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

MLD GROUP

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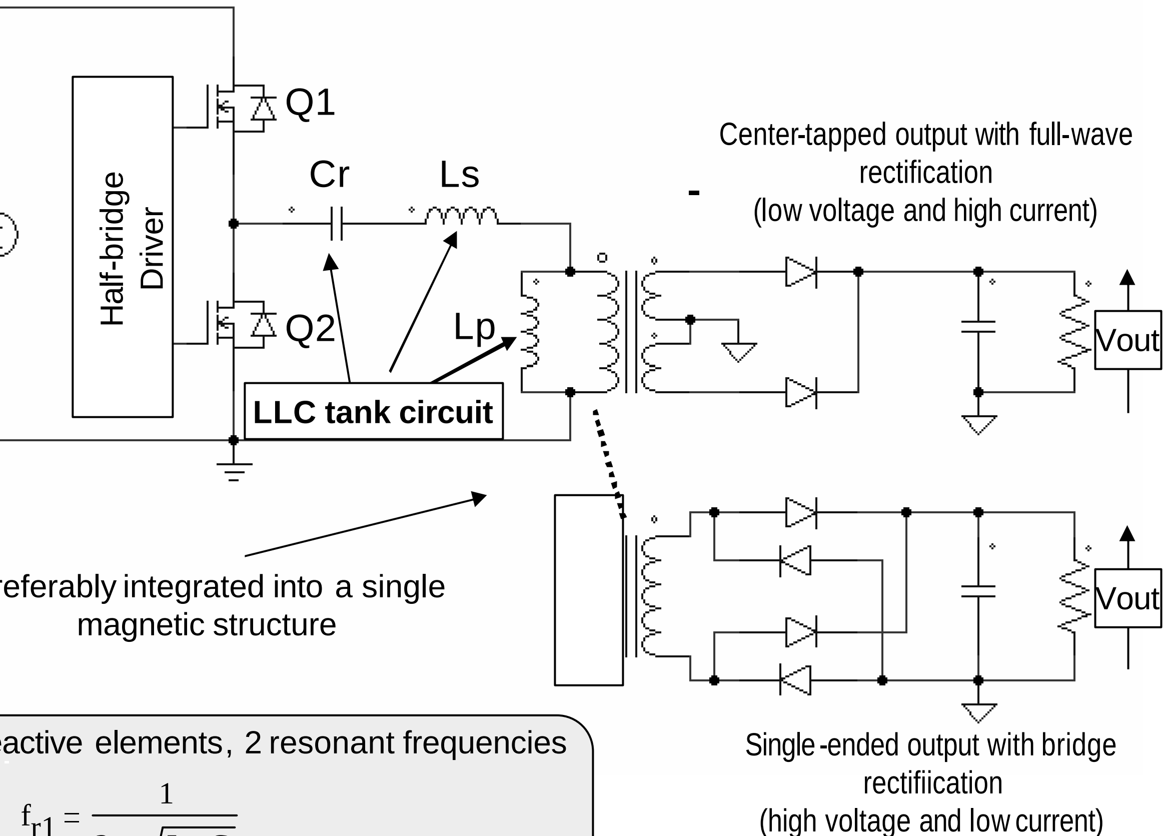
Application & Architecture Manager, System & Application Expert

Presentation Outline

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

eries-resonant LLC Half-Bridge opology and features



eactive elements, 2 resonant frequencies

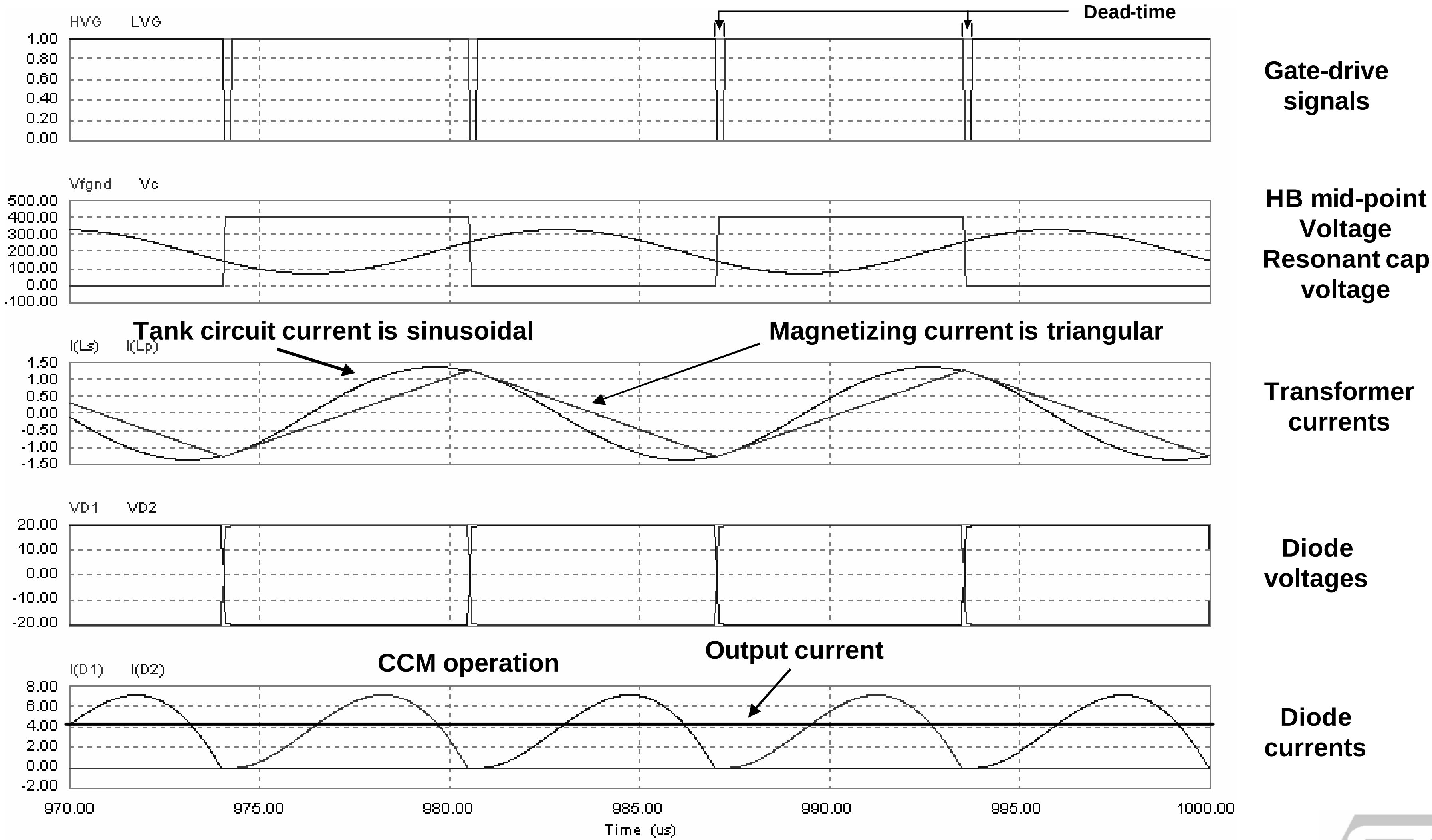
$$f_{r1} = \frac{1}{2\cdot\pi\cdot\sqrt{Ls\cdot Cr}}$$

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

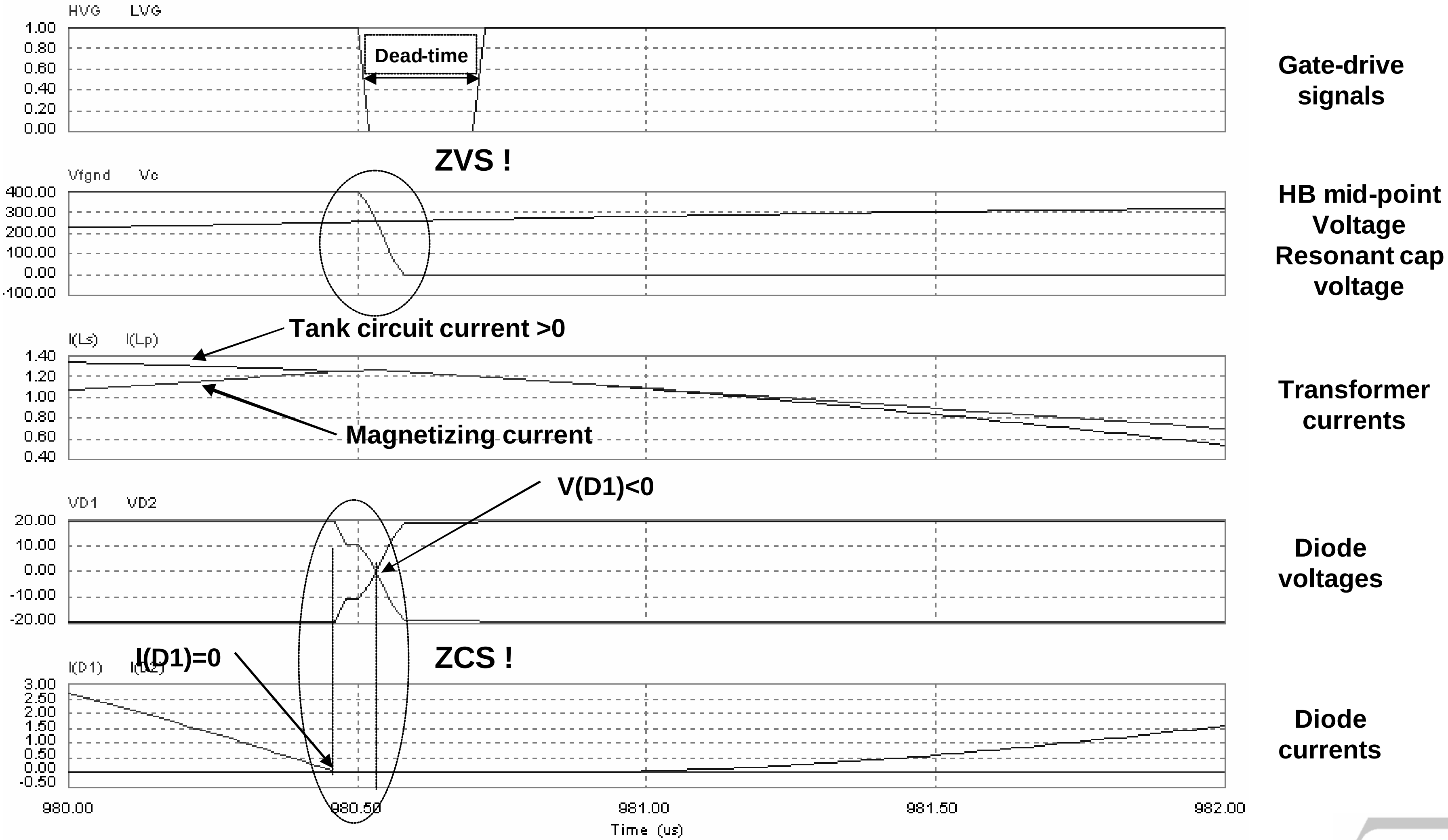
$$f_{r2} = \frac{1}{2\cdot\pi\cdot\sqrt{(Ls + Lp)\cdot Cr}}$$

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

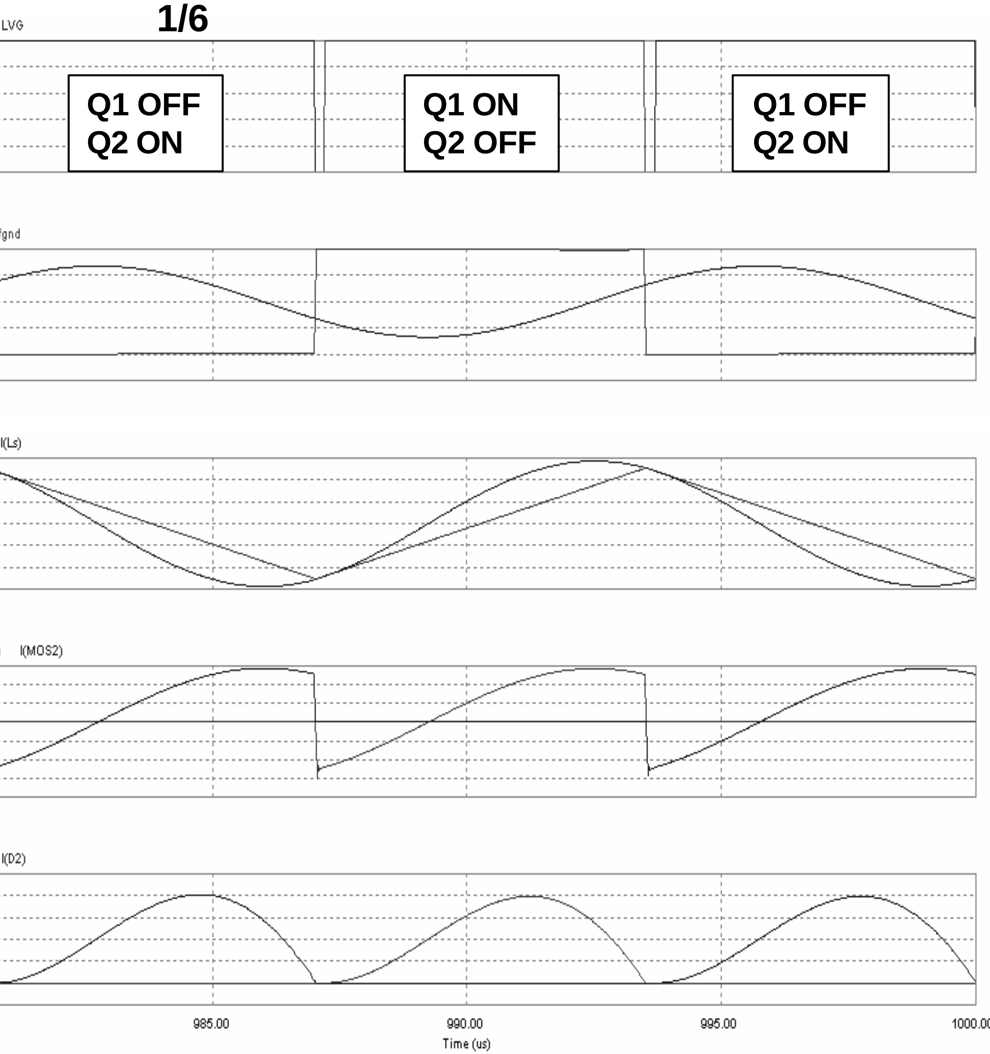
LC Resonant Half-bridge
Waveforms at resonance ($f_{sw} = f_{r1}$)

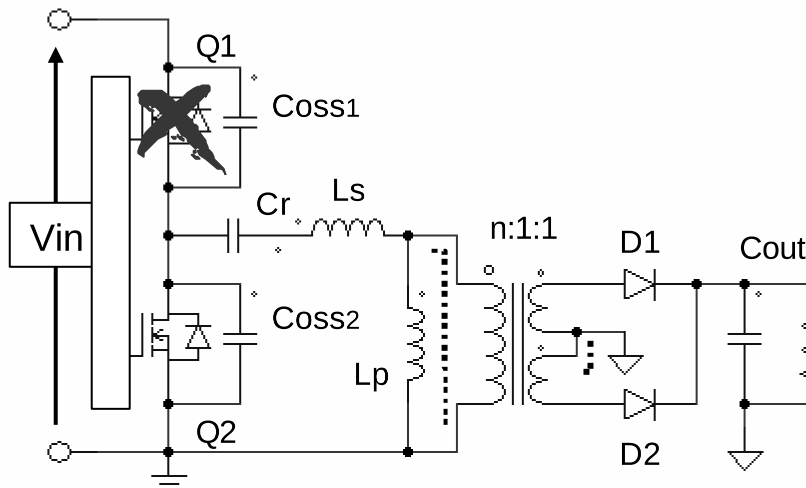


LC Resonant Half-bridge
witching details at resonance ($f_{sw} = f_{r1}$)



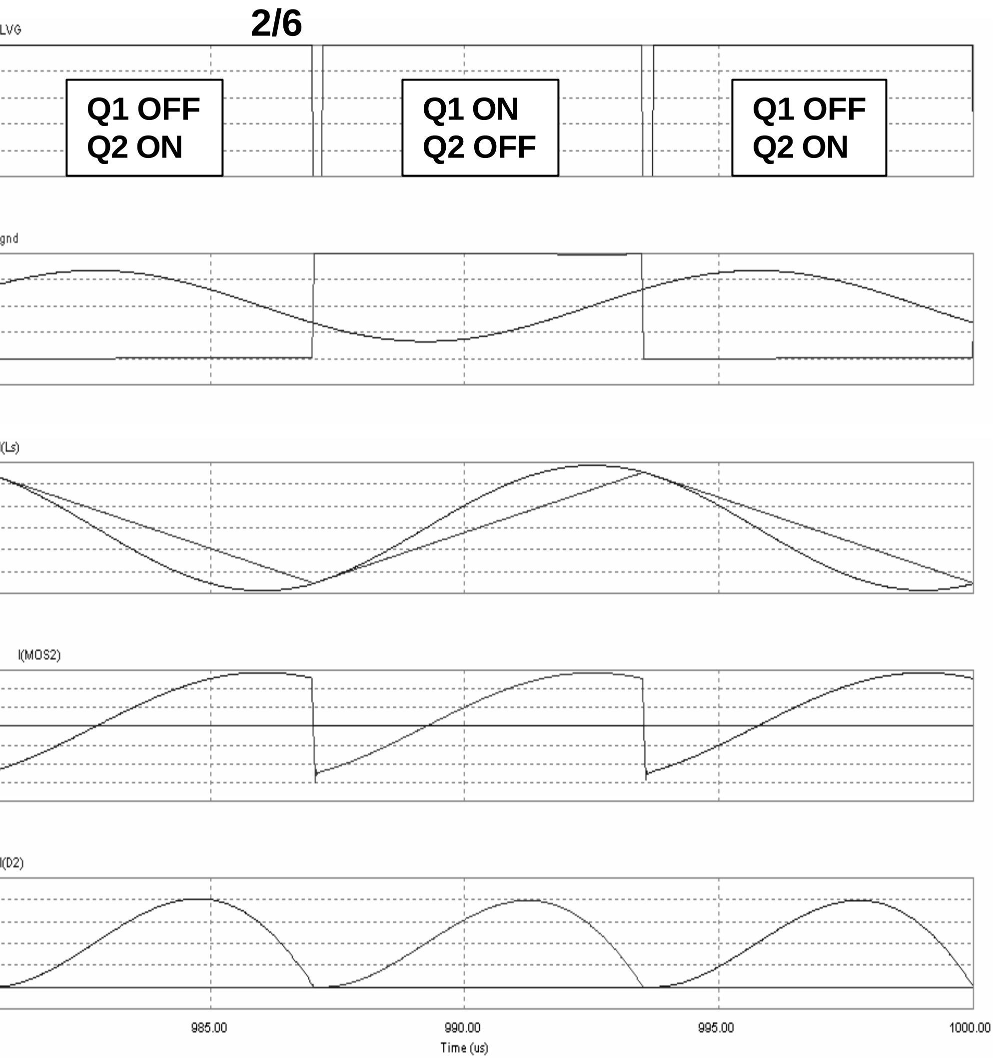
LC Resonant Half-bridge
perating Sequence at resonance (Phase 1/6)

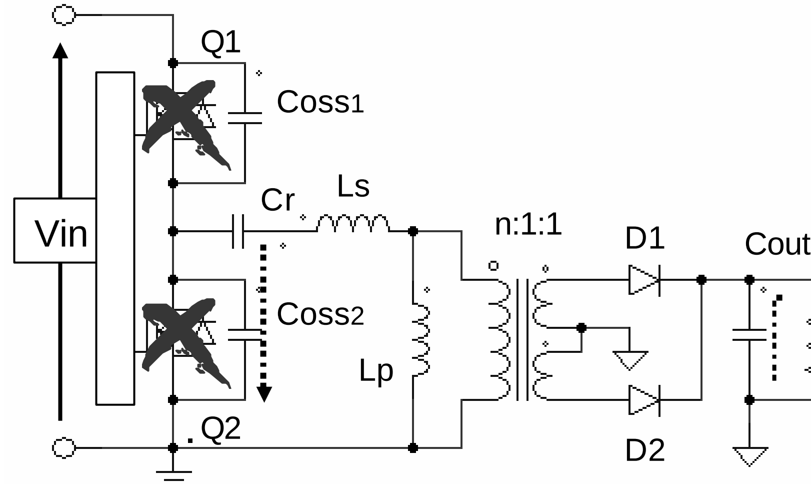




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·V
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when Q2 is switched off

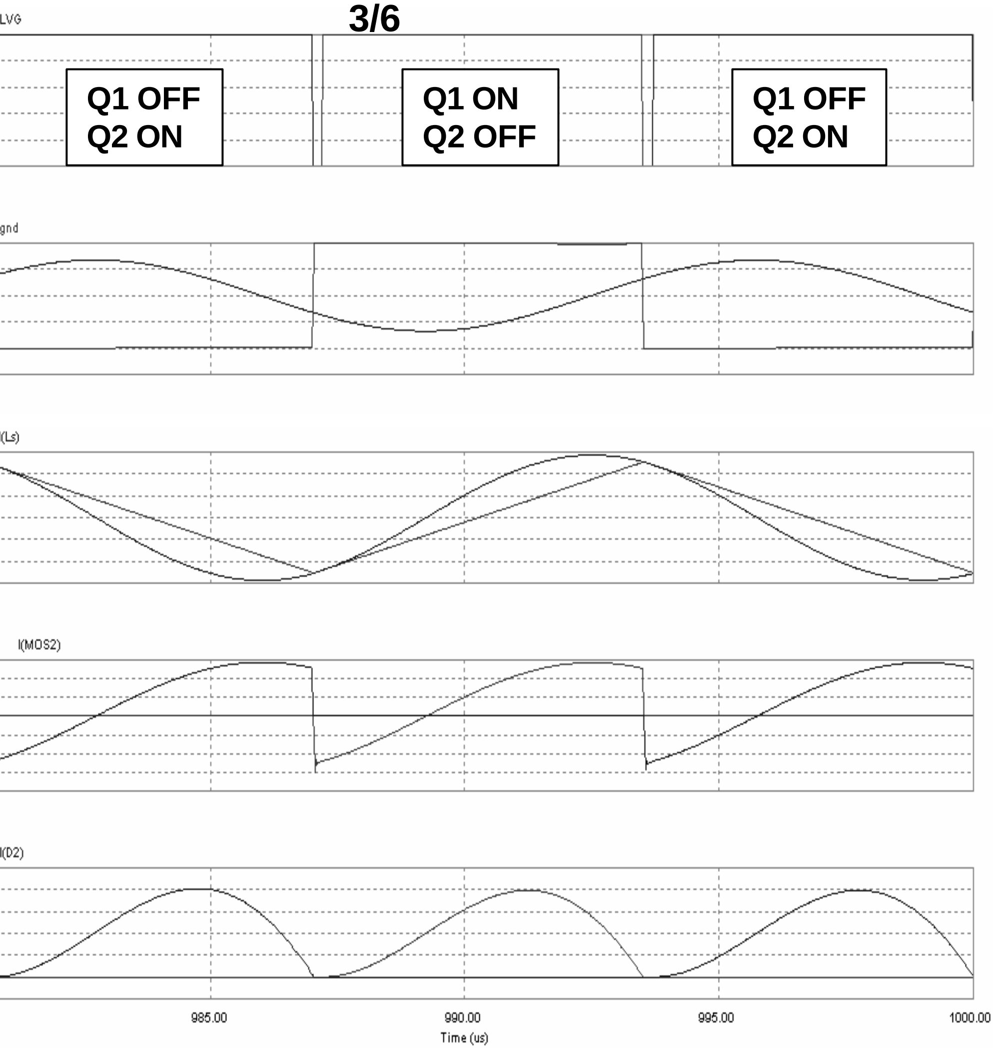
LC Resonant Half-bridge
perating Sequence at resonance (Phase 2/6)

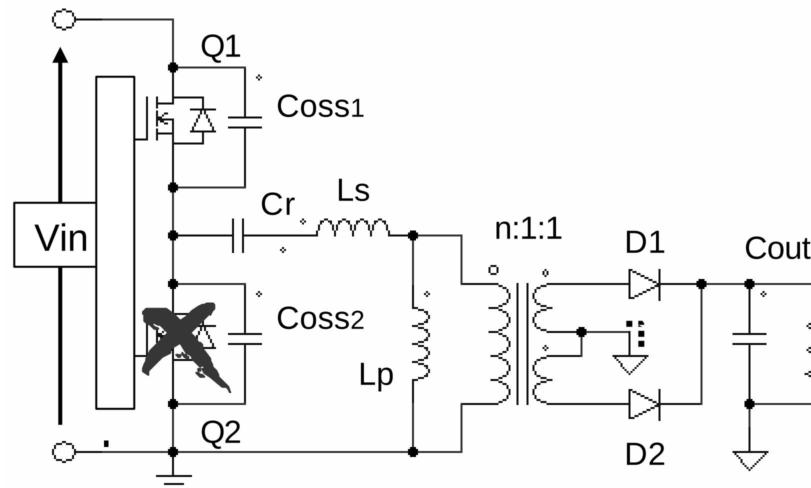




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharge C_{OSS1}, until V(C_{OSS2})=Vin; Q1's body d starts conducting, energy goes back
- I(D2) is exactly zero at Q2 switch o
- Phase ends when Q1 is switched on

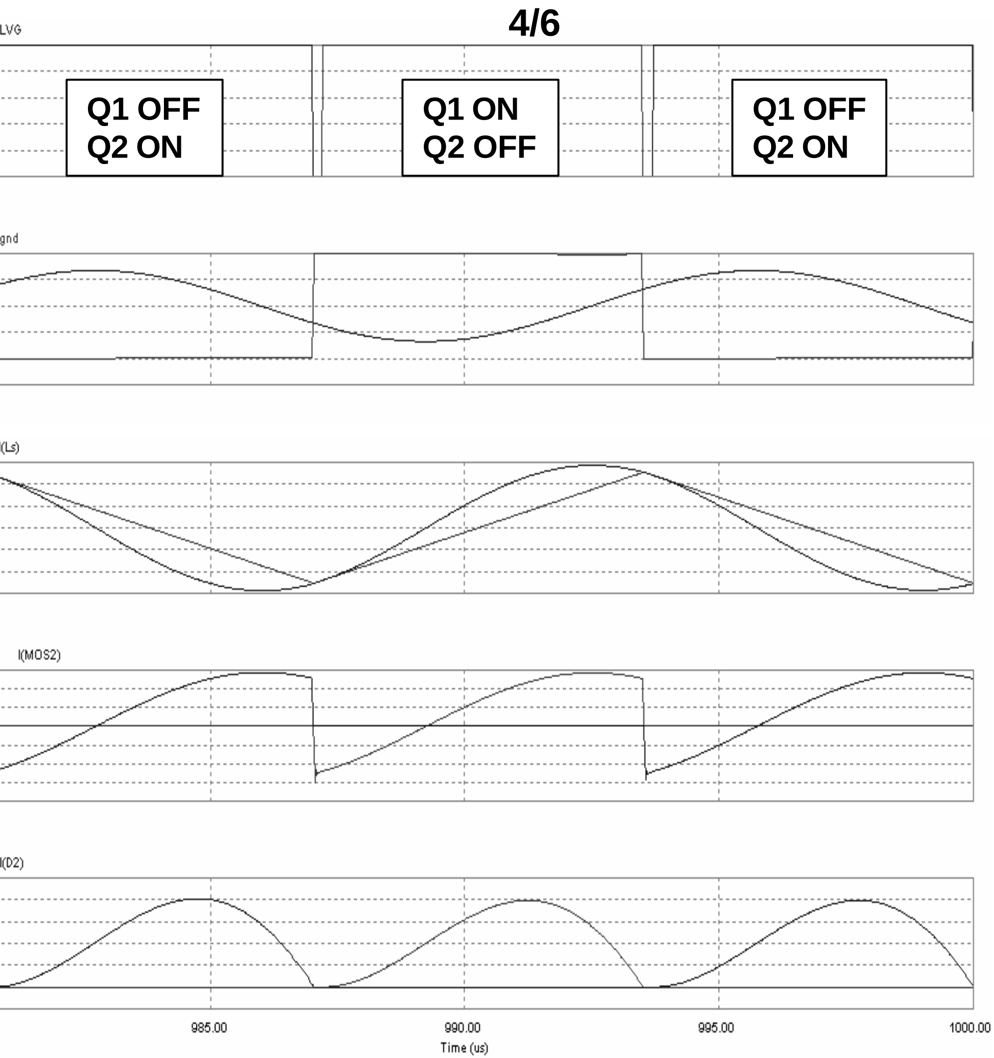
LC Resonant Half-bridge
perating Sequence at resonance (Phase 3/6)

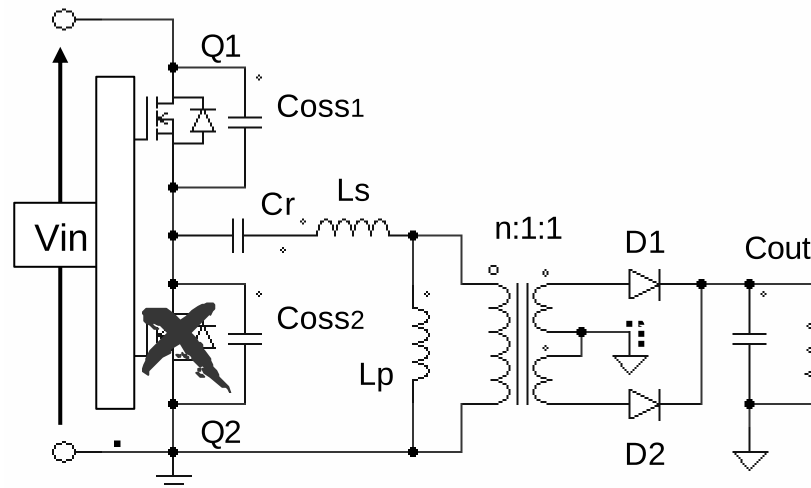




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back Vin (Q1 is working in the 3rd quadran
- Phase ends when I(Ls)=0

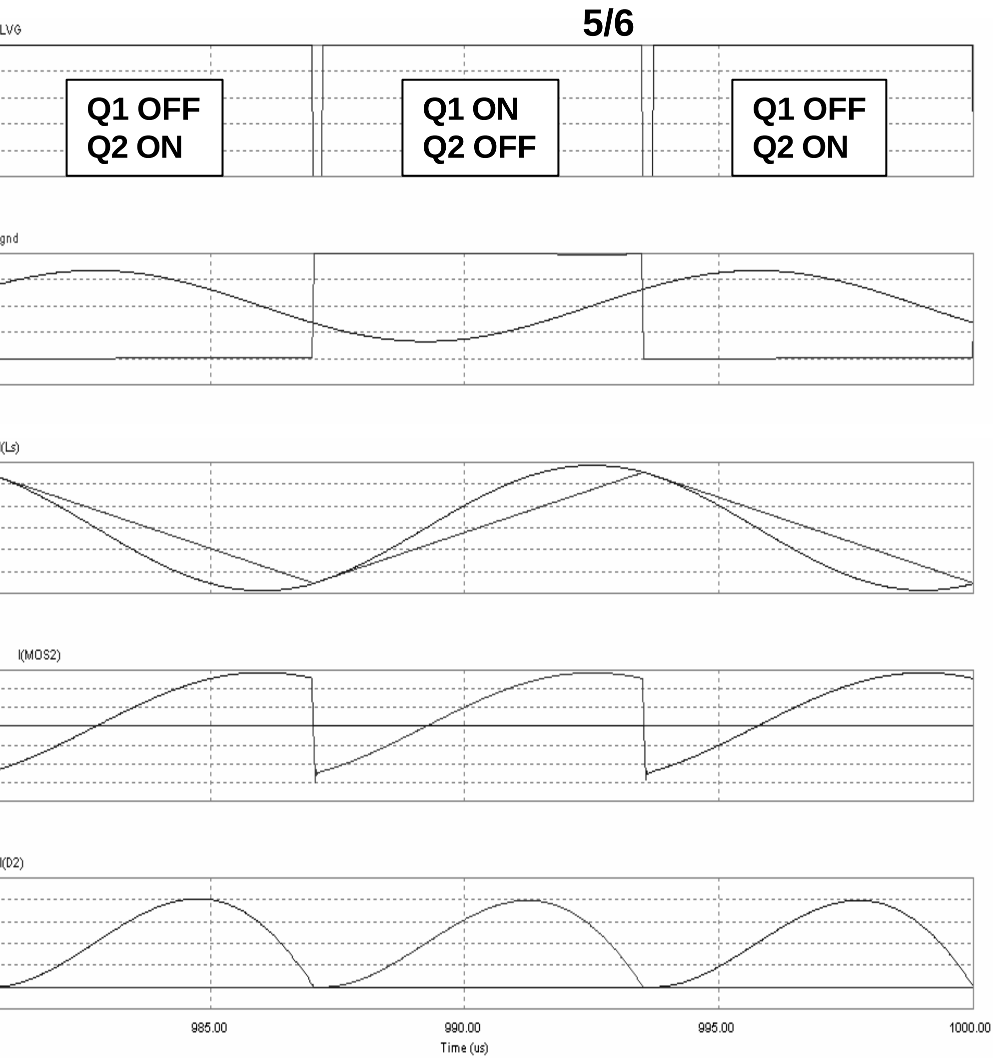
LC Resonant Half-bridge
perating Sequence at resonance (Phase 4/6)

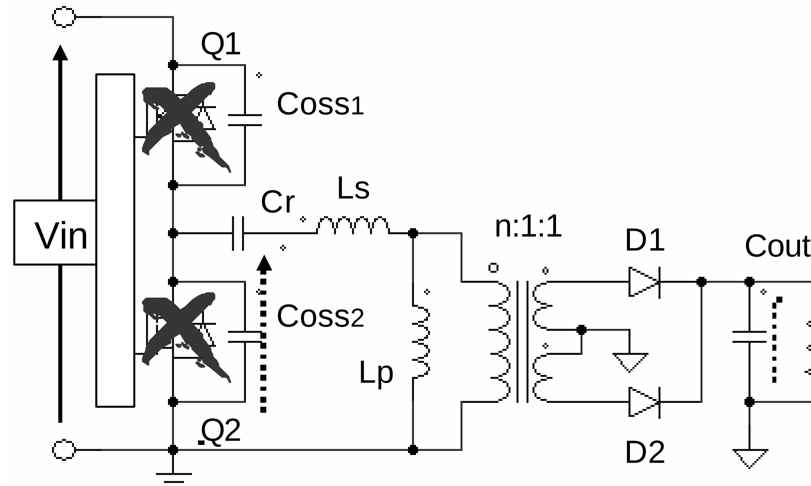




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from to ground
- Energy is taken from Vin and goes to
- Phase ends when Q1 is switched off

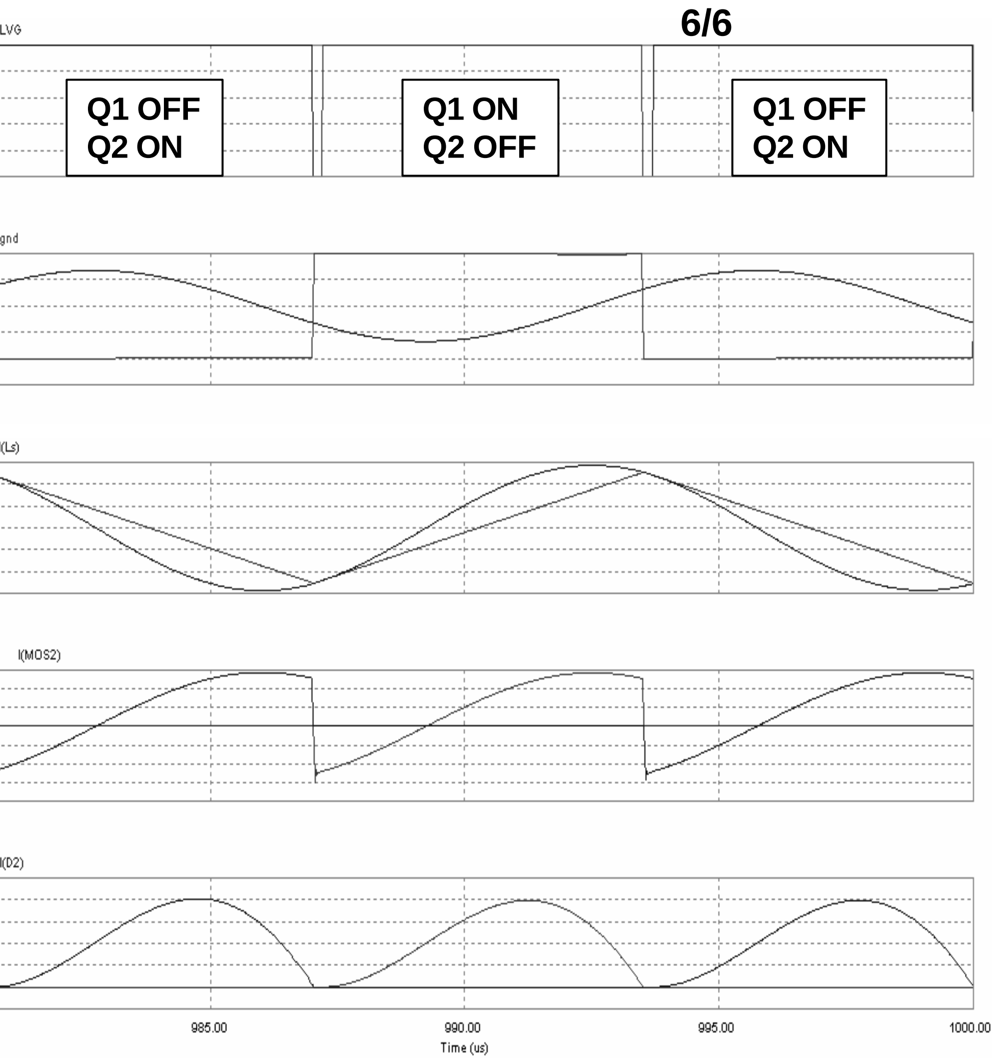
LC Resonant Half-bridge
perating Sequence at resonance (Phase 5/6)

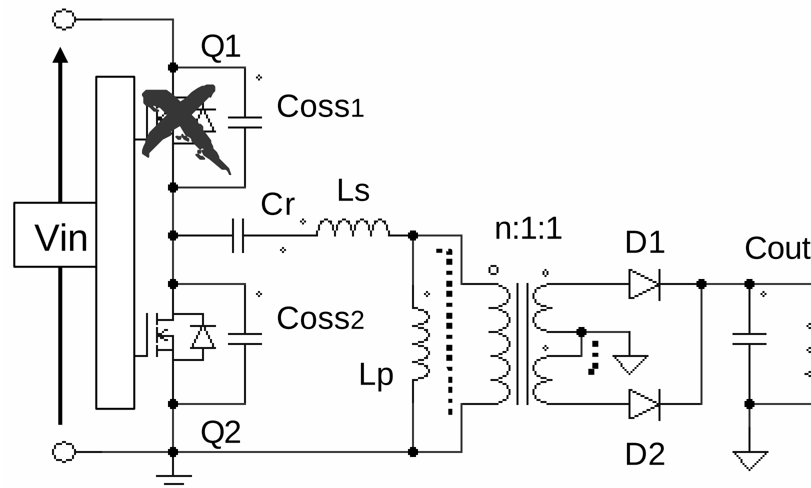




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharge C_{OSS2}, until $V(C_{OSS2})=0$; Q2's body dio starts conducting
- I(D1) is exactly zero at Q1 switch of
- Phase ends when Q2 is switched on

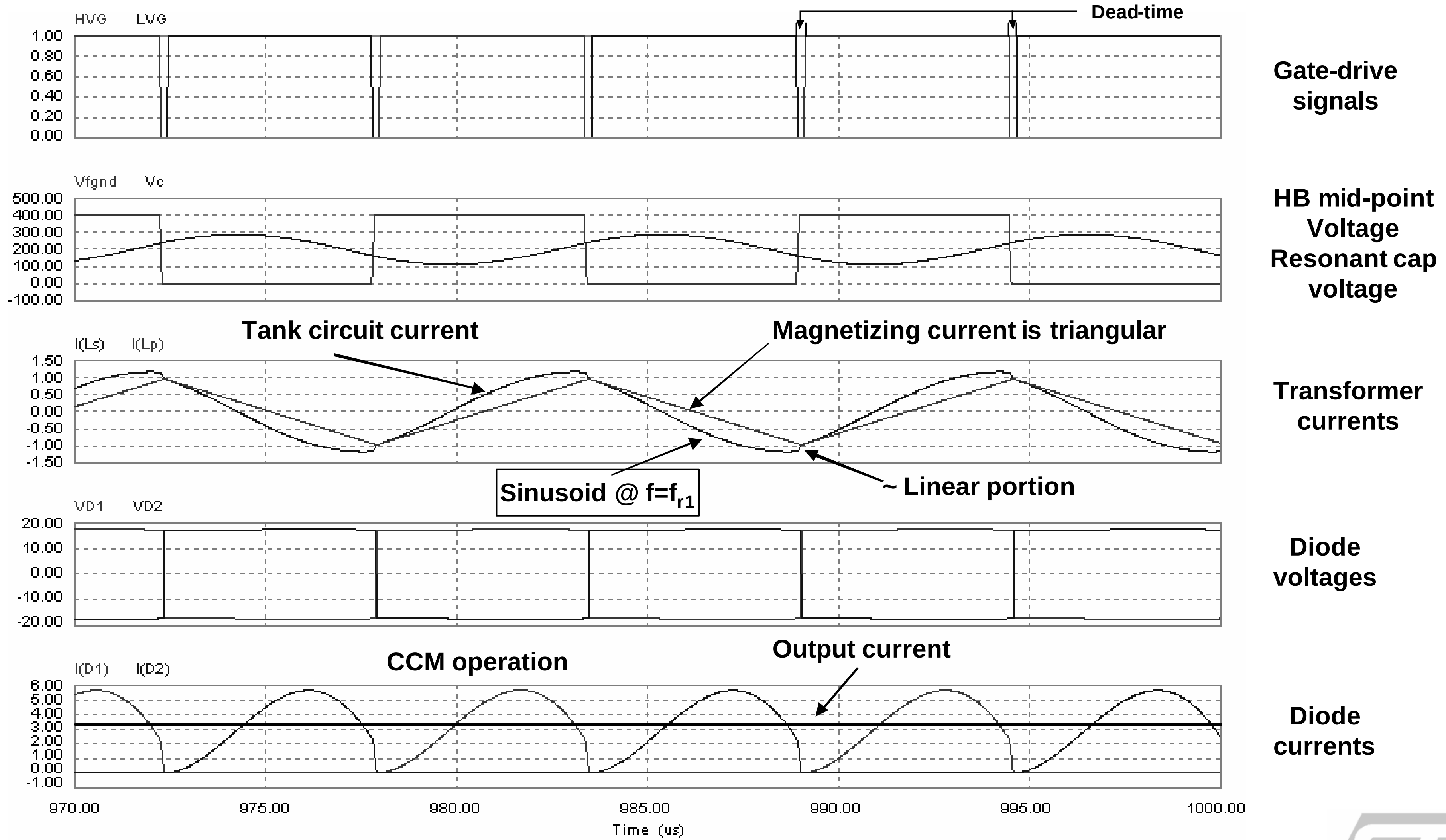
LC Resonant Half-bridge
perating Sequence at resonance (Phase 6/6)





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

LC Resonant Half-bridge
/aveforms above resonance ($f_{sw} > f_{r1}$)



LC Resonant Half-bridge
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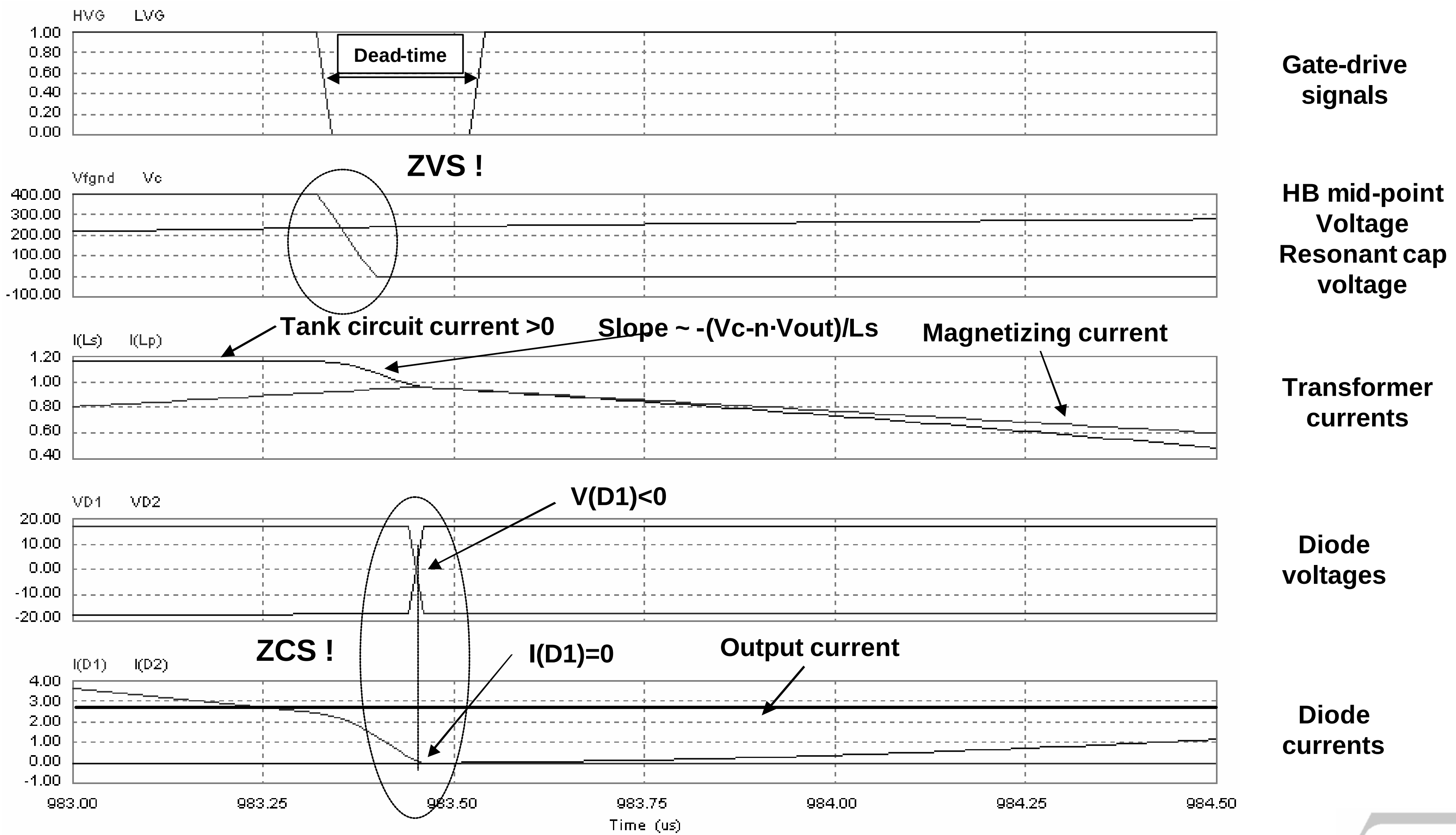
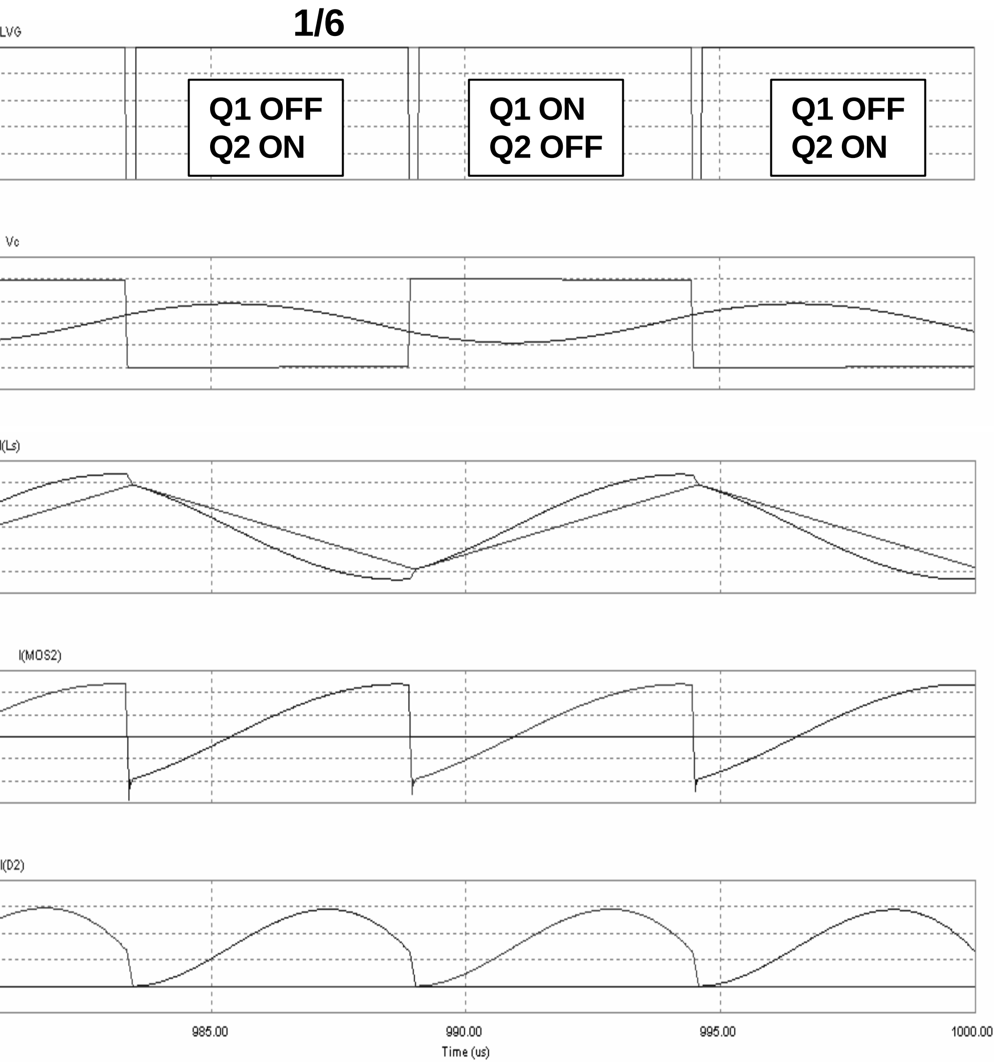
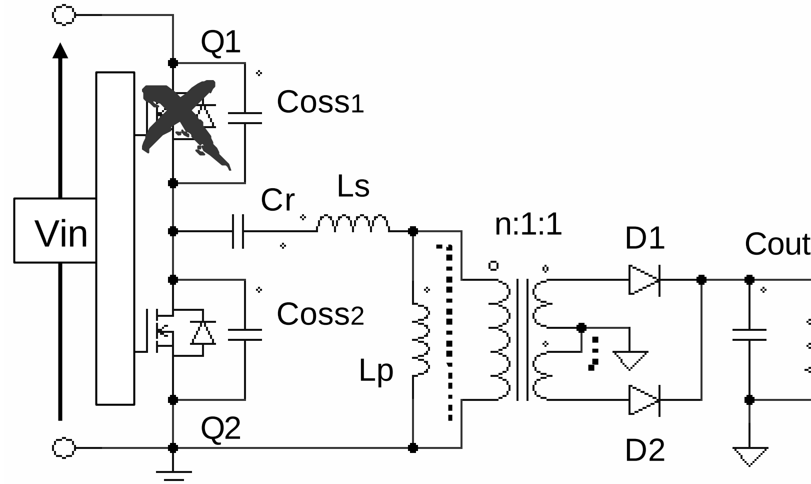


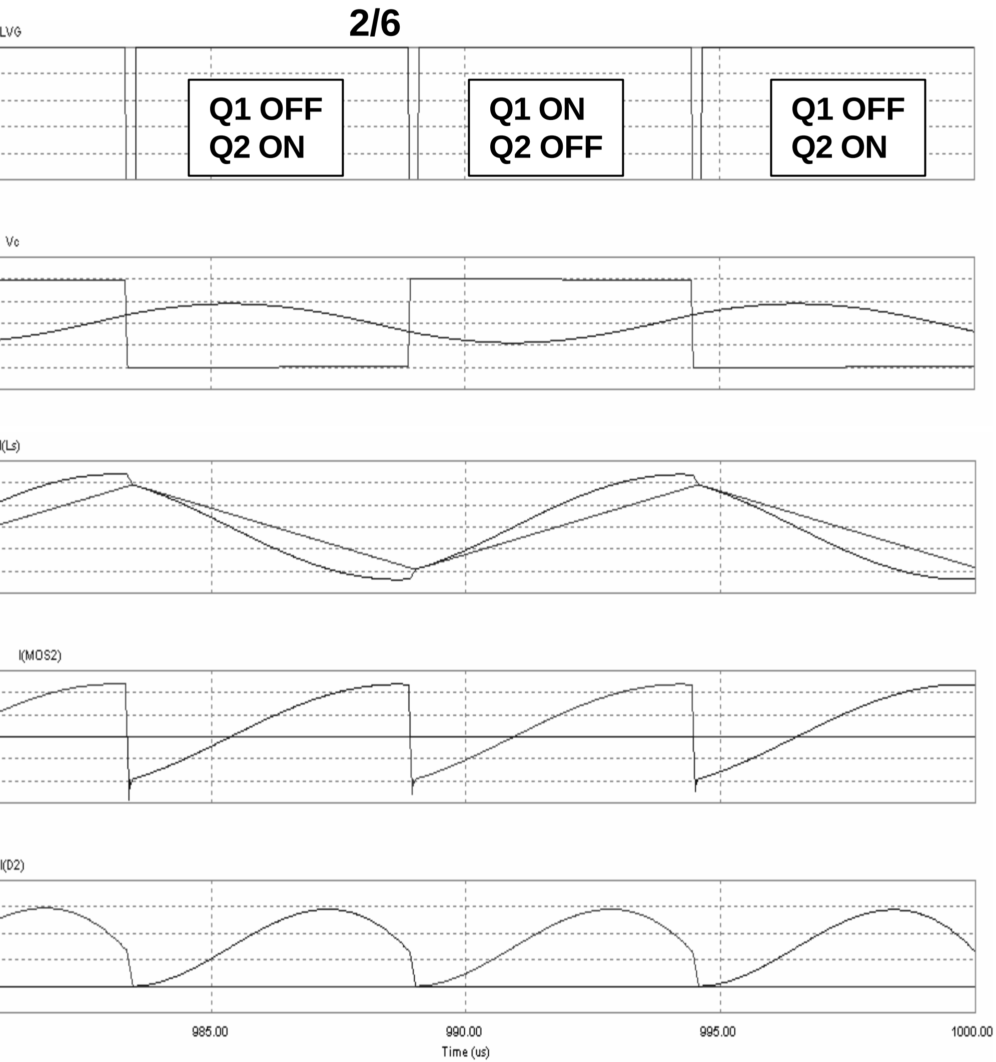
LC Resonant Half-bridge
perating Sequence above resonance (Phase 1/6)

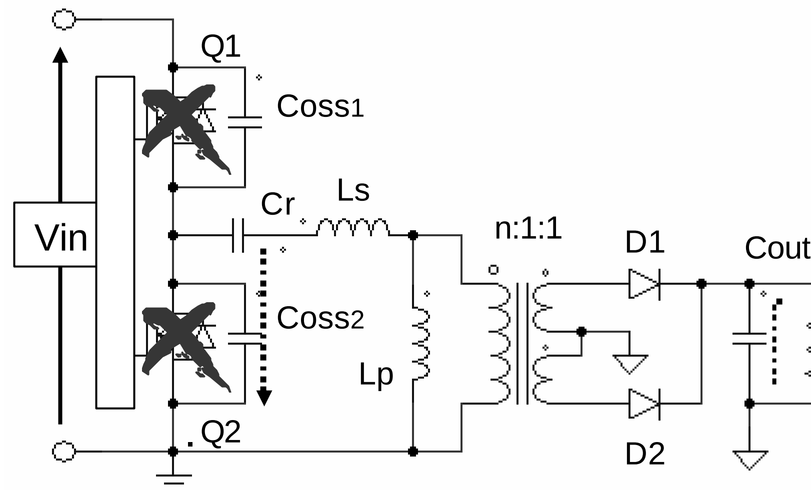




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·V
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when Q2 is switched off

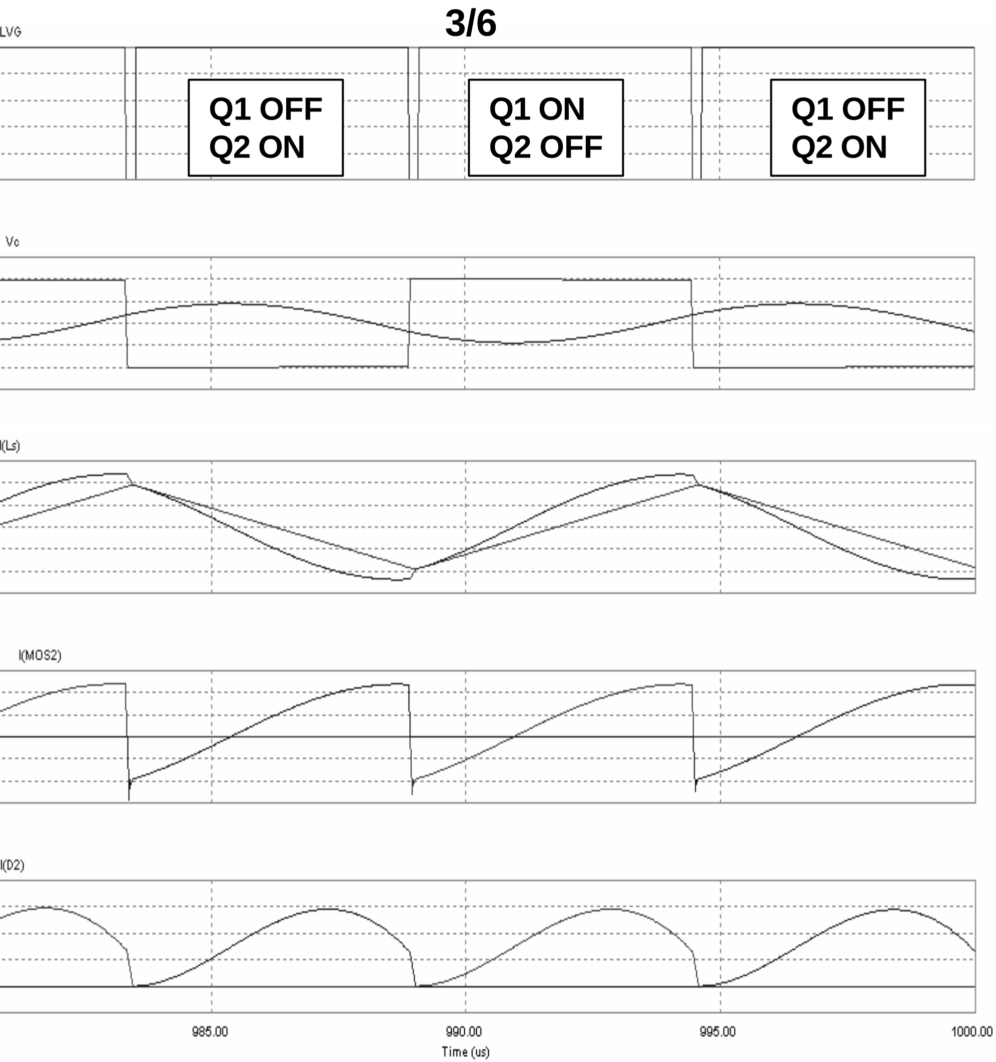
LC Resonant Half-bridge
perating Sequence above resonance (Phase 2/6)

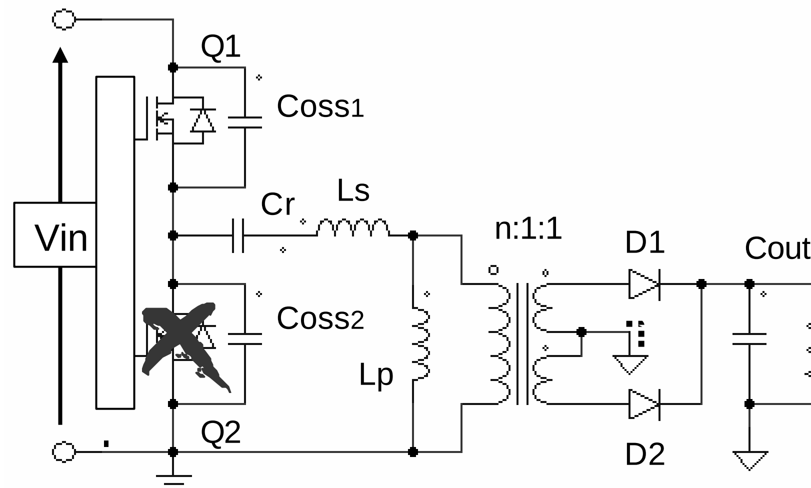




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharge C_{OSS1}, until $V(C_{OSS2})$=Vin; Q1's body d starts conducting, energy goes back
- V(D2) reverses as I(D2) goes to zero
- Phase ends when Q1 is switched on

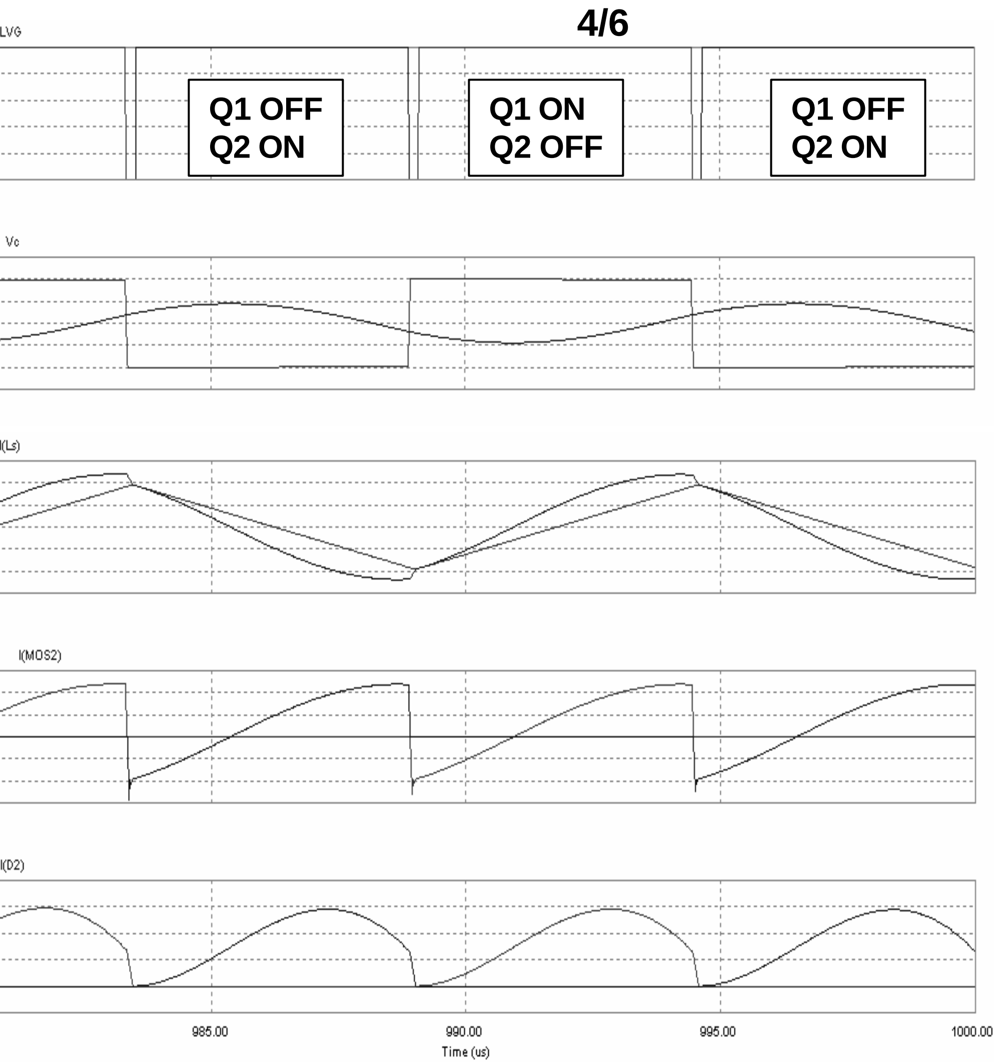
LC Resonant Half-bridge
perating Sequence above resonance (Phase 3/6)

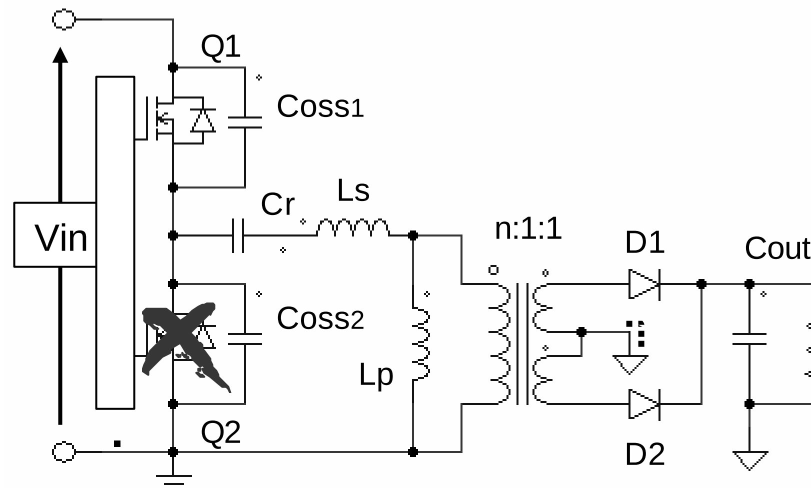




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back Vin (Q1 is working in the 3rd quadran
- Phase ends when I(Ls)=0

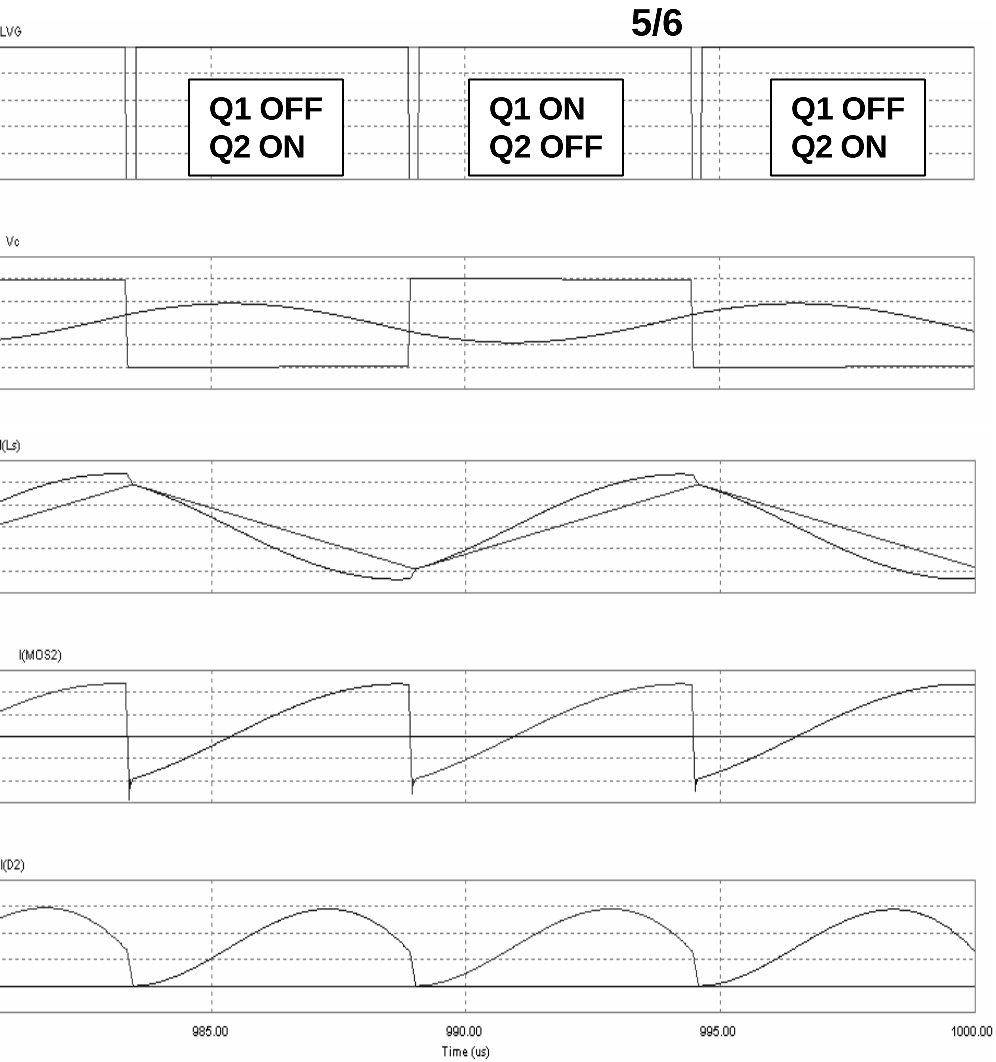
LC Resonant Half-bridge
perating Sequence above resonance (Phase 4/6)

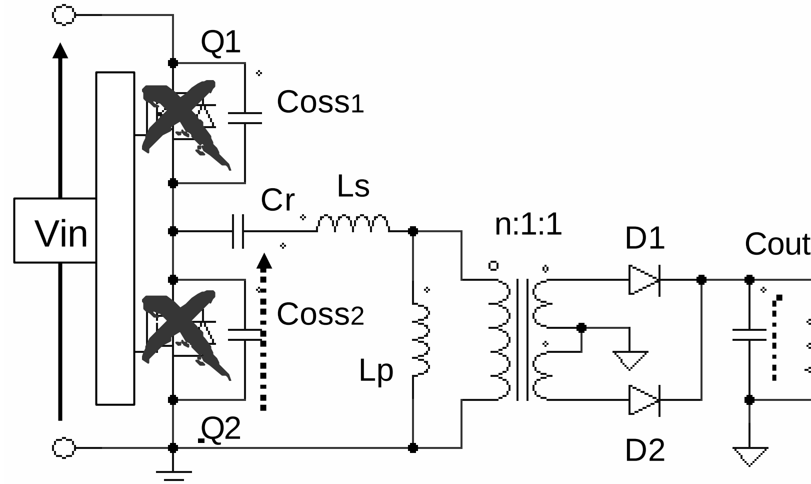




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from to ground
- Energy is taken from Vin and goes to
- Phase ends when Q1 is switched off

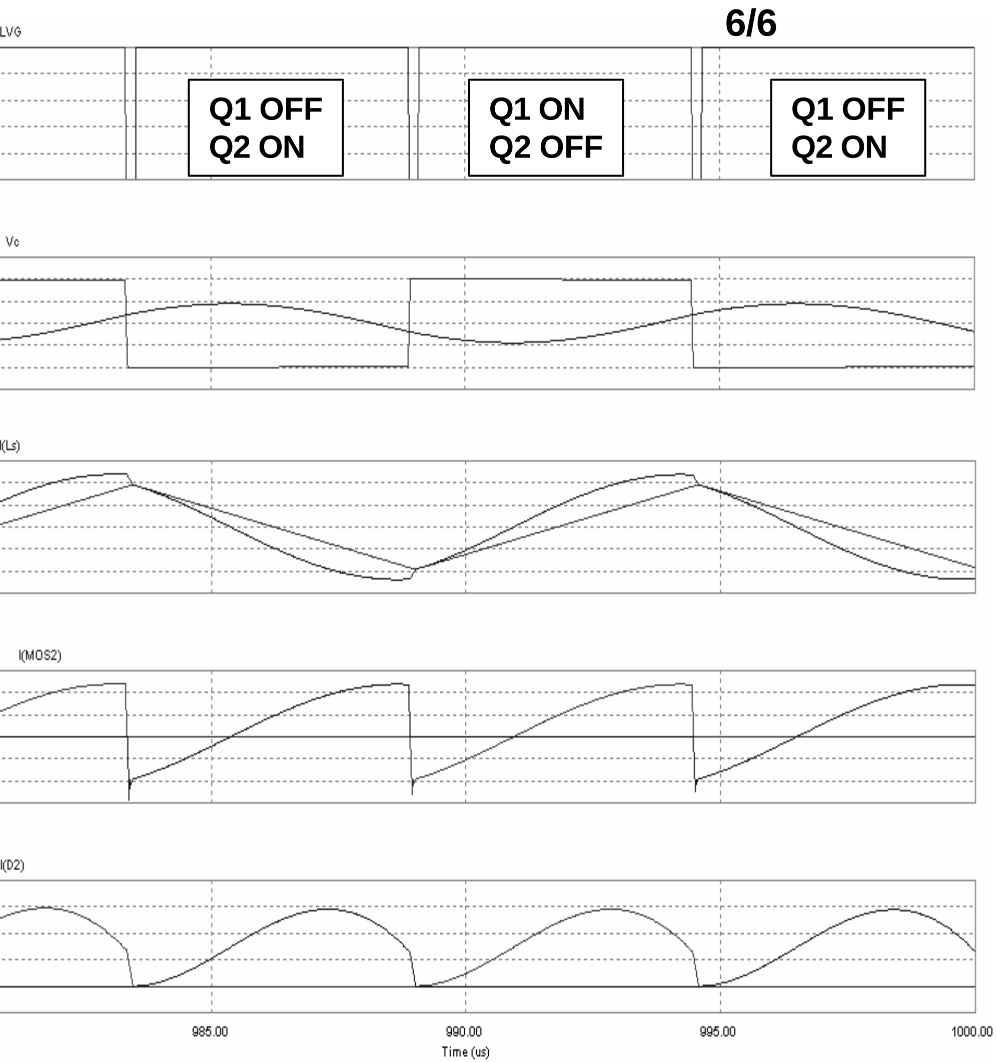
LC Resonant Half-bridge
perating Sequence above resonance (Phase 5/6)

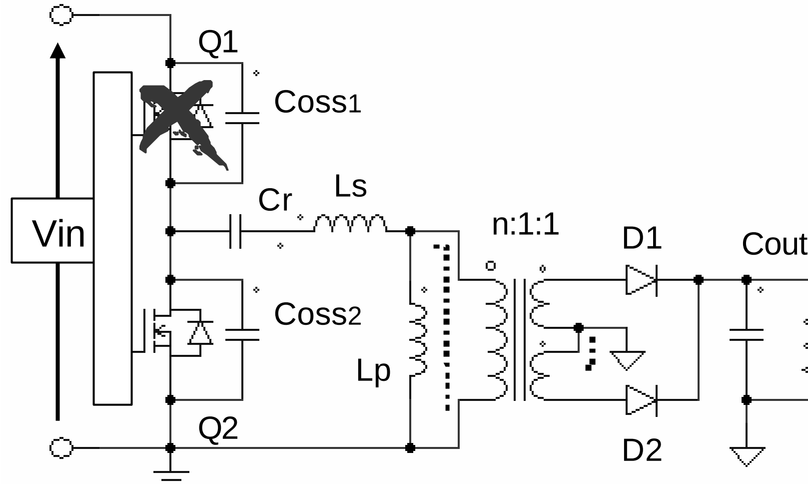




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharge C_{OSS2}, until $V(C_{OSS2})=0$; Q2's body dic starts conducting
- Output energy comes from Cout
- Phase ends when Q2 is switched on

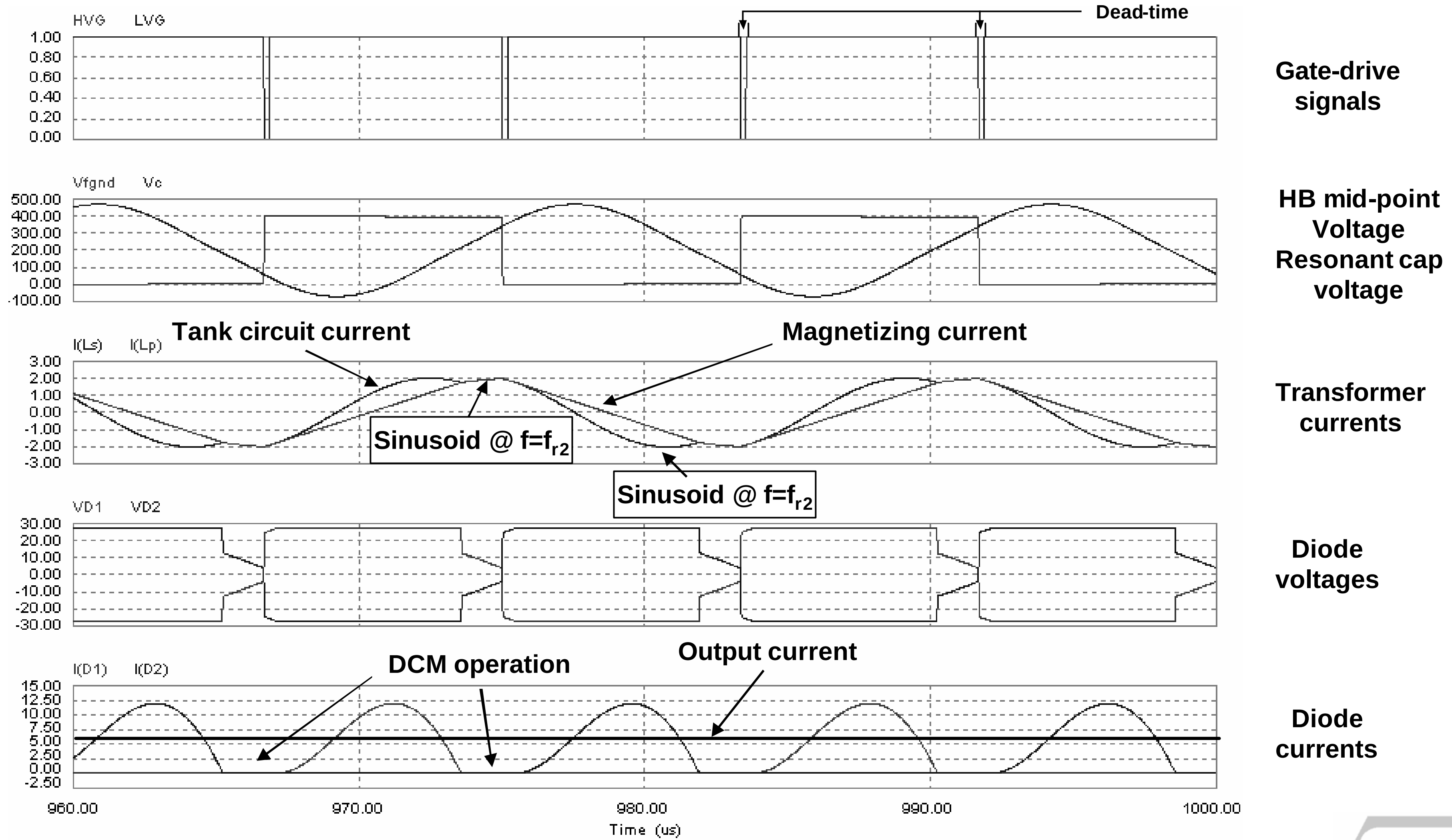
LC Resonant Half-bridge
perating Sequence above resonance (Phase 6/6)



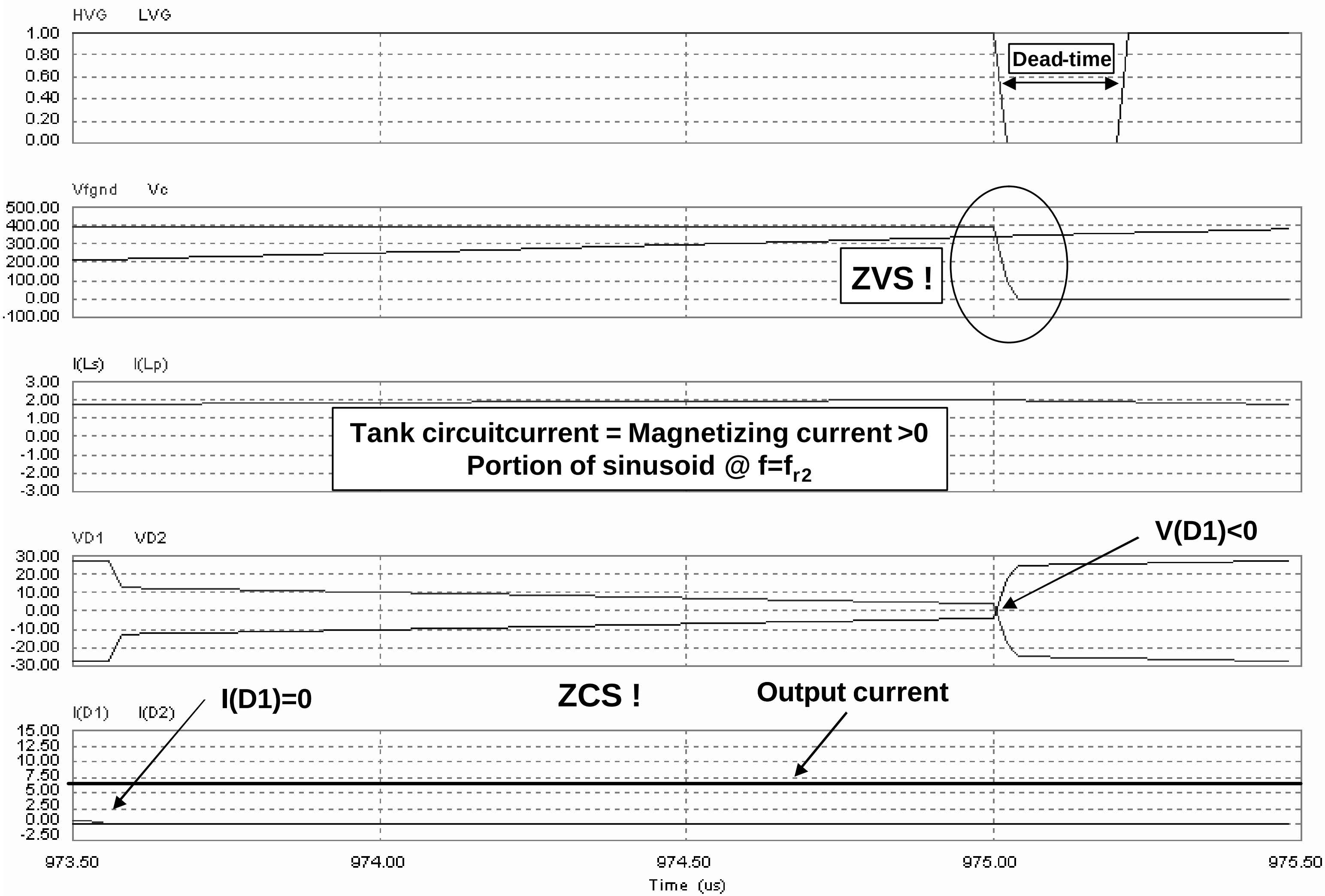


- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- Lp is dynamically shorted: V(Lp) =-n·V
- Cr resonates with Ls, fr1 appears
- I(Ls) flows through Q2's $R_{DS(on)}$ (Q2 working in the 3rd quadrant)
- Output energy comes from Cr and Ls
- Phase ends when I(Ls)=0, Phase 1 sta

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



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



Gate-drive signals

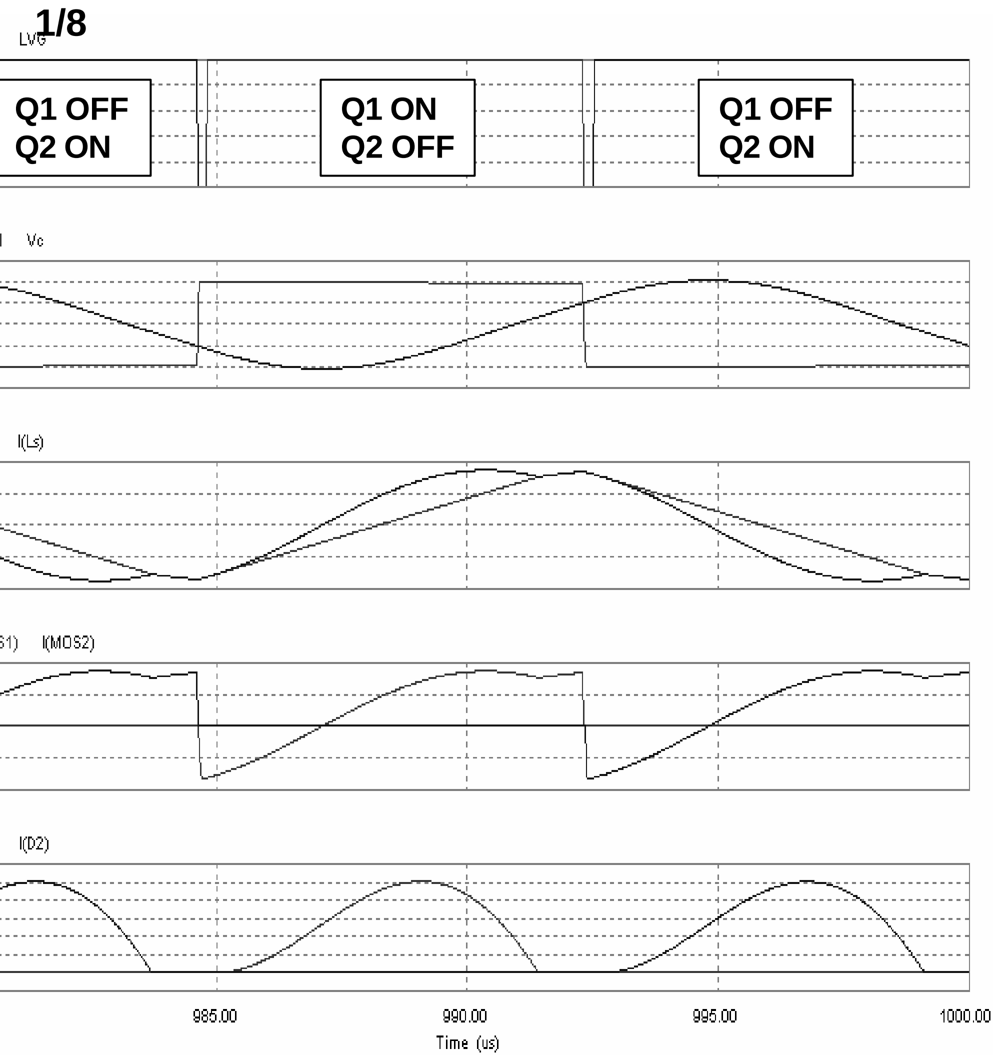
HB mid-point Voltage
Resonant cap voltage

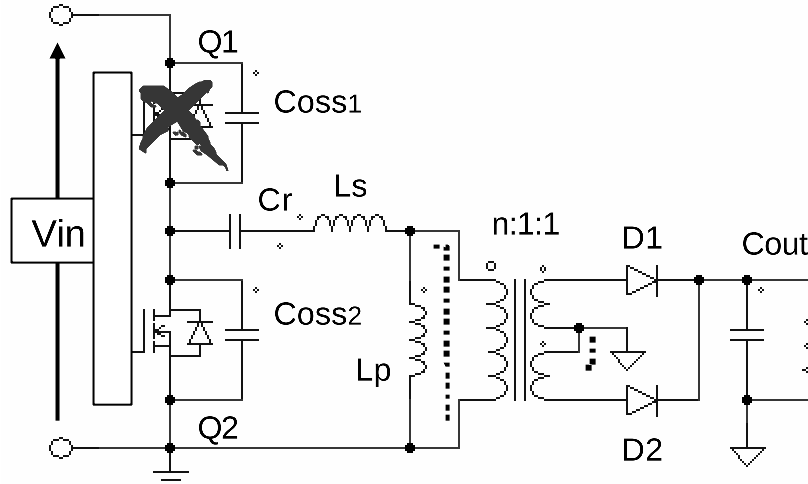
Transformer currents

Diode voltages

Diode currents

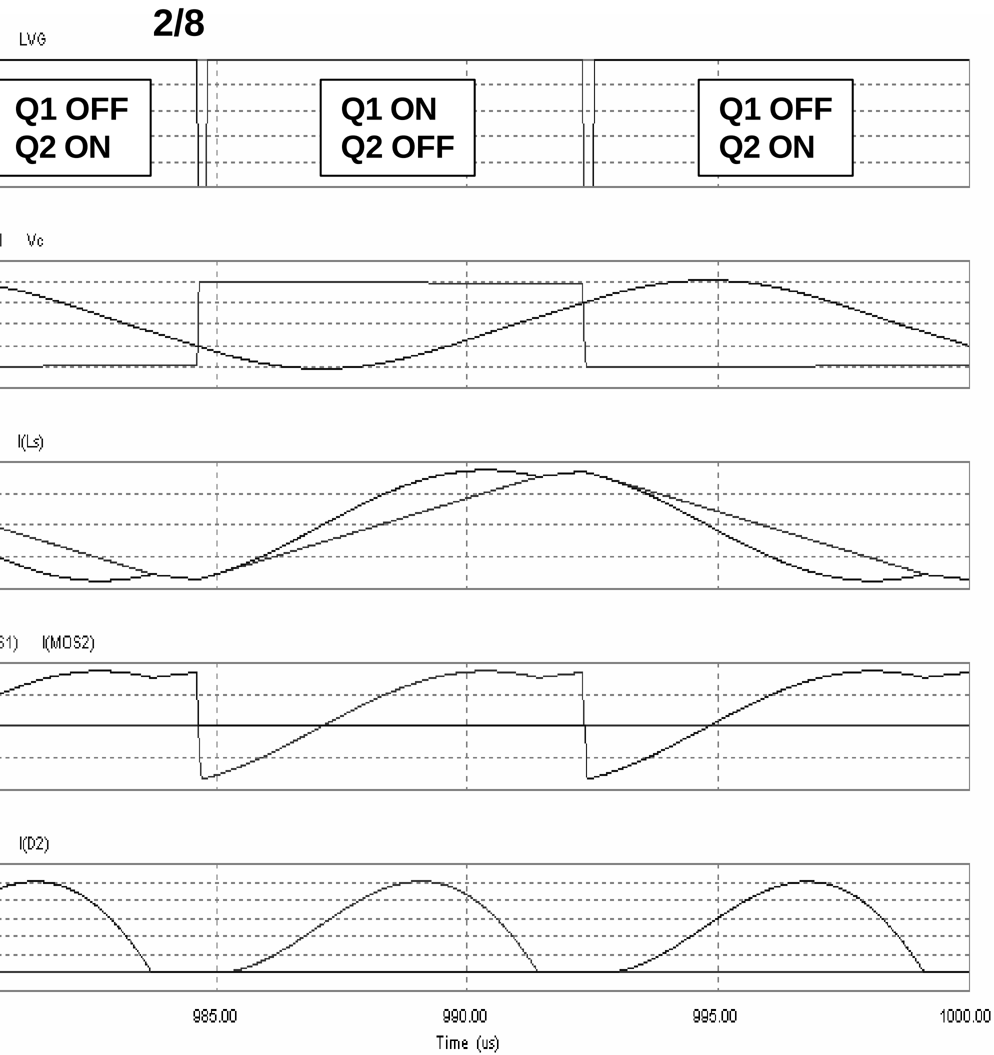
LC Resonant Half-bridge
perating Sequence below resonance (Phase 1/8)

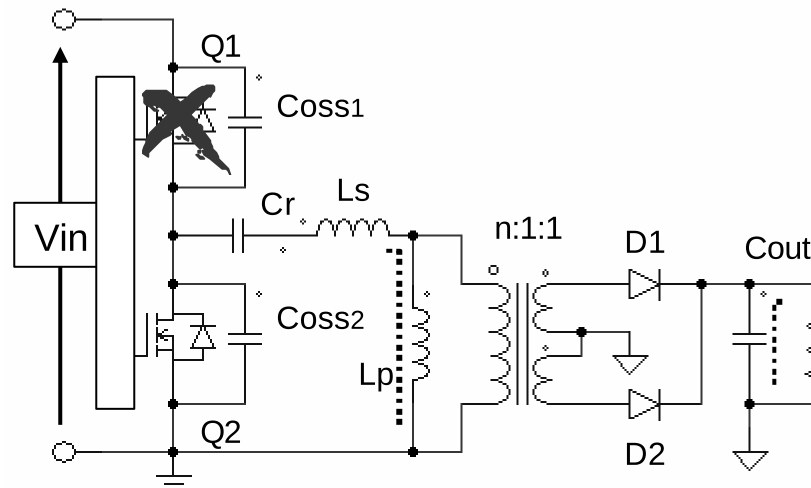




- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; V(D1)=-2·Vout
- Lp is dynamically shorted: V(Lp) =-n·V
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when I(D2)=0

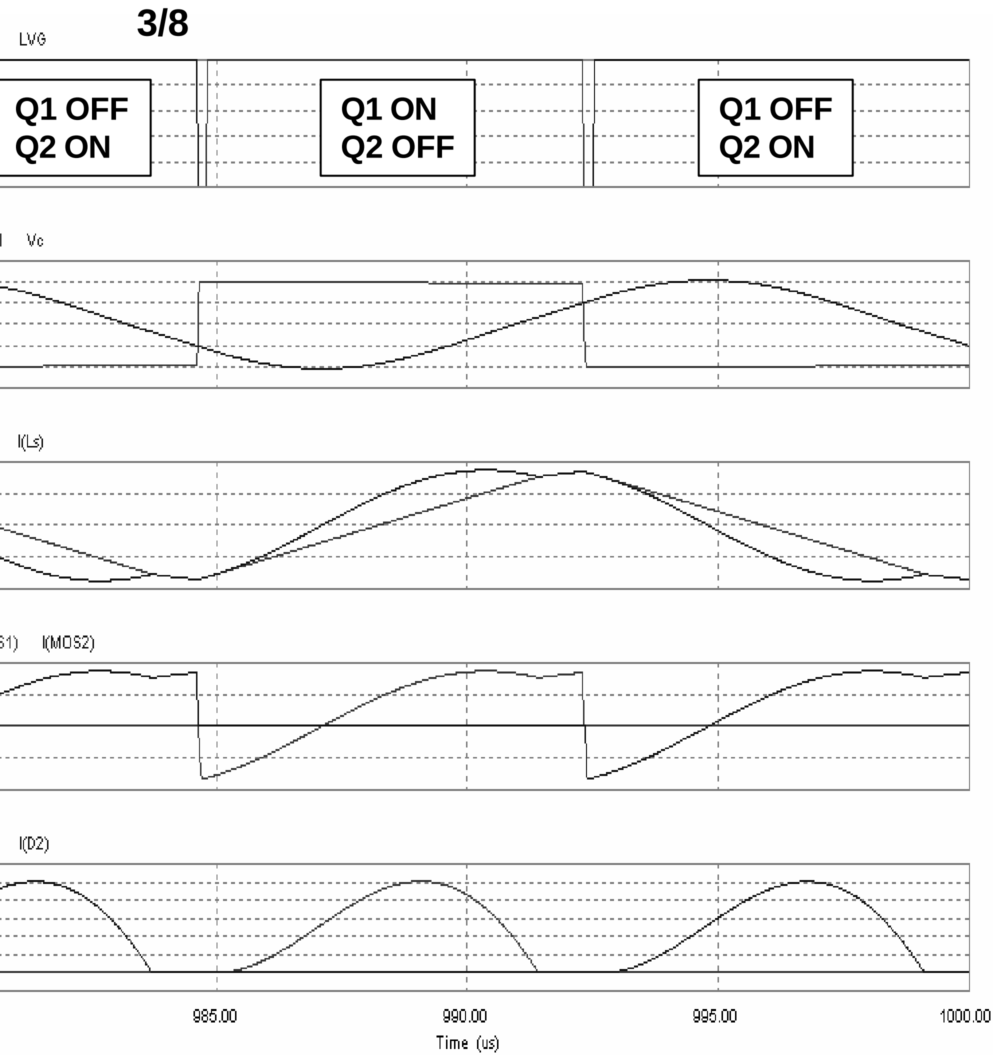
LC Resonant Half-bridge
perating Sequence below resonance (Phase 2/8)

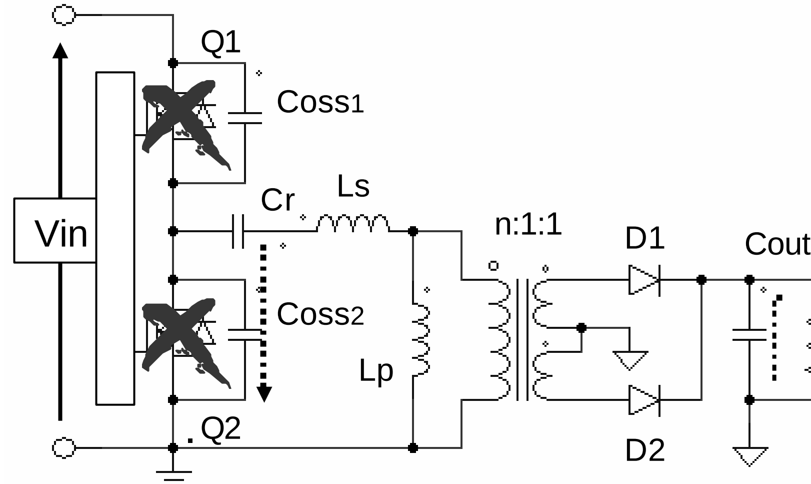




- Q2 is ON, Q1 is OFF
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- Cr resonates with Ls+Lp, f_{r2} appears
- Output energy comes from Cout
- Phase ends when Q2 is switched off

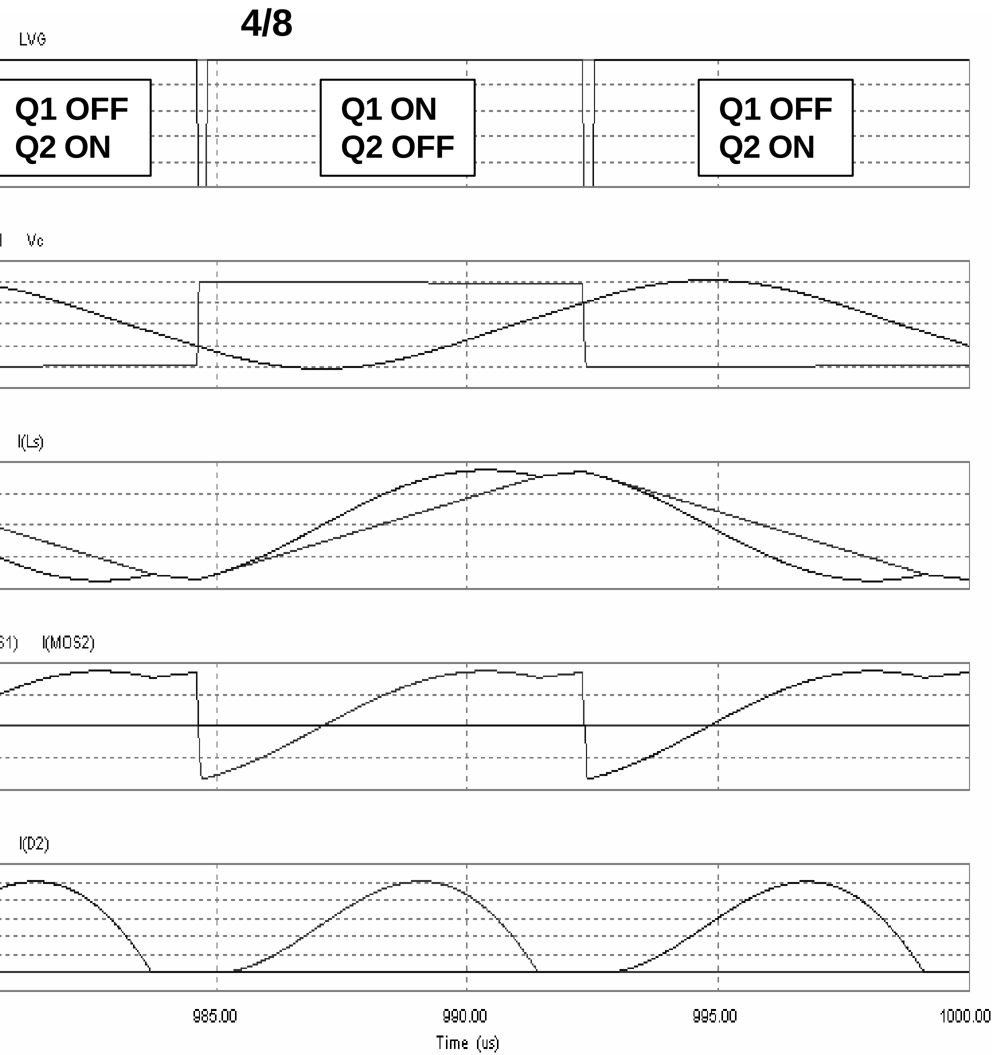
LC Resonant Half-bridge
perating Sequence below resonance (Phase 3/8)

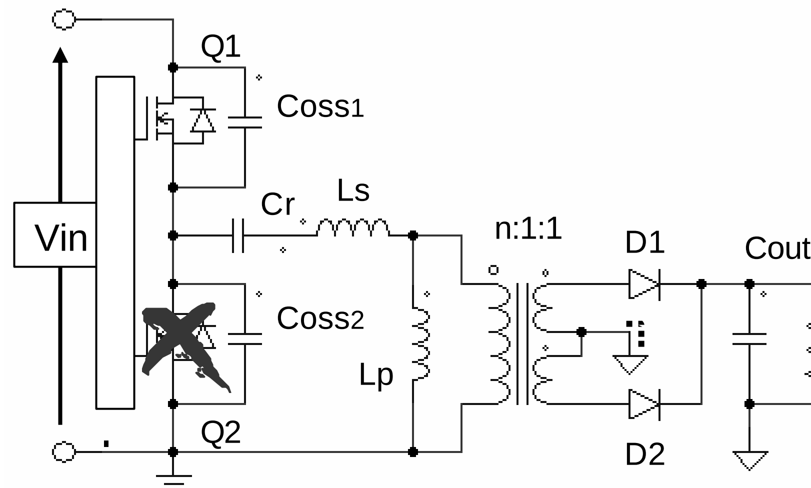




- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS2} and discharge C_{OSS1}, until $V(C_{OSS2})$=Vin; Q1's body d starts conducting, energy goes back
- Phase ends when Q1 is switched on

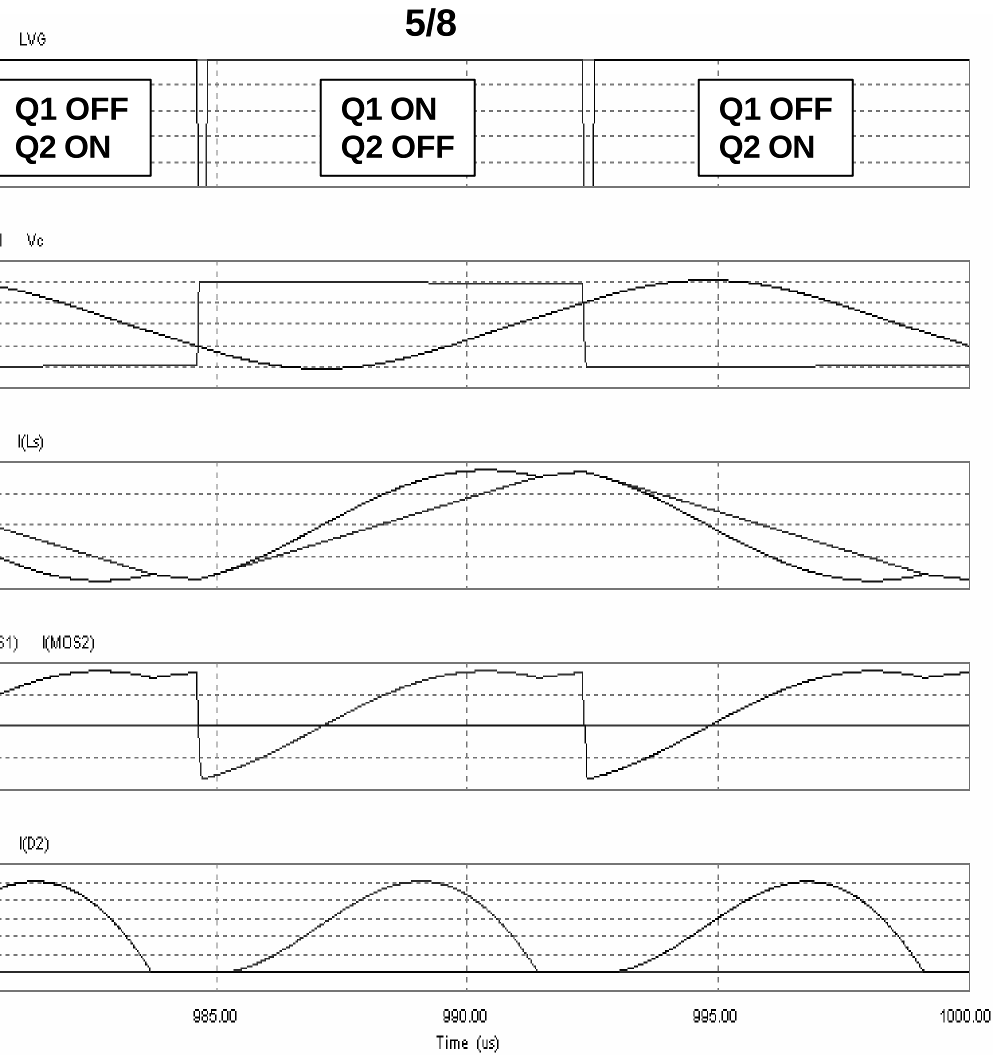
LC Resonant Half-bridge
perating Sequence below resonance (Phase 4/8)

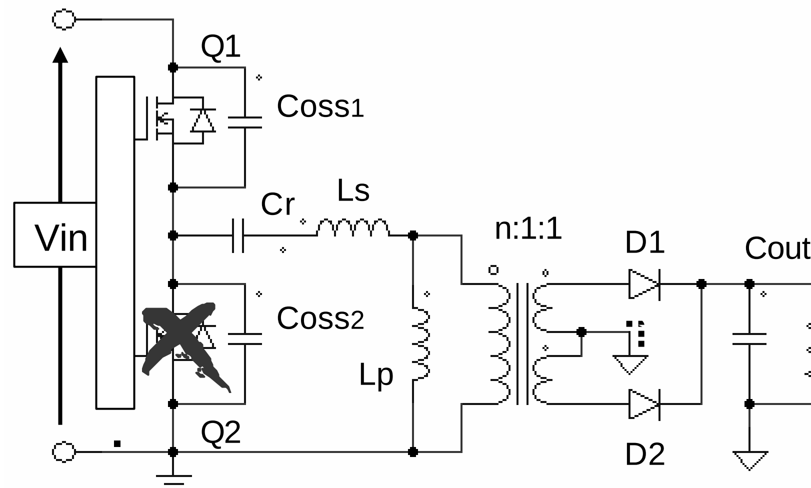




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ back
  Vin (Q1 is working in the 3rd quadran
- Energy is recirculating into Vin
- Phase ends when I(Ls)=0

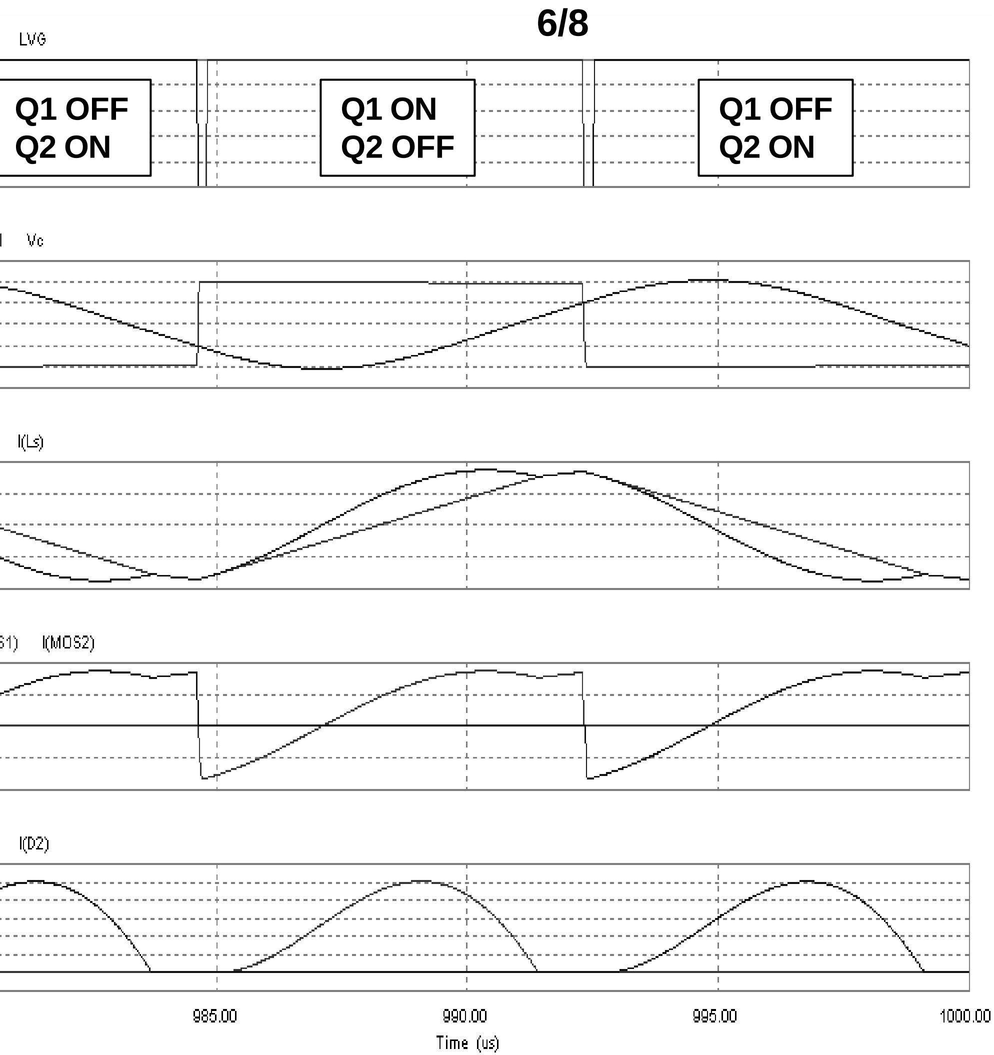
LC Resonant Half-bridge
perating Sequence below resonance (Phase 5/8)

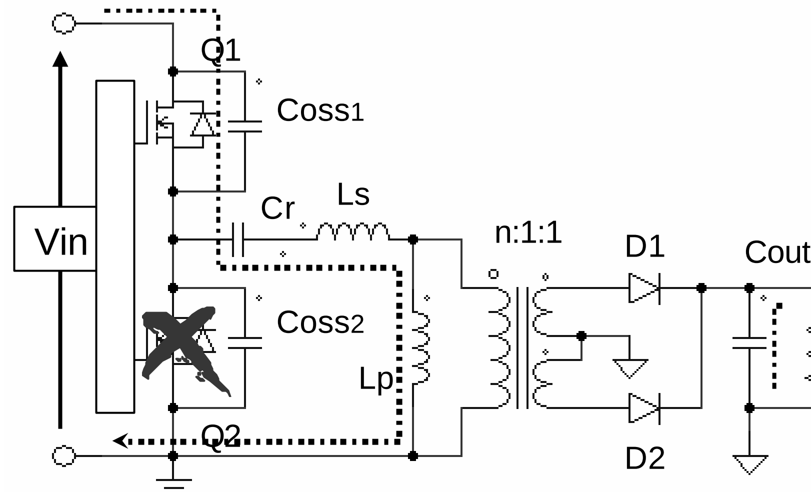




- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; V(D2)=-2·Vout
- Lp is dynamically shorted: V(Lp) = n·V
- Cr resonates with Ls, f_{r1} appears
- I(Ls) flows through Q1's $R_{DS(on)}$ from to ground
- Energy is taken from Vin and goes to
- Phase ends when I(D1)=0

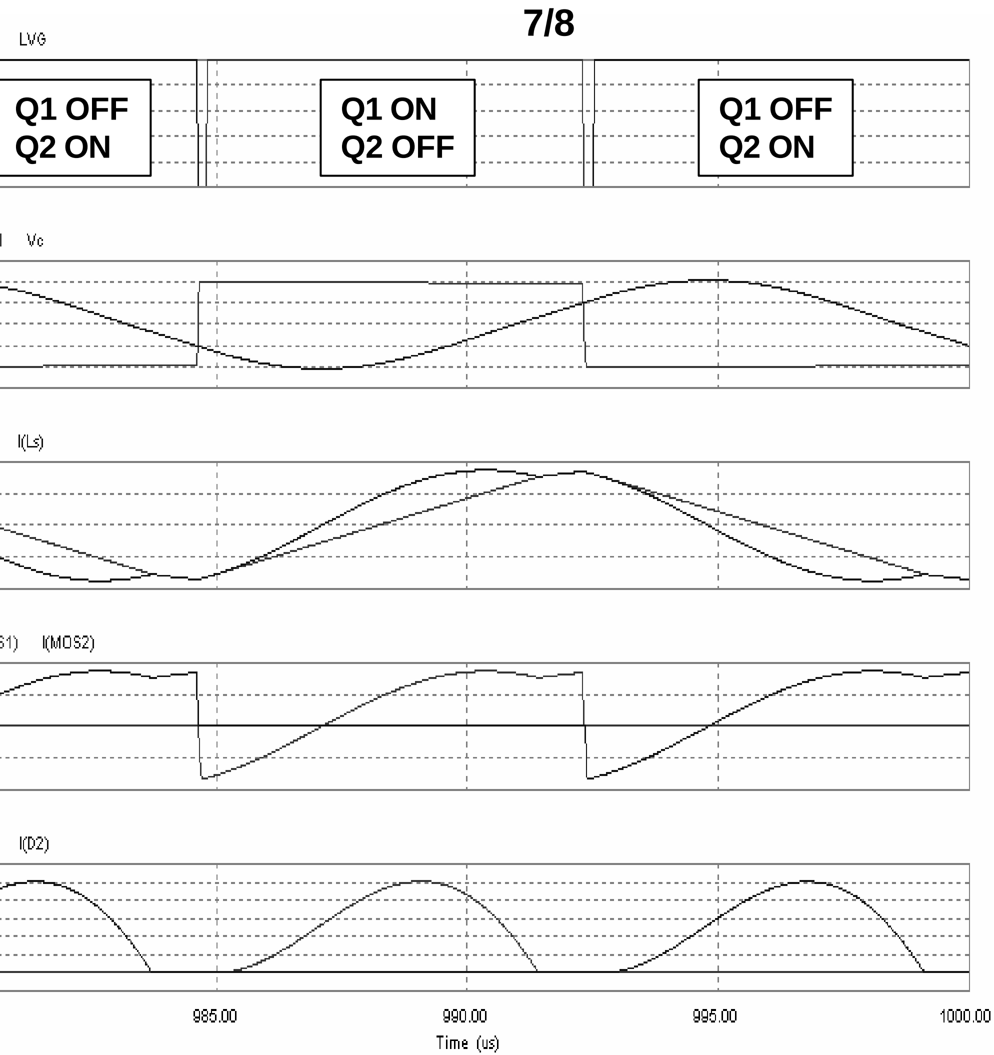
LC Resonant Half-bridge
perating Sequence below resonance (Phase 6/8)

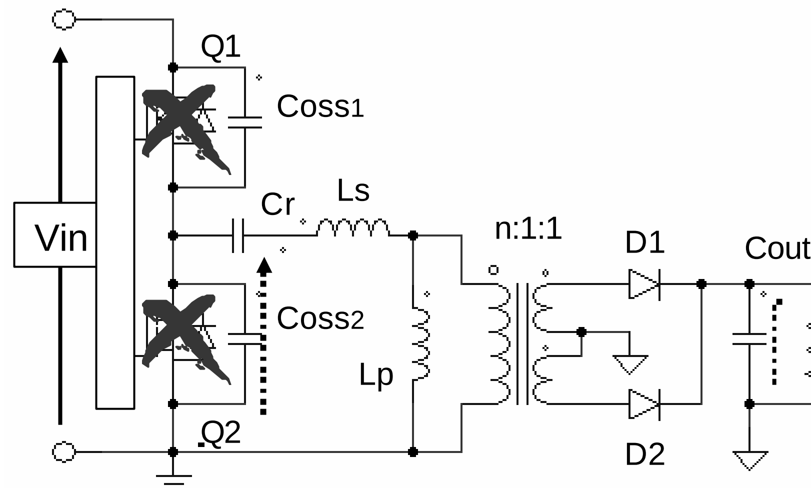




- Q1 is ON, Q2 is OFF
- D1 and D2 are OFF; V(D1)=V(D2)=0; transformer's secondary is open
- Cr resonates with Ls+Lp, f_{r2} appears
- Output energy comes from Cout
- Phase ends when Q1 is switched off

LC Resonant Half-bridge
perating Sequence below resonance (Phase 7/8)

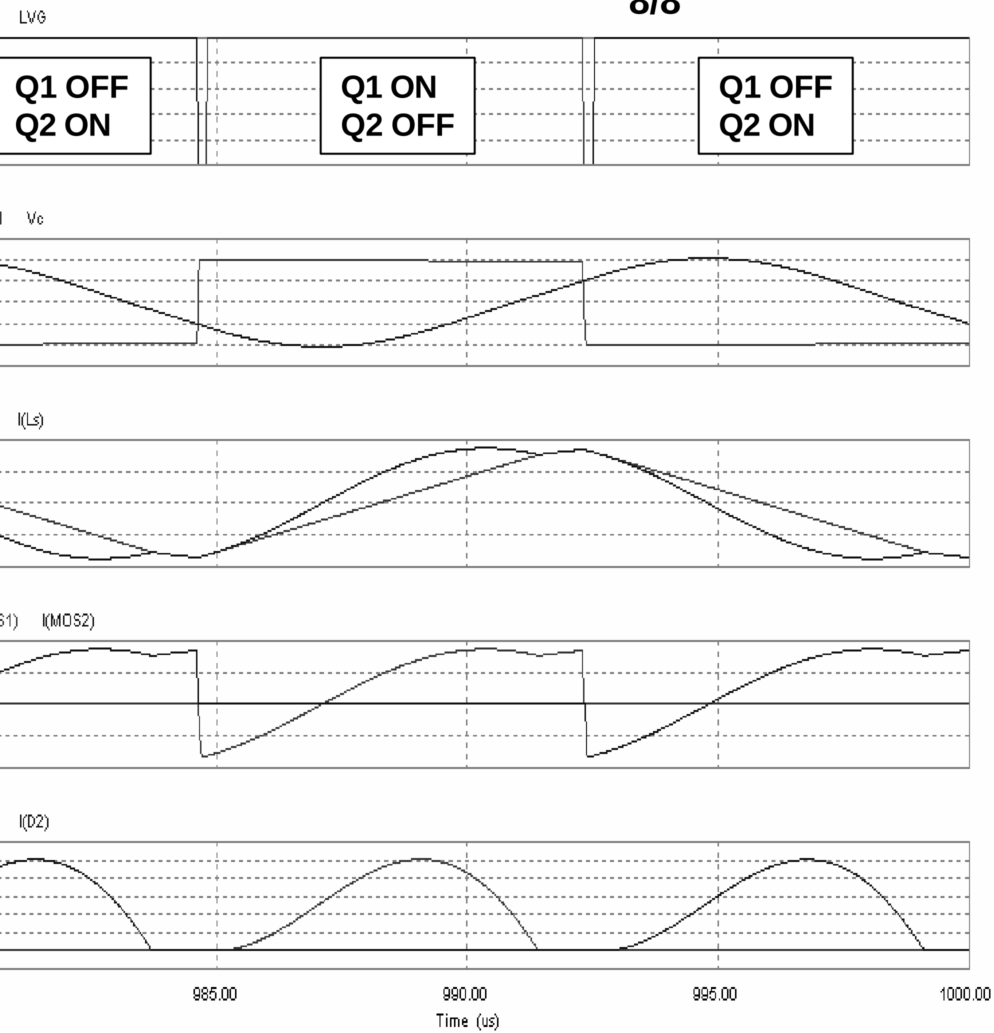


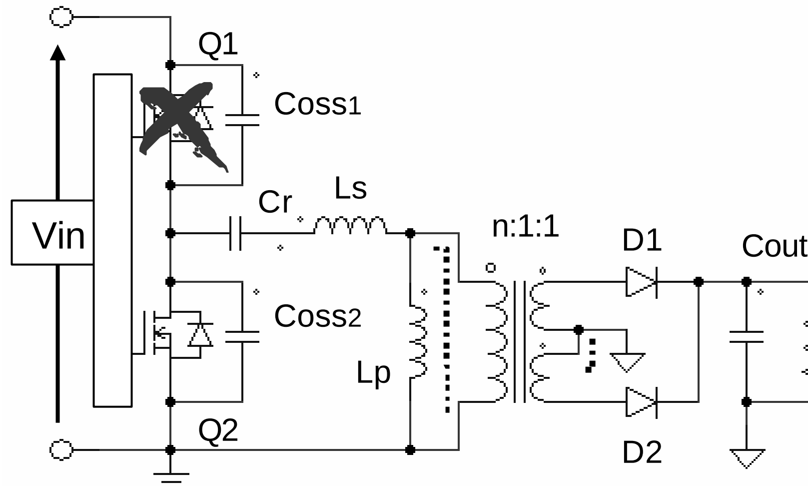


- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; V(D1)=VD(2)=0; transformer's secondary is open
- I(Ls+Lp) charges C_{OSS1} and discharge C_{OSS2}, until $V(C_{OSS2})=0$, then Q2's bo diode starts conducting
- Output energy comes from Cout
- Phase ends when Q2 is switched on

LC Resonant Half-bridge
perating Sequence below resonance (Phase 8/8)

8/8





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

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

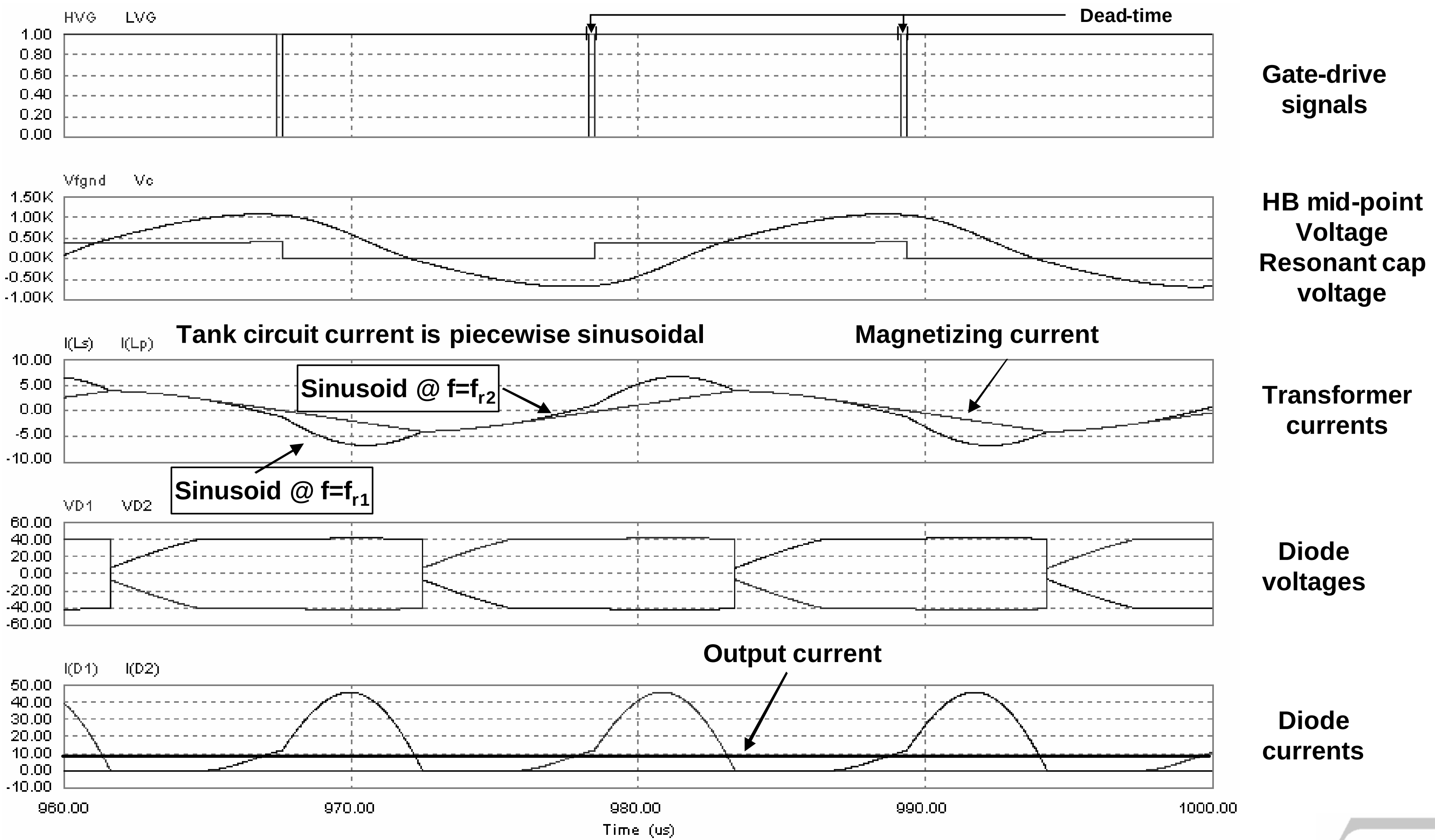
Capacitive mode is encountered when f_{sw} gets close to f_{r2}
Although in capacitive mode ZCS can be achieved, however ZVS is lost, which causes:

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, additiona 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

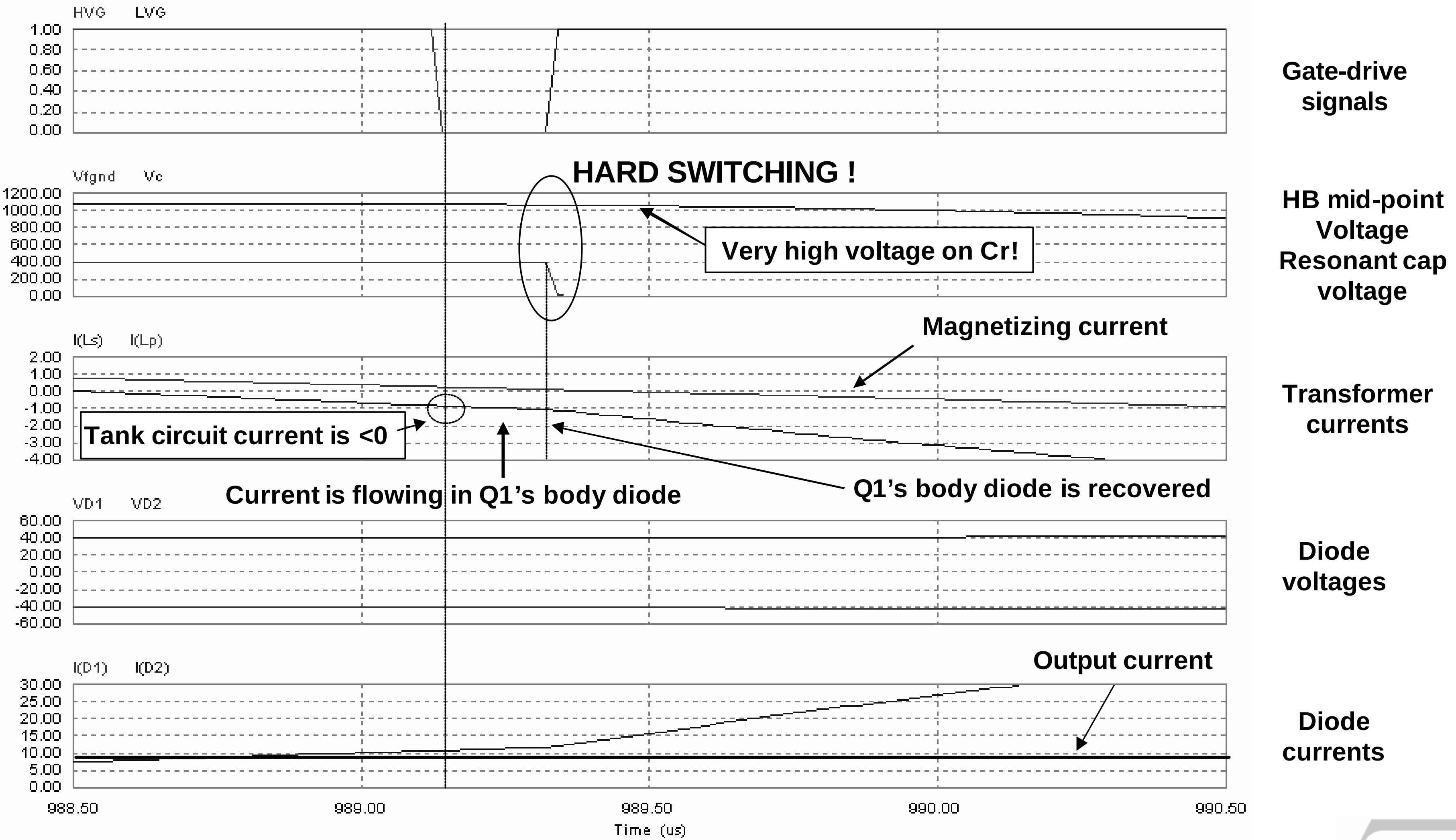
dditionally, feedback loop sign could change from negative to positive:

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

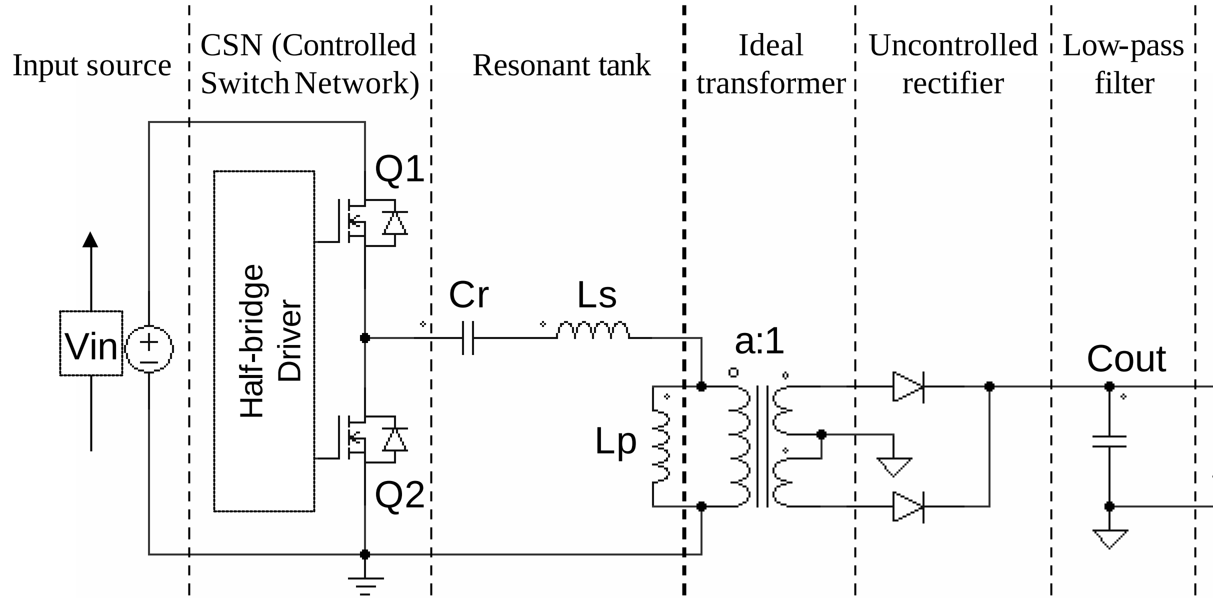
LC Resonant Half-bridge
/aveforms in capacitive mode ($f_{sw} \sim f_{r2}$)



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

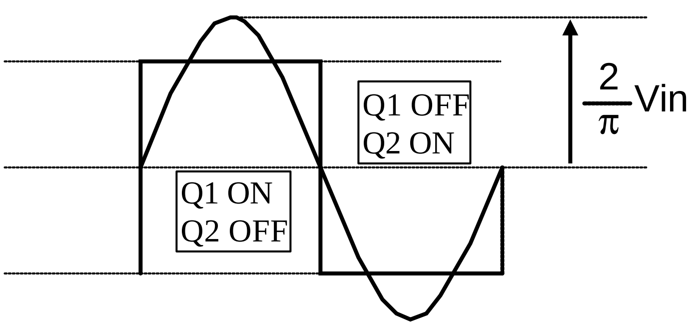


LC Resonant Half-bridge
pproximate analysis with FHA approach: Basics



BASIC PRINCIPLES

N provides a square wave voltage a frequency fsw, dead times are glected
sonant tank responds primarily to fundamental component, then:
nk waveforms are approximated their fundamental components
controlled rectifier + low-pass ter's effect is incorporated into e load.



Note:

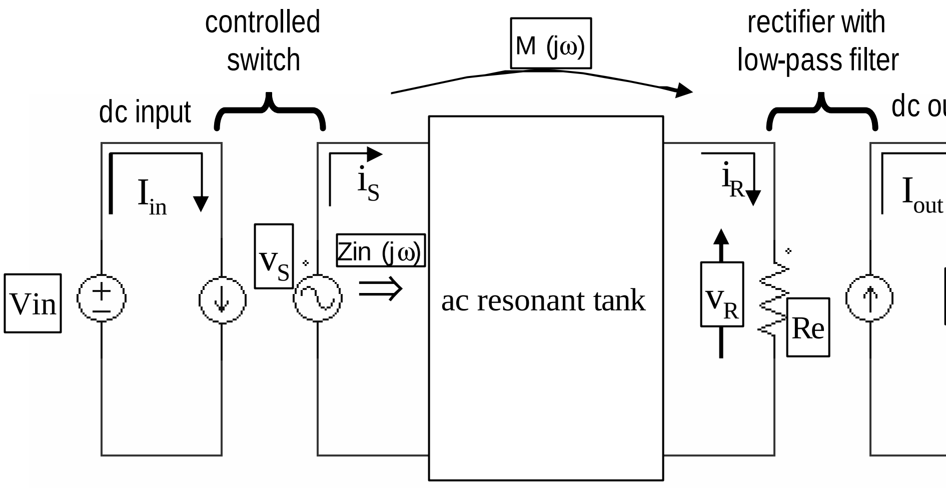
- Cr is both resonant and dc blocking capacitor
- Its ac voltage is superimposed on a dc component equal to Vin/2 (duty cyle is 50% for both Q1 and Q2)

LC Resonant Half-bridge
quivalent model with FHA approach

- e actual circuit turns into an equivalent ear circuit where the ac resonant tank is cited by an effective sinusoidal input rce and drives an effective resistive load.
- andard ac analysis can be used to solve the cuit
- nctions of interest: Input Impedance (jω) and Forward Transfer Function M(jω).
- s possible to show that the complete version ratio Vout/Vin is:

$$\frac{Vout}{Vin} = \| M(j\omega) \|$$

- is result is valid for any resonant topology



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

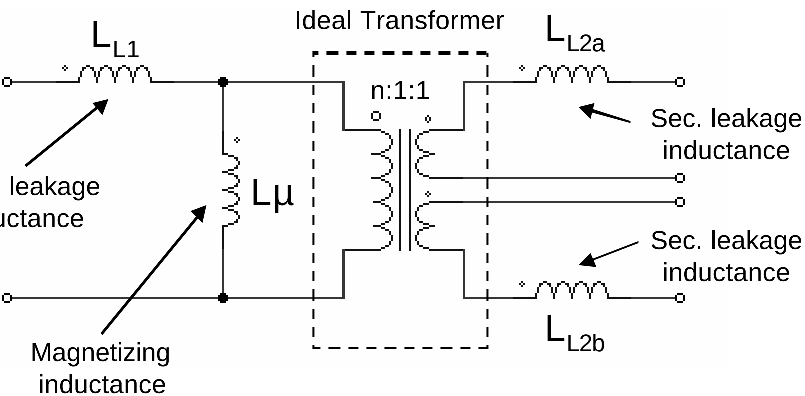
$$Re = \frac{8}{\pi^2} a$$

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

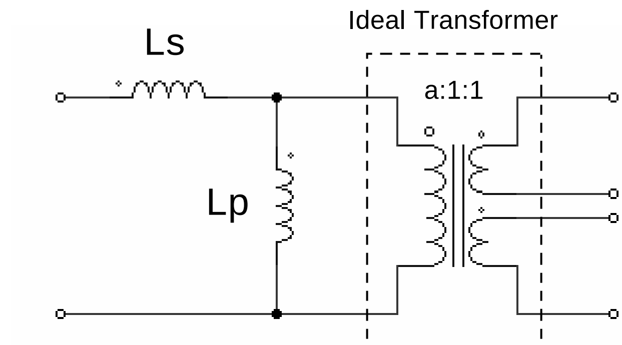
$$Iout = \frac{2}{\pi} a$$

LC Resonant Half-bridge
ransformer model (I)

Physical model



All-Primary-Side equivalent model used for LLC analysis

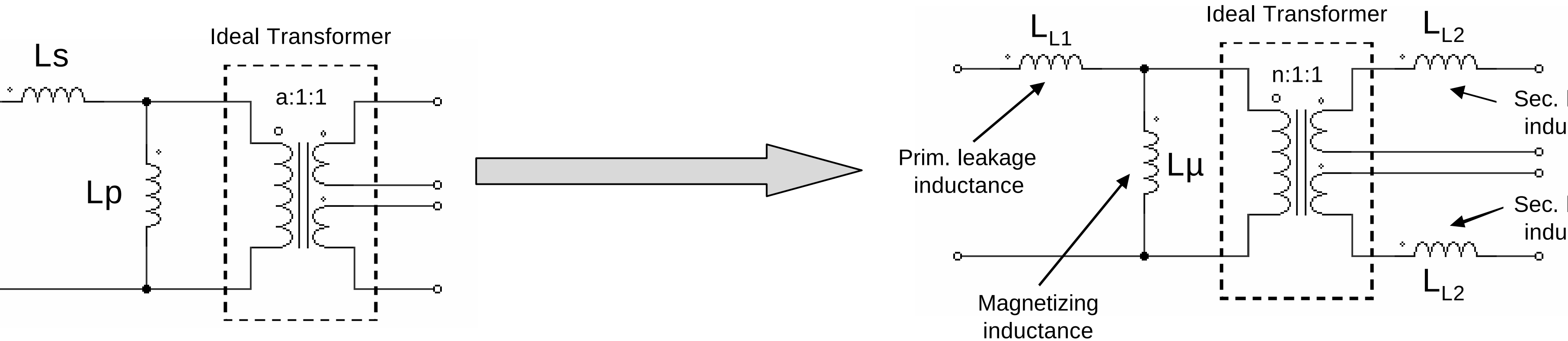


ults from the analysis of the magnetic
ucture (reluctance model appraach)
the actual primary-to-secondary turn ratio
nodels the magnetizing flux linking all windings
models the primary flux not linked to secondary
and L_{L2b} model the secondary flux not linked to
nary; symmetrical windings: $L_{L2a} = L_{L2b}$

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

NOTE: L_{L1} +Lμ = Ls + Lp = L1 primary winding inductance

LC Resonant Half-bridge transformer model (II)

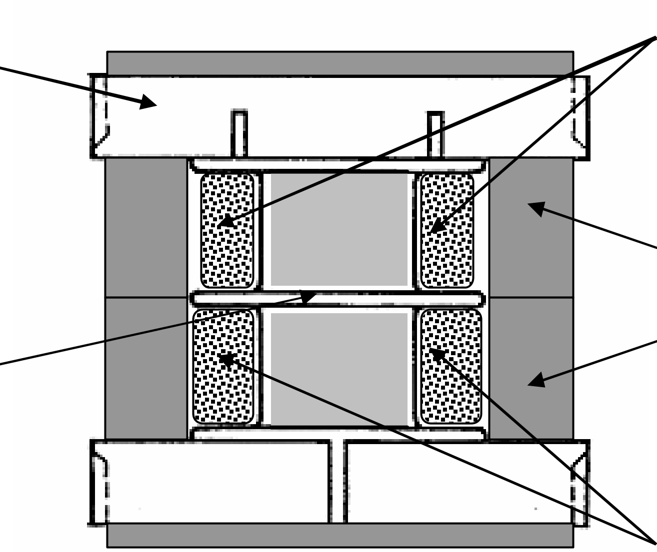


- We need to go from the APS model to the physical model to determine transformer specification
- Undetermined problem (4 unknowns, 3 conditions); one more condition needed (related to the physical magnetic structure)
- Only n is really missing: L1 = Ls + Lp = L_{L1} + Lμ is known and measurable, Ls 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:

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

LC Resonant Half-bridge
ransformer model (III)

mple of magnetically symmetrical structure



Top view

- 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>

LC Resonant Half-bridge
umerical 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):

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

where:

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

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

LC Resonant Half-bridge
esonant Tank Input Impedance Zin(jw)

ove resonance (x>1) Zin(jω) is always
uctive; current lags voltage, so when
0, i_S is still >0: ZVS

ow f_{r2} ($x<\sqrt{\frac{1}{1+k}}$), Zin(jω) is always
acitive; current leads voltage, so when
0, i_S is already <0: ZCS

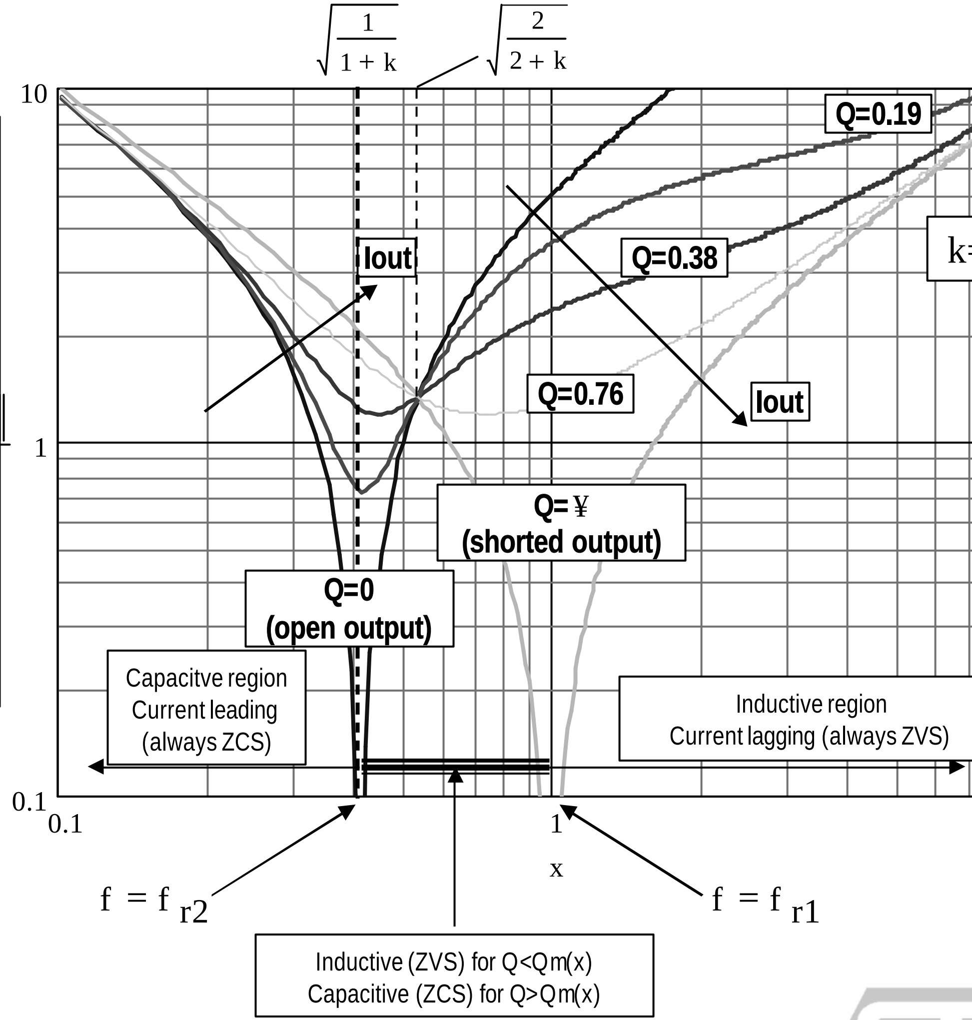
ow the first resonance ($\sqrt{\frac{1}{1+k}}$ <x<1)
e sign of Zin(jω) depends on Q: if
Q_m(x) it is inductive ⇒ ZVS; if
Q_m(x) it is capacitive ⇒ ZCS.

general, the ZVS-ZCS borderline is
fined by Im(Zin(jω))=0

r $x>\sqrt{\frac{2}{2+k}}$ |Zin(jω)| is concordant with
e load: the lower the load the lower
e input current

r $x<\sqrt{\frac{2}{2+k}}$ |Zin(jω)| is discordant with
e load: the lower the load the higher
e input current!

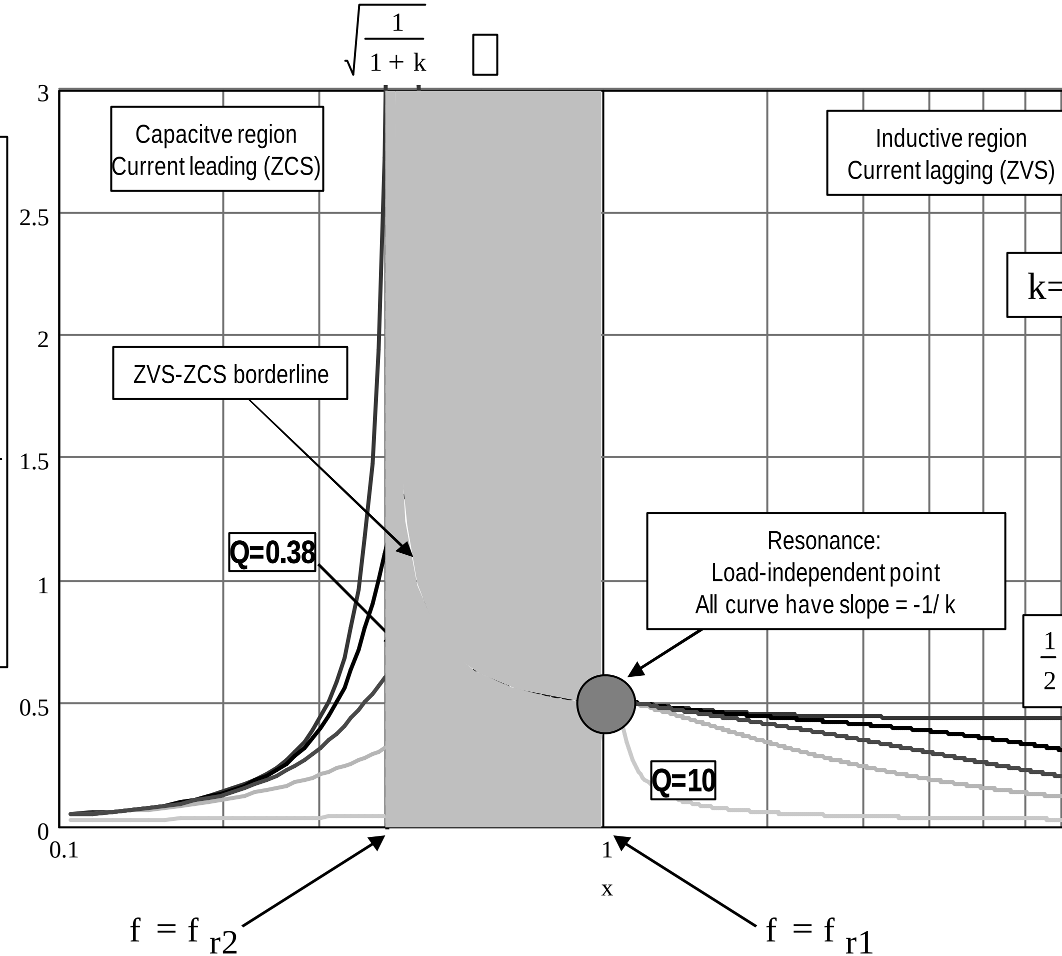
$$\frac{\|Zin(x,k,Q)\|}{Z_R}$$



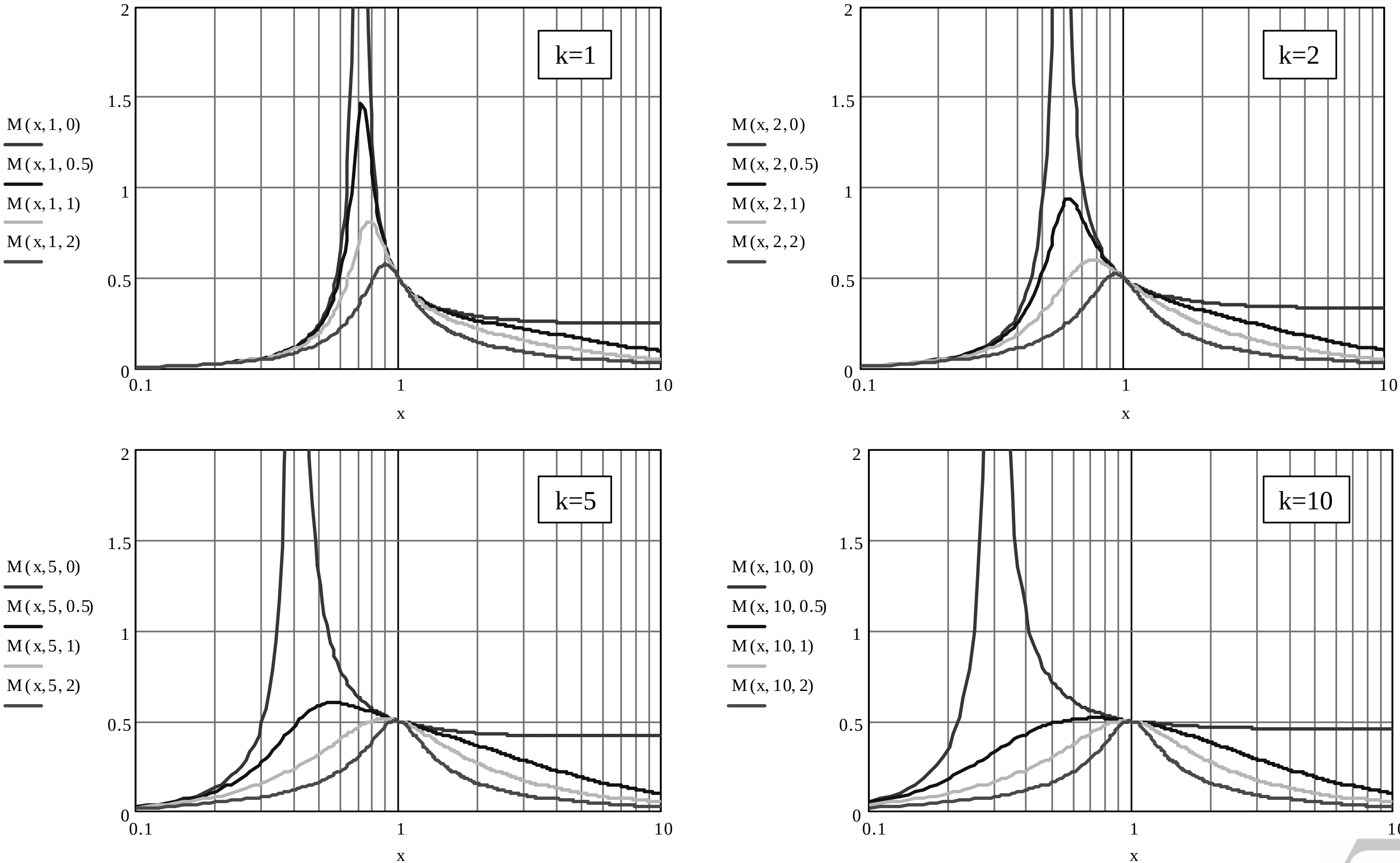
LC Resonant Half-bridge
oltage conversion ratio ||M(jw)||

- curves, for any Q, touch at x=1, =0.5, with a slope -1/k;
- e open output curve (Q=0) is the per boundary for converter's erating points in the x-M plane;
- $= \frac{1}{2} \times \frac{k}{1+k}$ for x? ∞;
- ? ∞ for x = $\sqrt{\frac{1}{1+k}}$
- curves with Q>0 have maxima at fall in the capacitive region.
- ove resonance it is always M<0.5
- 0.5 only below resonance
- 'S below resonance at a given equency occurs if M> M_{min}>0.5; if M_{min}>0.5 is fixed, it occurs if Q_m.

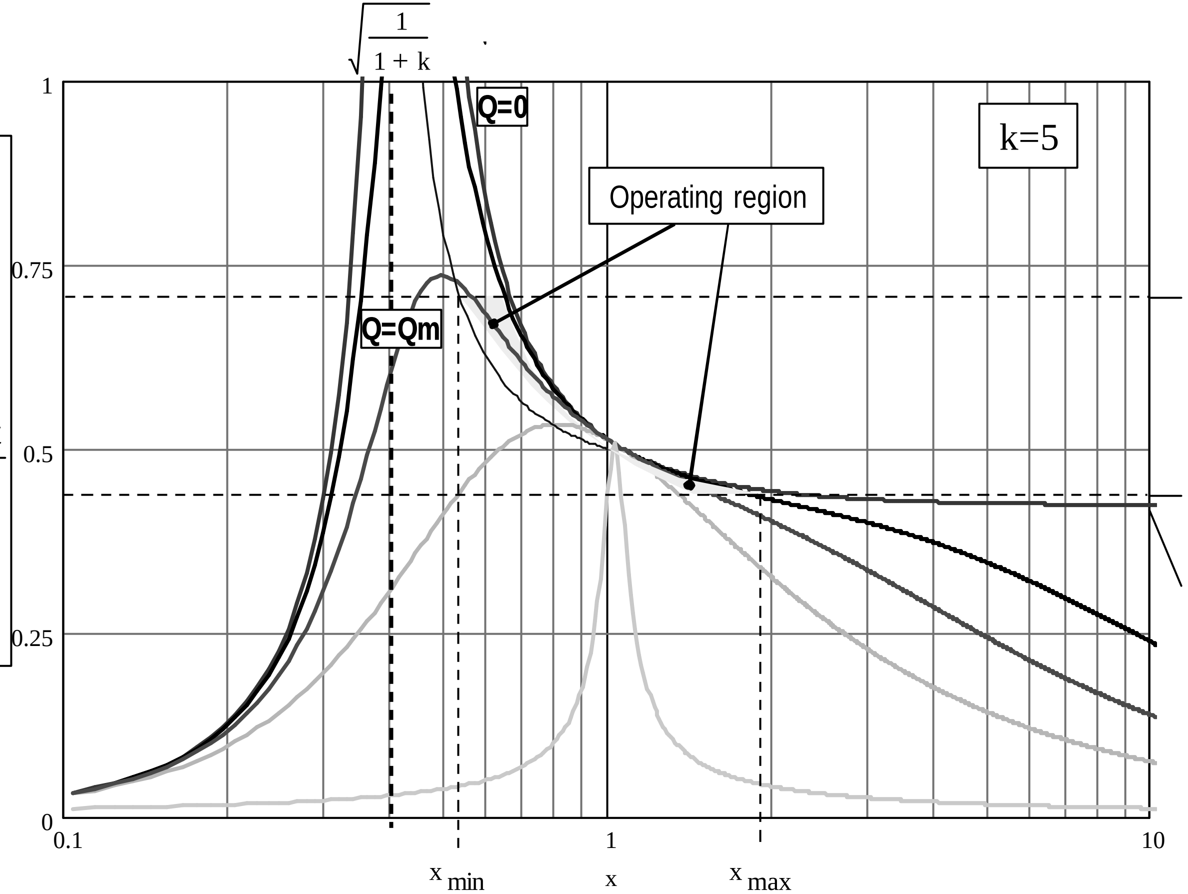
$$M = \frac{a \cdot Vout}{Vin}$$



LC Resonant Half-bridge
ffect of k on ||M(jw)||



LC Resonant Half-bridge
perating region on ||M(jw)|| diagrams



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

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

LC Resonant Half-bridge
ull-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. $Im[Zin(j\omega)] \ge 0$.

f $Q=Q_m$ ($Im[Zin(j\omega)] = 0$) the switched current is exactly zero, This is only a necessary condition for ZV
not sufficient because the parasitic capacitance of the HB midpoint, neglected in the FHA approach, nee
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 :

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

Coss is the MOSFET's output capacitance, Cstray an additional contribution due to transformer's winding
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 concerne

LC Resonant Half-bridge
o-load issues: regulation

C converter can regulate down to zero load,
ike the conventional LC series-resonant

a frequency >> f_{r1} Cr disappears and the output
tage is given by the inductive divider made up
Ls and Lp

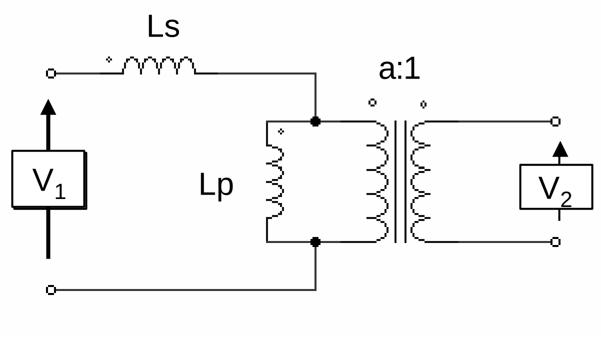
the minimum voltage conversion ratio is greater
an the inductive divider ratio, regulation will be
ssible at some finite frequency

is links the equivalent turn ratio a and the
luctance ratio k:

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

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

Equivalent schematic of LLC converter for x ?



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

LC Resonant Half-bridge
o-load issues: ZVS

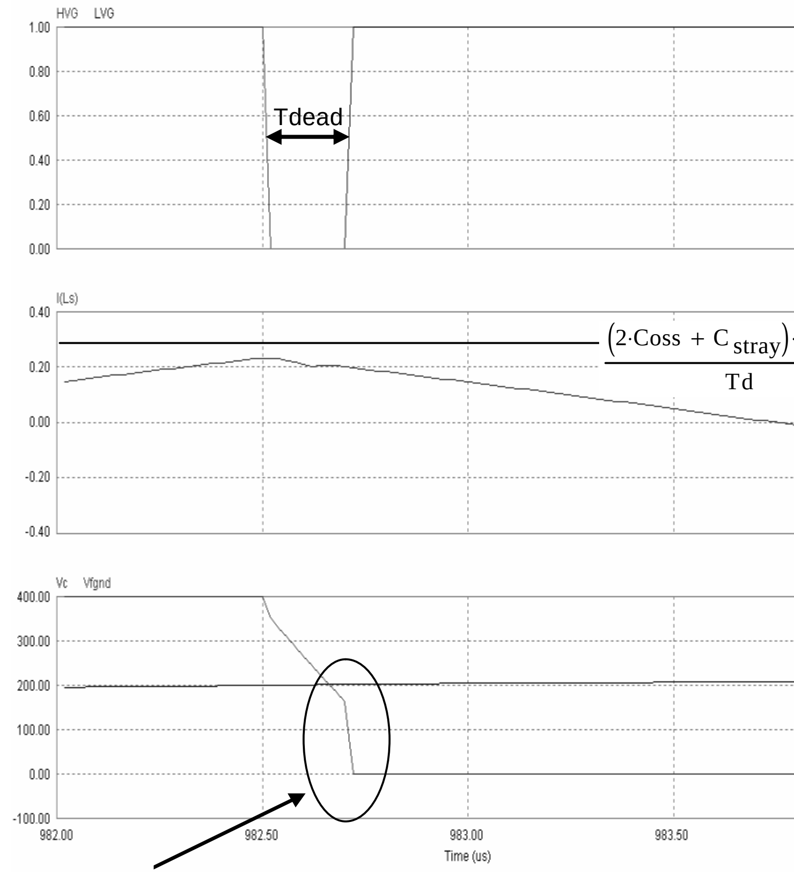
n(jω) analysis has shown that ZVS always occurs
r x>1, even at no load (Q=0)

1 is actually only a necessary condition for ZVS,
t sufficient because of the parasitic capacitance
the HB midpoint neglected in the FHA approach

minimum current must be ensured at no load to
the HB midpoint swing rail-to-rail within the
ad-time.

nis poses an additional constraint on the maximum
lue of Q at <u>full load</u>:

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



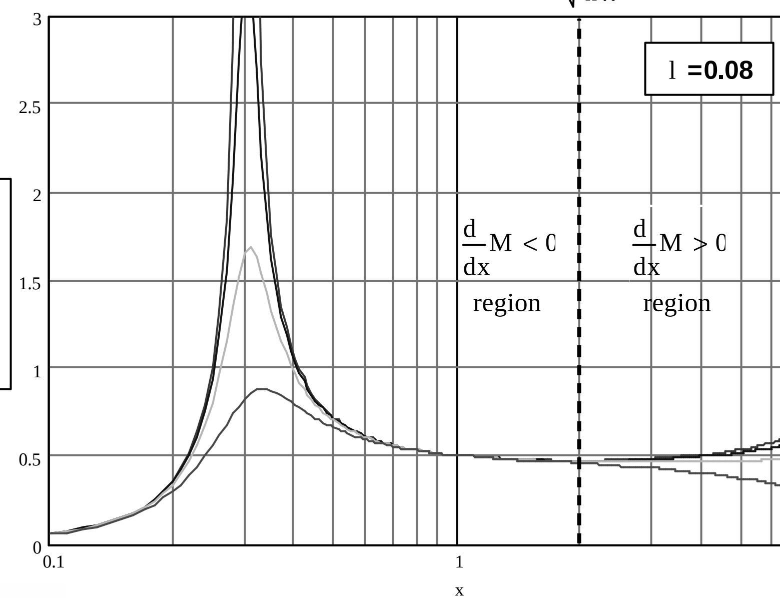
Hard Switching at no load

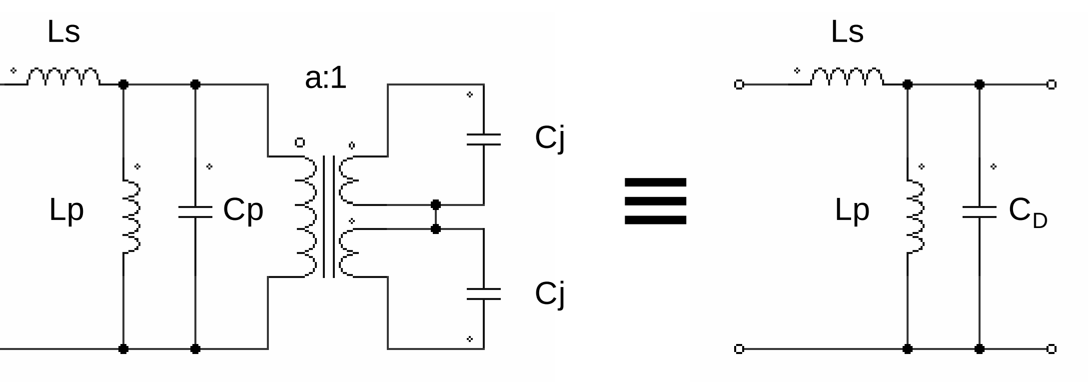
LC Resonant Half-bridge
o-load issues: Feedback inversion

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.

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

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





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

LC Resonant Half-bridge
esign 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

LC Resonant Half-bridge
esign 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:

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

LC Resonant Half-bridge
esign 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:

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

LC Resonant Half-bridge
esign 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	

LC Resonant Half-bridge
esign 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:

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

LC Resonant Half-bridge
esign example. 300W converter

6. Calculate the effective load resistance:

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

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 $Q_S \le \min(Q_{max1}, Q_{max2})$

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:

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

LC Resonant Half-bridge
esign 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:

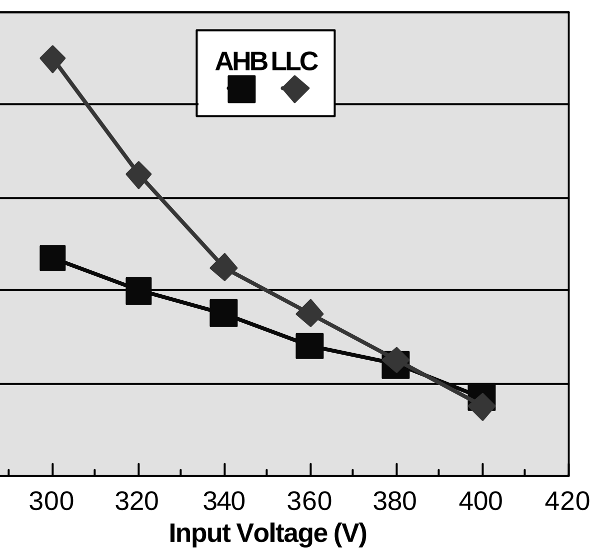
$$RF_{max} = \frac{RF_{min}}{\frac{f_{max}}{f_{min}} - 1} = \frac{13.3 \cdot 10^{3}}{\frac{180}{53.28} - 1} = 5.54\ k\Omega$$

Calculate Soft-start components:

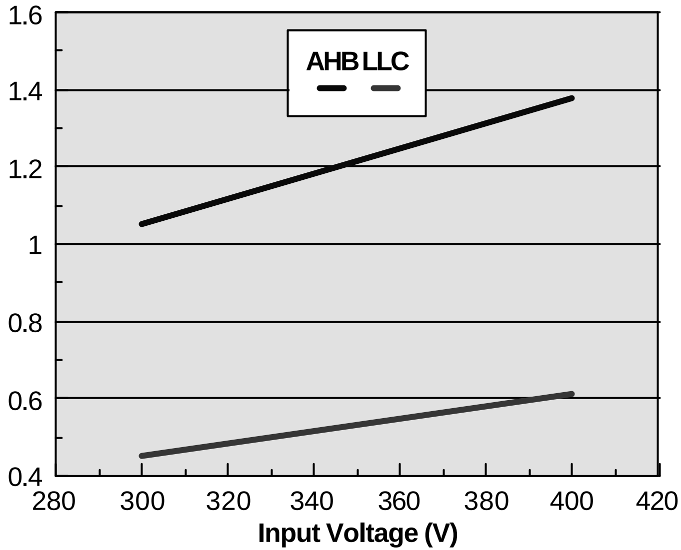
$$R_{SS} = \frac{RF_{min}}{\frac{f_{start}}{f_{min}} - 1} = \frac{13.3 \cdot 10^{3}}{\frac{300}{53.28} - 1} = 2.87\ k\Omega \qquad C_{SS} = \frac{3 \cdot 10^{-3}}{R_{SS}} = \frac{3 \cdot 10^{-3}}{2.87 \cdot 10^{-3}} = 1\ \mu F$$

LC Resonant Half-bridge
omparison with ZVS Half-bridge (I)

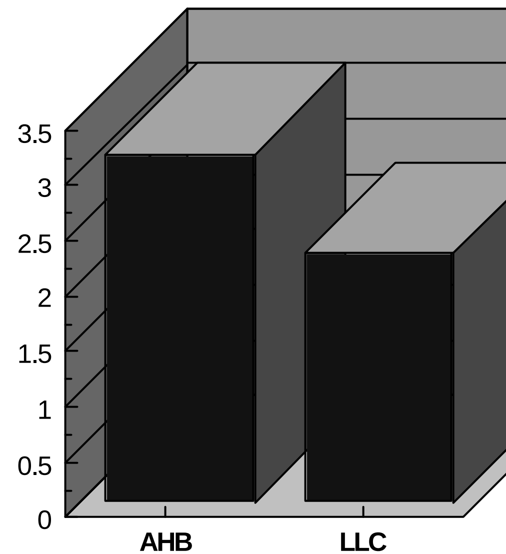
y Conduction Losses (W)



Primary Switching Losses (W)



Secondary Conduction Losses

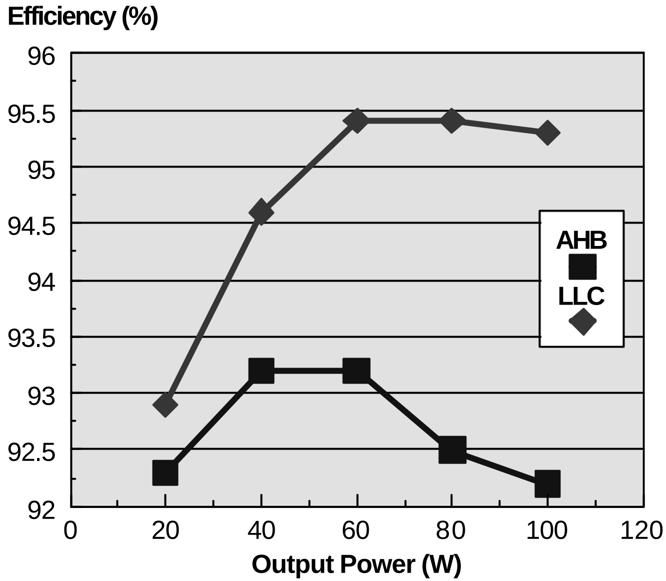


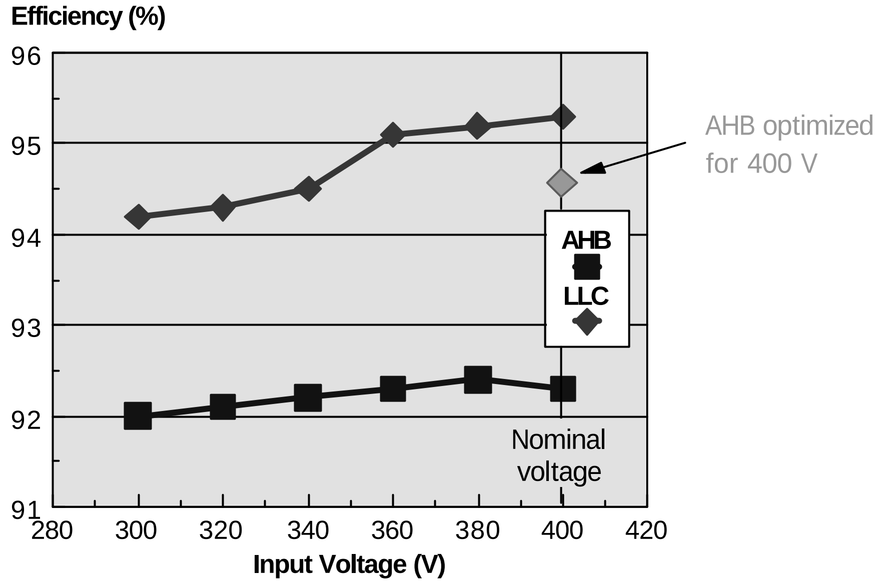
LECTRICAL SPECIFICATION	
put Voltage:	300 to 400(*) Vdc
utput voltage:	20 Vdc
utput power:	100 W
witching frequency:	200 kHz

300 V holdup, 400 V nominal voltage

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

LC Resonant Half-bridge omparison 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