r1}$)



Dead-time

Gate-drive signals

HB mid-point Voltage

Resonant cap voltage

Tank circuit current

Magnetizing current is triangular

Transformer currents

Sinusoid @ $f=f_{r1}$

~ Linear portion

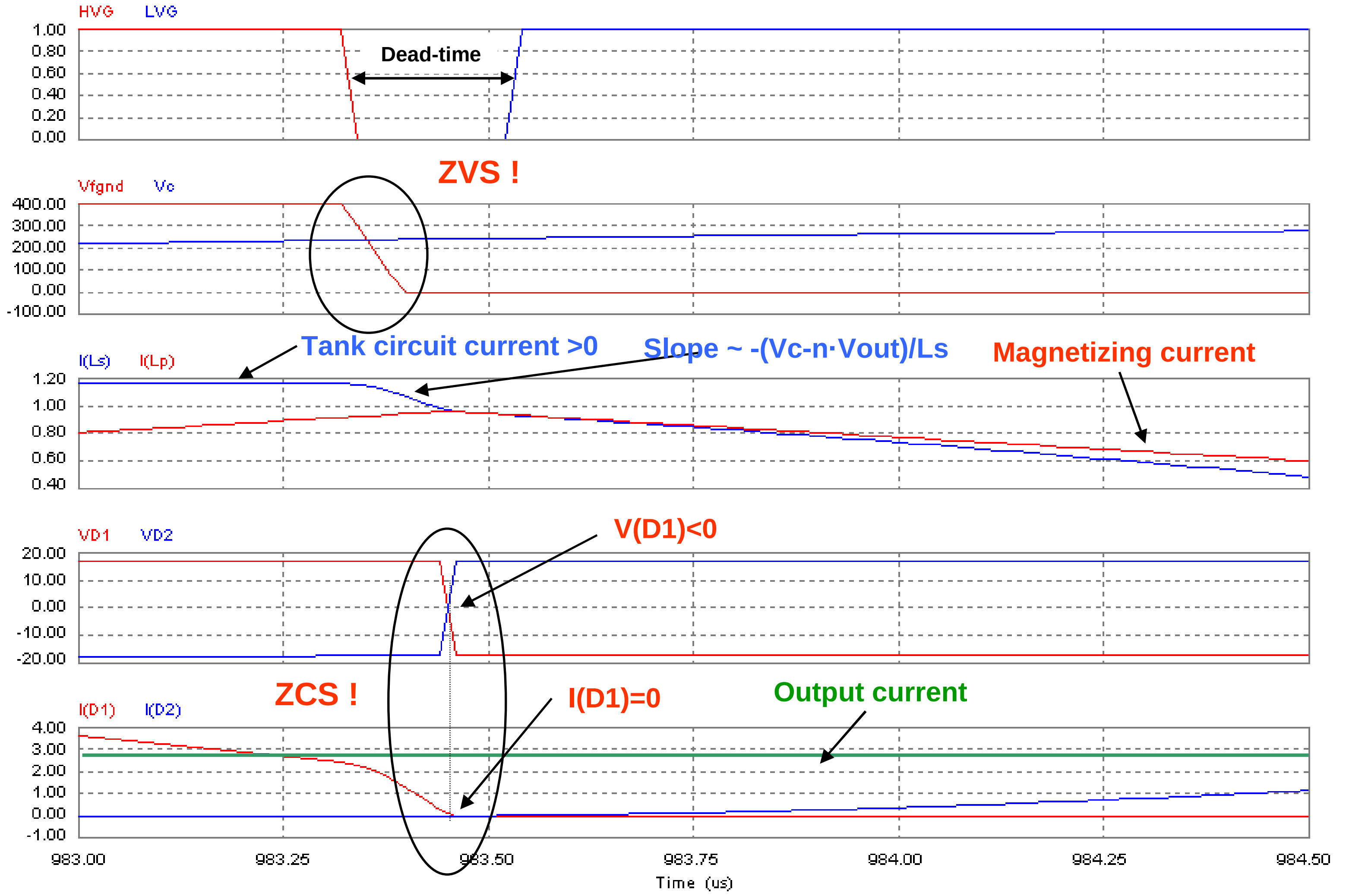
Diode voltages

CCM operation

Output current

Diode currents

LLC Resonant Half-bridge
Switching details above resonance ($f_{sw} > f_{r1}$)



Gate-drive signals

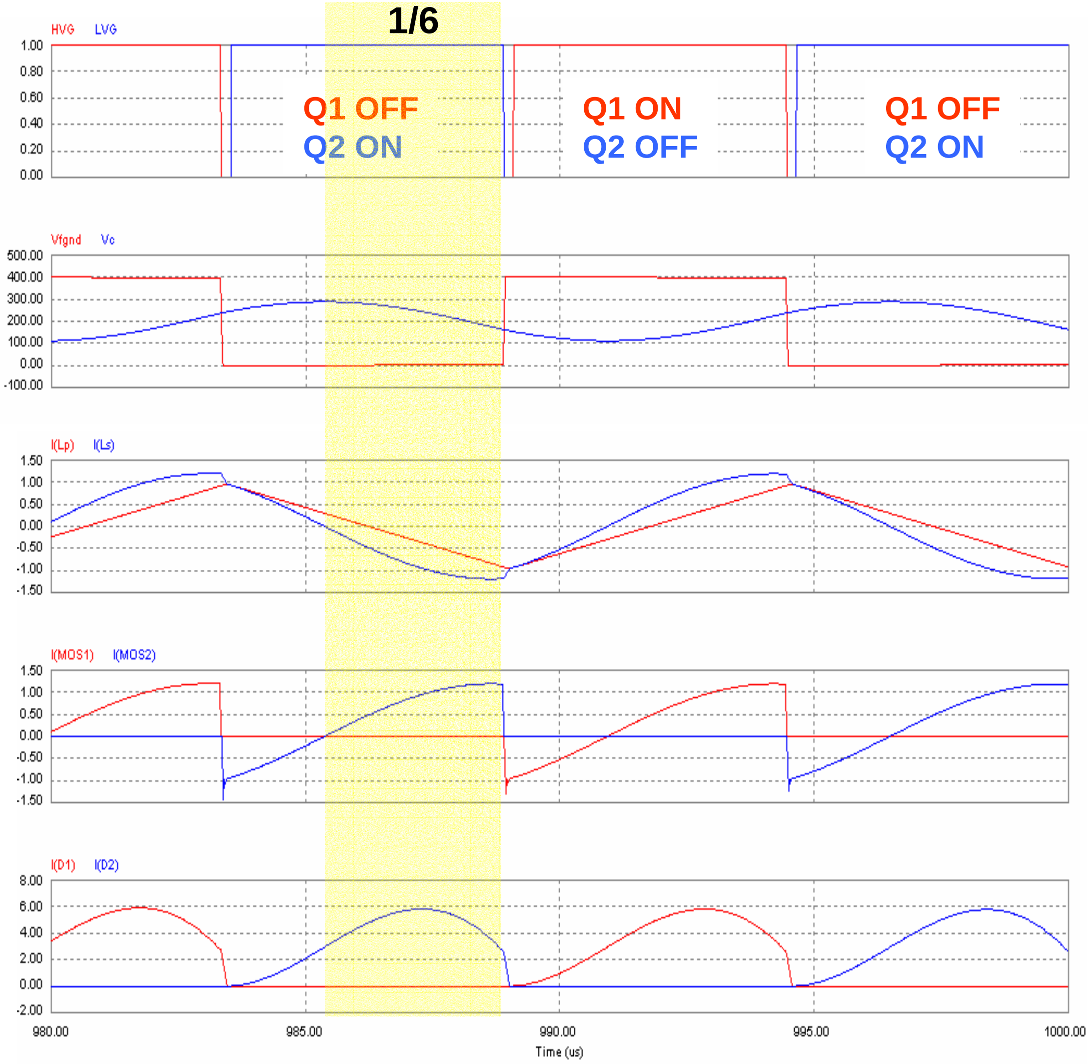
HB mid-point Voltage
Resonant cap voltage

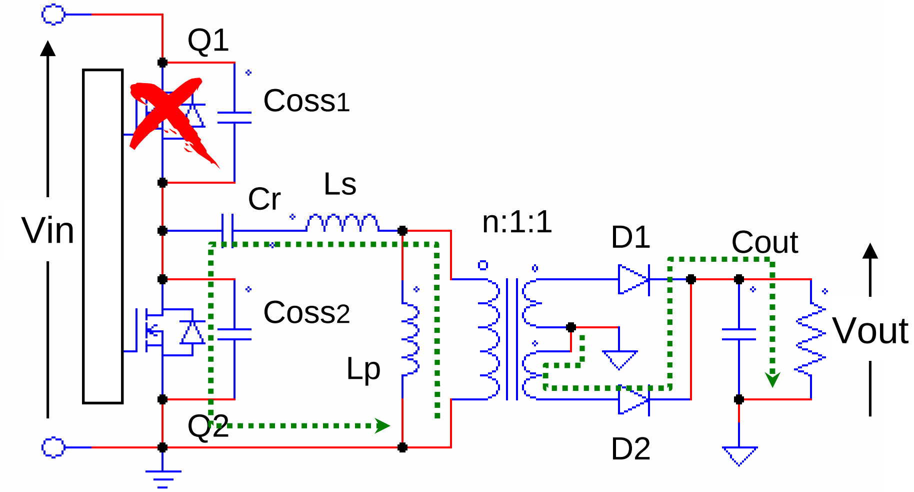
Transformer currents

Diode voltages

Diode currents

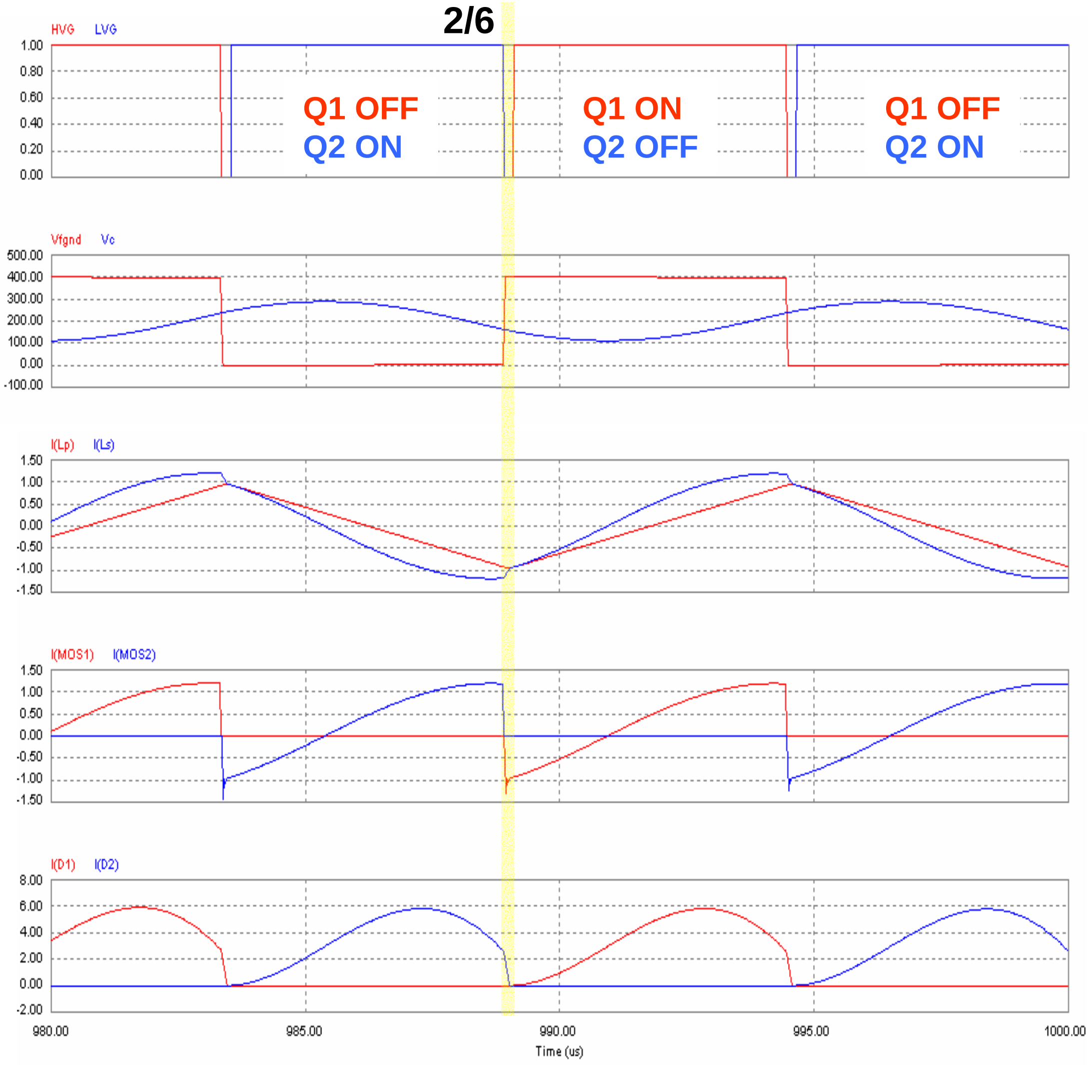
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 1/6)

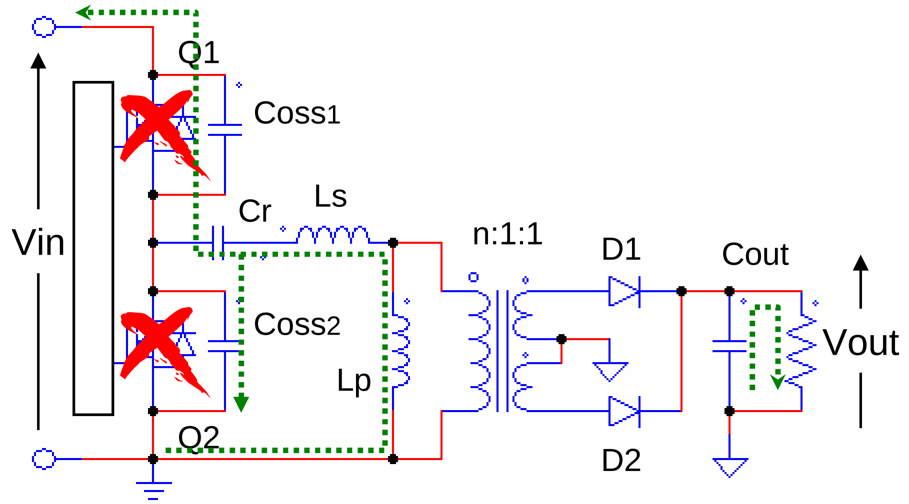




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when Q2 is switched off

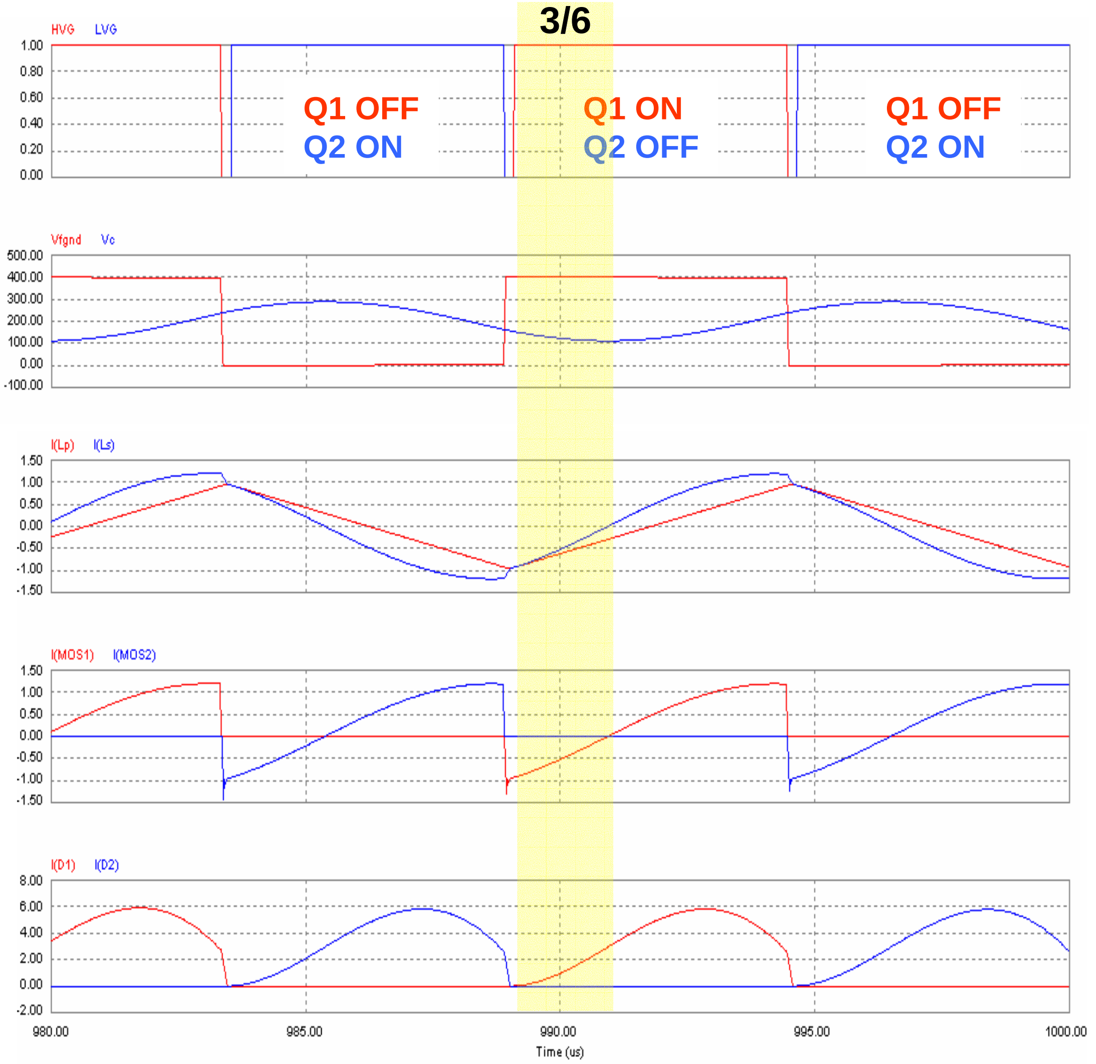
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 2/6)

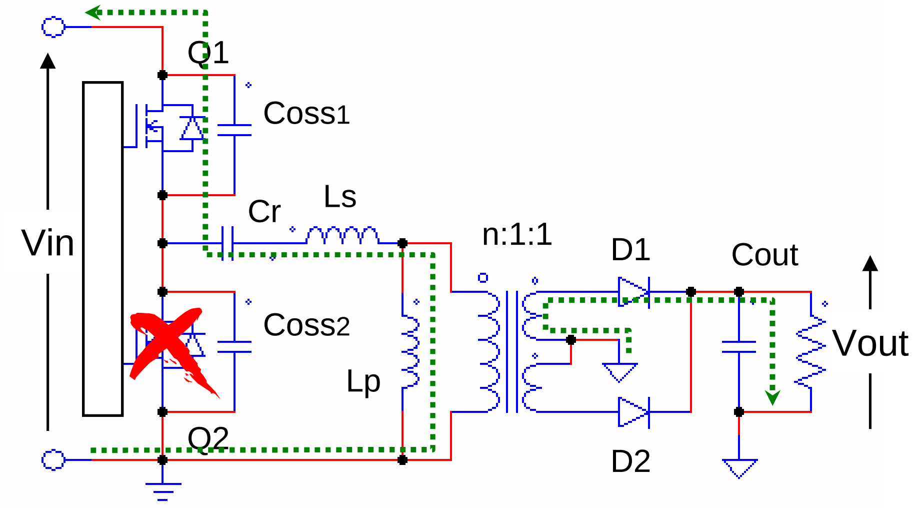




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharges C_{OSS1}, until V(C_{OSS2})=Vin; Q1's body diode starts conducting, energy goes back to Vin
- V(D2) reverses as I(D2) goes to zero
- Phase ends when Q1 is switched on

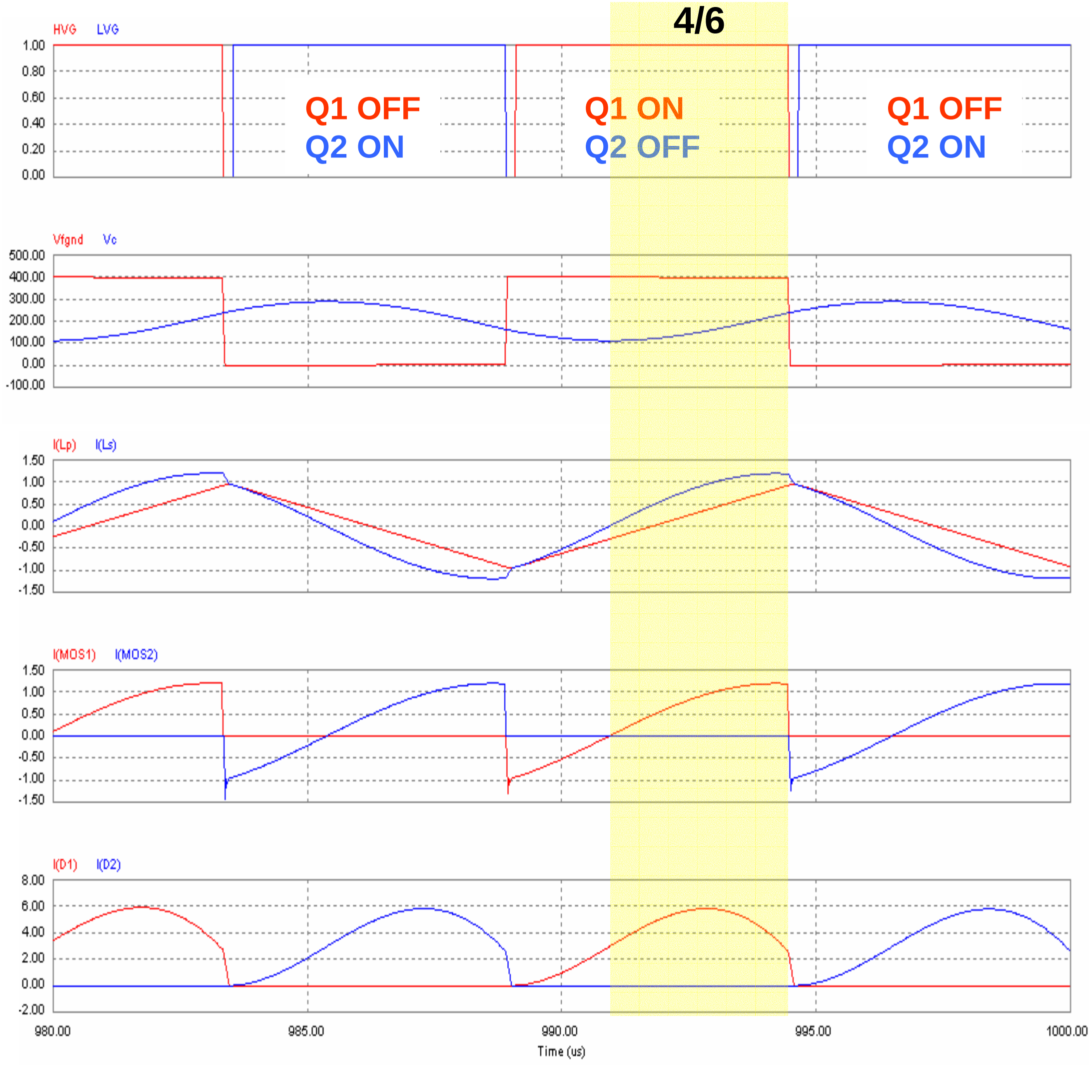
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 3/6)

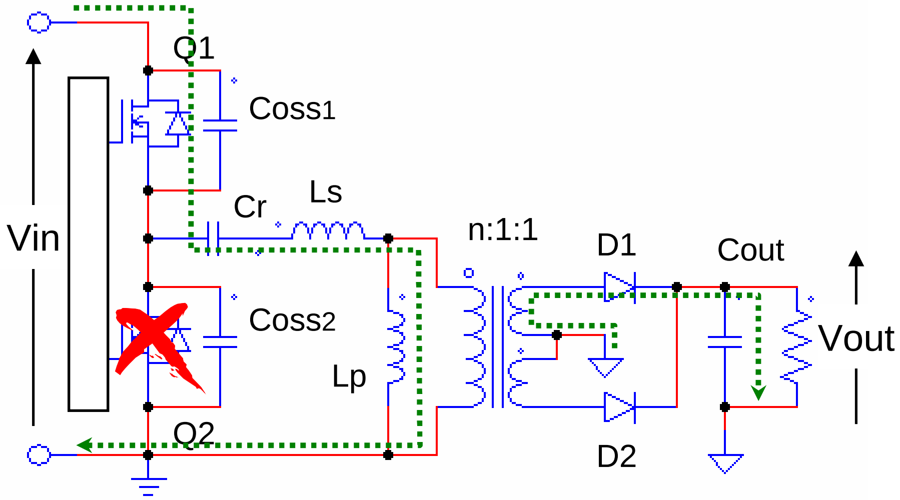




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back to Vin (Q1 is working in the 3rd quadrant)
- Phase ends when I(Ls)=0

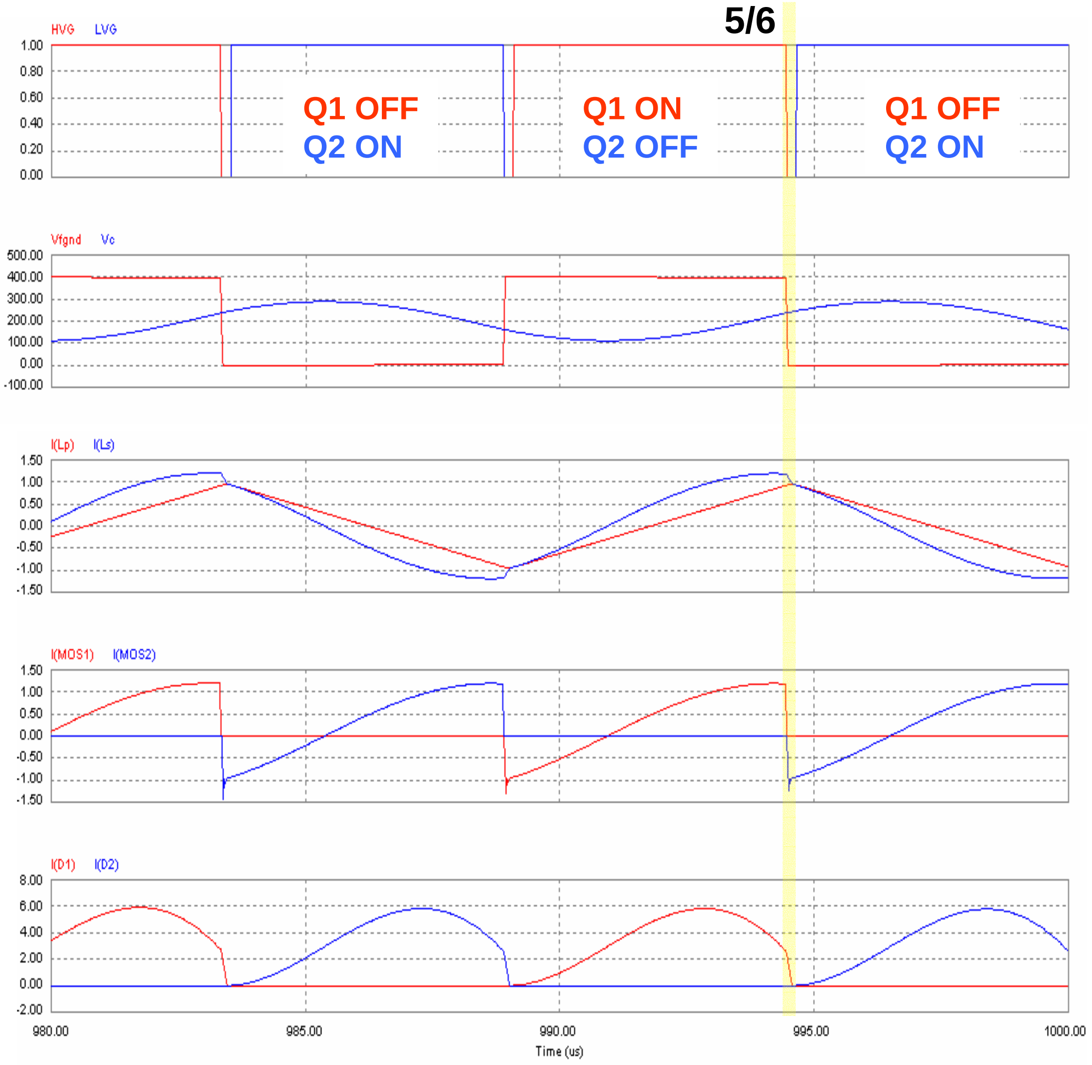
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 4/6)

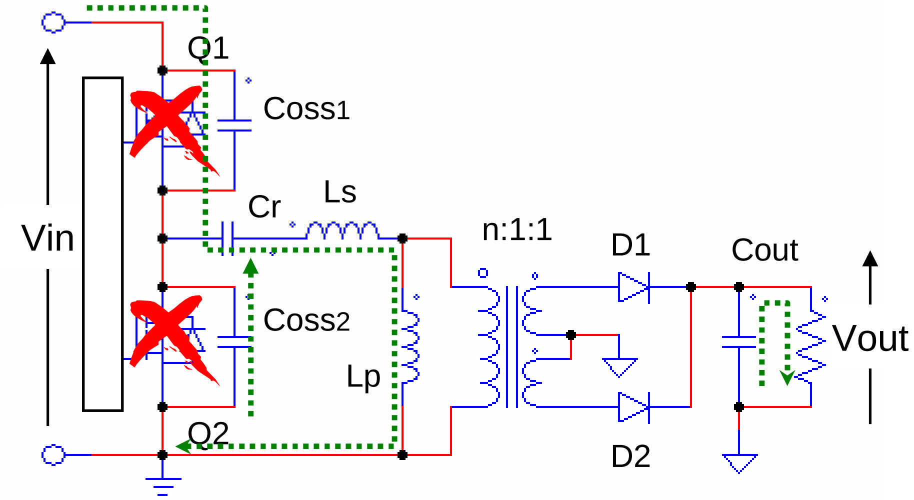




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from Vin to ground
- Energy is taken from Vin and goes to Vout
- Phase ends when Q1 is switched off

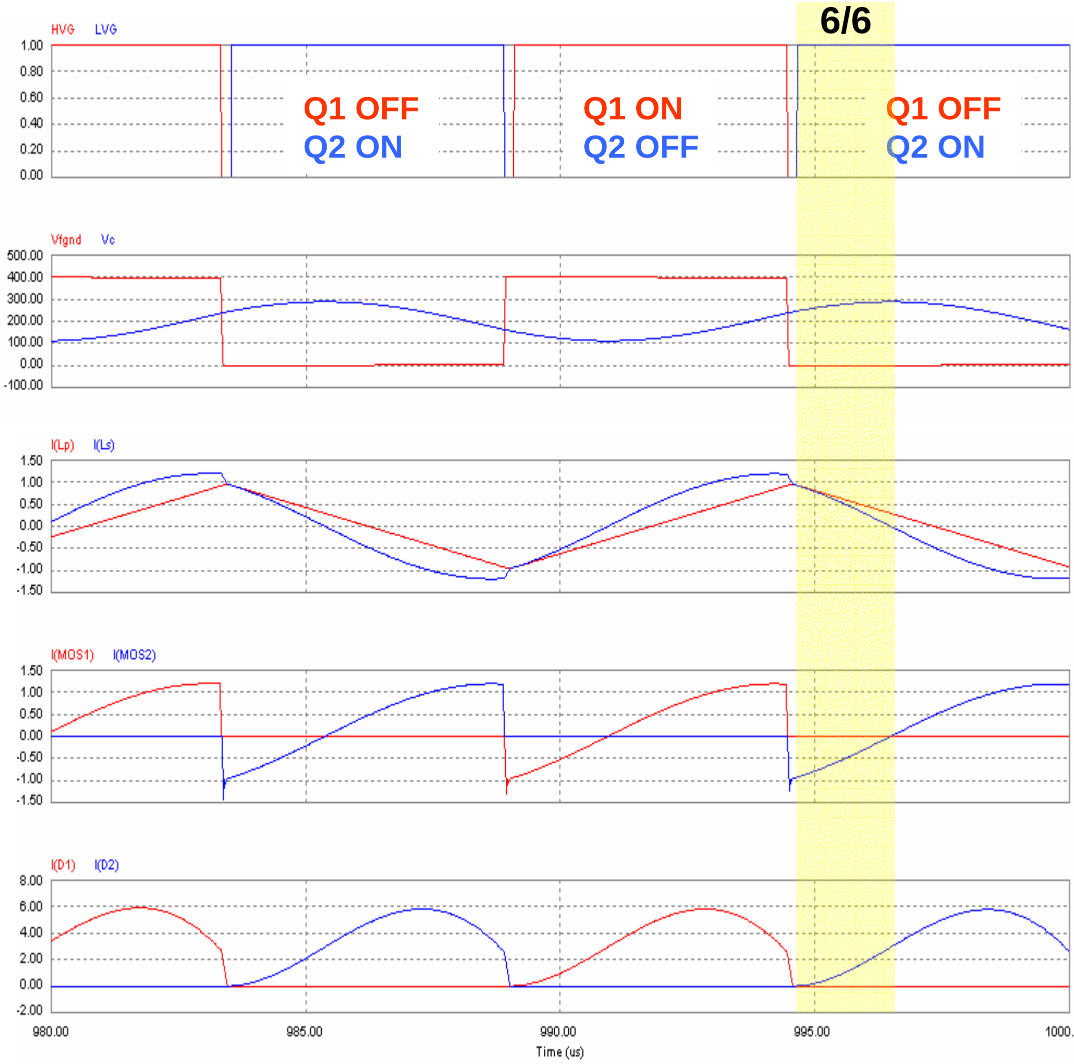
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 5/6)

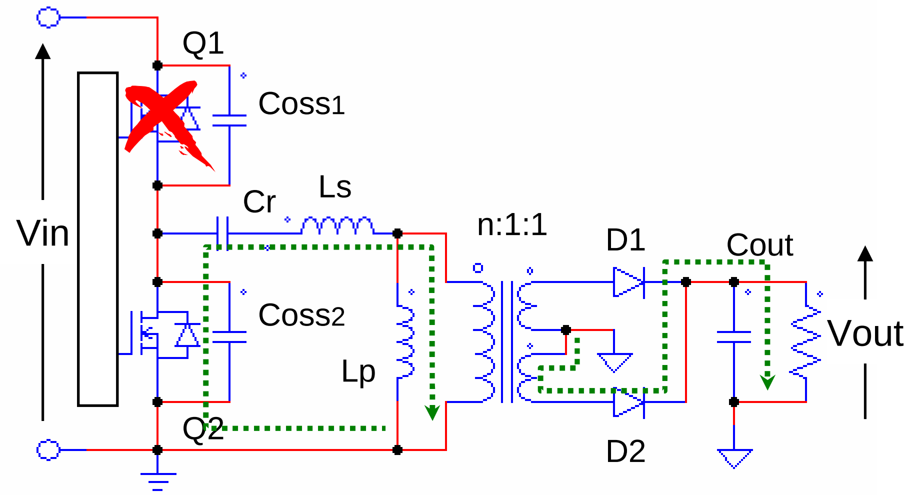




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharges C_{OSS2}, until V(C_{OSS2})=0; Q2's body diode starts conducting
- Output energy comes from Cout
- Phase ends when Q2 is switched on

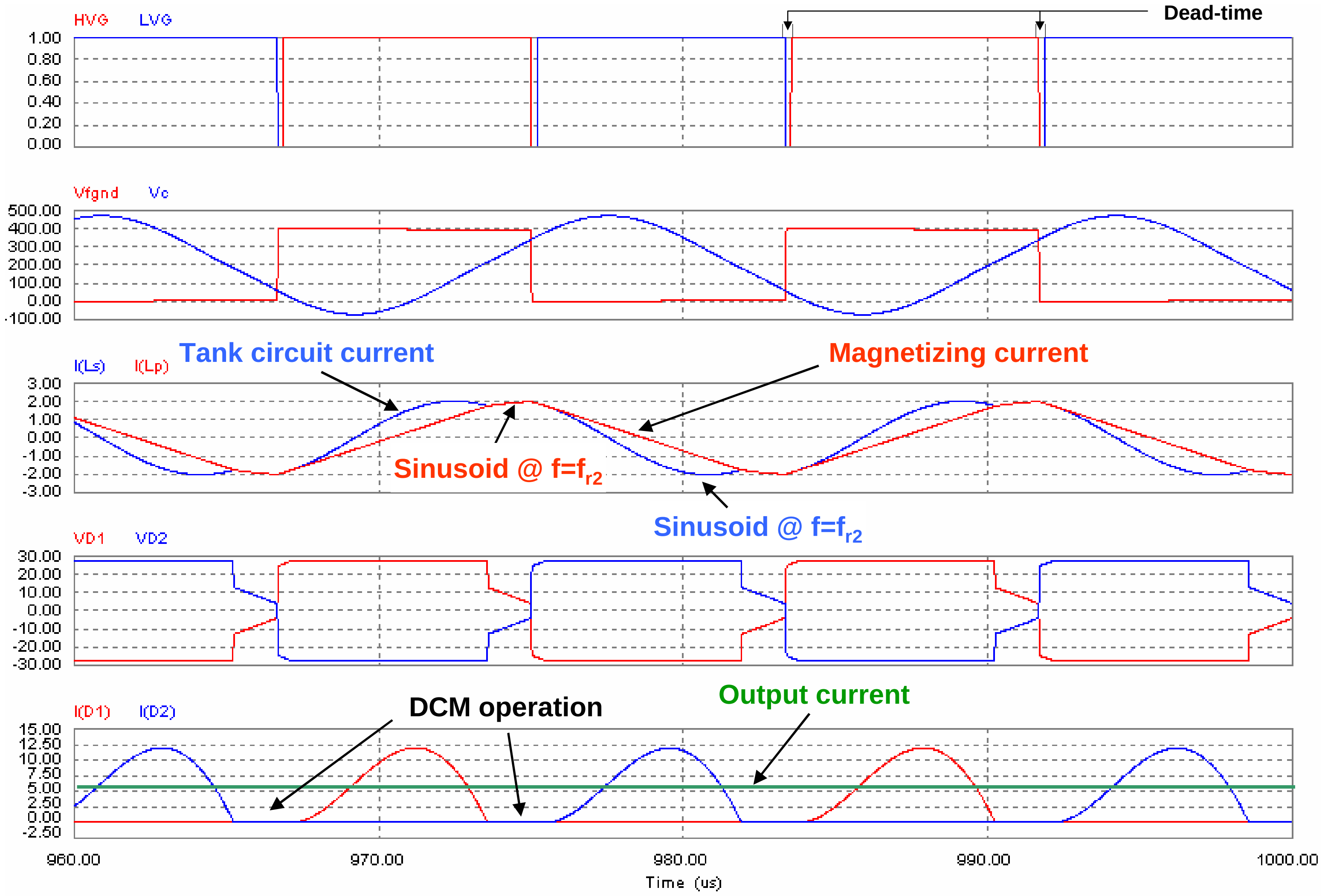
LLC Resonant Half-bridge
Operating Sequence above resonance (Phase 6/6)





- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, fr1 appears
- I(Ls) flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from Cr and Ls
- Phase ends when I(Ls)=0, Phase 1 starts

LLC Resonant Half-bridge
Waveforms below resonance ($f_{sw} < f_{r1}$)



Dead-time

Gate-drive signals

HB mid-point Voltage

Resonant cap voltage

Tank circuit current

Magnetizing current

Sinusoid @ $f=f_{r2}$

Sinusoid @ $f=f_{r2}$

Transformer currents

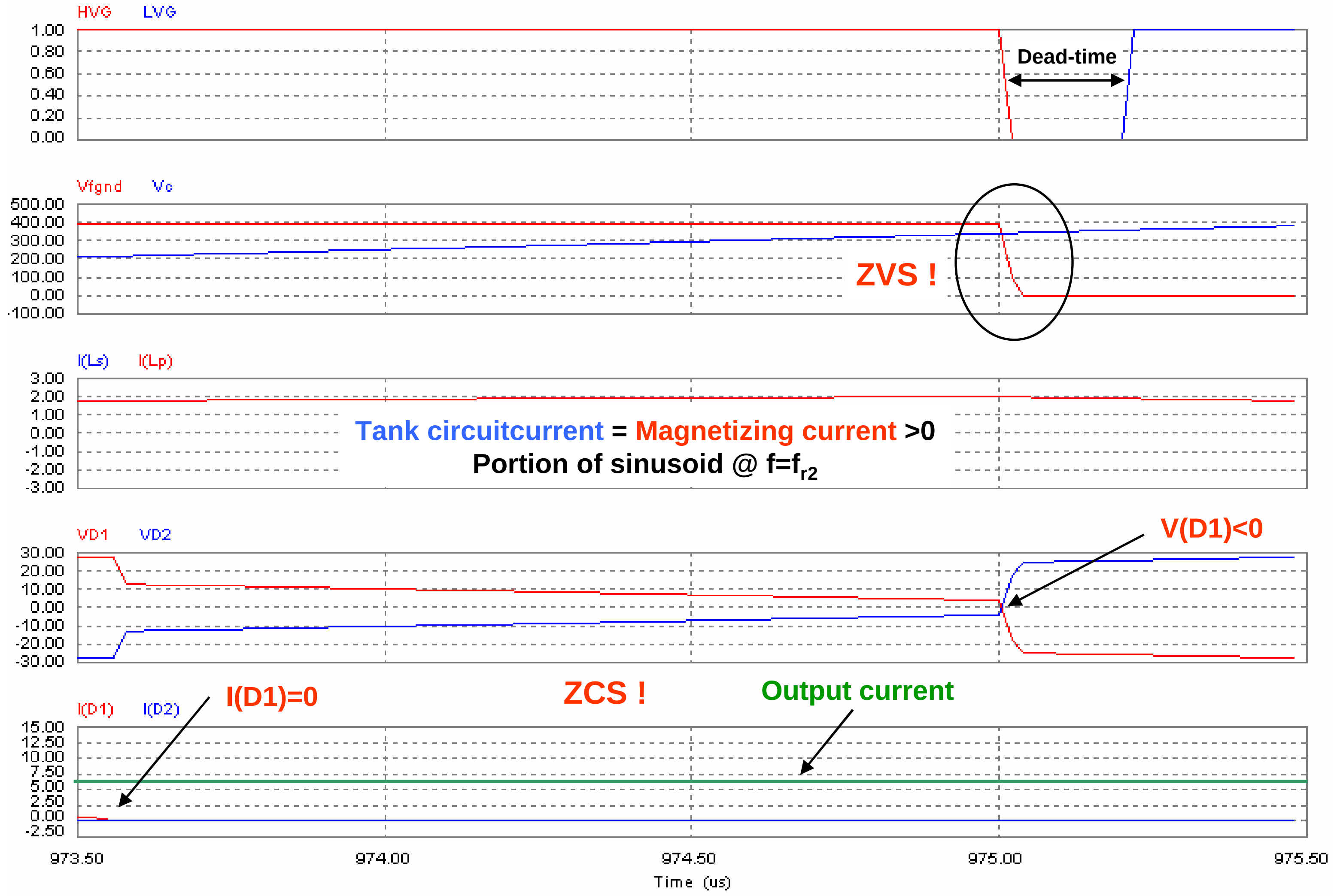
Diode voltages

DCM operation

Output current

Diode currents

LLC Resonant Half-bridge
Switching details below resonance ($f_{sw} < f_{r1}$)



Tank circuitcurrent = Magnetizing current >0

Portion of sinusoid @ $f=f_{r2}$

Gate-drive signals

HB mid-point Voltage

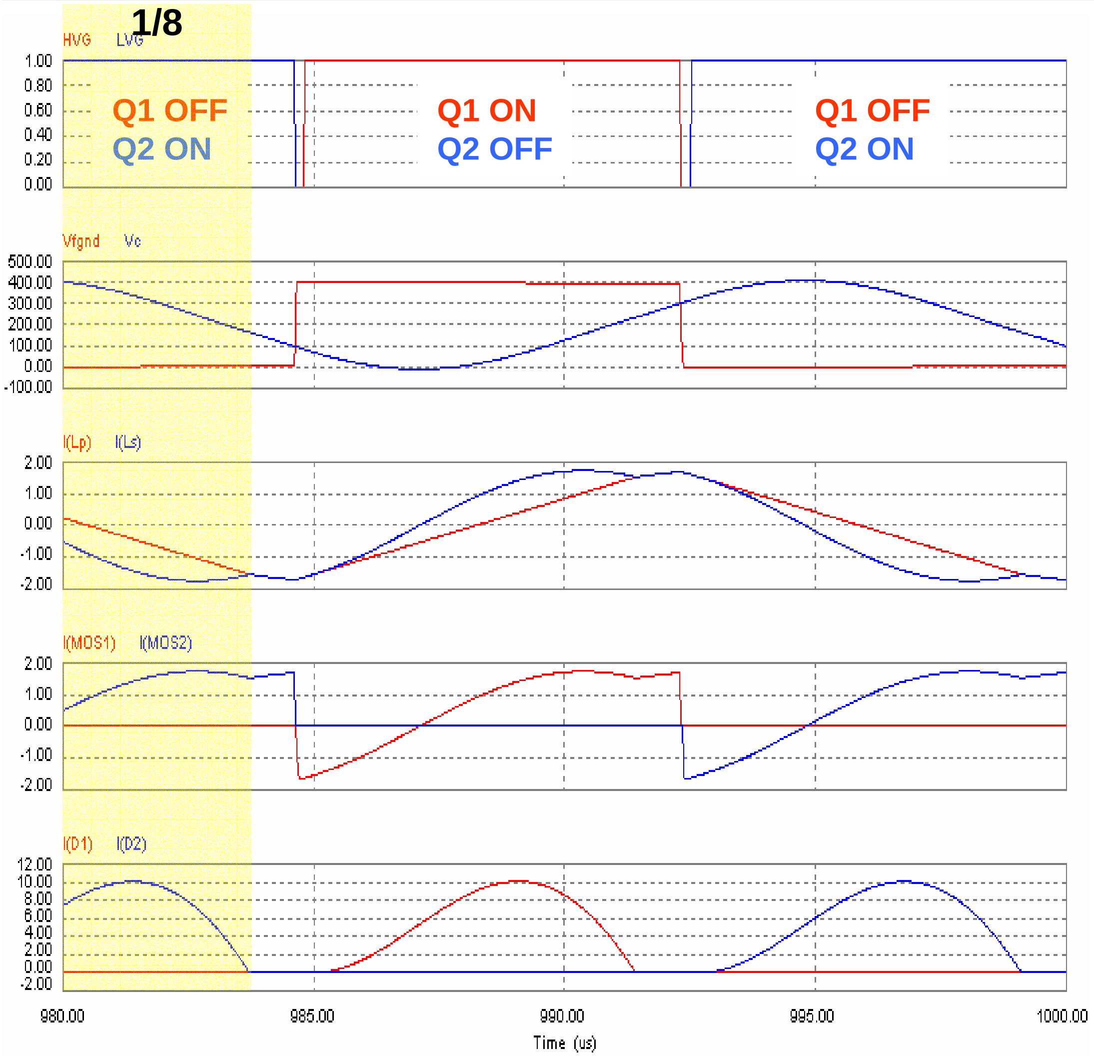
Resonant cap voltage

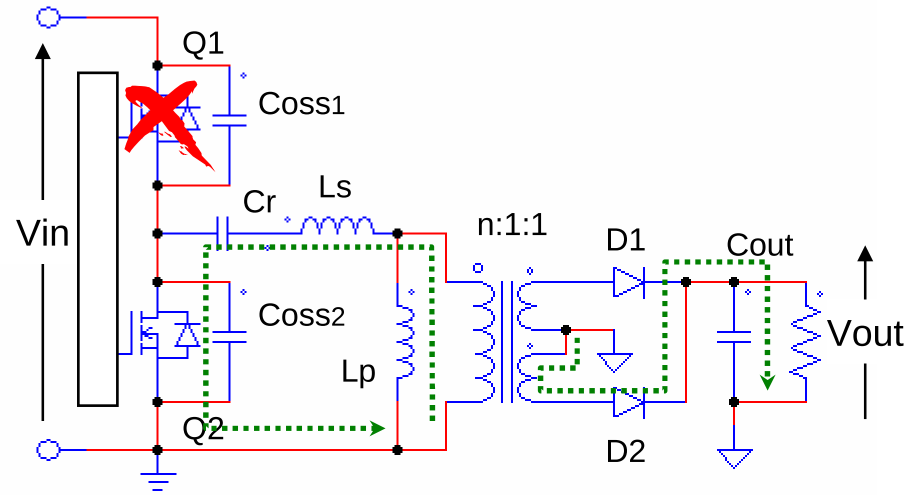
Transformer currents

Diode voltages

Diode currents

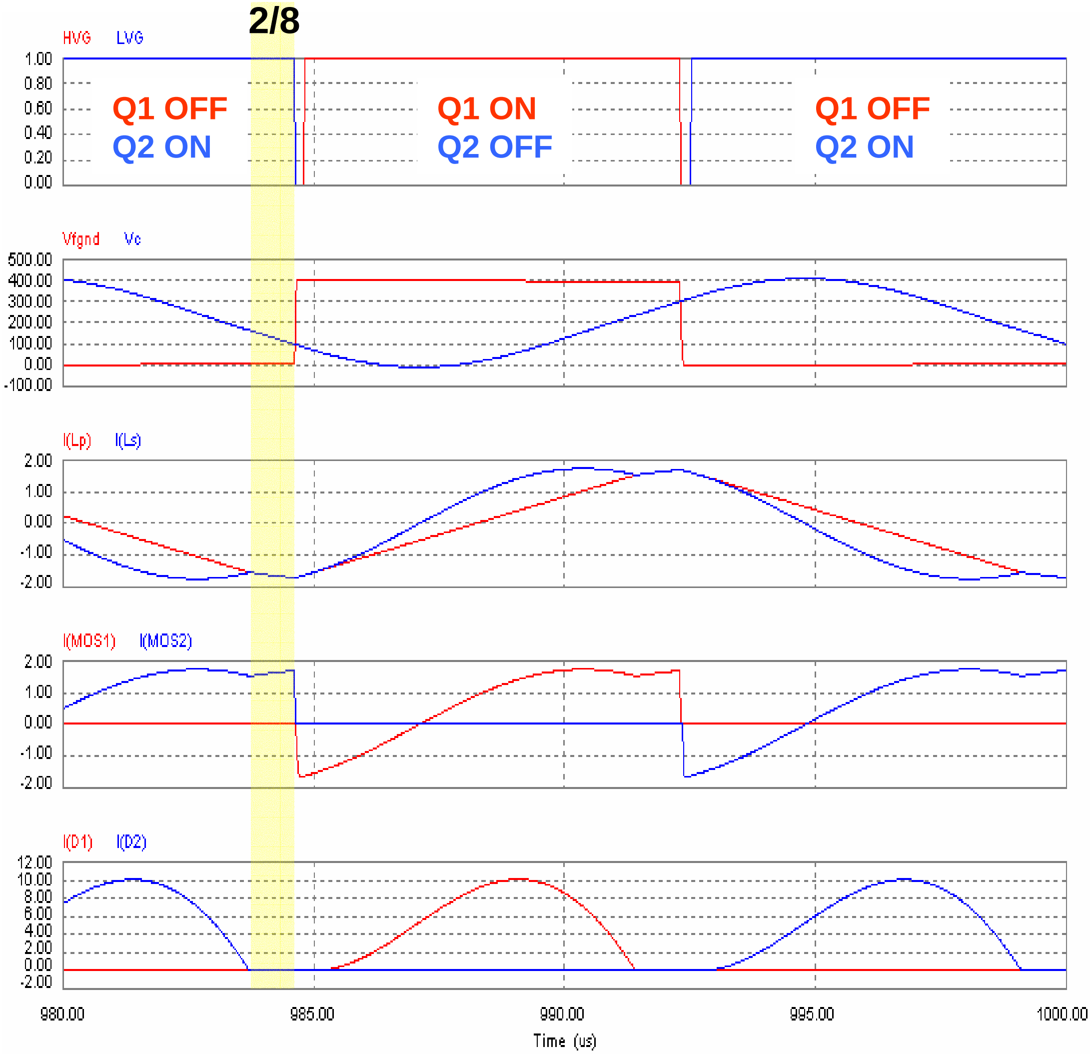
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 1/8)

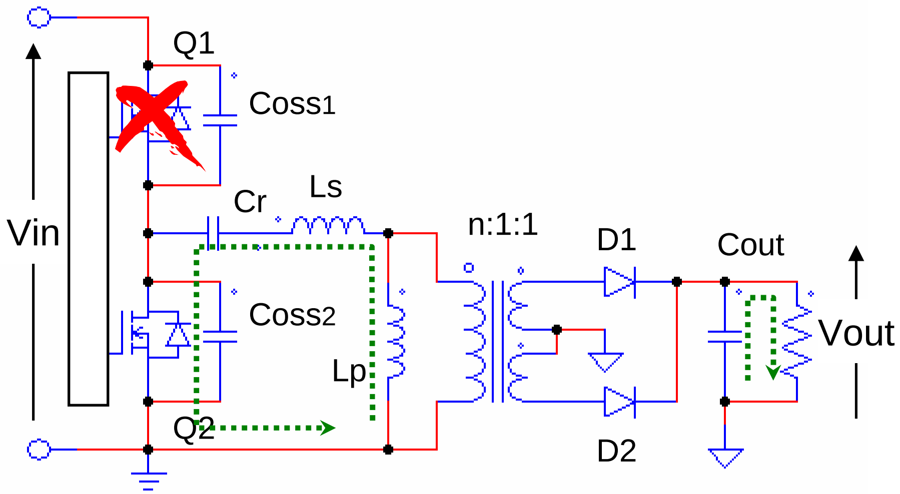




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when I(D2)=0

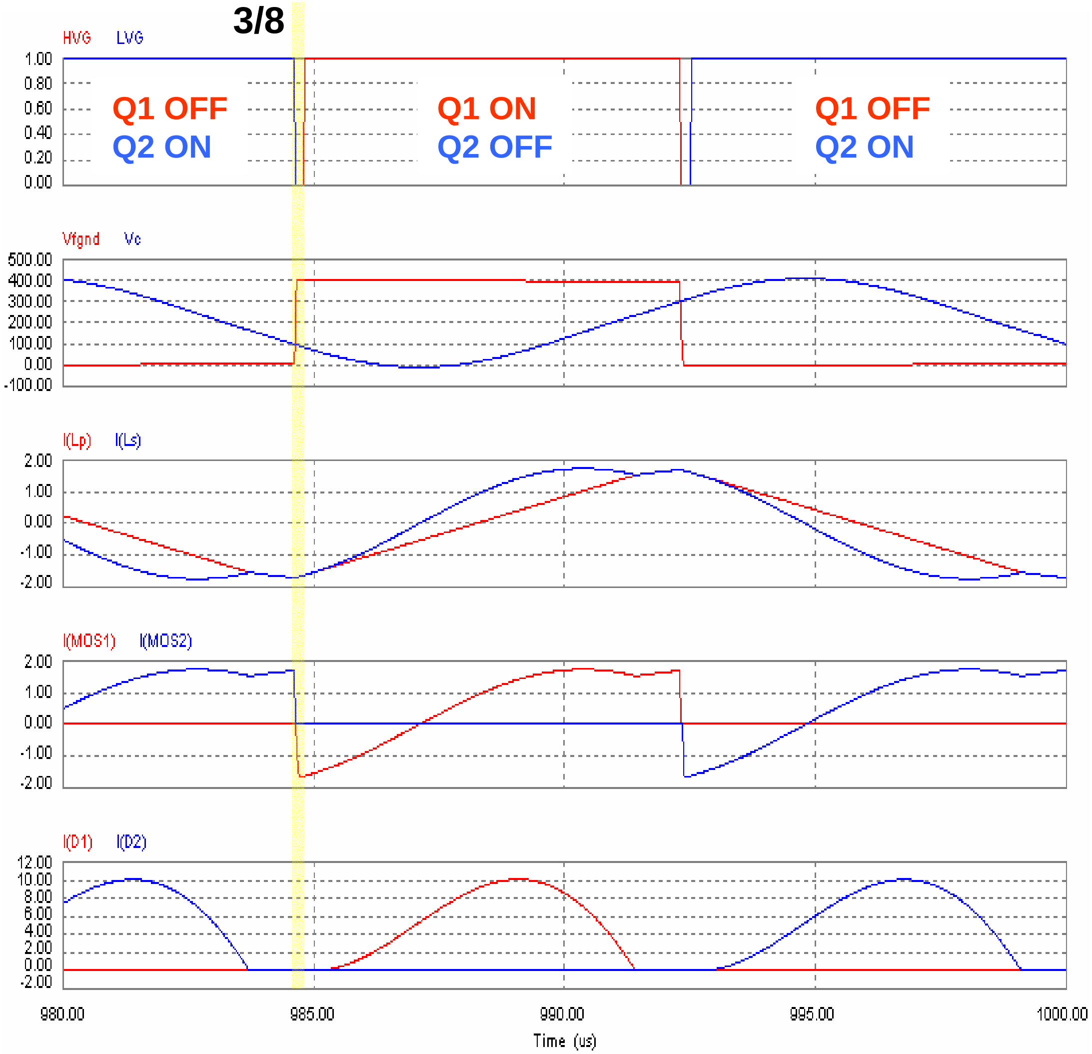
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 2/8)

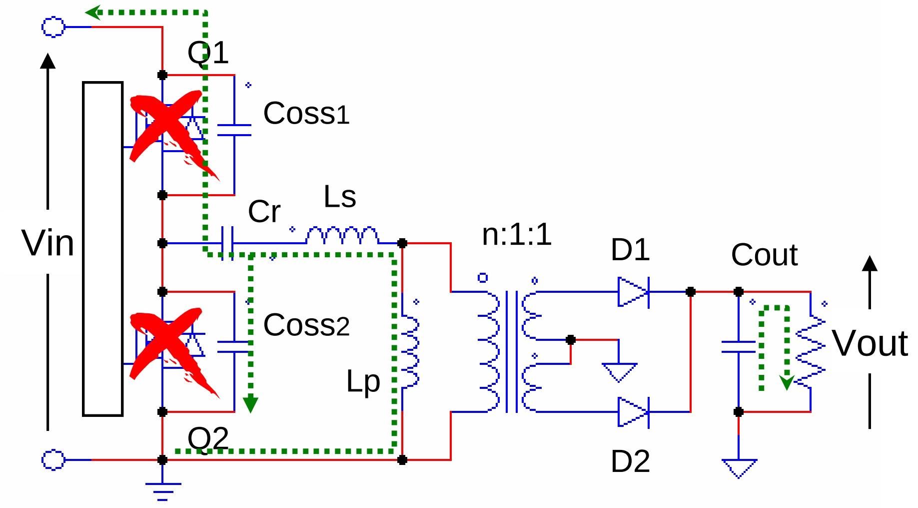




- Q2 is ON, Q1 is OFF
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- Cr resonates with Ls+Lp, f_{r2} appears
- Output energy comes from Cout
- Phase ends when Q2 is switched off

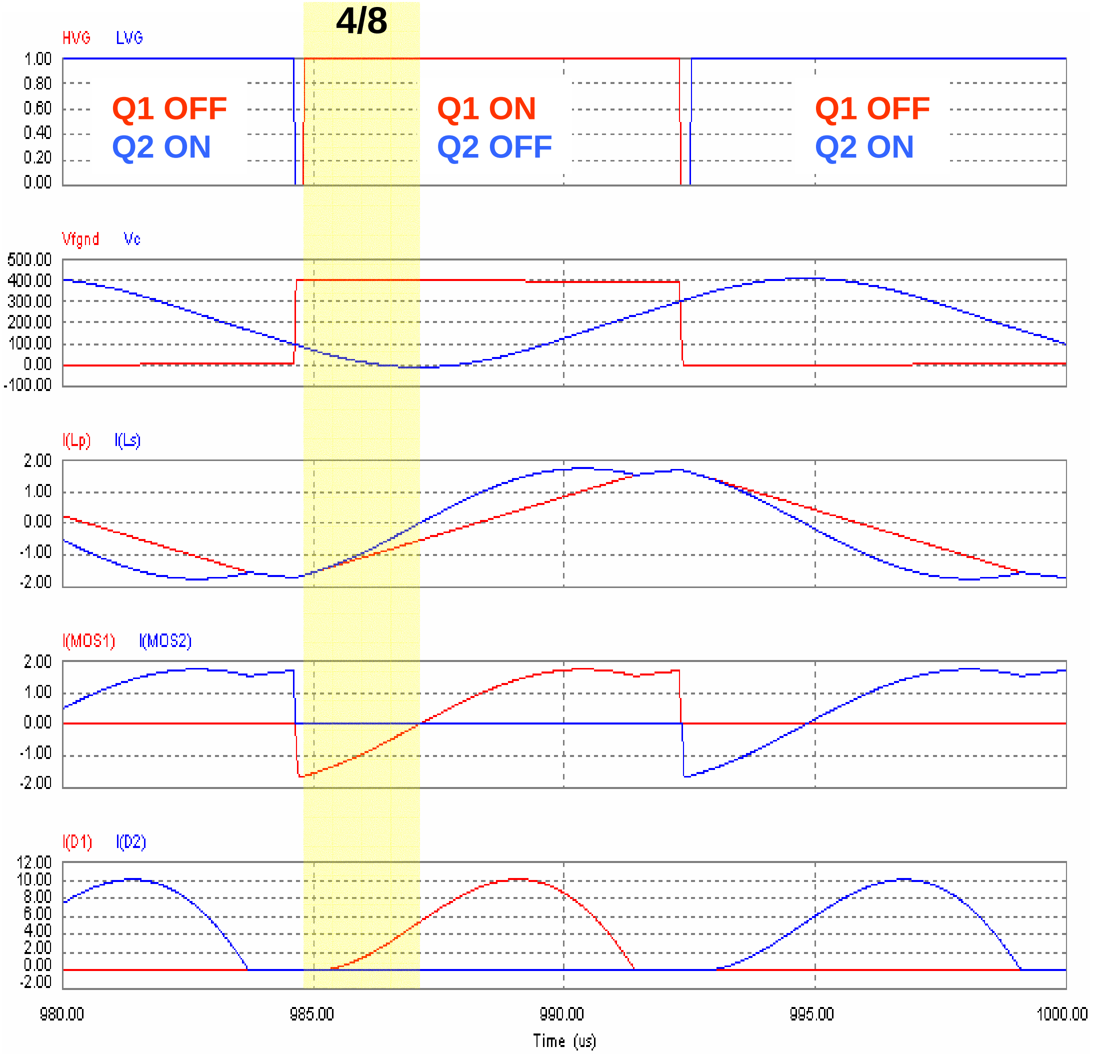
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 3/8)

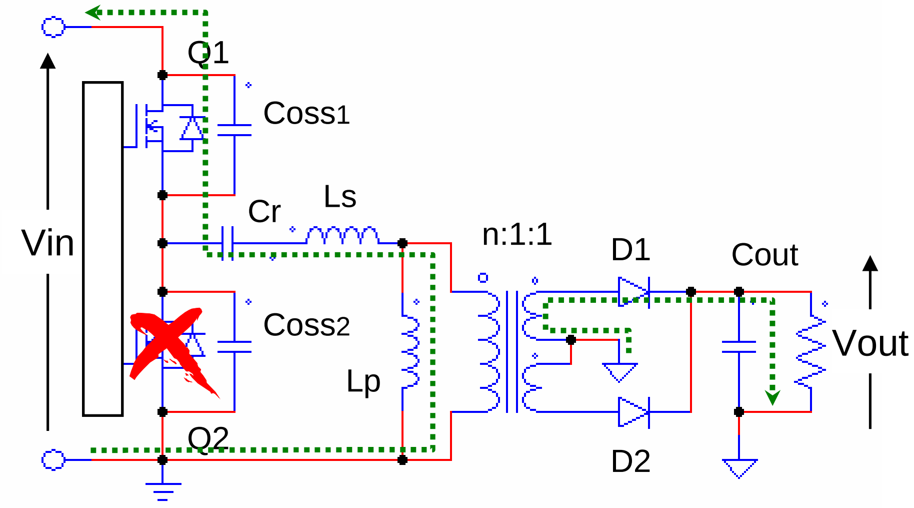




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharges C_{OSS1}, until V(C_{OSS2})=Vin; Q1's body diode starts conducting, energy goes back to Vin
- Phase ends when Q1 is switched on

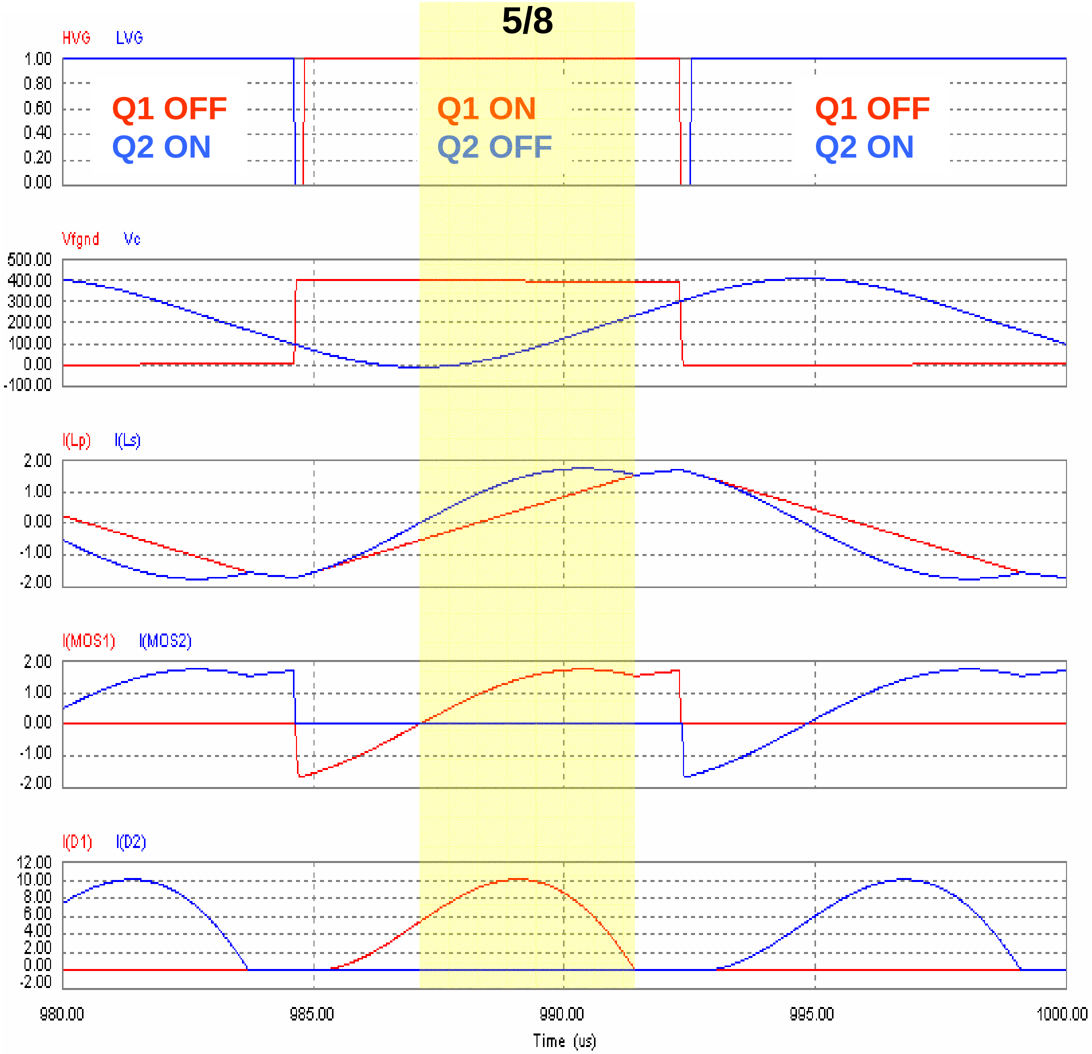
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 4/8)

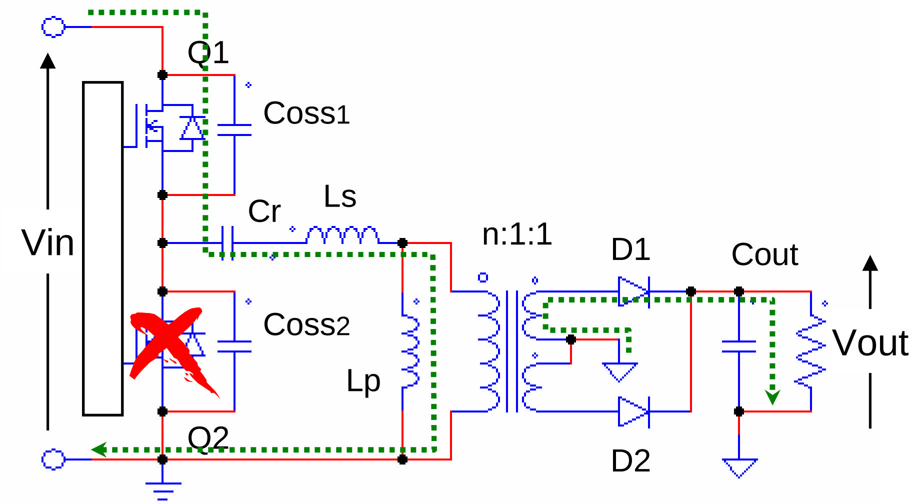




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back to Vin (Q1 is working in the 3rd quadrant)
- Energy is recirculating into Vin
- Phase ends when I(Ls)=0

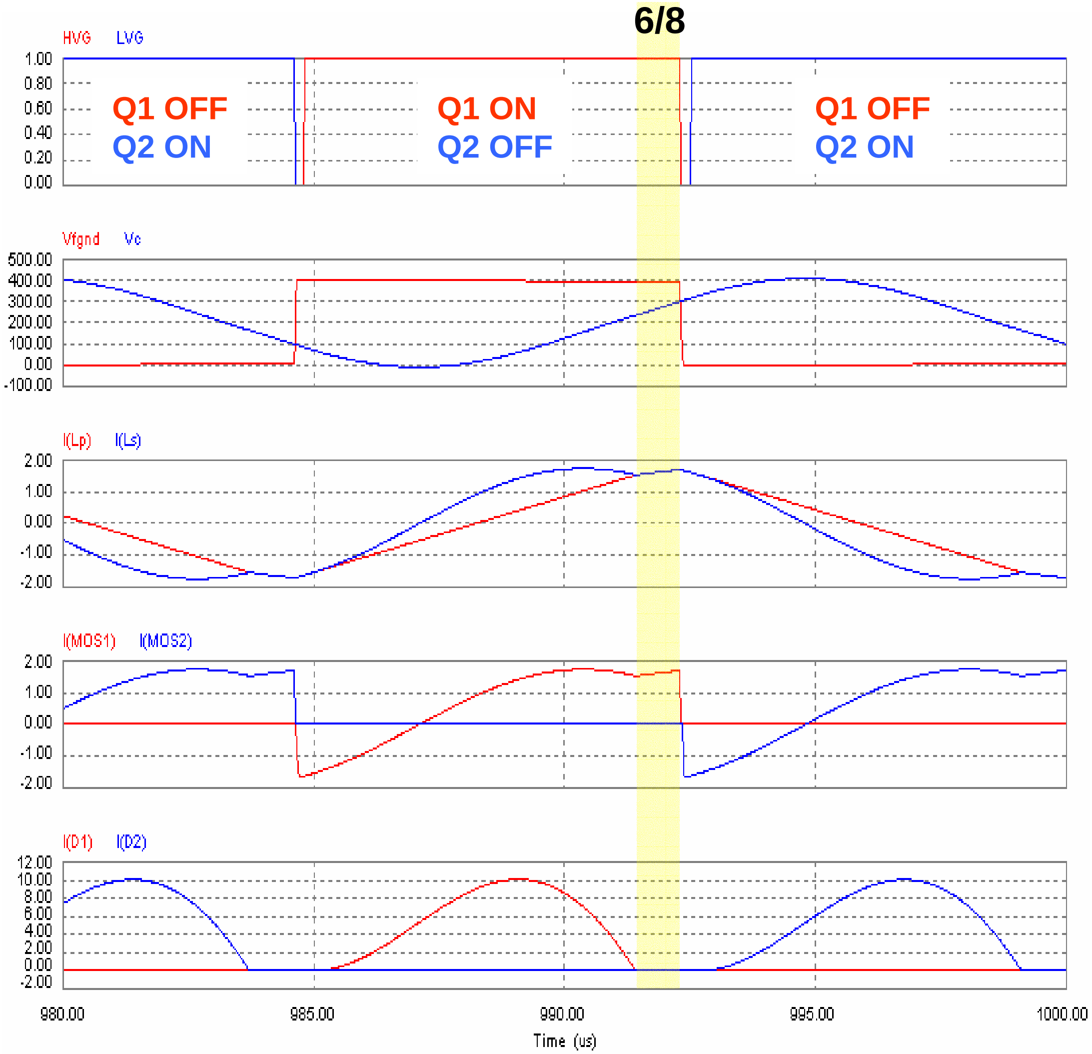
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 5/8)

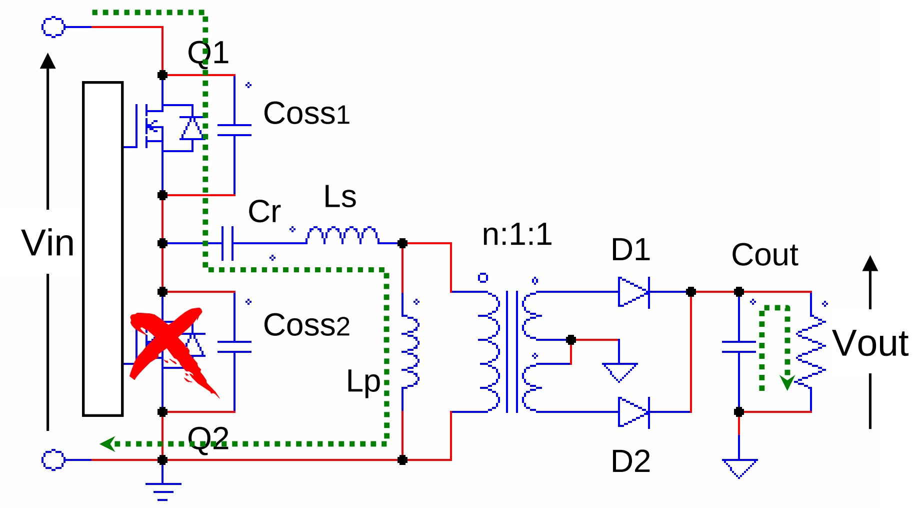




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·Vout.
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from Vin to ground
- Energy is taken from Vin and goes to Vout
- Phase ends when I(D1)=0

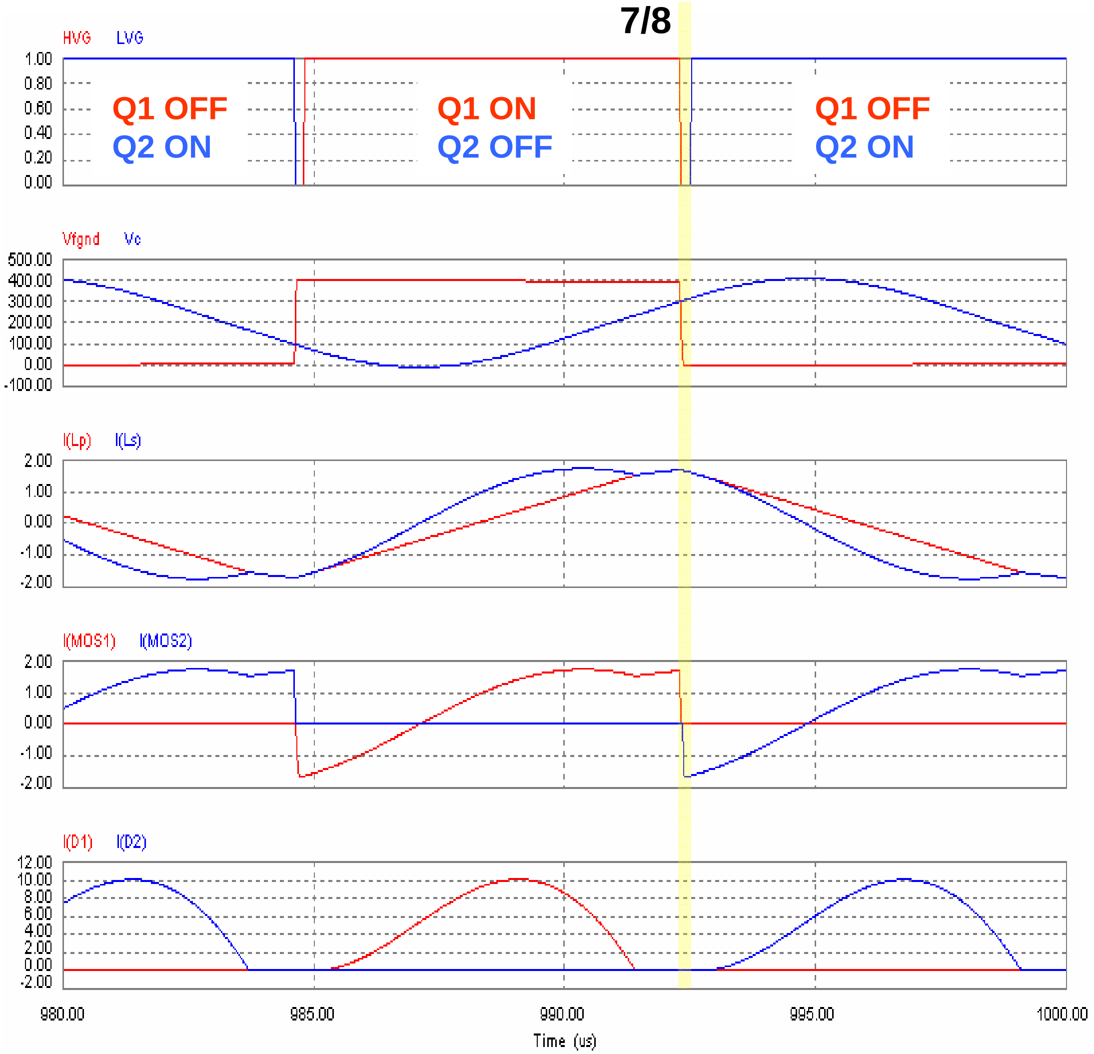
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 6/8)

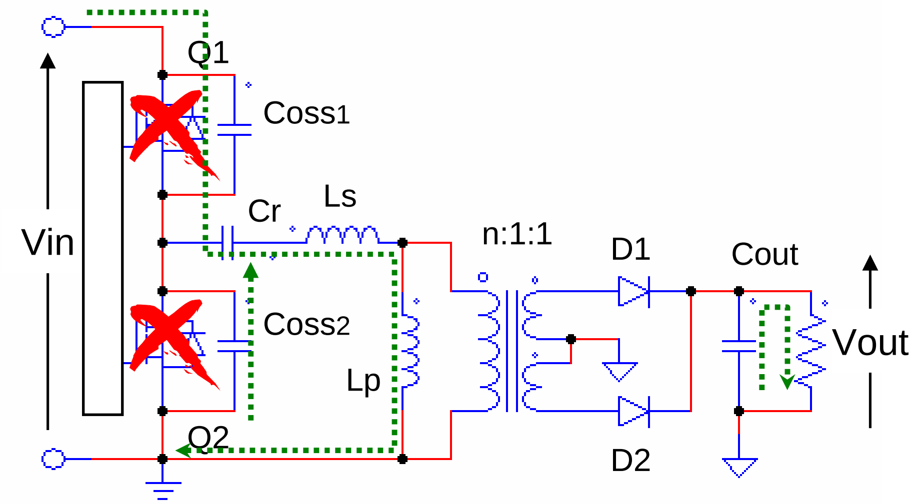




- Q1 is ON, Q2 is OFF
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- Cr resonates with Ls+Lp, f_{r2} appears
- Output energy comes from Cout
- Phase ends when Q1 is switched off

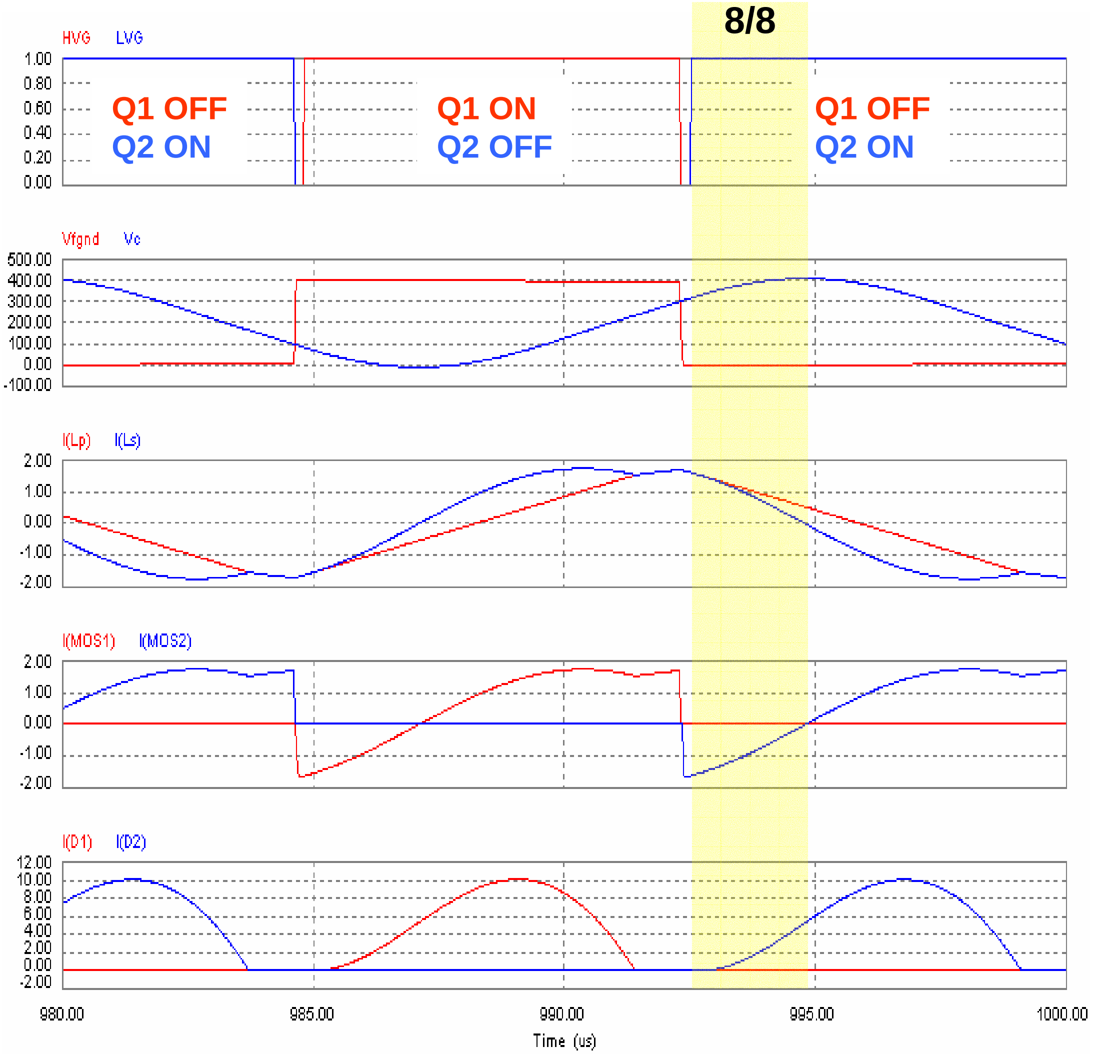
LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 7/8)

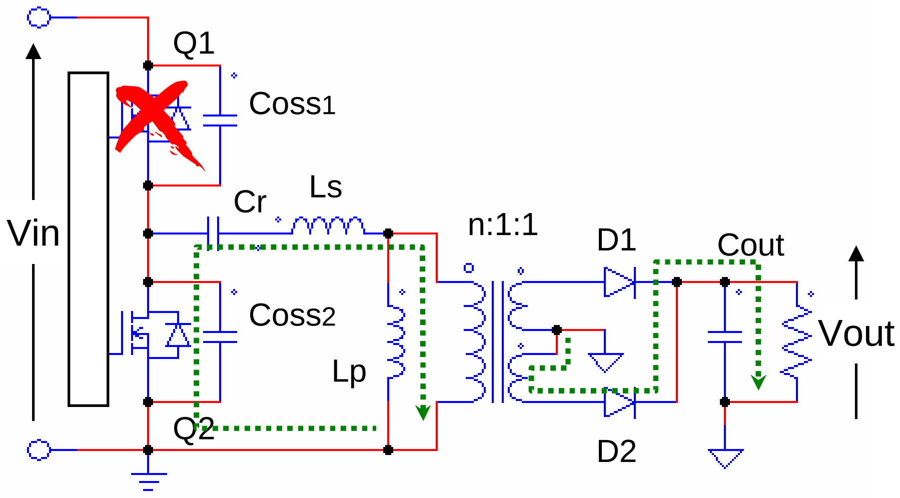




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharges C_{OSS2}, until V(C_{OSS2})=0, then Q2's body diode starts conducting
- Output energy comes from Cout
- Phase ends when Q2 is switched on

LLC Resonant Half-bridge
Operating Sequence below resonance (Phase 8/8)





- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- Lp is dynamically shorted: V(Lp) =-n·Vout.
- Cr resonates with Ls, fr1 appears
- I(Ls) flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from Cr and Ls
- Phase ends when I(Ls)=0, Phase 1 starts

LLC Resonant Half-bridge
Capacitive mode ($f_{sw} \sim f_{r2}$): why it must be avoided

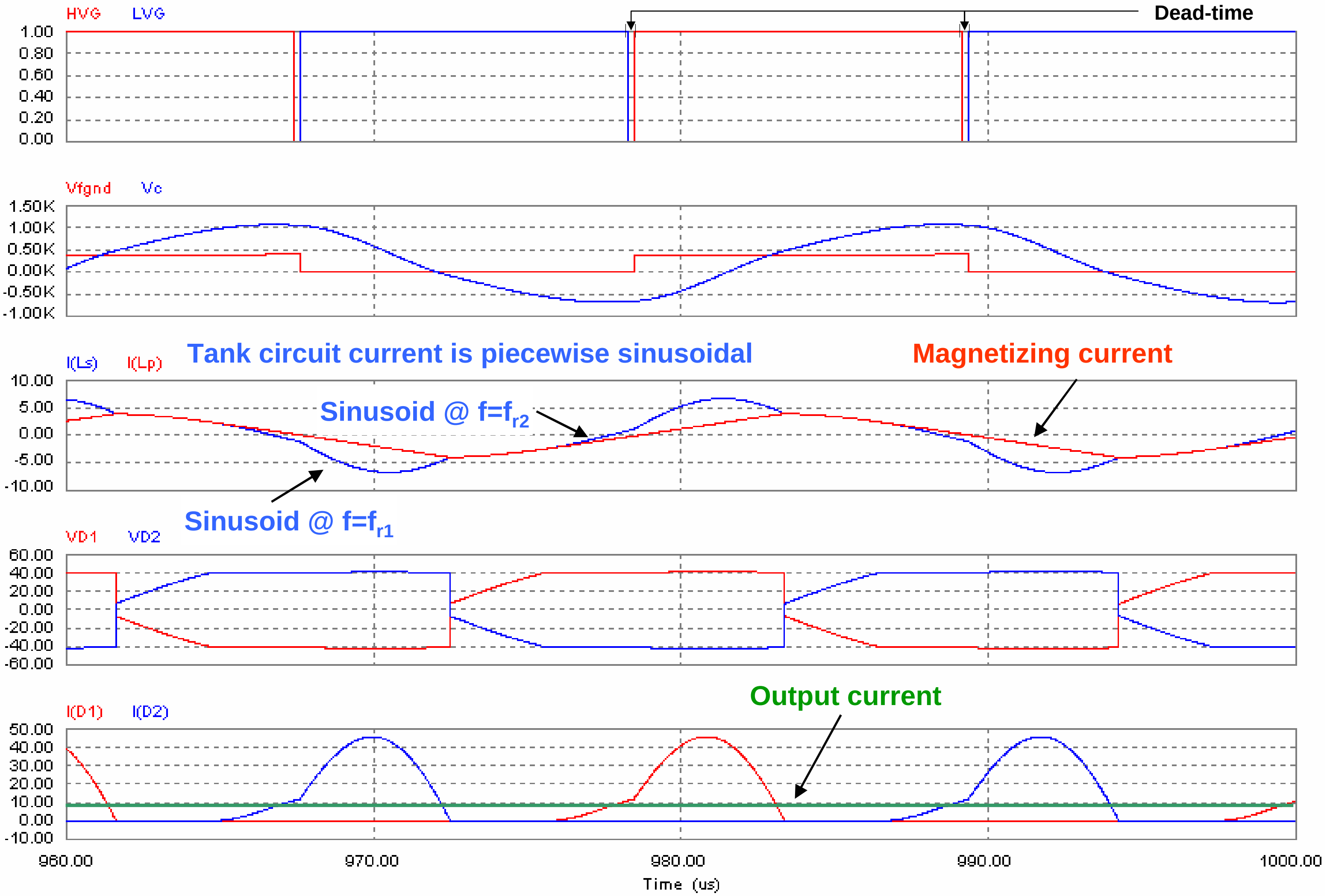
Capacitive mode is encountered when f_{sw} gets close to f_{r2}
Although in capacitive mode ZCS can be achieved, however ZVS is lost, which causes:

- Hard switching of Q1 & Q2: high switching losses at turn-on and very high capacitive losses at turn-off
- Body diode of Q1 & Q2 is reverse-recovered: high current spikes at turn-on, additional power dissipation; MOSFETs will easily blow up.
- High level of generated EMI
- Large and energetic negative voltage spikes in the HB midpoint that may cause the control IC to fail

Additionally, feedback loop sign could change from negative to positive:

- In capacitive mode the energy vs. frequency relationship is reversed
- Converter operating frequency would run away towards its minimum (if MOSFETs have not blown up already!)

LLC Resonant Half-bridge
Waveforms in capacitive mode ($f_{sw} \sim f_{r2}$)



Dead-time

Tank circuit current is piecewise sinusoidal

Magnetizing current

Sinusoid @ $f=f_{r2}$

Sinusoid @ $f=f_{r1}$

Output current

Gate-drive signals

HB mid-point Voltage

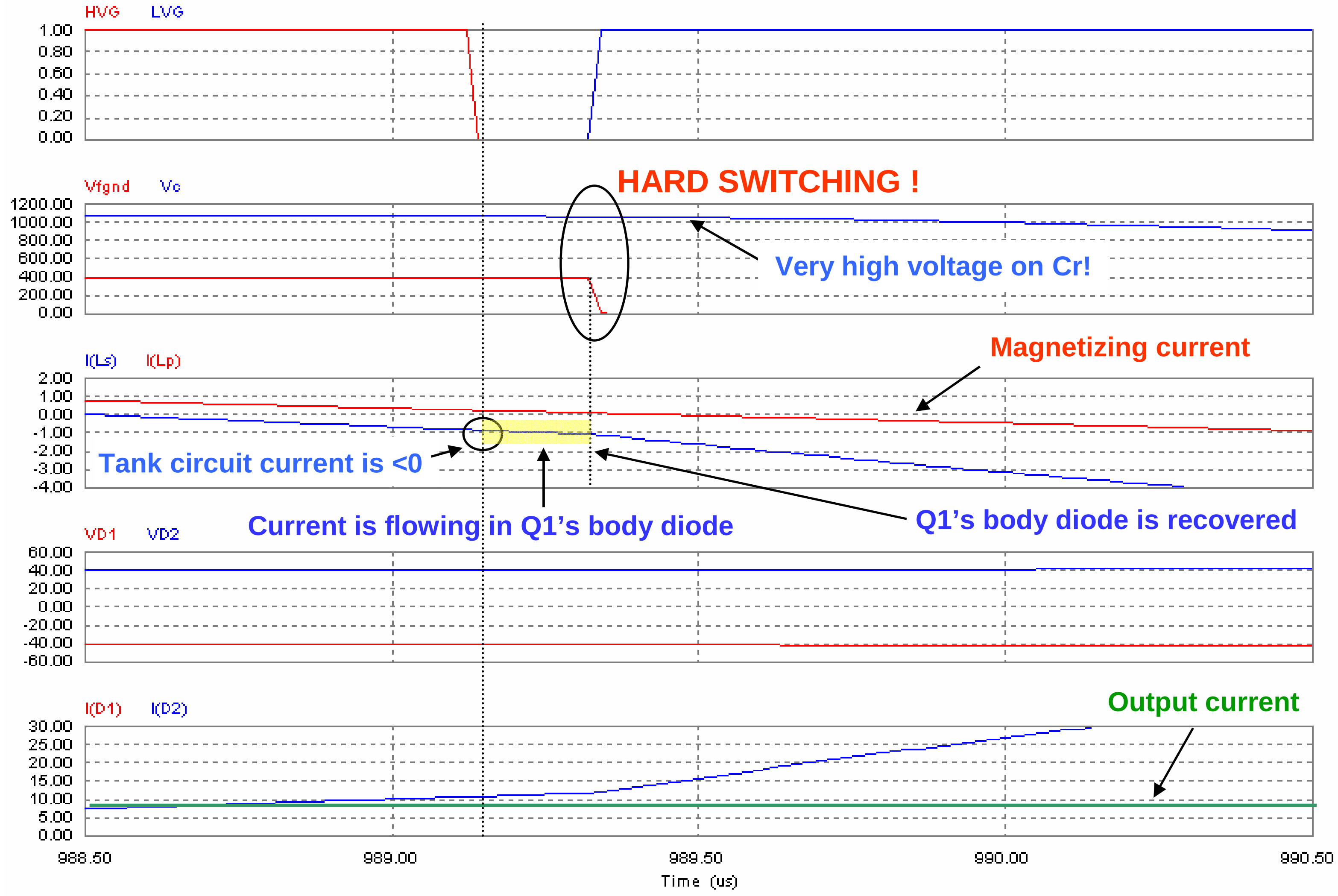
Resonant cap voltage

Transformer currents

Diode voltages

Diode currents

LLC Resonant Half-bridge
Switching details in capacitive mode ($f_{sw} \sim f_{r2}$)



Gate-drive signals

HARD SWITCHING !

Very high voltage on Cr!

HB mid-point Voltage

Resonant cap voltage

Magnetizing current

Transformer currents

Tank circuit current is <0

Current is flowing in Q1's body diode

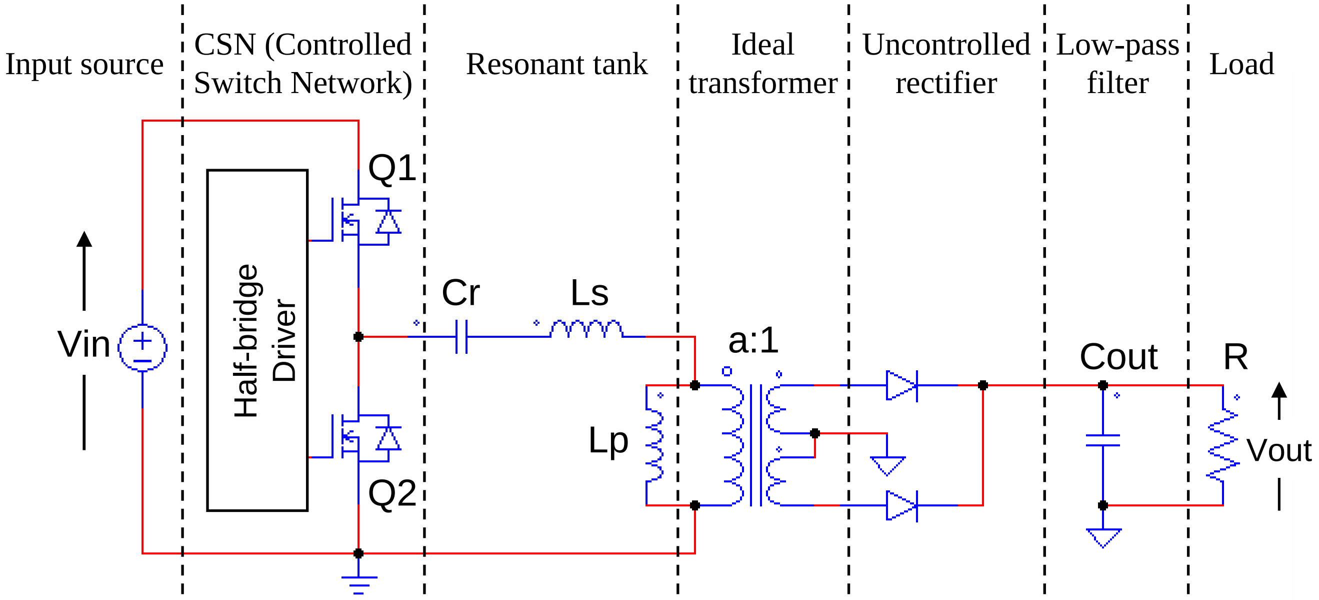
Q1's body diode is recovered

Diode voltages

Output current

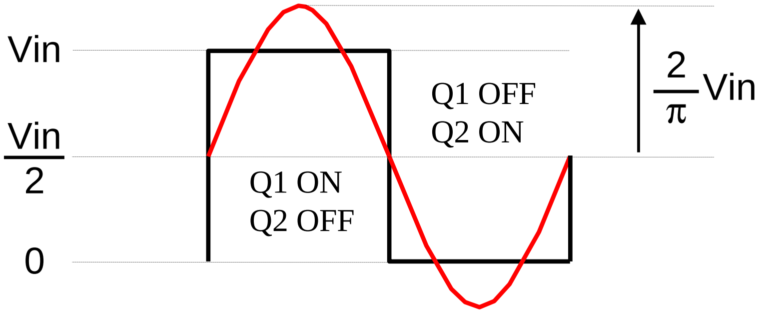
Diode currents

LLC Resonant Half-bridge
Approximate analysis with FHA approach: Basics



BASIC PRINCIPLES

- CSN provides a square wave voltage at a frequency fsw, dead times are neglected
- Resonant tank responds primarily to its fundamental component, then:
- Tank waveforms are approximated by their fundamental components
- Uncontrolled rectifier + low-pass filter's effect is incorporated into the load.



Note:

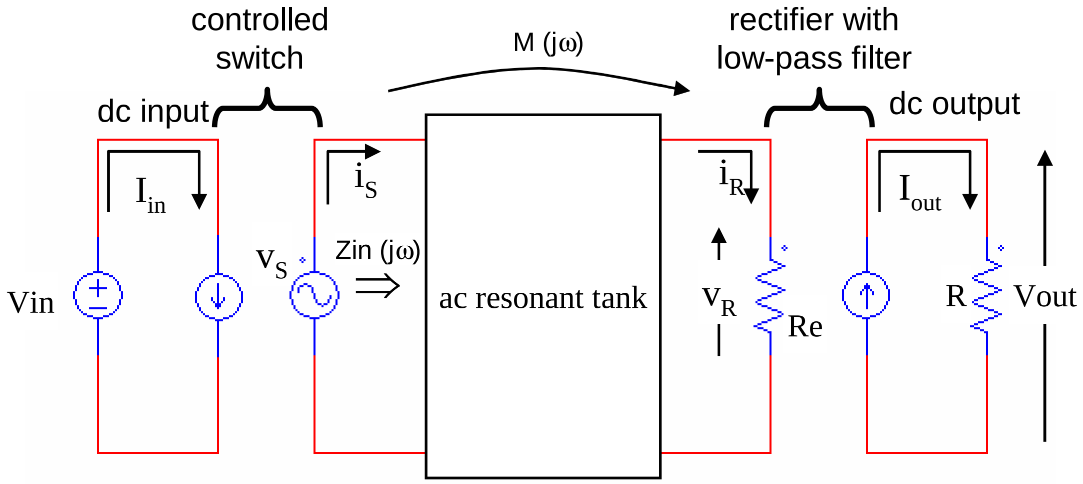
- Cr is both resonant and dc blocking capacitor
- Its ac voltage is superimposed on a dc component equal to Vin/2 (duty cyle is 50% for both Q1 and Q2)

LLC Resonant Half-bridge
Equivalent model with FHA approach

- The actual circuit turns into an equivalent linear circuit where the ac resonant tank is excited by an effective sinusoidal input source and drives an effective resistive load.
- Standard ac analysis can be used to solve the circuit
- Functions of interest: Input Impedance Zin(jω) and Forward Transfer Function M(jω).
- It is possible to show that the complete conversion ratio Vout/Vin is:

$$\boxed{\frac{\mathrm{Vout}}{\mathrm{Vin}} = \left\| M(j\omega) \right\|}$$

- This result is valid for any resonant topology



$$v_S = \frac{2}{\pi} \mathrm{Vin} \cdot \sin(2\pi \cdot fs \cdot t)$$

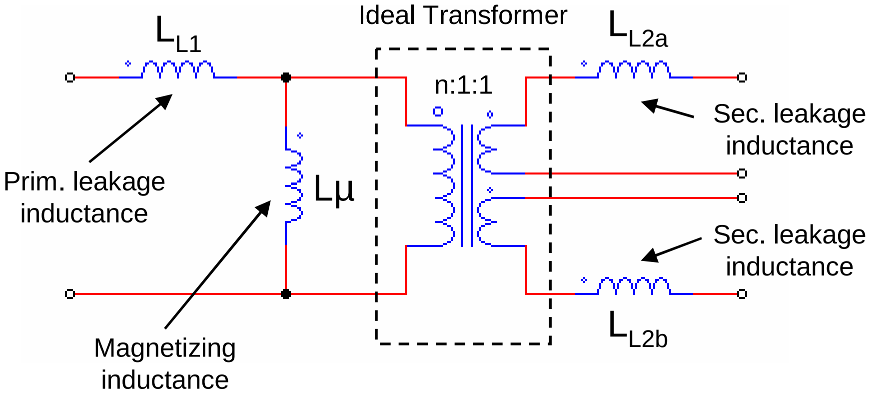
$$\mathrm{Re} = \frac{8}{\pi^2} a^2 R$$

$$I_{in} = \frac{2}{\pi} \left\| i_s \right\| \cos(\varphi_S) = \frac{2}{\pi} \left\| v_S \right\| \mathrm{Re}\left(\frac{1}{Z_i} \right)$$

$$\mathrm{Iout} = \frac{2}{\pi} a \left\| i_R \right\|$$

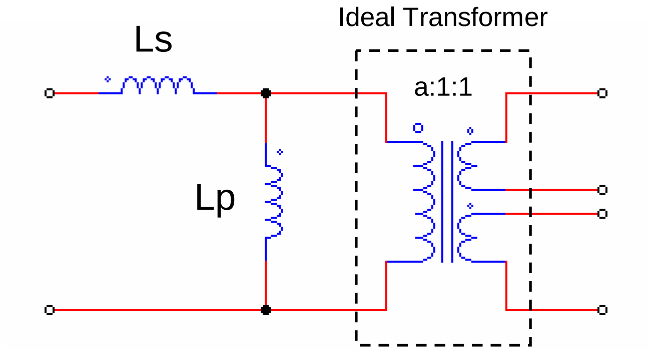
LLC Resonant Half-bridge Transformer model (I)

Physical model



- Results from the analysis of the magnetic structure (reluctance model appraach)
- n is the actual primary-to-secondary turn ratio
- $L\mu$ models the magnetizing flux linking all windings
- L_{L1} models the primary flux not linked to secondary
- L_{L2a} and L_{L2b} model the secondary flux not linked to primary; symmetrical windings: $L_{L2a} = L_{L2b}$

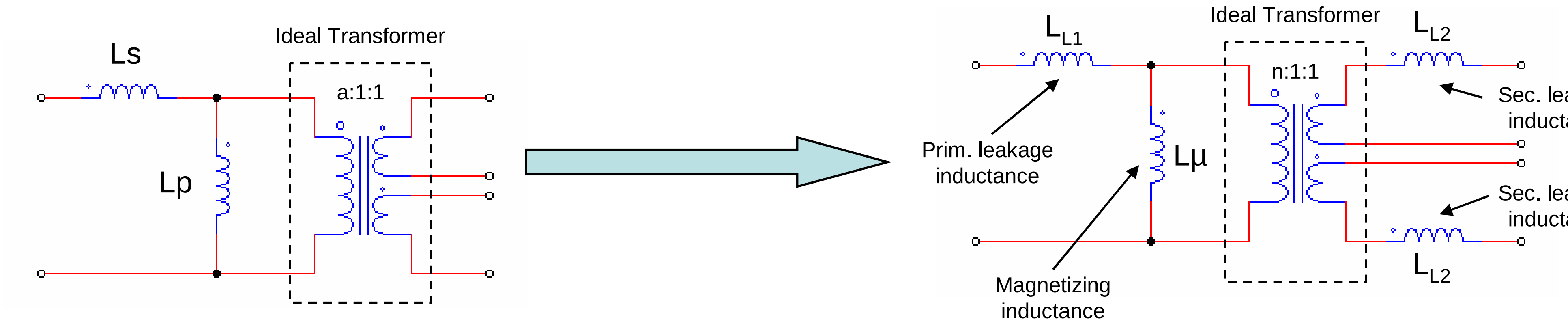
All-Primary-Side equivalent model used for LLC analysis



- *APS equivalent model: terminal equations are the same, internal parameters are different*
- a is not the actual primary-to-secondary turn ratio
- Ls is the primary inductance measured with all secondaries shorted out
- Lp is the difference between the primary inductance measured with secondaries open and Ls

NOTE: $L_{L1} + L\mu$ = Ls + Lp = L1 primary winding inductance

LLC Resonant Half-bridge Transformer model (II)

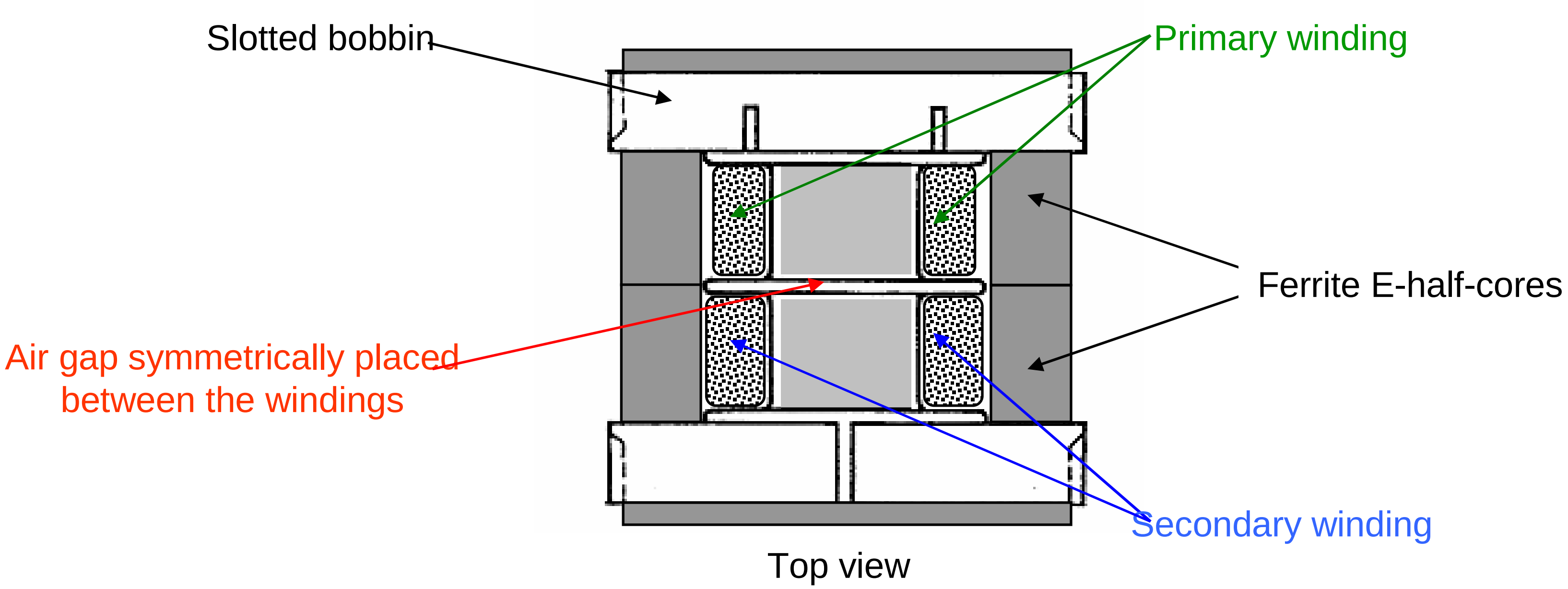


- We need to go from the APS model to the physical model to determine transformer specification
- Undetermined problem (4 unknowns, 3 conditions); one more condition needed (related to the physical magnetic structure)
- Only n is really missing: $L1 = Ls + Lp = L_{L1} + L\mu$ is known and measurable, Ls is measurable
- Magnetic circuit symmetry will be assumed: equal leakage flux linkage for both primary and secondary ⇒ $L_{L1} = n^2 \cdot L_{L2}$; then:

$$\boxed{n = a\sqrt{\frac{Lp}{Lp + Ls}}}$$

LLC Resonant Half-bridge
Transformer model (III)

Example of magnetically symmetrical structure



- Like in any ferrite core it is possible to define a specific inductance A_L (which depends on air gap thickness) such that $L1 = Np^2 \cdot A_L$
- In this structure it is also possible to define a specific leakage inductance A_{Llk} such that $Ls = Np^2 \cdot A_{Llk}$. A_{Llk} is a function of bobbin's geometry; it depends on air gap position but <u>not on its thickness</u>

LLC Resonant Half-bridge
Numerical results of ac analysis

The ac analysis of the resonant tank leads to the following result:

- Input Impedance:

$$Z_{in}(x,k,Q) = Z_R \cdot \left[Q \cdot \frac{x^2 \cdot k^2}{1 + x^2 \cdot k^2 \cdot Q^2} + j \cdot \left(x - \frac{1}{x} + \frac{x \cdot k}{1 + x^2 \cdot k^2 \cdot Q^2} \right) \right]$$

- Module of the Forward transfer function (voltage conversion ratio):

$$\left| M(x,k,Q) \right| = \frac{1}{2} \cdot \frac{1}{\sqrt{\left[1 + \frac{1}{k} \cdot \left(1 - \frac{1}{x^2} \right) \right]^2 + Q^2 \cdot \left(x - \frac{1}{x} \right)^2}}$$

where:

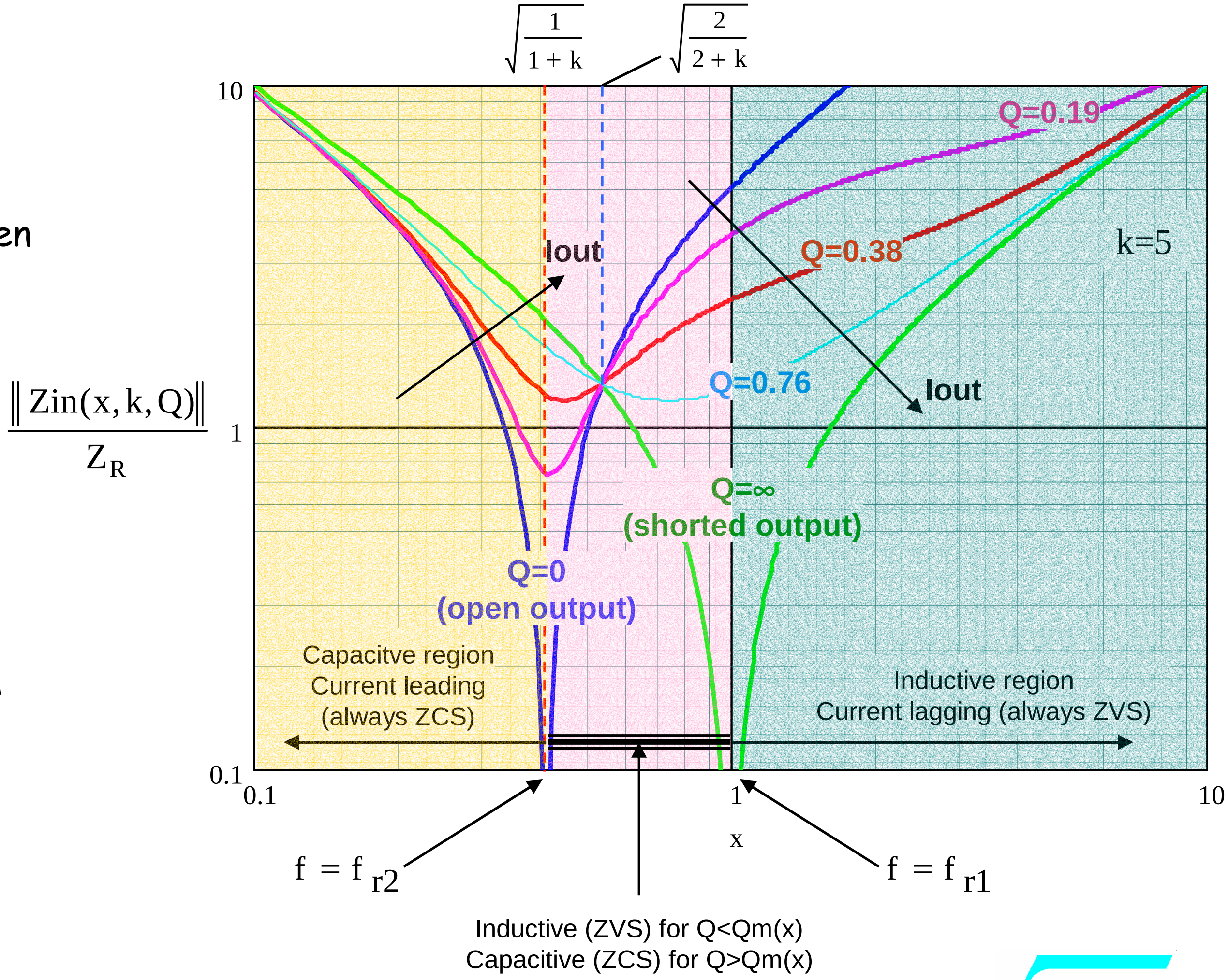
$$f_{r1} = \frac{1}{2 \cdot \pi \cdot \sqrt{Ls \cdot Cr}} \; ; \quad x = \frac{f}{f_{r1}} \; ; \quad k = \frac{Lp}{Ls} \; ; \quad Z_R = \sqrt{\frac{Ls}{Cr}} \; ; \quad Re = \frac{8}{\pi^2} \cdot a^2 \cdot R \; ; \quad Q = \frac{Z_R}{Re}$$

NOTES:

- x is the “normalized frequency”; x<1 is “below resonance”, x>1 is “above resonance”
- Z_R is the characteristic impedance of the tank circuit;
- Q, the quality factor, is related to load: Q=0 means Re=∞ (open load), Q=∞ means Re=0 (short circuit); one can think of Q as proportional to Iout

LLC Resonant Half-bridge
Resonant Tank Input Impedance Zin(jω)

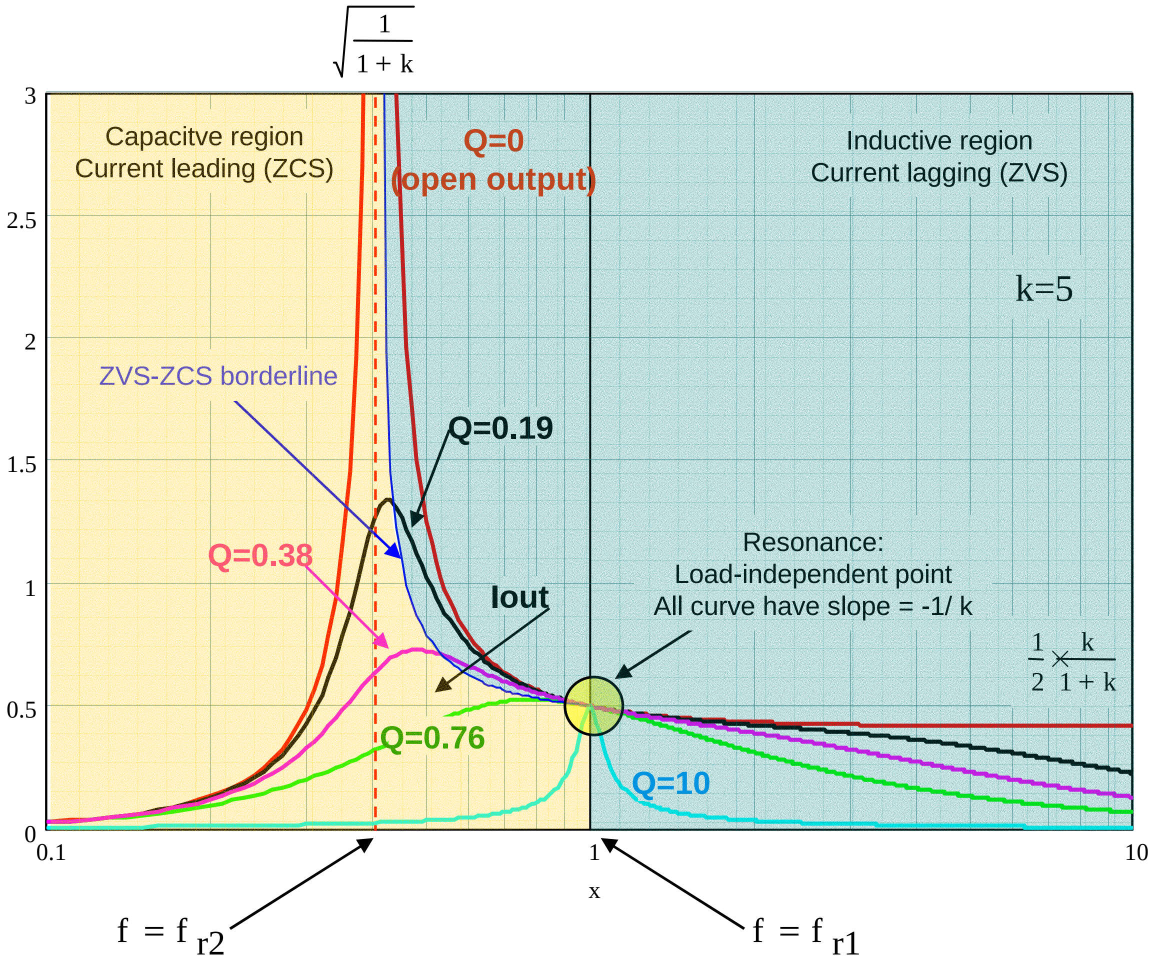
- Above resonance ($x>1$) Zin(jω) is always inductive; current lags voltage, so when $v_S=0$, i_S is still >0: ZVS
- Below f_{r2} ($x<\sqrt{\frac{1}{1+k}}$), Zin(jω) is always capacitive; current leads voltage, so when $v_S=0$, i_S is already <0: ZCS
- Below the first resonance ($\sqrt{\frac{1}{1+k}}<x<1$) the sign of Zin(jω) depends on Q: if $Q<Q_m(x)$ it is inductive ⇒ ZVS; if $Q>Q_m(x)$ it is capacitive ⇒ ZCS.
- In general, the ZVS-ZCS borderline is defined by Im(Zin(jω))=0
- For $x>\sqrt{\frac{2}{2+k}}$ |Zin(jω)| is concordant with the load: the lower the load the lower the input current
- For $x<\sqrt{\frac{2}{2+k}}$ |Zin(jω)| is discordant with the load: the lower the load the higher the input current!



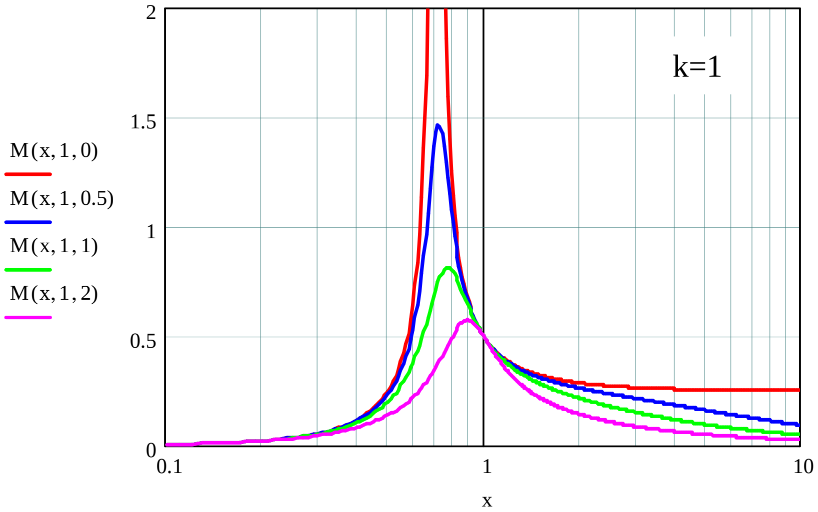
LLC Resonant Half-bridge
Voltage conversion ratio $||M(j\omega)||$

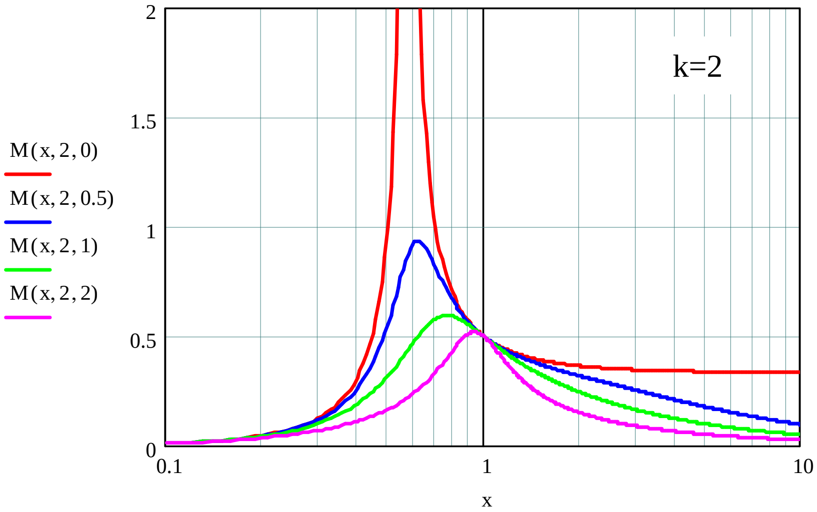
- All curves, for any Q, touch at x=1, M=0.5, with a slope -1/k;
- The open output curve (Q=0) is the upper boundary for converter's operating points in the x-M plane;
  $M = \frac{1}{2} \times \frac{k}{1+k}$ for $x \to \infty$;
  $M \to \infty$ for $x = \sqrt{\frac{1}{1+k}}$
- All curves with Q>0 have maxima that fall in the capacitive region.
- Above resonance it is always M<0.5
- M>0.5 only below resonance
- ZVS below resonance at a given frequency occurs if M> M_{min}>0.5; if M> M_{min}>0.5 is fixed, it occurs if Q>Q_m.

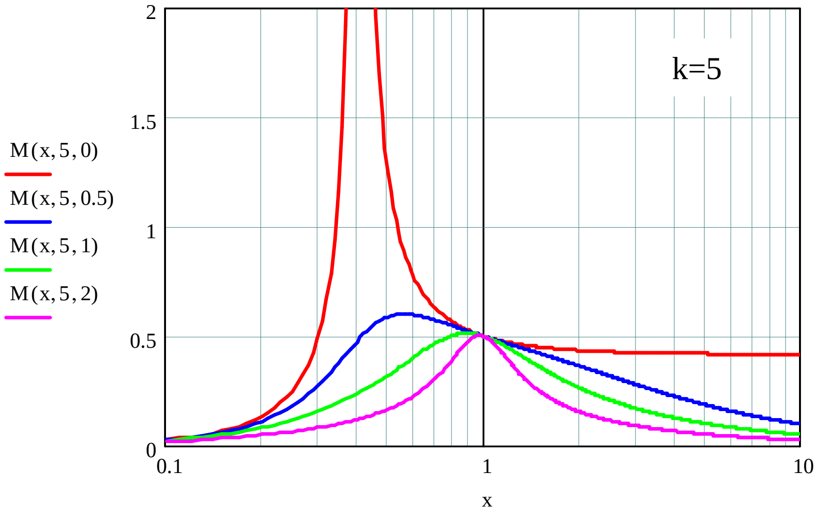
$$M = \frac{a \cdot Vout}{Vin}$$

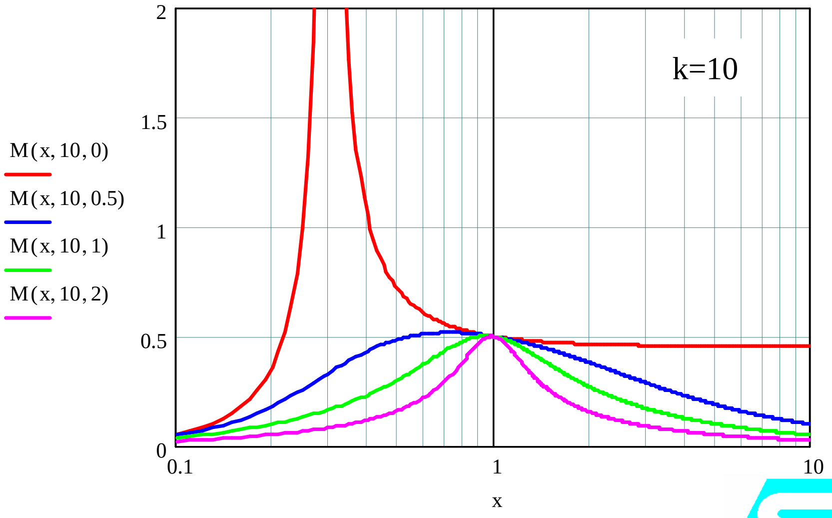


LLC Resonant Half-bridge
Effect of k on ||M(jω)||



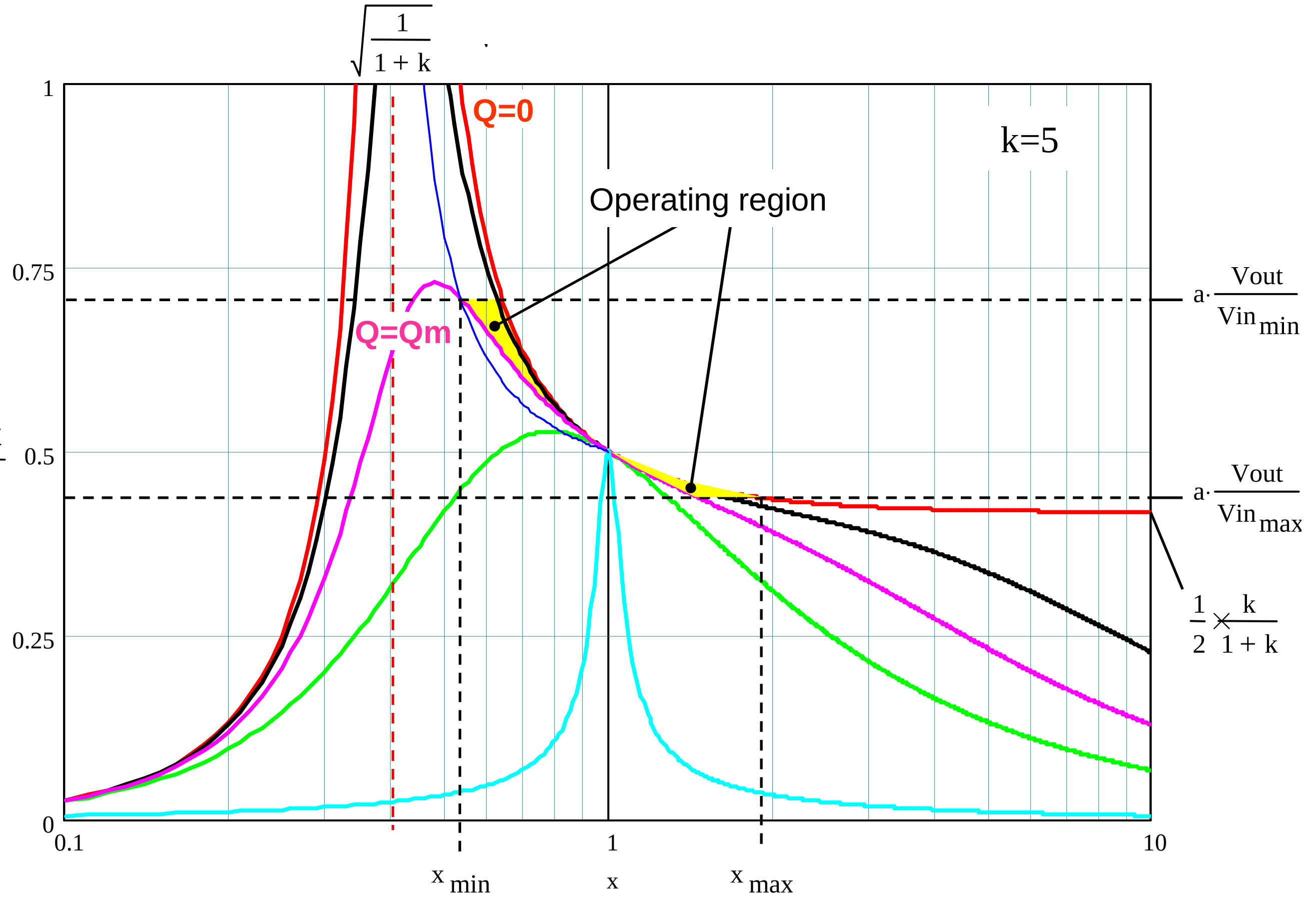






LLC Resonant Half-bridge
Operating region on ||M(jω)|| diagrams

$$M = \frac{a \cdot Vout}{Vin}$$



- M-axis can be rescaled in terms of Vin: Vout is regulated
- Given the input voltage range ($Vin_{min} \div Vin_{max}$), 3 types of possible operation:
  1. always below M<0.5 (step-down)
  2. always above M>0.5 (step-up)
  3. across M=0.5 (step-up/down, shown in the diagram)

LLC Resonant Half-bridge
Full-load issue: ZVS at min. input voltage

- Zin(jω) analysis has shown that ZVS occurs for $x<1$, provided $Q \le Q_m$, i.e. $\mathrm{Im}[Zin(j\omega)] \ge 0$.
- If $Q=Q_m$ ($\mathrm{Im}[Zin(j\omega)] = 0$) the switched current is exactly zero, This is only a necessary condition for ZVS, not sufficient because the parasitic capacitance of the HB midpoint, neglected in the FHA approach, needs some energy (i.e. current) to be fully charged or depleted within the dead-time ($i = C\, dv/dt$)
- A minimum current must be switched to make sure that the HB midpoint can swing rail-to-rail within the dead-time. Then, it must be $Q \le Q_Z < Q_m$.
- Mathematically, the ZVS condition is :

$$\frac{\mathrm{Im}\left(\left(Z_{in}(x,k,Q)\right)\right)}{\mathrm{Re}\left(\left(Z_{in}(x,k,Q)\right)\right)} \ge \frac{2\cdot Coss + C_{stray}}{\pi \cdot Td} \cdot \frac{Vin_{min}^{\,2}}{Pin_{max}}$$

- Coss is the MOSFET's output capacitance, Cstray an additional contribution due to transformer's windings and the layout
- Analytic expression of Q_Z is not handy; a good rule of thumb is to consider the value of Q_m and take 10% margin for component tolerance: FHA gives conservative results as far as the ZVS condition is concerned.

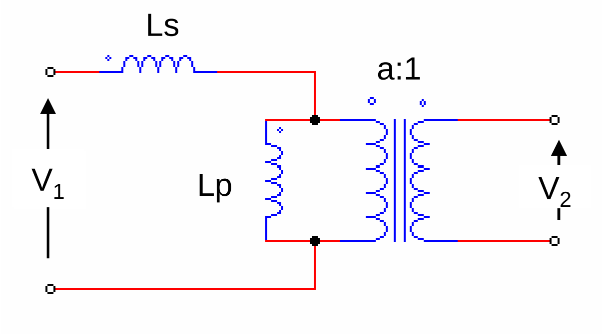
LLC Resonant Half-bridge
No-load issues: regulation

- LLC converter can regulate down to zero load, unlike the conventional LC series-resonant
- At a frequency >> f_{r1} Cr disappears and the output voltage is given by the inductive divider made up by Ls and Lp
- If the minimum voltage conversion ratio is greater than the inductive divider ratio, regulation will be possible at some finite frequency
- This links the equivalent turn ratio a and the inductance ratio k:

$$a \cdot \frac{Vout}{Vin_{max}} > \frac{1}{2} \cdot \frac{k}{1 + k}$$

- This is equivalent to the graphical constraint that the horizontal line a·Vout/Vin_{max} must cross the Q=0 curve

Equivalent schematic of LLC converter for x →∞

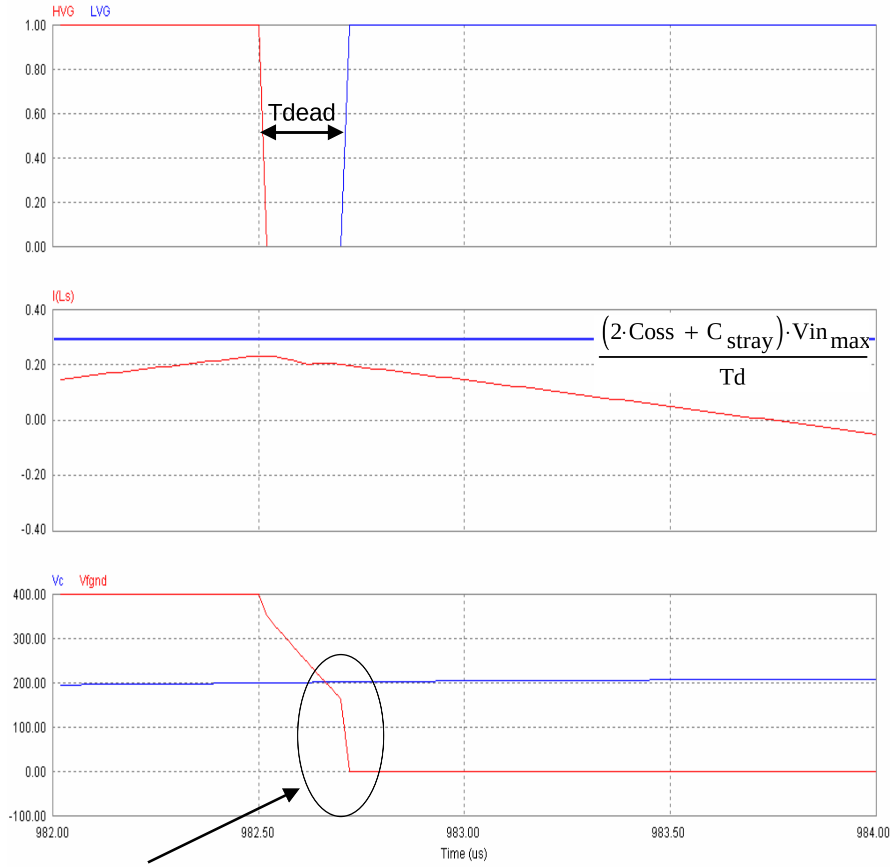


$$V_2 = V_1 \cdot \frac{1}{a} \cdot \frac{Lp}{Ls + Lp}$$

LLC Resonant Half-bridge
No-load issues: ZVS

- Zin(jω) analysis has shown that ZVS always occurs for x>1, even at no load (Q=0)
- x>1 is actually only a necessary condition for ZVS, not sufficient because of the parasitic capacitance of the HB midpoint neglected in the FHA approach
- *A minimum current must be ensured at no load to let the HB midpoint swing rail-to-rail within the dead-time.*
- This poses an additional constraint on the maximum value of Q at <u>full load</u>:

$$Q \le \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{max}} \cdot \frac{Td}{Re \cdot \left(2 \cdot Coss + C_{stray}\right)}$$



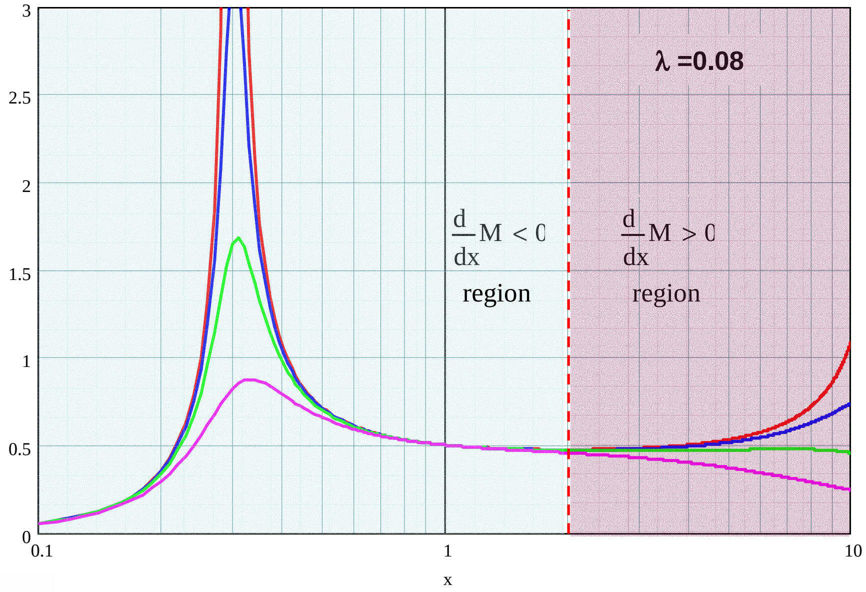
Hard Switching at no load

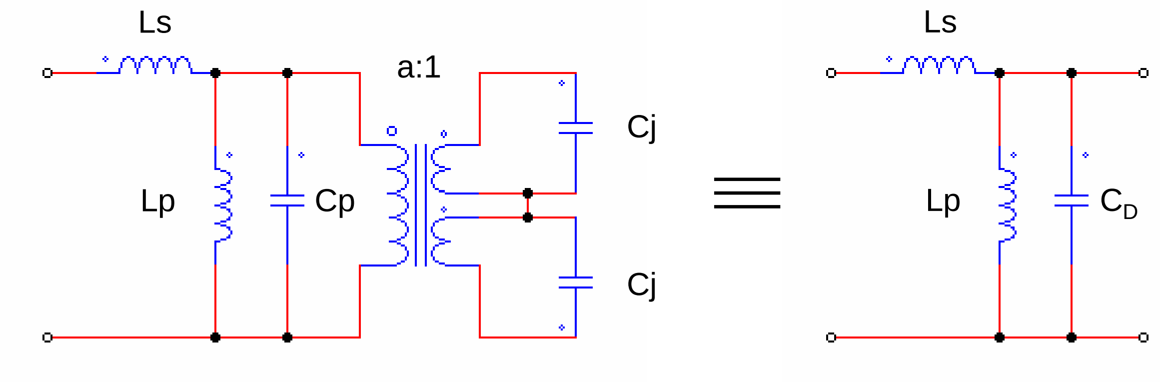
LLC Resonant Half-bridge
No-load issues: Feedback inversion

- Parasitic intrawinding and interwinding capacitance are summarized in Cp
- Cj is the junction capacitance of the output rectifiers; each contributes for half cycle
- Under no-load, rectifiers have low reverse voltage applied, Cj increases.
- The parasitic tank has a high-frequency resonance that makes M increase at some point: feedback becomes positive, system loses control
- Cure: minimize Cp and Cj, limit max fsw.

$$x = \sqrt[4]{\frac{1}{k \cdot \lambda^2}}$$

$$M = \frac{a \cdot Vout}{Vin}$$





$$C_D = Cp + \frac{C_j}{a^2} \qquad \lambda = \sqrt{\frac{C_D}{Cr}}$$

LLC Resonant Half-bridge
Design procedure. General criteria.

DESIGN SPECIFICATION

- Vin range, holdup included ($Vin_{min} \div Vin_{max}$)
- Nominal input voltage (Vin_{nom})
- Regulated Output Voltage (Vout)
- Maximum Output Power ($Pout_{max}$)
- Resonance frequency: (f_r)
- Maximum operating frequency (f_{max})

ADDITIONAL INFO

- C_{oss} and C_{stray} estimate
- Minimum dead-time

- The converter will be designed to work at resonance at nominal Vin
- Step-up capability (i.e. operation below resonance) will be used to handle holdup
- The converter must be able to regulate down to zero load at max. Vin
- Q will be chosen so that the converter will always work in ZVS, from zero load to $Pout_{max}$

- There are many degrees of freedom, then many design procedures are possible. We will choose one of the simplest ones

LLC Resonant Half-bridge
Design procedure. Proposed algorithm (I).

1. Calculate min., max. and nominal conversion ratio with a=1:

$$M_{min}=\frac{Vout}{Vin_{max}} \qquad M_{max}=\frac{Vout}{Vin_{min}} \qquad M_{nom}=\frac{Vout}{Vin_{nom}}$$

2. Calculate the max. normalized frequency x_{max}:

$$x_{max}=\frac{f_{max}}{f_r}$$

3. Calculate a so that the converter will work at resonance at nominal voltage

$$a=\frac{1}{2\cdot M_{nom}}$$

4. Calculate k so that the converter will work at x_{max} at zero load and max. input voltage:

$$k=\frac{2\cdot a\cdot M_{min}}{1-2\cdot a\cdot M_{min}}\cdot\left(1-\frac{1}{{x_{max}}^{2}}\right)$$

5. Calculate the max. Q value, Q_{max1}, to stay in the ZVS region at min. Vin and max. load:

$$Q_{max1}=\frac{1}{k}\cdot\frac{1}{2\cdot a\cdot M_{max}}\cdot\sqrt{\frac{\left(2\cdot a\cdot M_{max}\right)^{2}}{\left(2\cdot n\cdot M_{max}\right)^{2}-1}+k}$$

LLC Resonant Half-bridge
Design procedure. Proposed algorithm (II).

6. Calculate the effective load resistance:

$$Re = \frac{8}{\pi^2} \cdot a^2 \cdot R = \frac{8}{\pi^2} \cdot a^2 \cdot \frac{Vout^2}{Pout_{max}}$$

7. Calculate the max. Q value, Q_{max2}, to ensure ZVS region at zero load and max. Vin:

$$Q_{max2} = \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{max}} \cdot \frac{Td}{Re \cdot \left(2 \cdot Coss + C_{stray}\right)}$$

8. Choose a value of Q, Q_S, such that $Q_S \leq \min(Q_{max1}, Q_{max2})$

9. Calculate the value x_{min} the converter will work at, at min. input voltage and max. load:

$$x_{min} = \sqrt{\frac{1}{1 + k \cdot \left[1 - \frac{1}{\left(2 \cdot n \cdot M_{max}\right)^{1 + \left(\frac{Q_S}{Q_{max1}}\right)^4}}\right]}}$$

10. Calculate the characteristic impedance of the tank circuits and all component values:

$$Z_R = Re \cdot Q_S \qquad Cs = \frac{1}{2 \cdot fr \cdot Z_R \cdot \pi} \qquad Ls = \frac{Z_R}{2 \cdot \pi \cdot fr} \qquad Lp = k \cdot Ls$$

LLC Resonant Half-bridge
Design example. 300W converter

ELECTRICAL SPECIFICATION

Vin range	320 to 450 Vdc	320V after 1 missing cycle; 450 V is the OVP theshold of the PFC pre-regulator
Nominal input voltage	400 Vdc	Nominal output voltage of PFC
Regulated ouput voltage Maximum output Current	24 V 12 A	Total Pout is 300 W
Resonance frequency	90 kHz	
Maximum switching frequency	180 kHz	
Start-up switching frequency	300 kHz	
HB midpoint estimated parasitic capacitance	200 pF	
Minimum dead-time (L6599)	200 ns	

LLC Resonant Half-bridge
Design example. 300W converter

1. Calculate min. and max. and nominal conversion ratio referring to 24V output:

$$M_{min} = \frac{Vout}{Vin_{max}} = \frac{24}{450} = 0.053 \qquad M_{max} = \frac{Vout}{Vin_{min}} = \frac{24}{320} = 0.075 \qquad M_{nom} = \frac{Vout}{Vin_{nom}} = \frac{24}{400} = 0.06$$

2. Calculate the max. normalized frequency x_{max}:

$$x_{max} = \frac{f_{max}}{f_r} = \frac{180}{90} = 2$$

3. Calculate a so that the converter will work at resonance at nominal voltage

$$a = \frac{1}{2 \cdot M_{nom}} = \frac{1}{2 \cdot 0.06} = 8.333$$

4. Calculate k so that the converter will work at x_{max} at zero load and max. input voltage:

$$k = \frac{2 \cdot a \cdot M_{min}}{1 - 2 \cdot a \cdot M_{min}} \cdot \left(1 - \frac{1}{x_{max}^{2}}\right) = 6$$

5. Calculate the max. Q value, Q_{max1}, to stay in the ZVS region at min. Vin and max. load:

$$Q_{max1} = \frac{1}{k} \cdot \frac{1}{2 \cdot a \cdot M_{max}} \cdot \sqrt{\frac{(2 \cdot a \cdot M_{max})^2}{(2 \cdot n \cdot M_{max})^2 - 1} + k} = 0.395$$

LLC Resonant Half-bridge
Design example. 300W converter

6. Calculate the effective load resistance:

$$Re = \frac{8}{\pi^2} \cdot a^2 \cdot R = \frac{8}{\pi^2} \cdot a^2 \cdot \frac{Vout^2}{Pout_{max}} = 108.067 \ \Omega$$

7. Calculate the max. Q value, Q_{max2}, to ensure ZVS at zero load:

$$Q_{max2} = \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{max}} \cdot \frac{Td}{Re \cdot \left(2 \cdot Coss + C_{stray}\right)} = 0.519$$

8. Choose a value of Q, Q_S, such that $Q_S \leq \min(Q_{max1}, Q_{max2})$

Considering 10% margin: $Q_S = 0.9 \cdot 0.395 = 0.356$

9. Calculate the value x_{min} the converter will work at, at min. input voltage and max. load:

$$x_{min} = \sqrt{\frac{1}{1 + k \cdot \left[1 - \frac{1}{\left(2 \cdot n \cdot M_{max}\right)^{1+\left(\frac{Q_S}{Q_{max1}}\right)^4}}\right]}} = 0.592 \qquad f_{min} = 90 \cdot 0.592 = 53.28 \ \text{kHz}$$

10. Calculate the characteristic impedance of the tank circuits and all component values:

$$Z_R = Re \cdot Q_S = 38.472 \, \Omega \qquad Cs = \frac{1}{2 \cdot fr \cdot Z_R \cdot \pi} = 46 \ \text{nF} \qquad Ls = \frac{Z_R}{2 \cdot \pi \cdot fr} = 68 \ \mu\text{H} \qquad Lp = k \cdot Ls = 408 \ \mu\text{H}$$

LLC Resonant Half-bridge
Design example. 300W converter

11. Calculate components around the L6599:

- Oscillator setting. Choose C_F (e.g. 470 pF as in the datasheet). Calculate RFmin:

$$RF_{min} = \frac{1}{3 \cdot CF \cdot f_{min}} = \frac{1}{3 \cdot 470 \cdot 10^{-12} \cdot 53.28 \cdot 10^{3}} = 13.3\ k\Omega$$

Calculate RFmax:

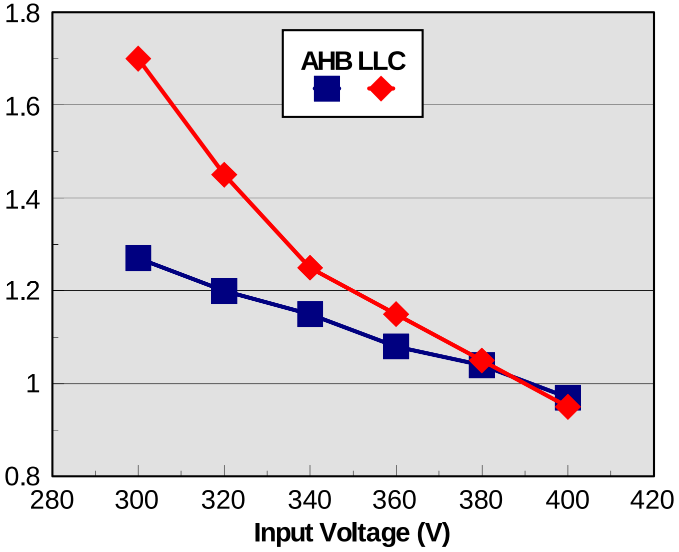
$$RF_{max} = \frac{RF_{min}}{\frac{f_{max}}{f_{min}} - 1} = \frac{13.3 \cdot 10^{3}}{\frac{180}{53.28} - 1} = 5.54\ k\Omega$$

Calculate Soft-start components:

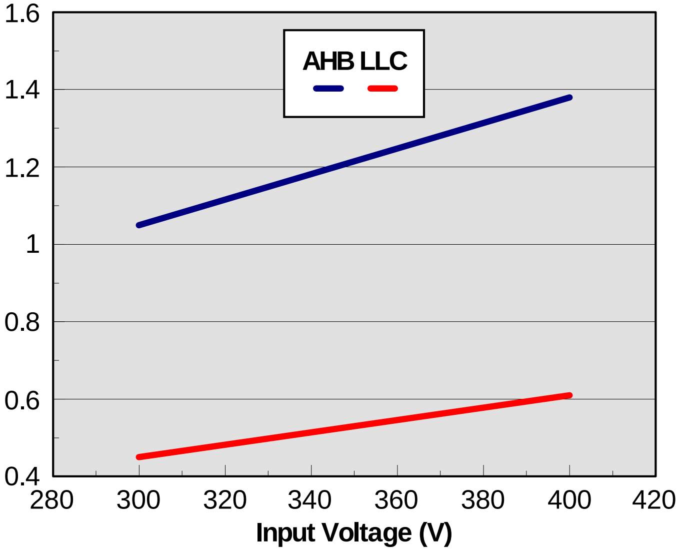
$$R_{SS} = \frac{RF_{min}}{\frac{f_{start}}{f_{min}} - 1} = \frac{13.3 \cdot 10^{3}}{\frac{300}{53.28} - 1} = 2.87\ k\Omega \qquad C_{SS} = \frac{3 \cdot 10^{-3}}{R_{SS}} = \frac{3 \cdot 10^{-3}}{2.87 \cdot 10^{-3}} = 1\ \mu F$$

LLC Resonant Half-bridge
Comparison with ZVS Half-bridge (I)

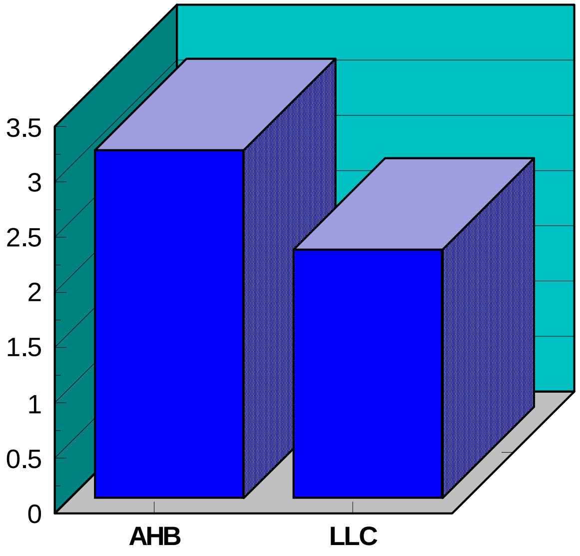
Primary Conduction Losses (W)



Primary Switching Losses (W)



Secondary Conduction Losses

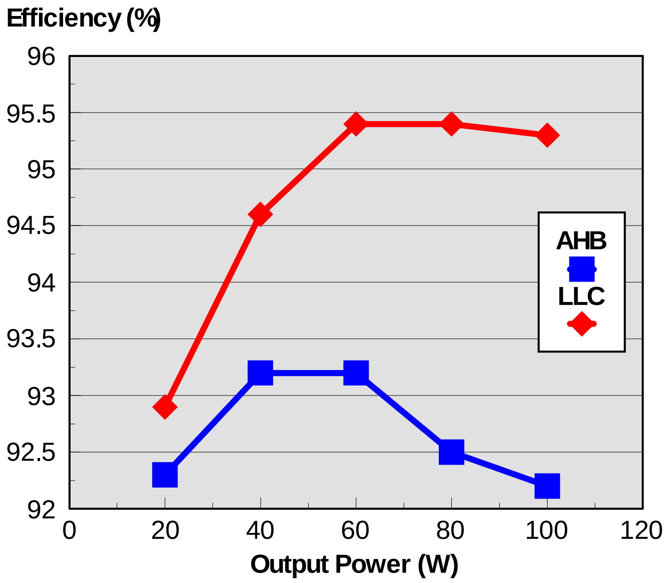


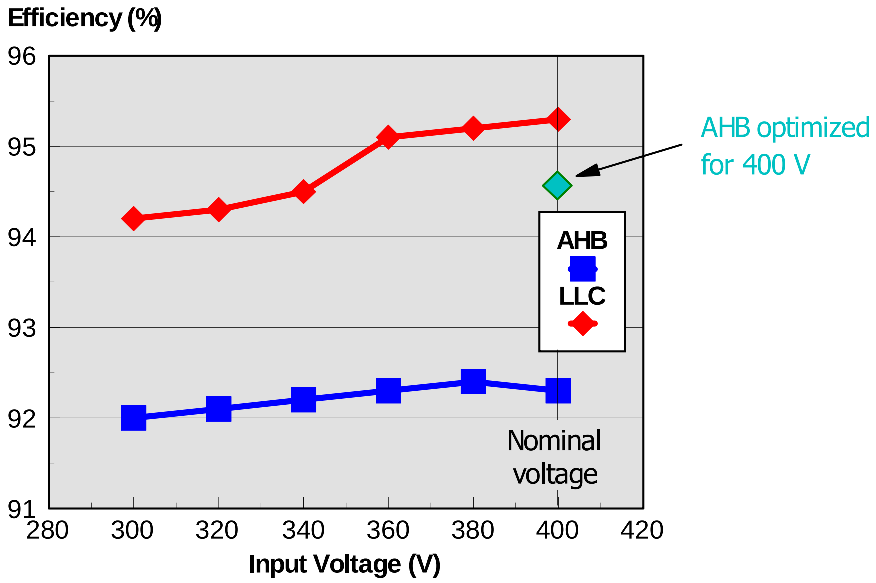
ELECTRICAL SPECIFICATION	
Input Voltage:	300 to 400(*) Vdc
Output voltage:	20 Vdc
Output power:	100 W
Switching frequency:	200 kHz

(*) 300 V holdup, 400 V nominal voltage

	AHB	LLC
Primary Conduction Losses	0.97 W	0.95 W
Primary Switching Losses	1.38 W	0.61 W
Secondary Conduction Losses	3.15 W	2.25 W
Secondary Switching Losses	?	0 W
Total Losses	5.92 + ? W	3.81 W

LLC Resonant Half-bridge
Comparison with ZVS Half-bridge (II)





ZVS Half-bridge

- MOSFETs: high turn-off losses; ZVS at light load difficult to achieve
- Diodes: high voltage stress ⇒ higher V_F ⇒ higher conduction losses; recovery losses
- Holdup requirements worsen efficiency at nominal input voltage

LLC resonant half-bridge

- MOSFETs: low turn-off losses; ZVS at light load easy to achieve
- Diodes: low voltage stress (2·Vout) ⇒ lower V_F ⇒ low conduction losses; ZCS ⇒ no recovery losses
- Operation can be optimized at nominal input voltage