



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

MLD GROUP

INDUSTRIAL & POWER CONVERSION DIVISION

Off-line SMPS BU Application Lab

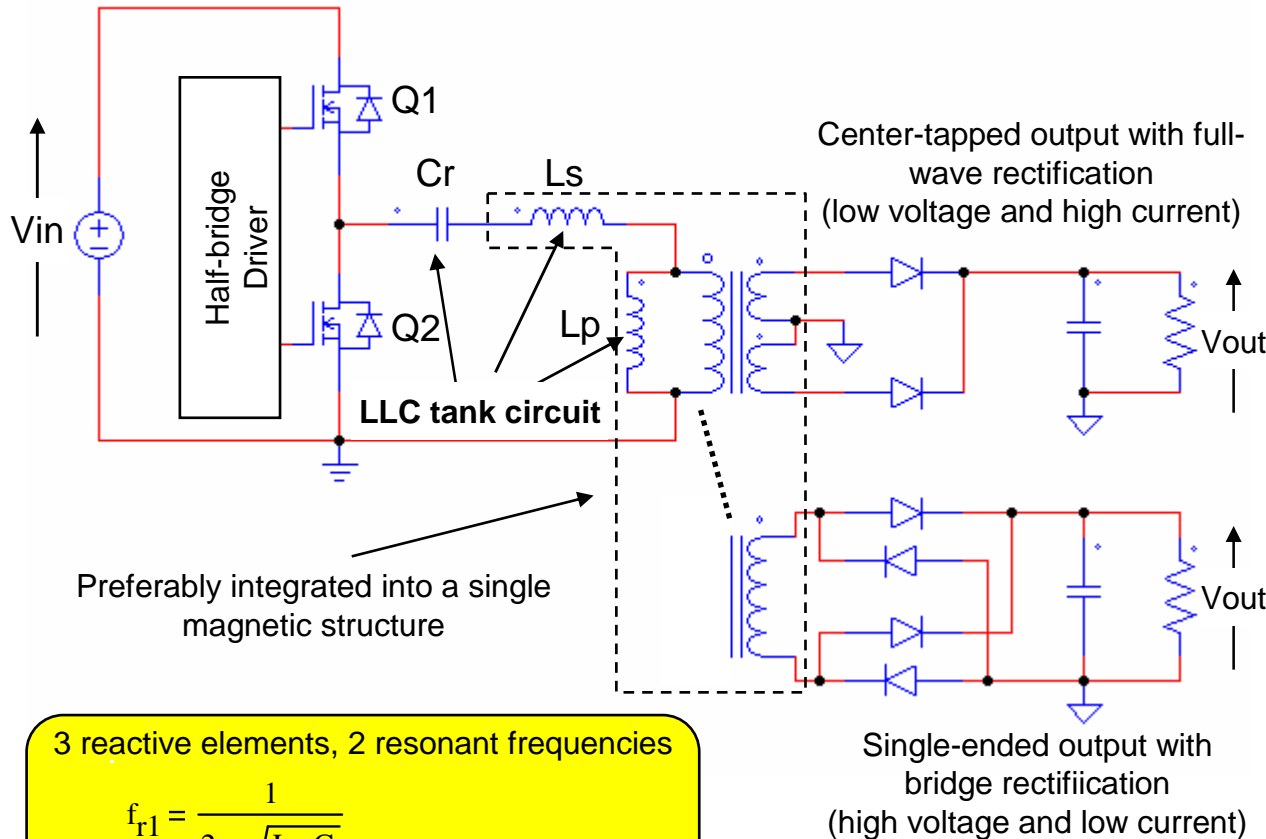


Presentation Outline

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

Series-resonant LLC Half-Bridge

Topology and features



3 reactive elements, 2 resonant frequencies

$$f_{r1} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_s \cdot C_r}}$$

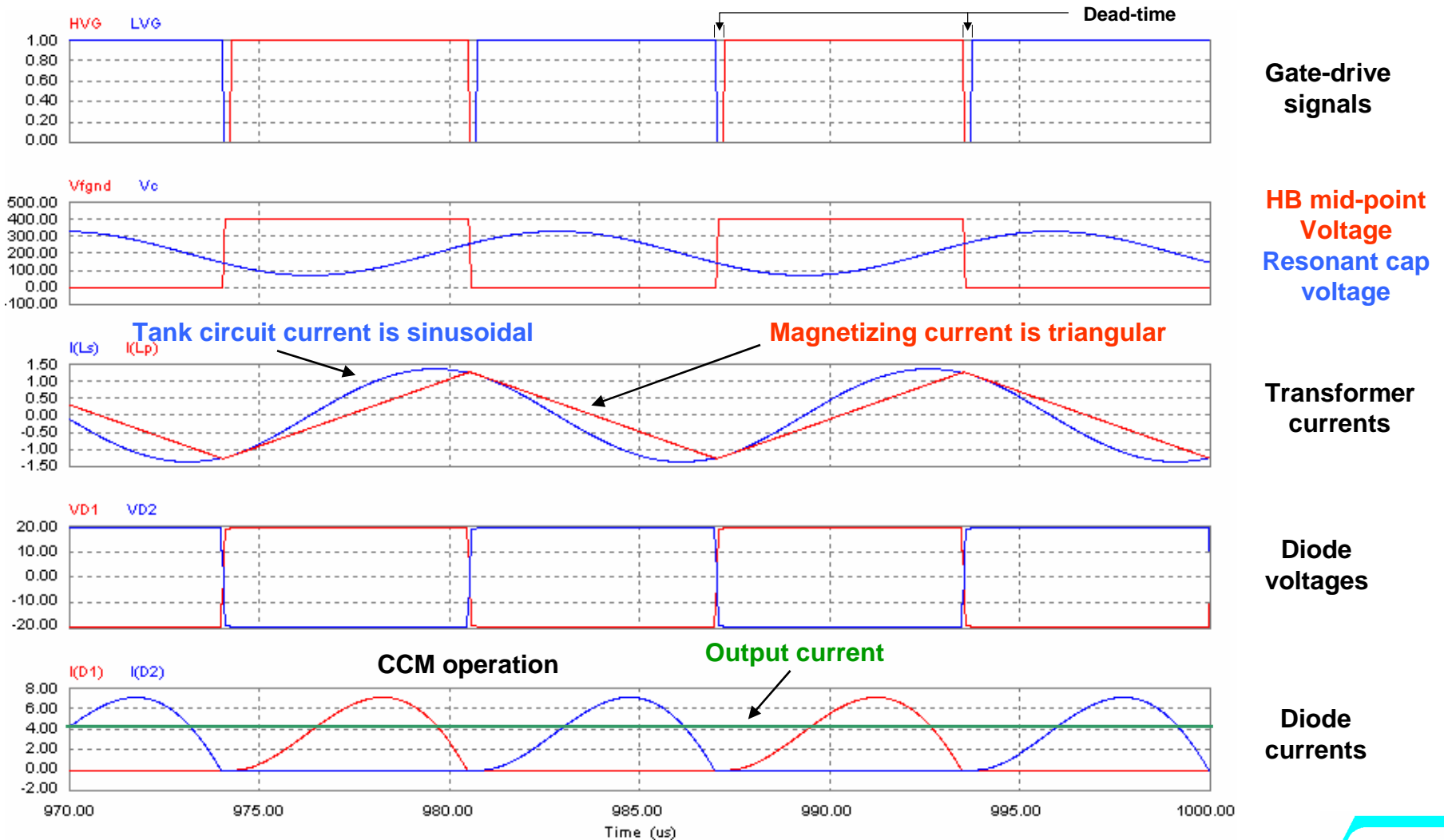
$$f_{r1} > f_{r2}$$

$$f_{r2} = \frac{1}{2 \cdot \pi \cdot \sqrt{(L_s + L_p) \cdot C_r}}$$

- 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
- $f_{sw} \approx f_r$, 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

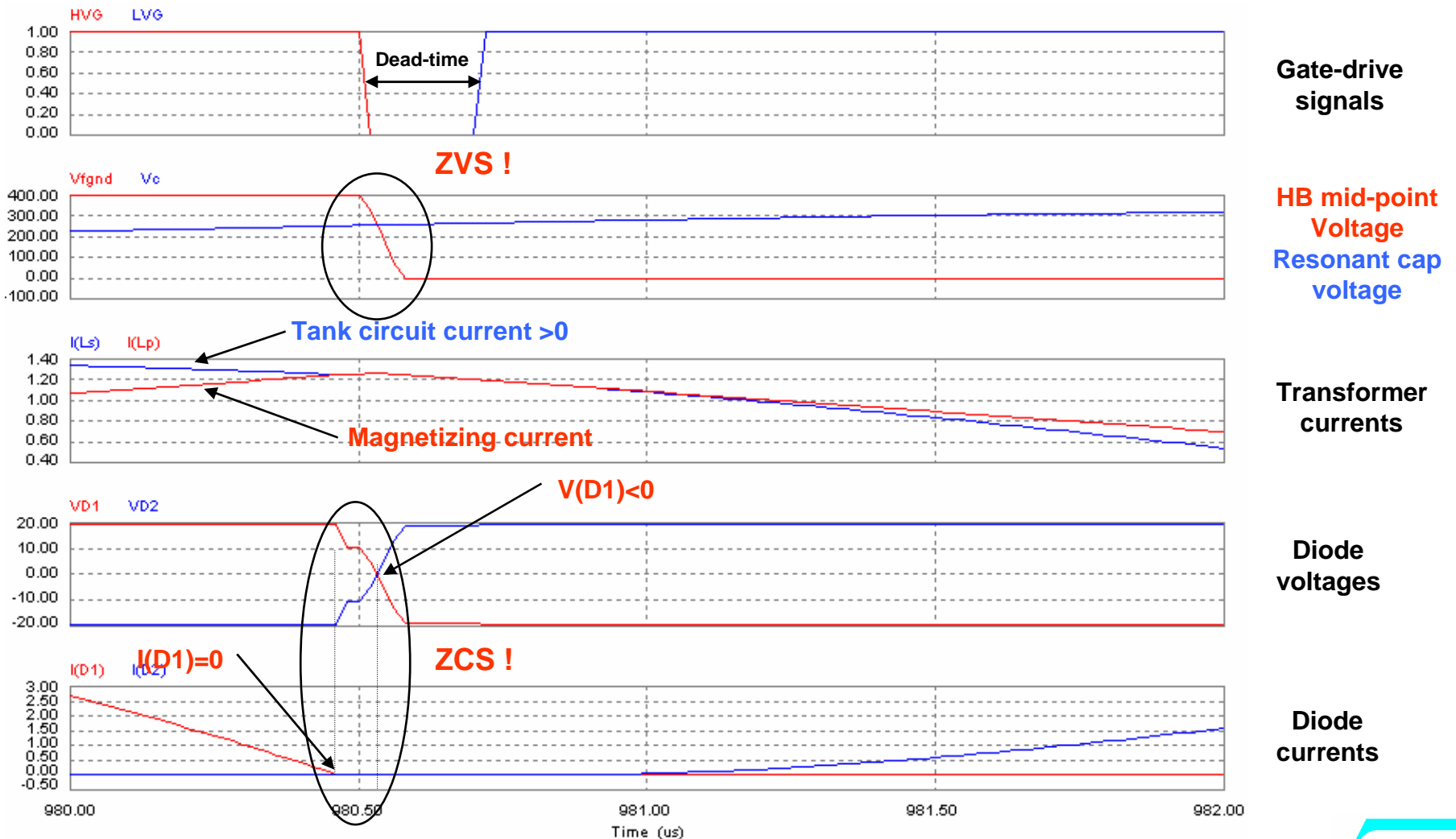
LLC Resonant Half-bridge

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



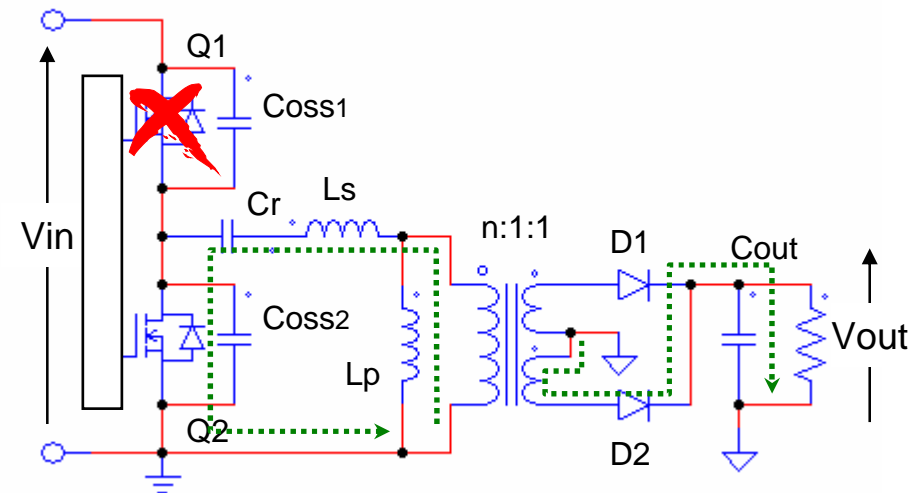
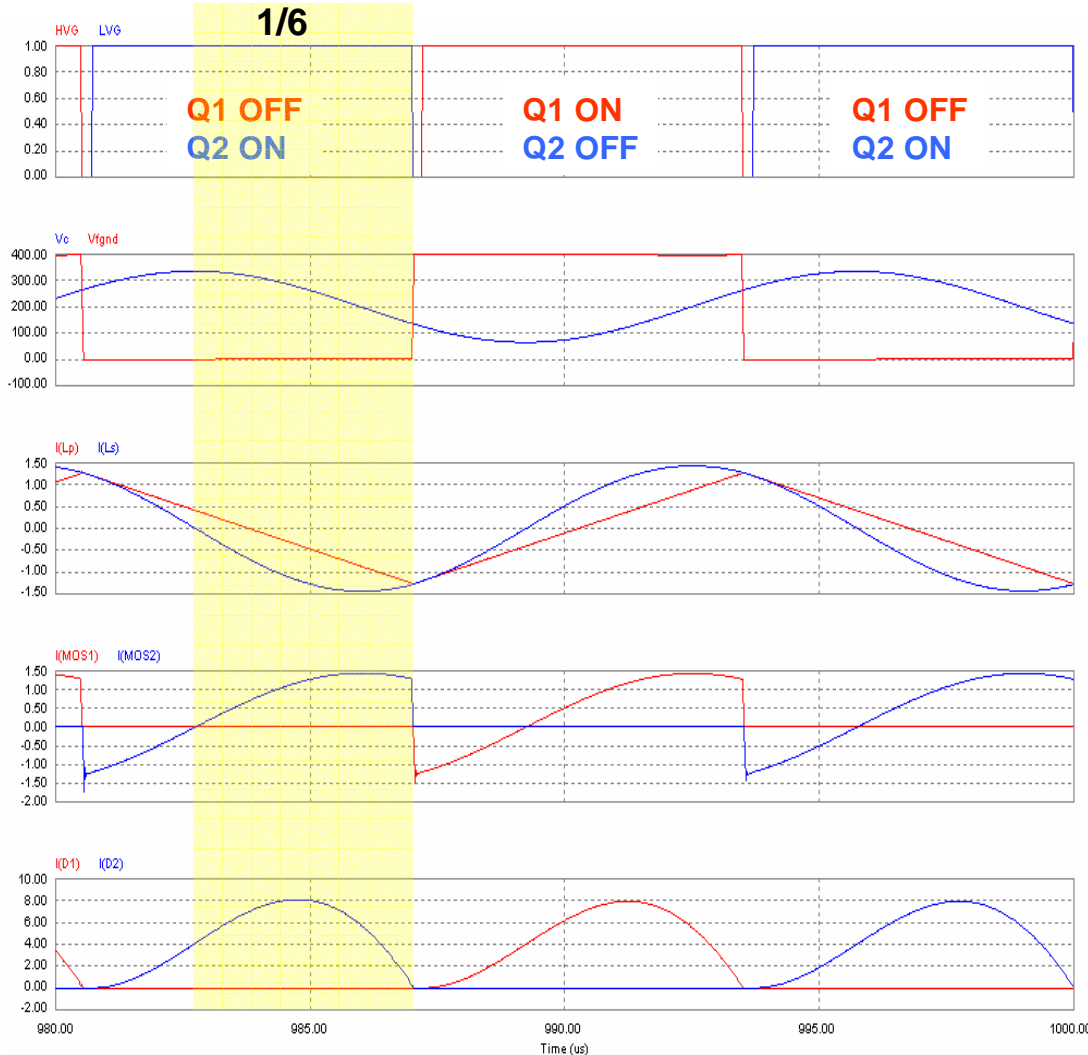
LLC Resonant Half-bridge

Switching details at resonance ($f_{sw} = f_{r1}$)



LLC Resonant Half-bridge

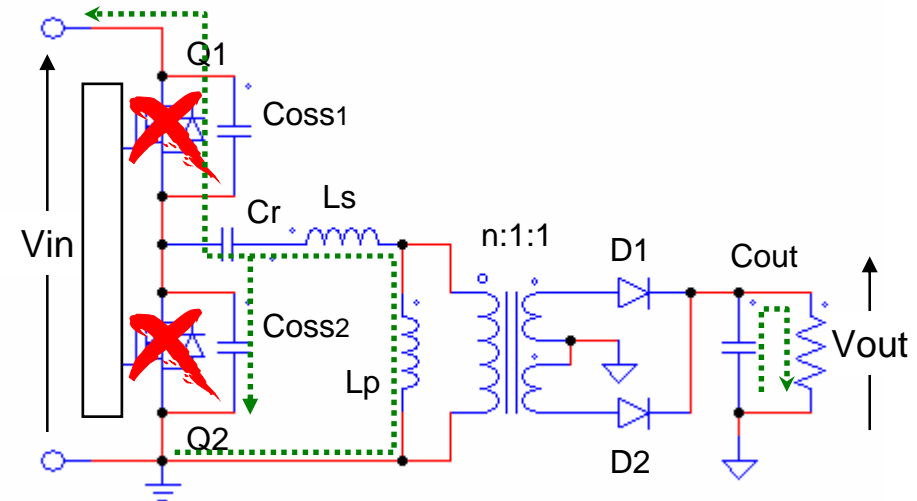
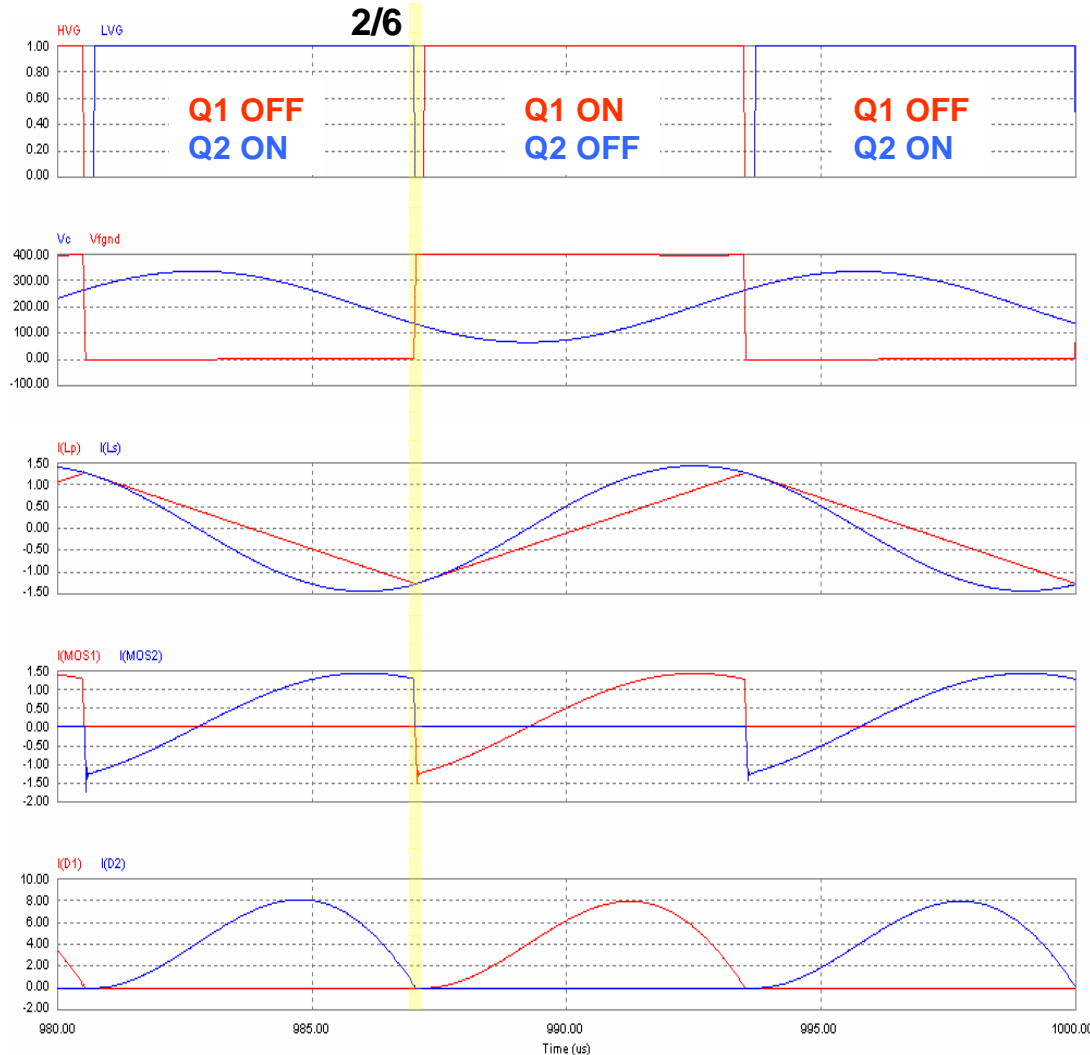
Operating Sequence at resonance (Phase 1/6)



- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; $V(D1) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = -n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- Output energy comes from C_r and L_s
- Phase ends when Q2 is switched off

LLC Resonant Half-bridge

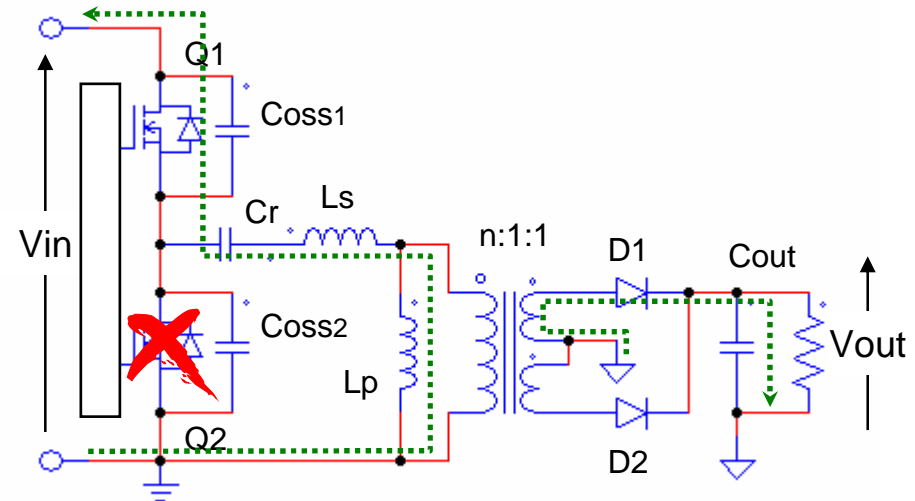
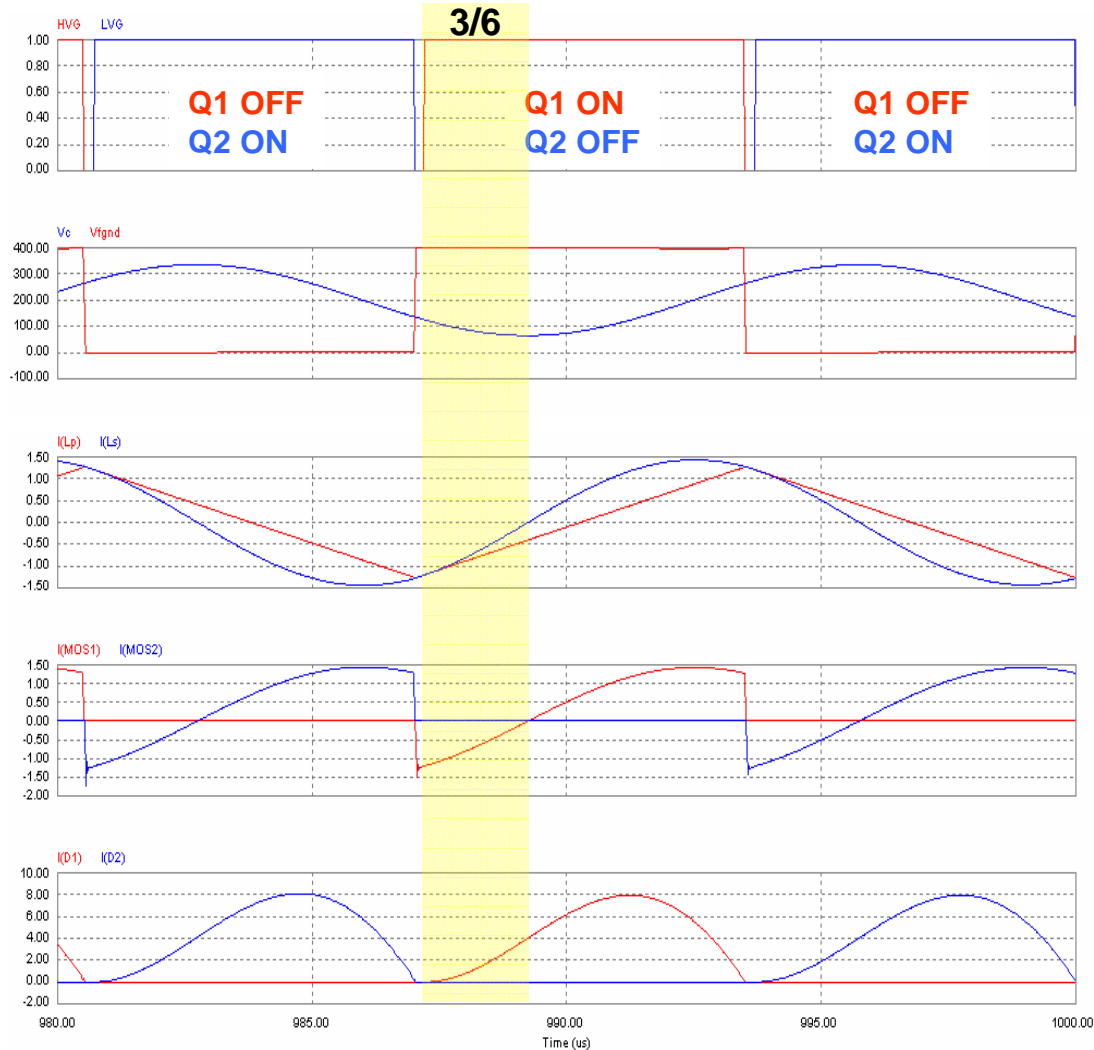
Operating Sequence at resonance (Phase 2/6)



- 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 $V(C_{OSS2})=V_{in}$; Q1's body diode starts conducting, energy goes back to V_{in}
- $I(D2)$ is exactly zero at Q2 switch off
- Phase ends when Q1 is switched on

LLC Resonant Half-bridge

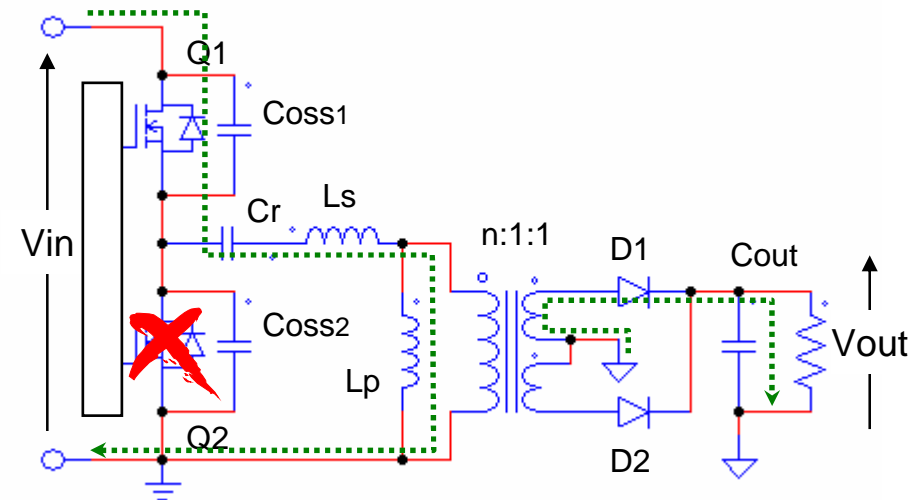
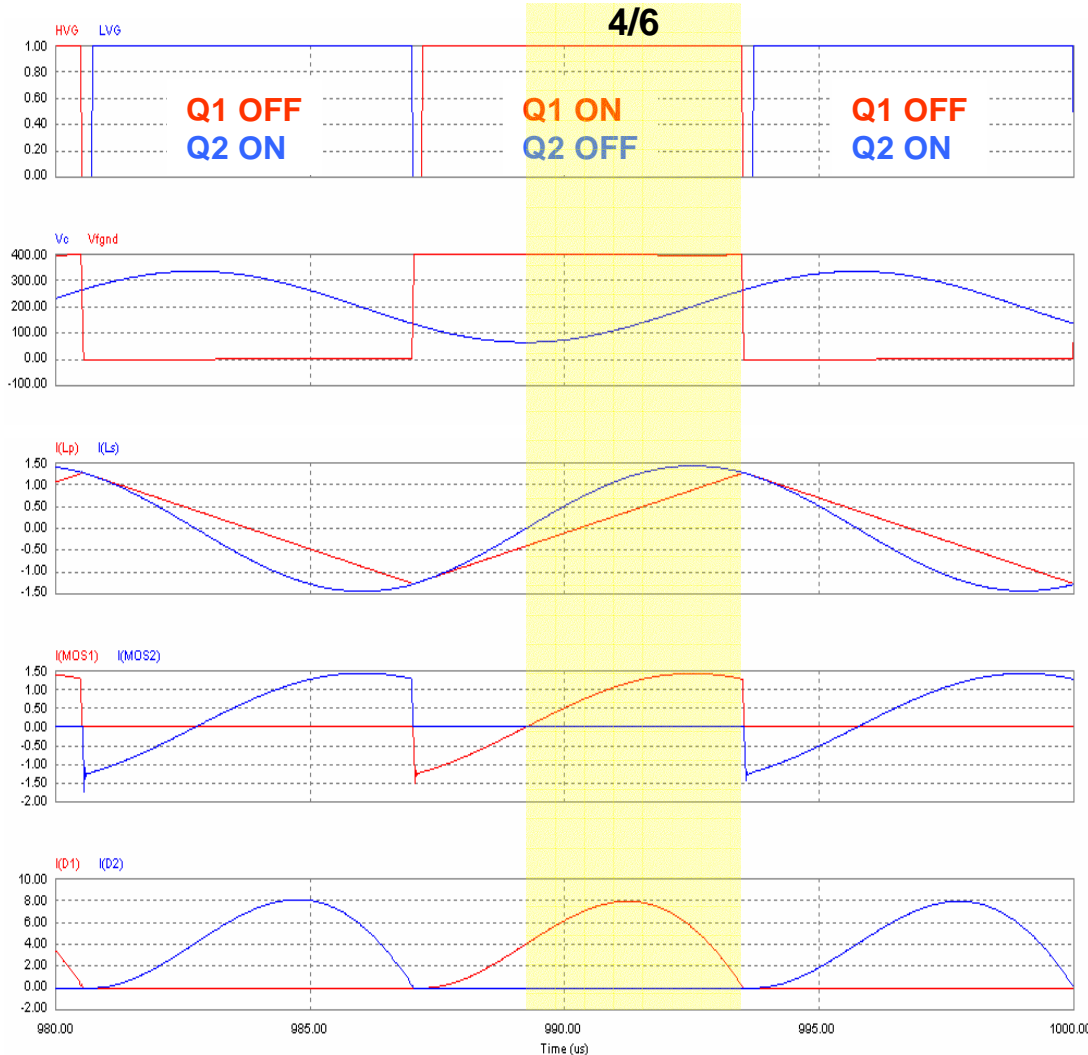
Operating Sequence at resonance (Phase 3/6)



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q1's $R_{DS(on)}$ back to V_{in} (Q1 is working in the 3rd quadrant)
- Phase ends when $I(L_s) = 0$

LLC Resonant Half-bridge

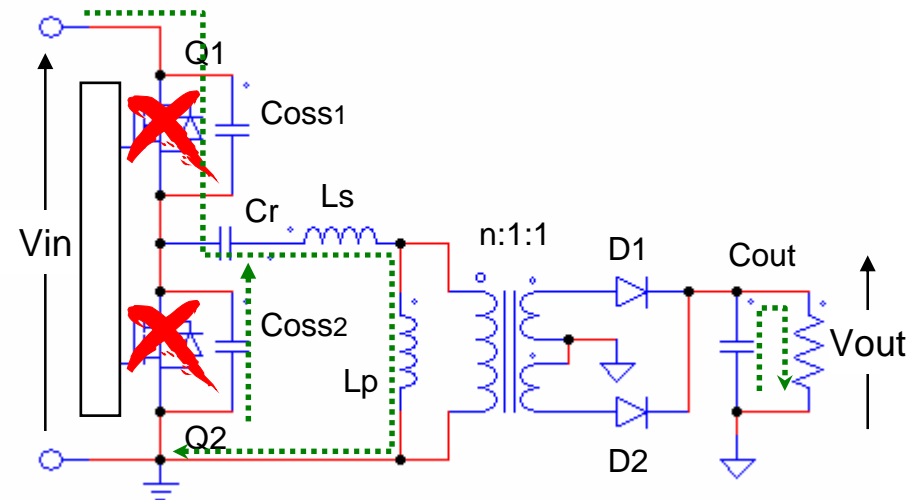
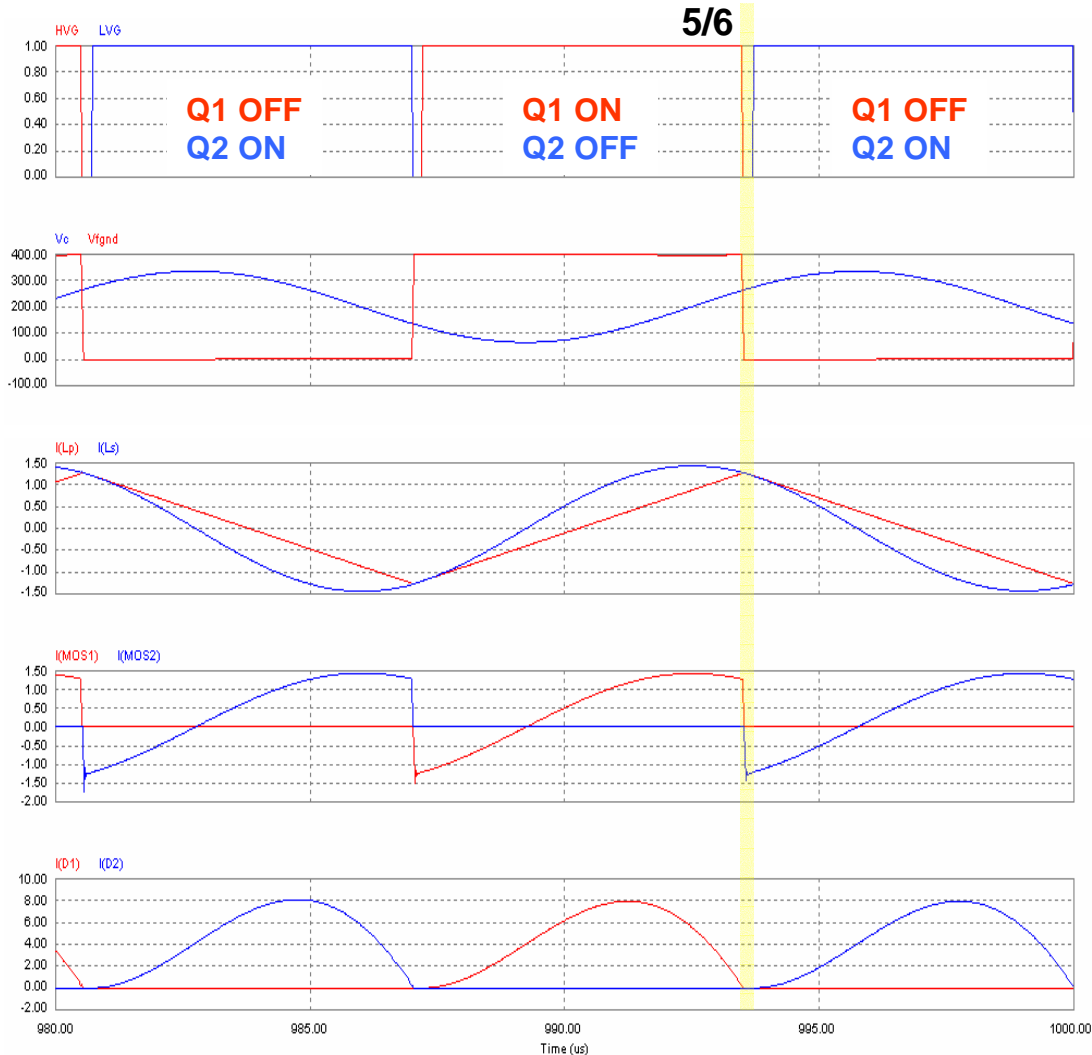
Operating Sequence at resonance (Phase 4/6)



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q1's $R_{DS(on)}$ from V_{in} to ground
- Energy is taken from V_{in} and goes to V_{out}
- Phase ends when Q1 is switched off

LLC Resonant Half-bridge

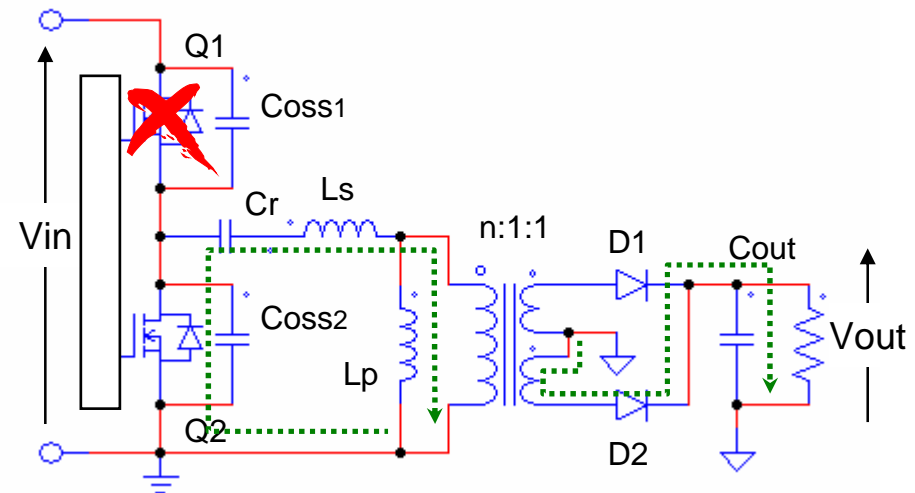
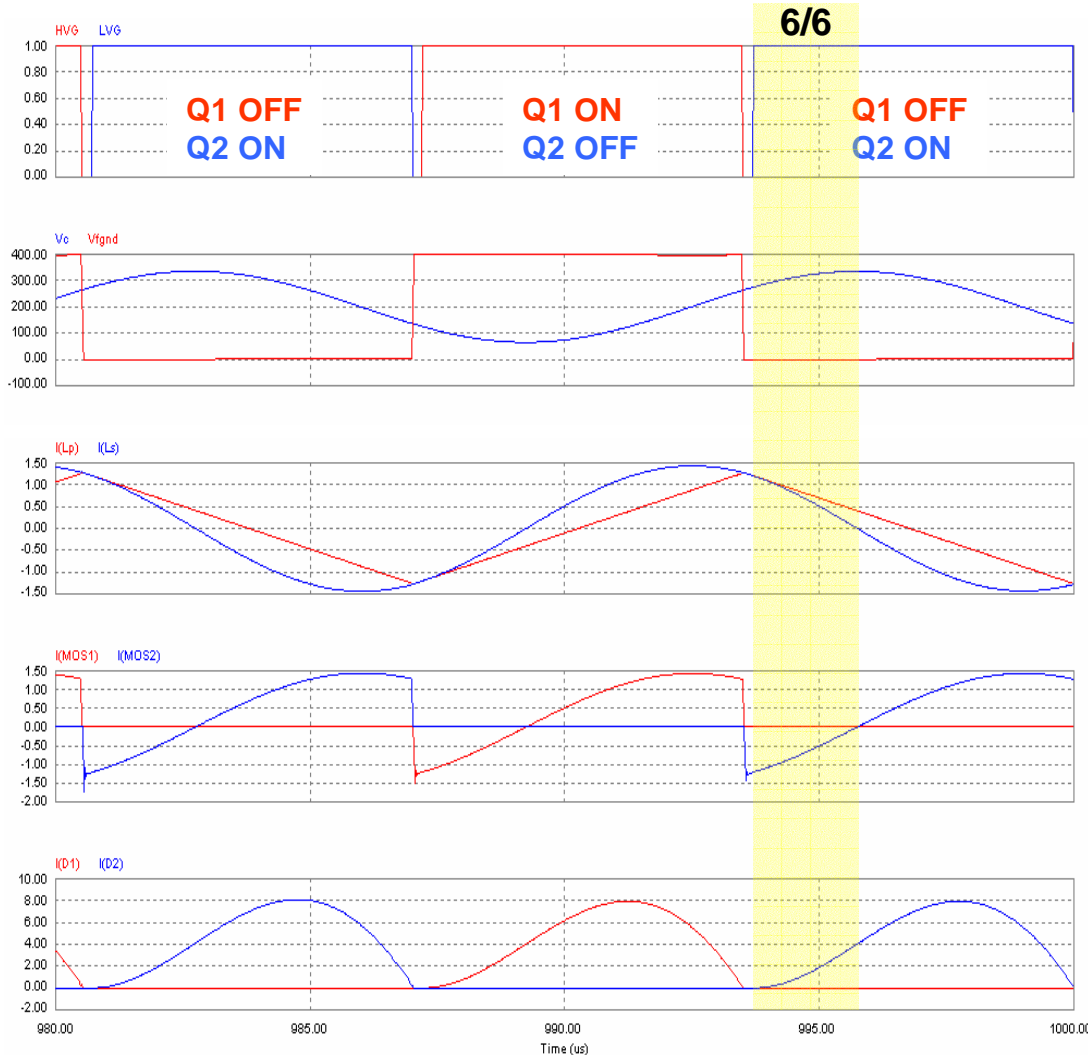
Operating Sequence at resonance (Phase 5/6)



- $Q1$ and $Q2$ are OFF (dead-time)
- $D1$ and $D2$ are OFF; $V(D1)=V(D2)=0$; transformer's secondary is open
- $I(L_s+L_p)$ 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

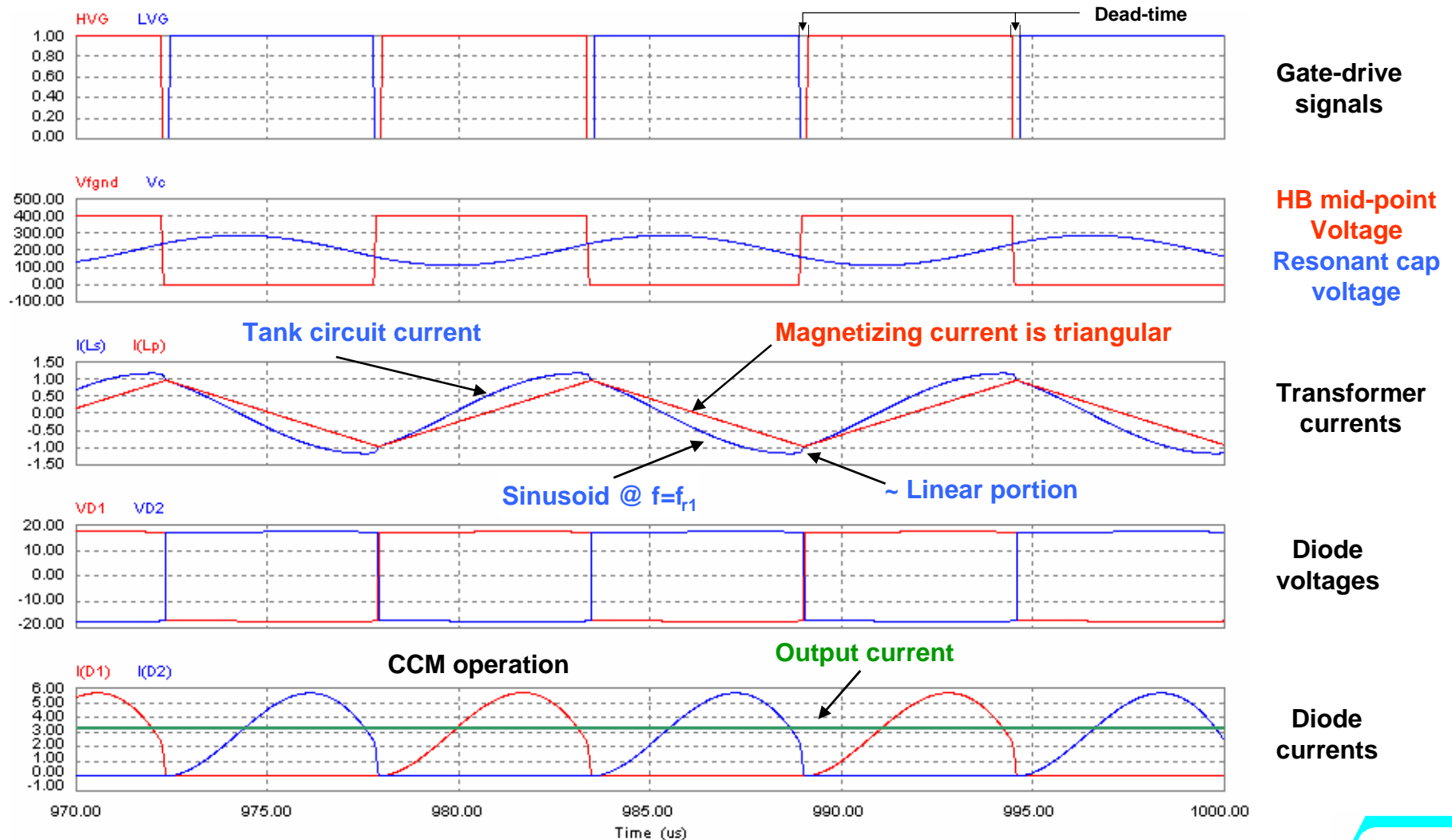
Operating Sequence at resonance (Phase 6/6)



- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- L_p is dynamically shorted: $V(L_p) = -n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from C_r and L_s
- Phase ends when $I(L_s) = 0$, Phase 1 starts

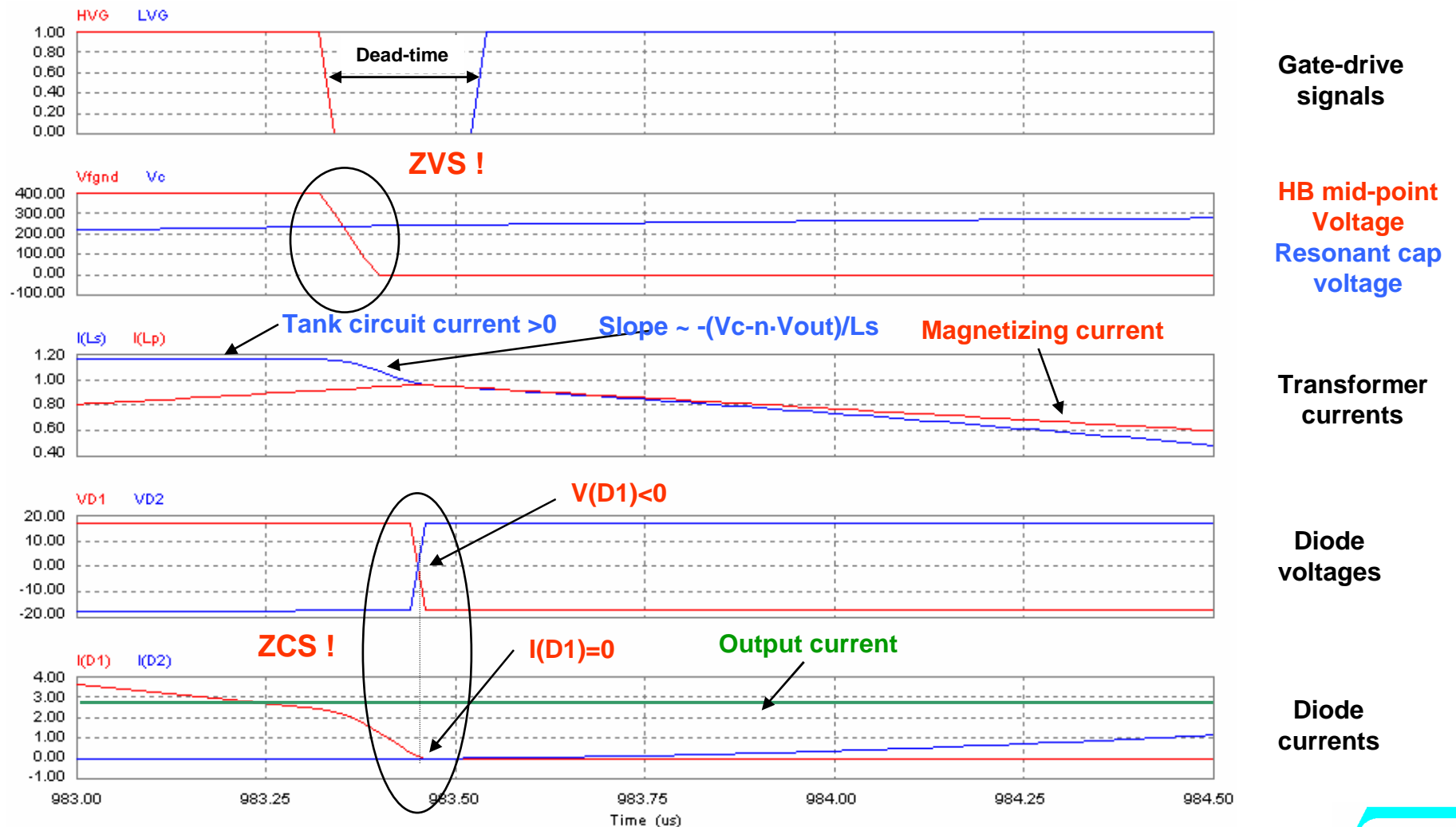
LLC Resonant Half-bridge

Waveforms above resonance ($f_{sw} > f_{r1}$)



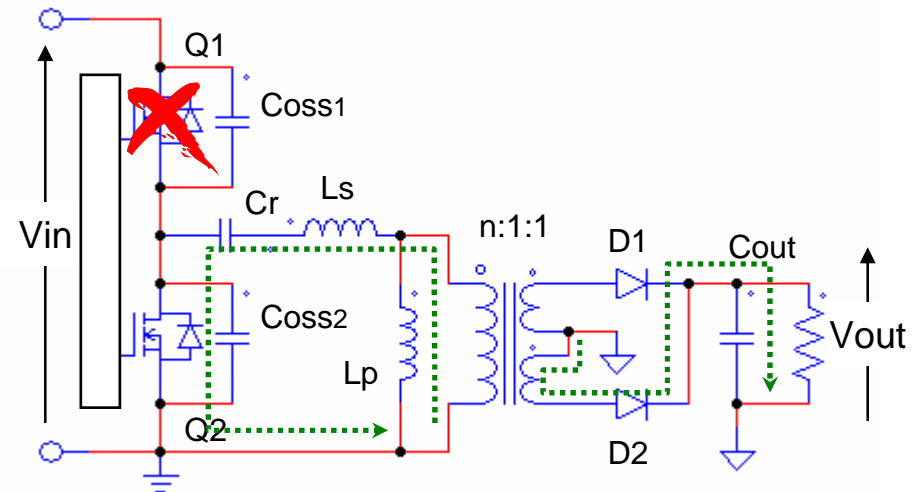
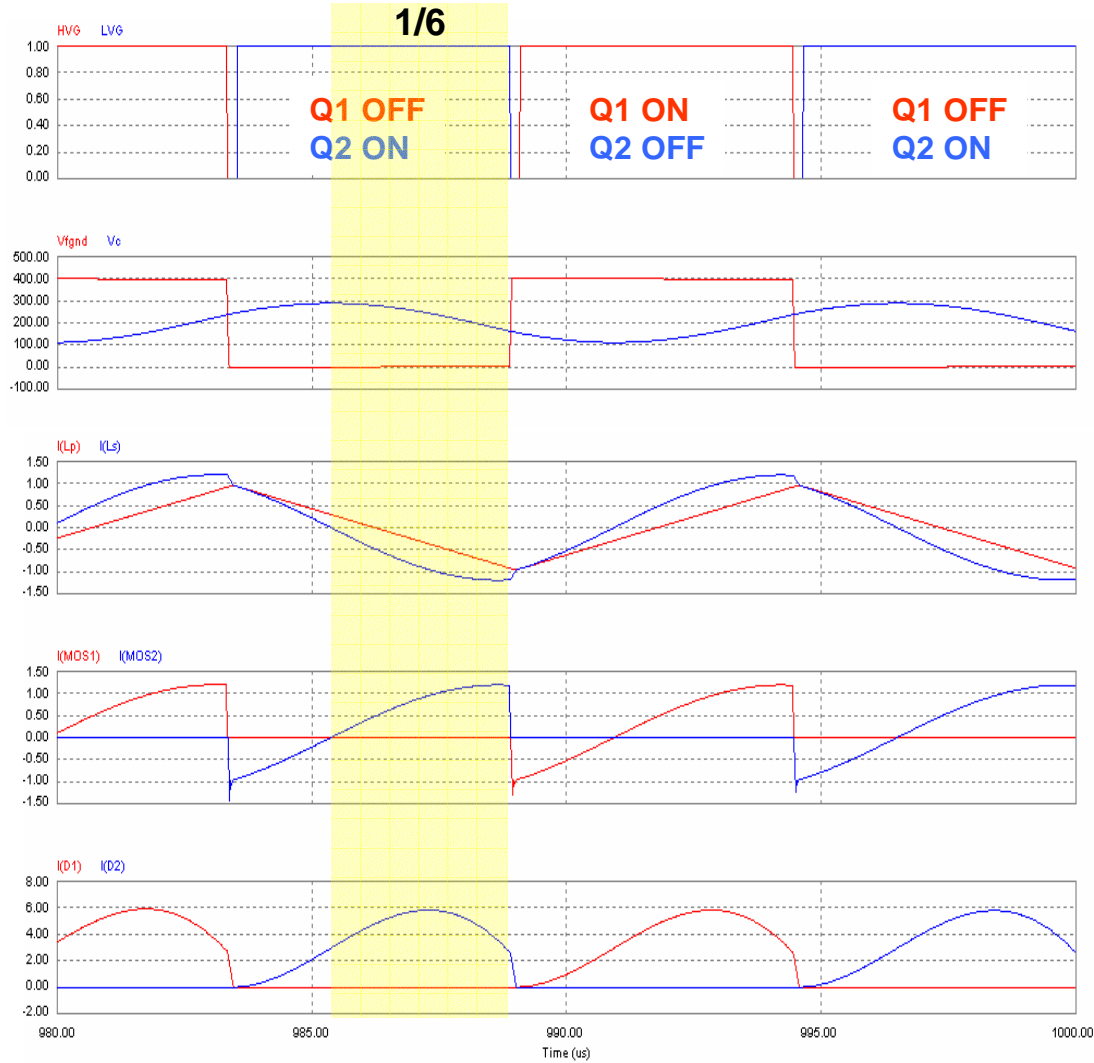
LLC Resonant Half-bridge

Switching details above resonance ($f_{sw} > f_{r1}$)



LLC Resonant Half-bridge

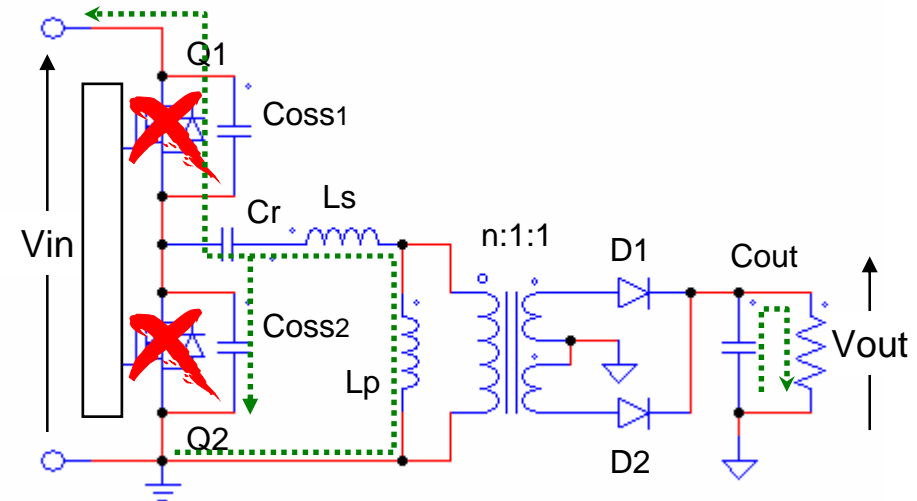
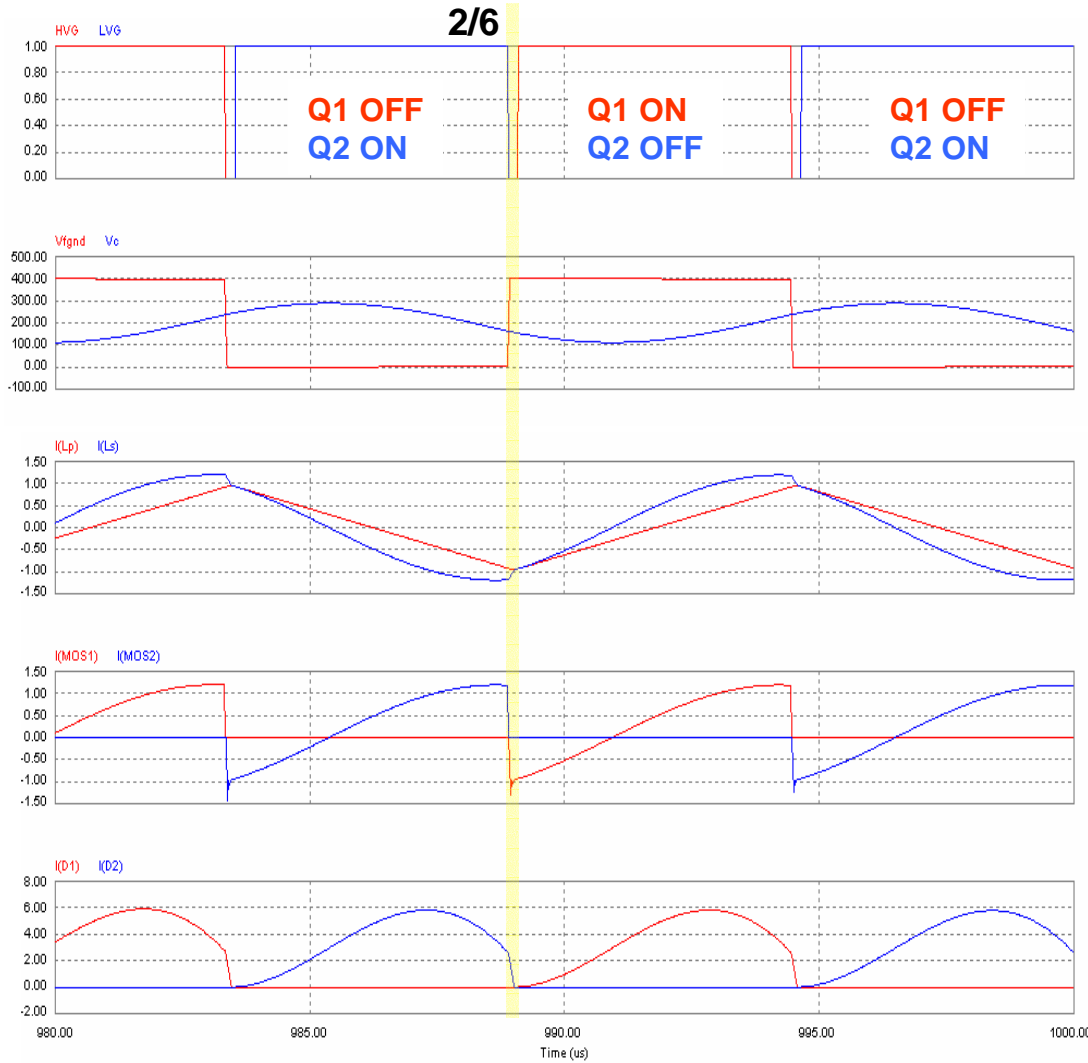
Operating Sequence above resonance (Phase 1/6)



- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; $V(D1) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = -n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- Output energy comes from C_r and L_s
- Phase ends when Q2 is switched off

LLC Resonant Half-bridge

Operating Sequence above resonance (Phase 2/6)

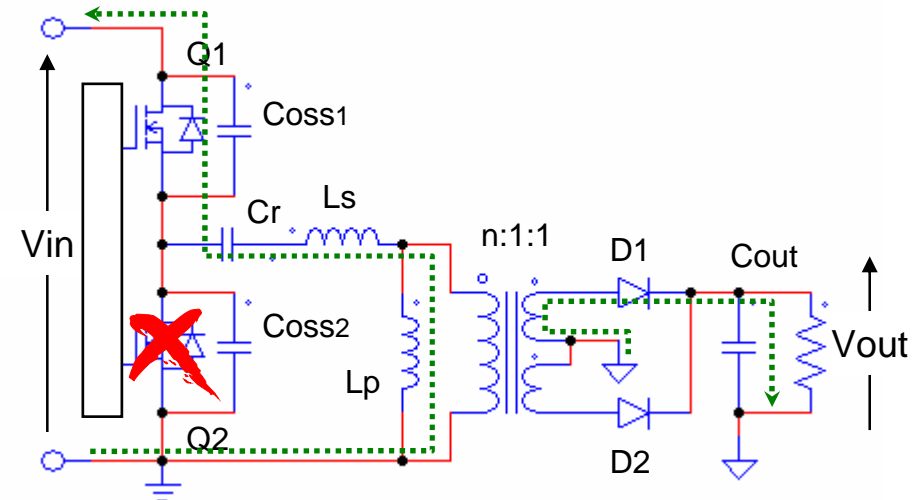
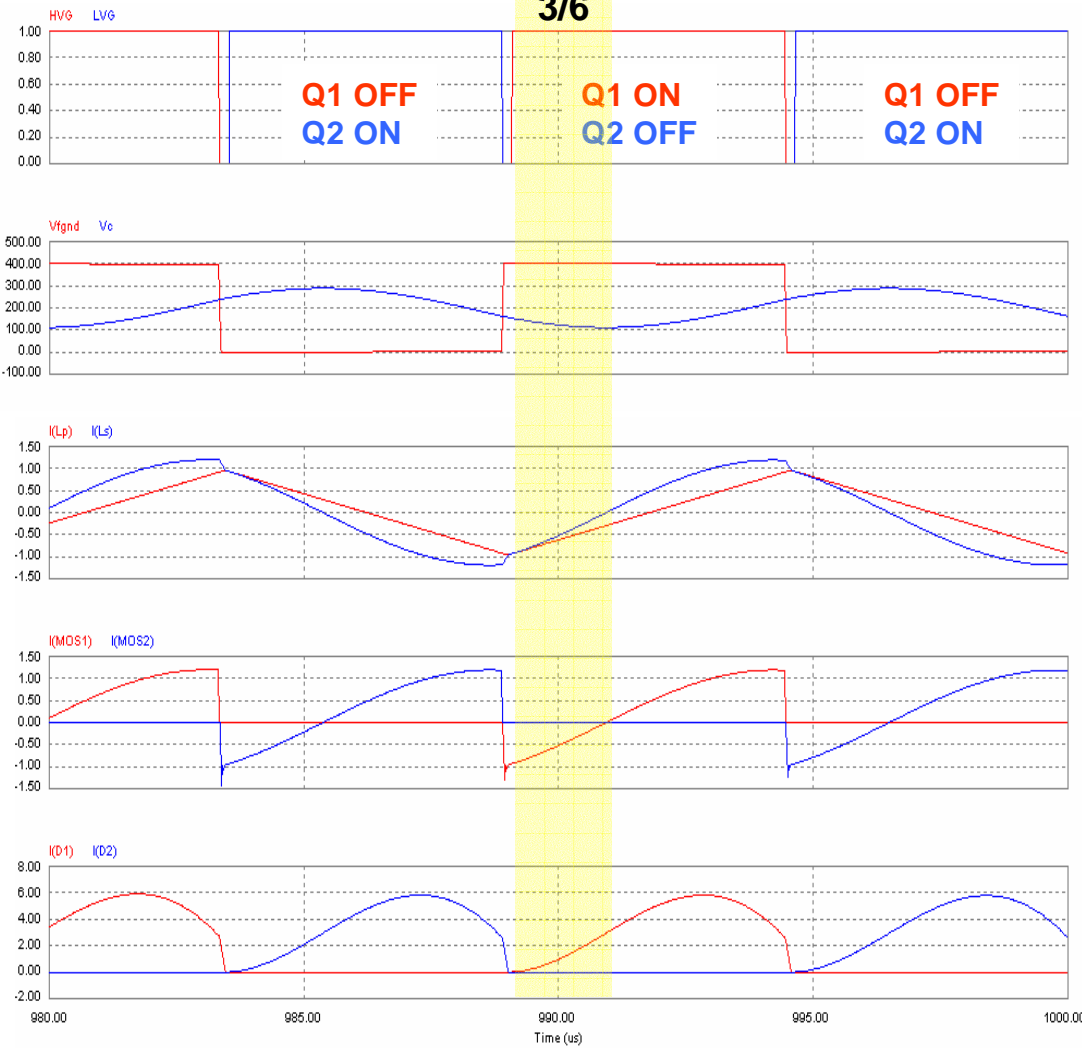


- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; $V(D1)=V(D2)=0$; transformer's secondary is open
- $I(Ls+Lp)$ charges C_{OSS2} and discharges C_{OSS1} , until $V(C_{OSS2})=V_{in}$; Q1's body diode starts conducting, energy goes back to V_{in}
- $V(D2)$ reverses as $I(D2)$ goes to zero
- Phase ends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

LLC Resonant Half-bridge

Operating Sequence above resonance (Phase 3/6)

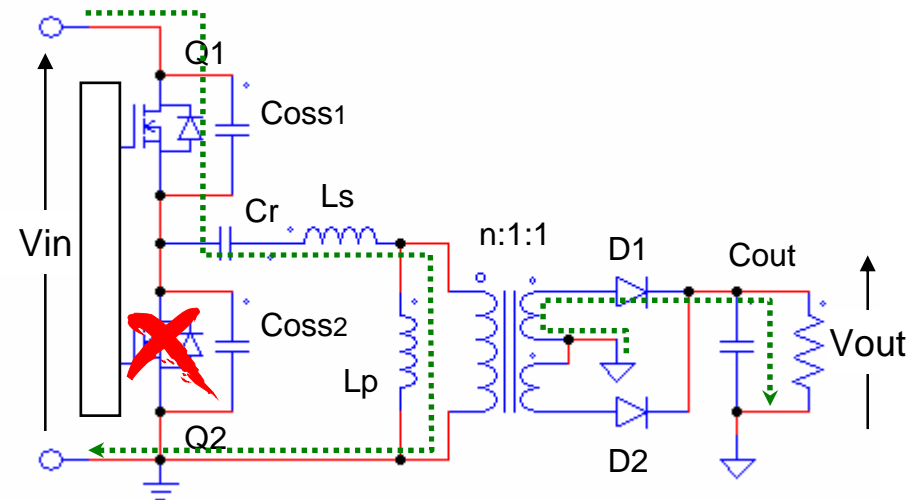
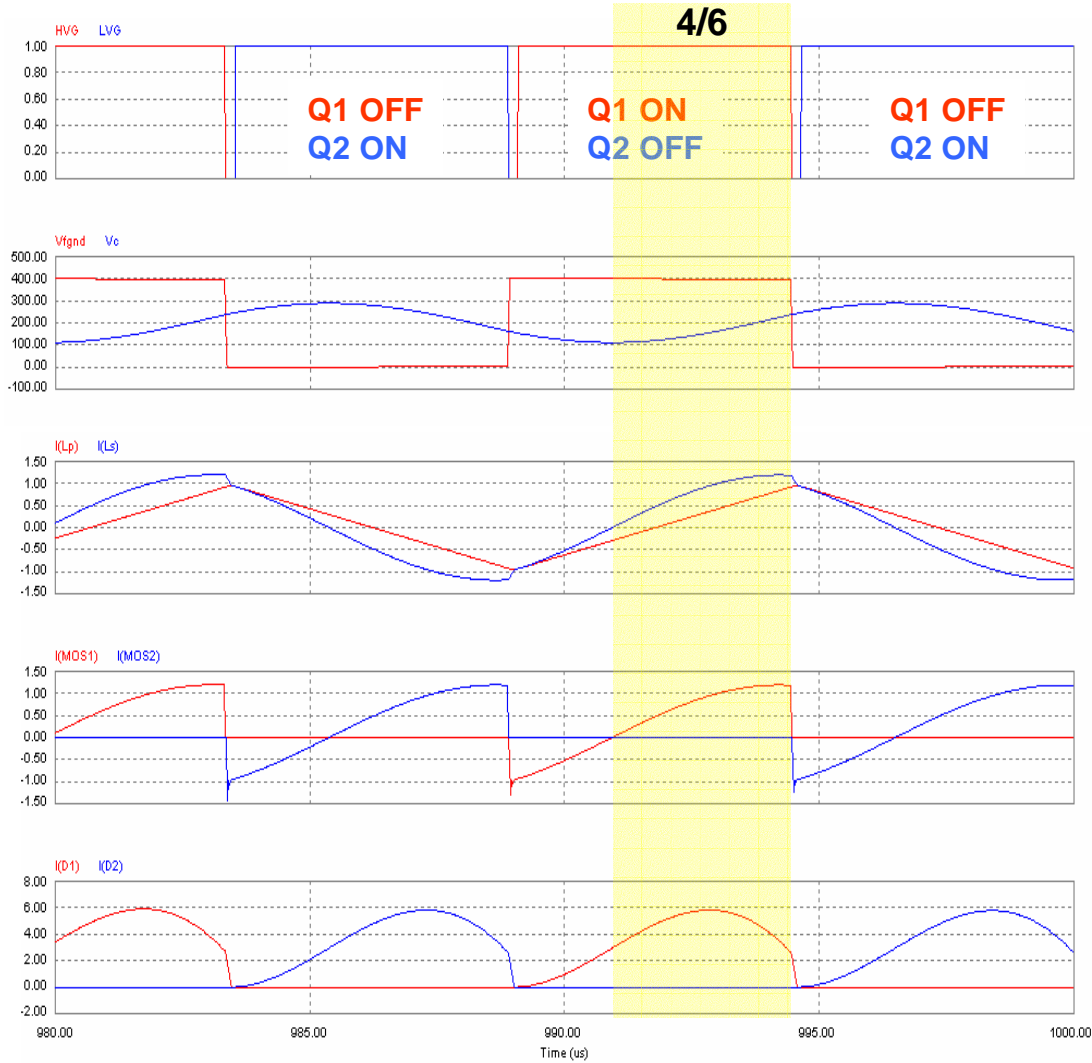
3/6



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through $Q1$'s $R_{DS(on)}$ back to V_{in} (Q1 is working in the 3rd quadrant)
- Phase ends when $I(L_s) = 0$

LLC Resonant Half-bridge

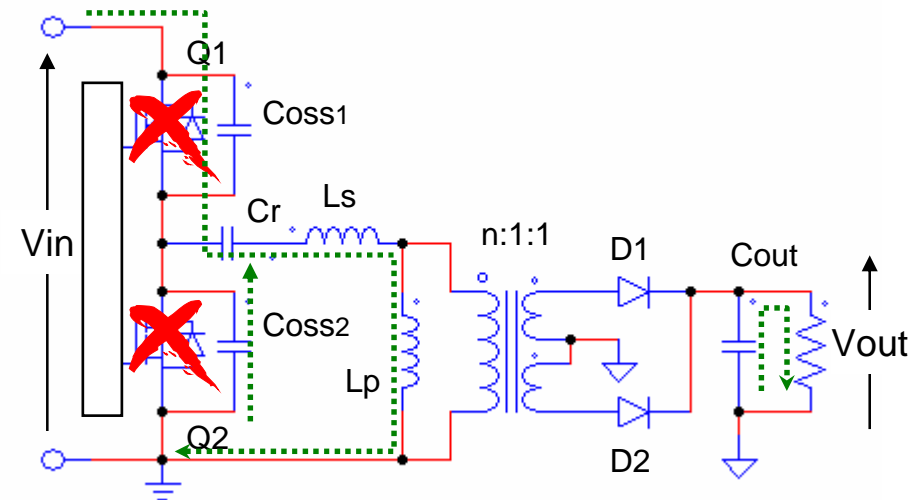
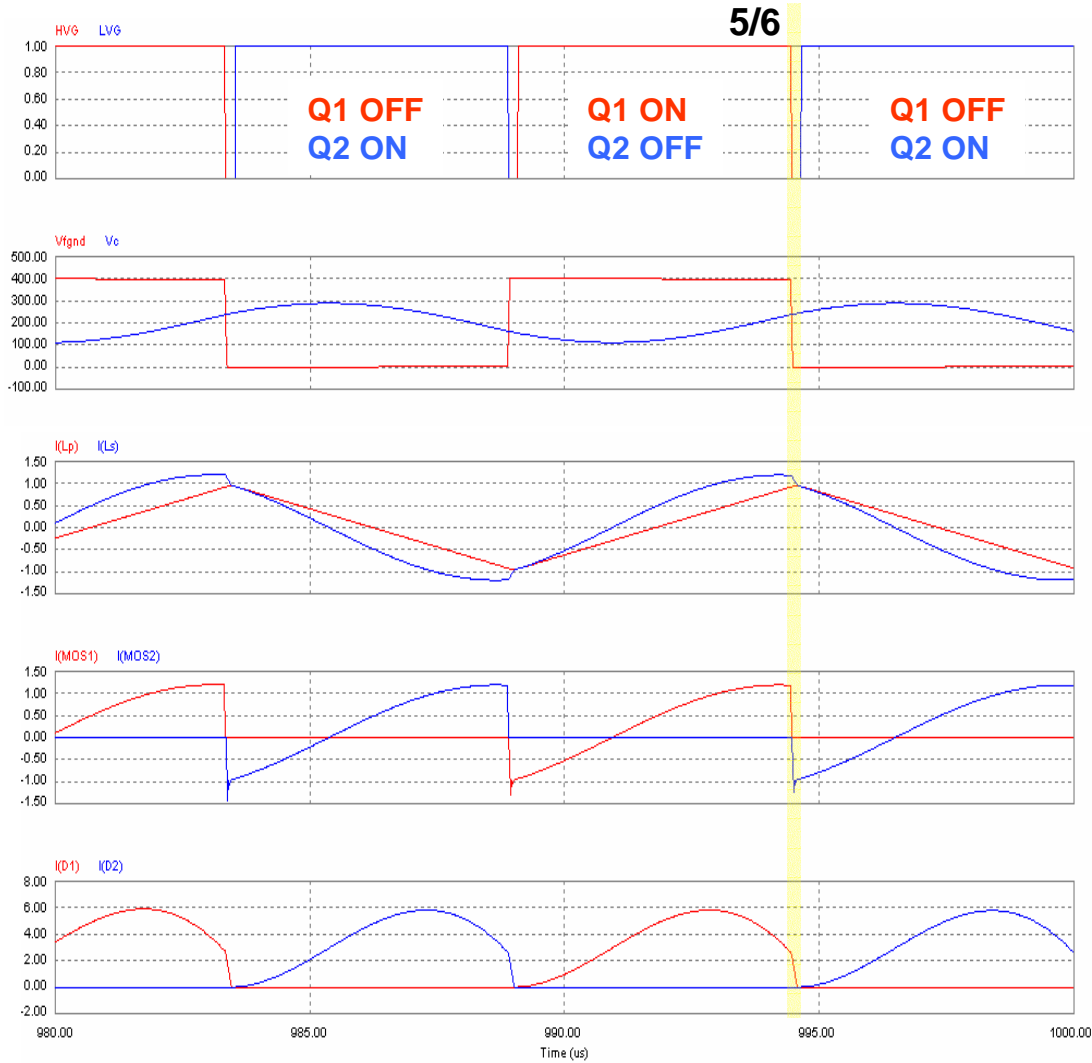
Operating Sequence above resonance (Phase 4/6)



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q1's $R_{DS(on)}$ from V_{in} to ground
- Energy is taken from V_{in} and goes to V_{out}
- Phase ends when Q1 is switched off

LLC Resonant Half-bridge

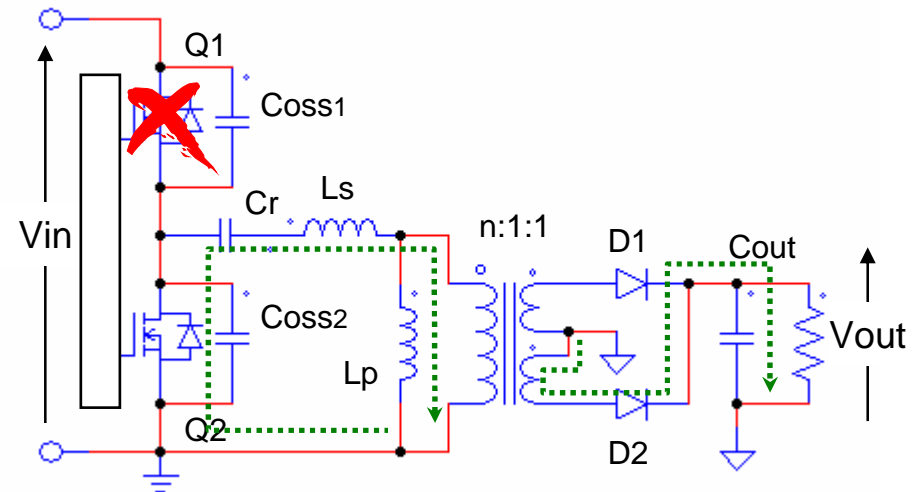
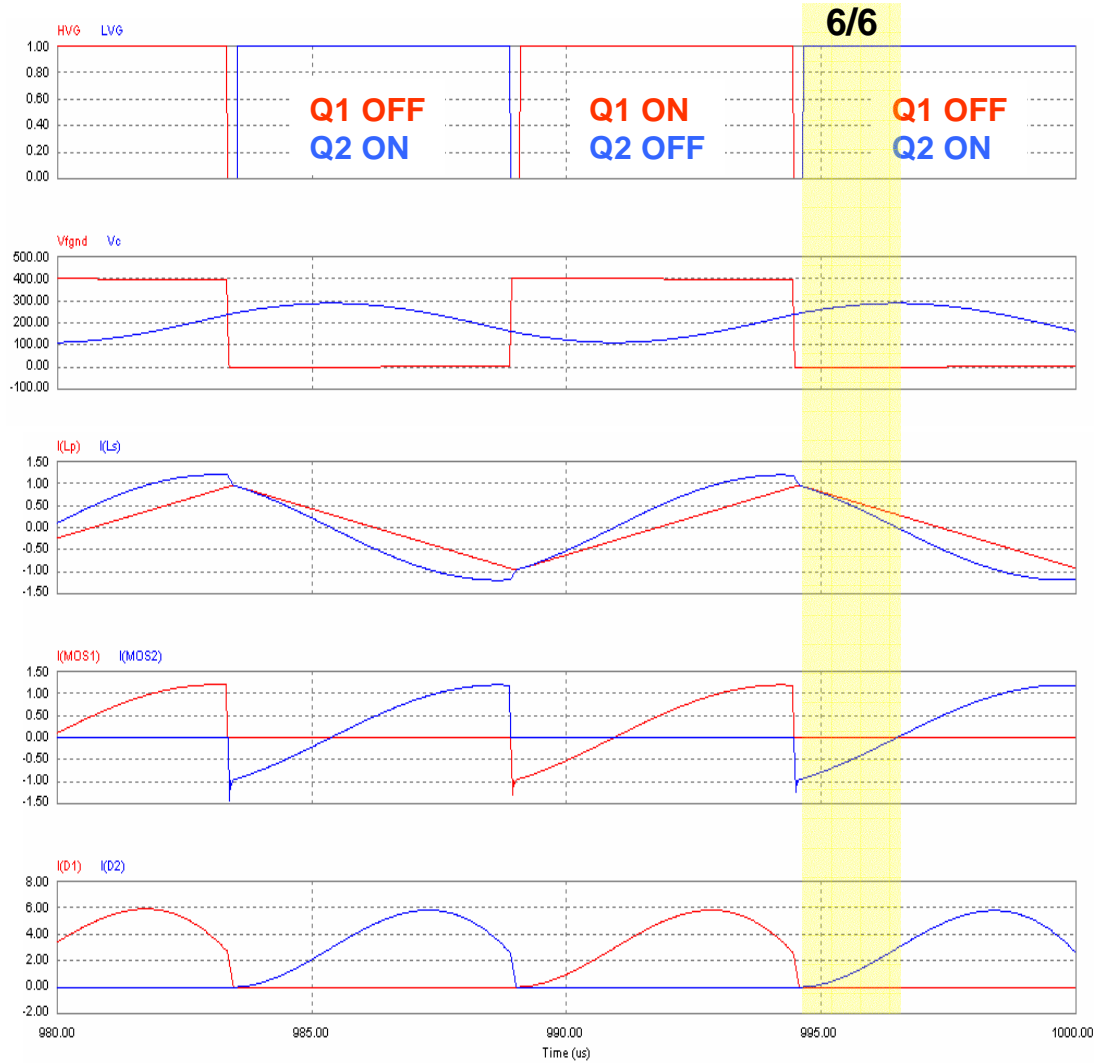
Operating Sequence above resonance (Phase 5/6)



- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; $V(D1)=V(D2)=0$; 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 C_{out}
- Phase ends when Q2 is switched on

LLC Resonant Half-bridge

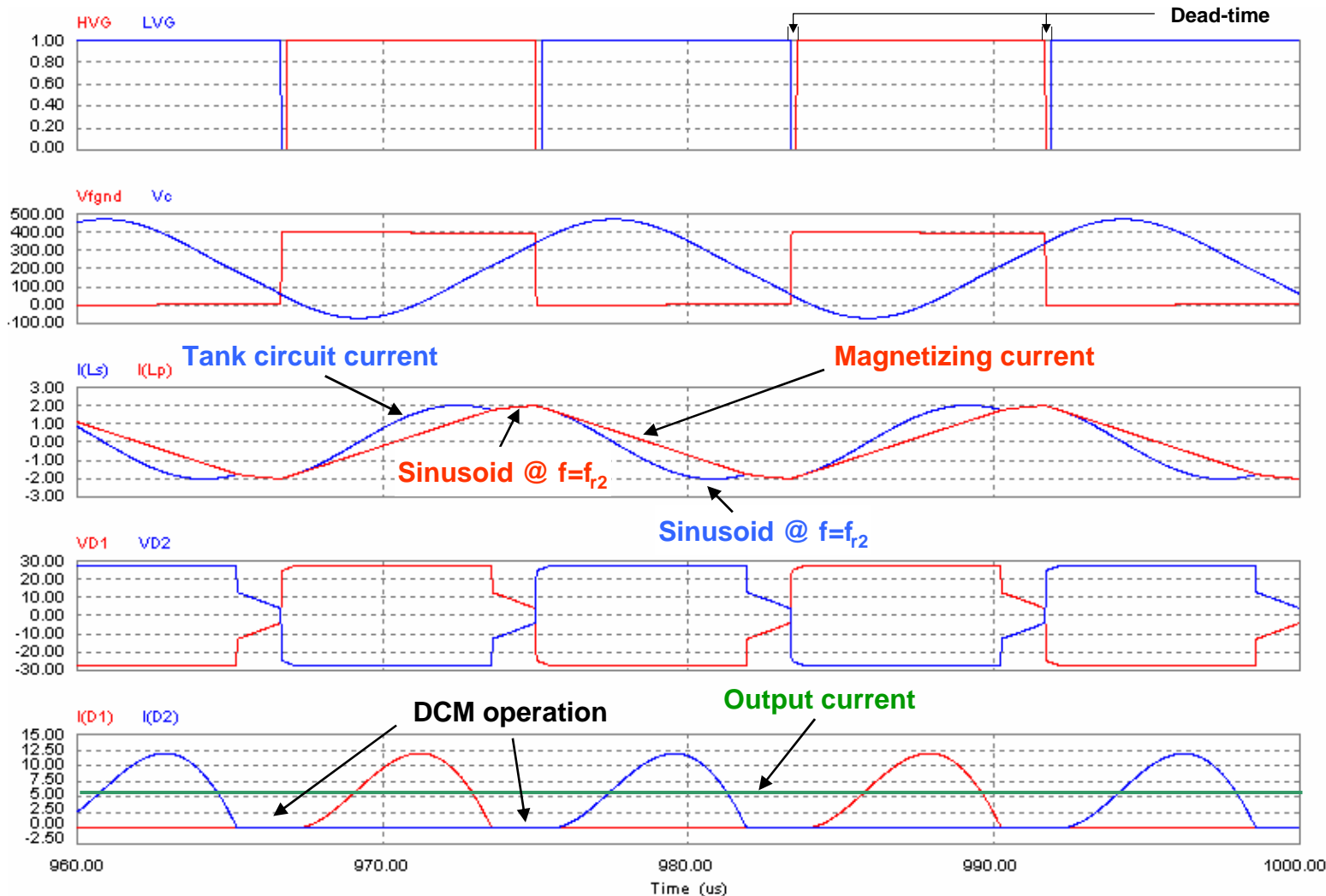
Operating Sequence above resonance (Phase 6/6)



- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON
- L_p is dynamically shorted: $V(L_p) = -n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from C_r and L_s
- Phase ends when $I(L_s)=0$, Phase 1 starts

LLC Resonant Half-bridge

Waveforms below resonance ($f_{sw} < f_{r1}$)



Gate-drive
signals

HB mid-point
Voltage
Resonant cap
voltage

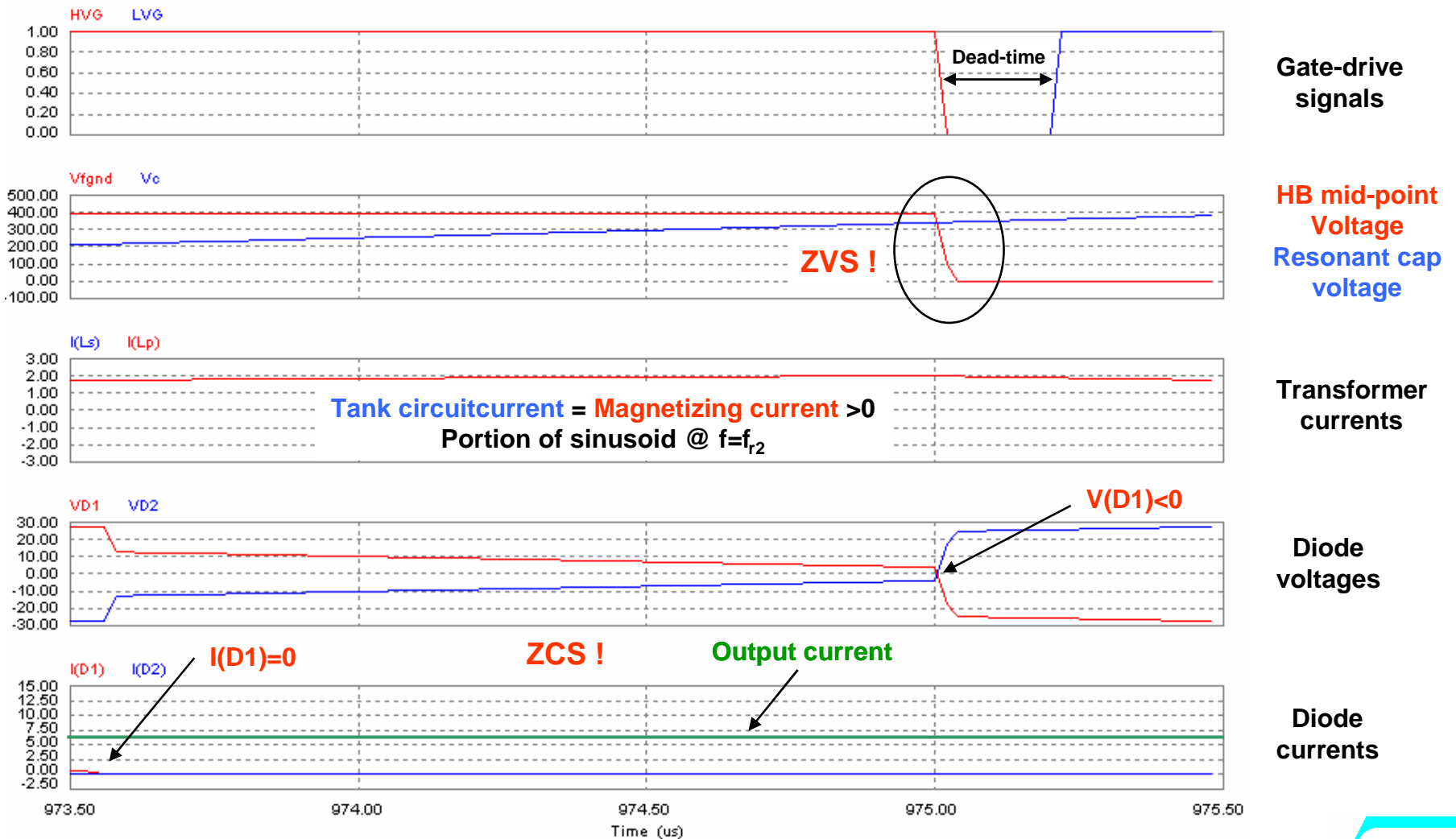
Transformer
currents

Diode
voltages

Diode
currents

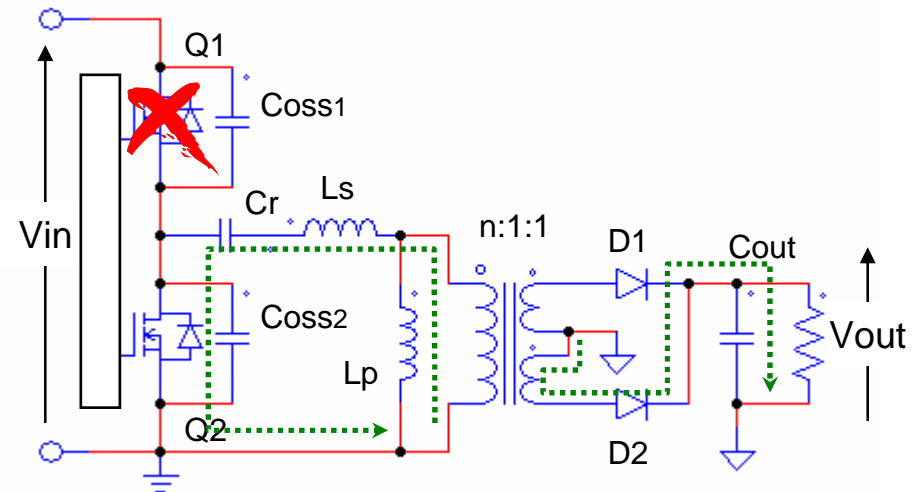
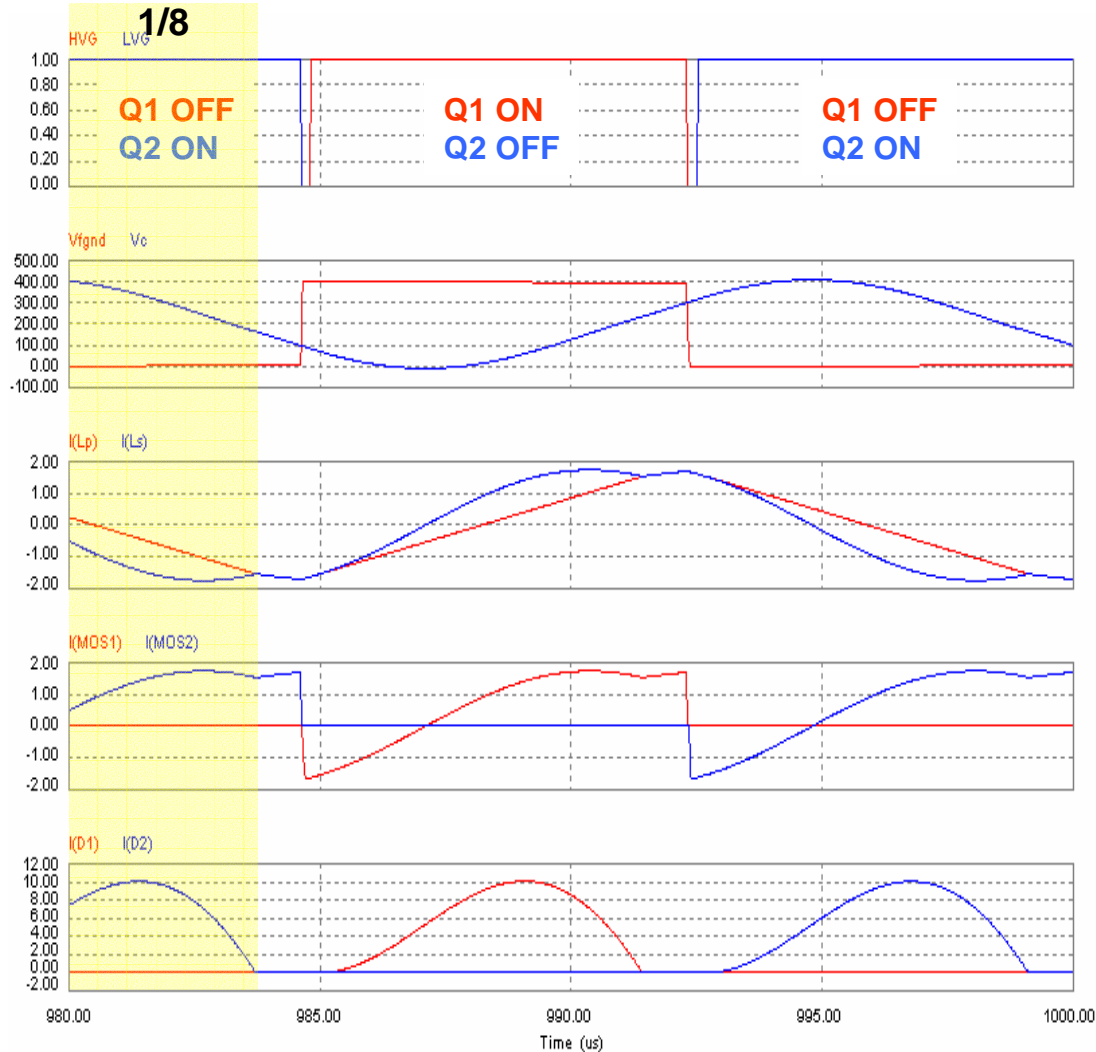
LLC Resonant Half-bridge

Switching details below resonance ($f_{sw} < f_{r1}$)



LLC Resonant Half-bridge

Operating Sequence below resonance (Phase 1/8)

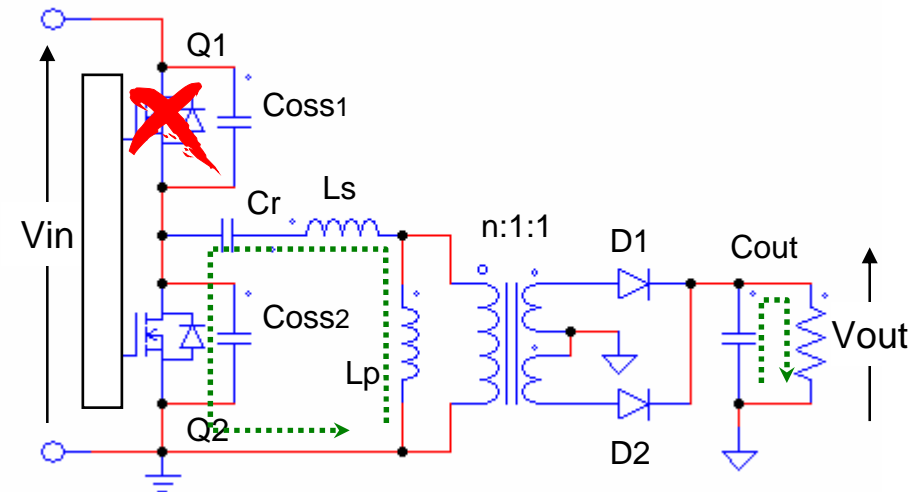
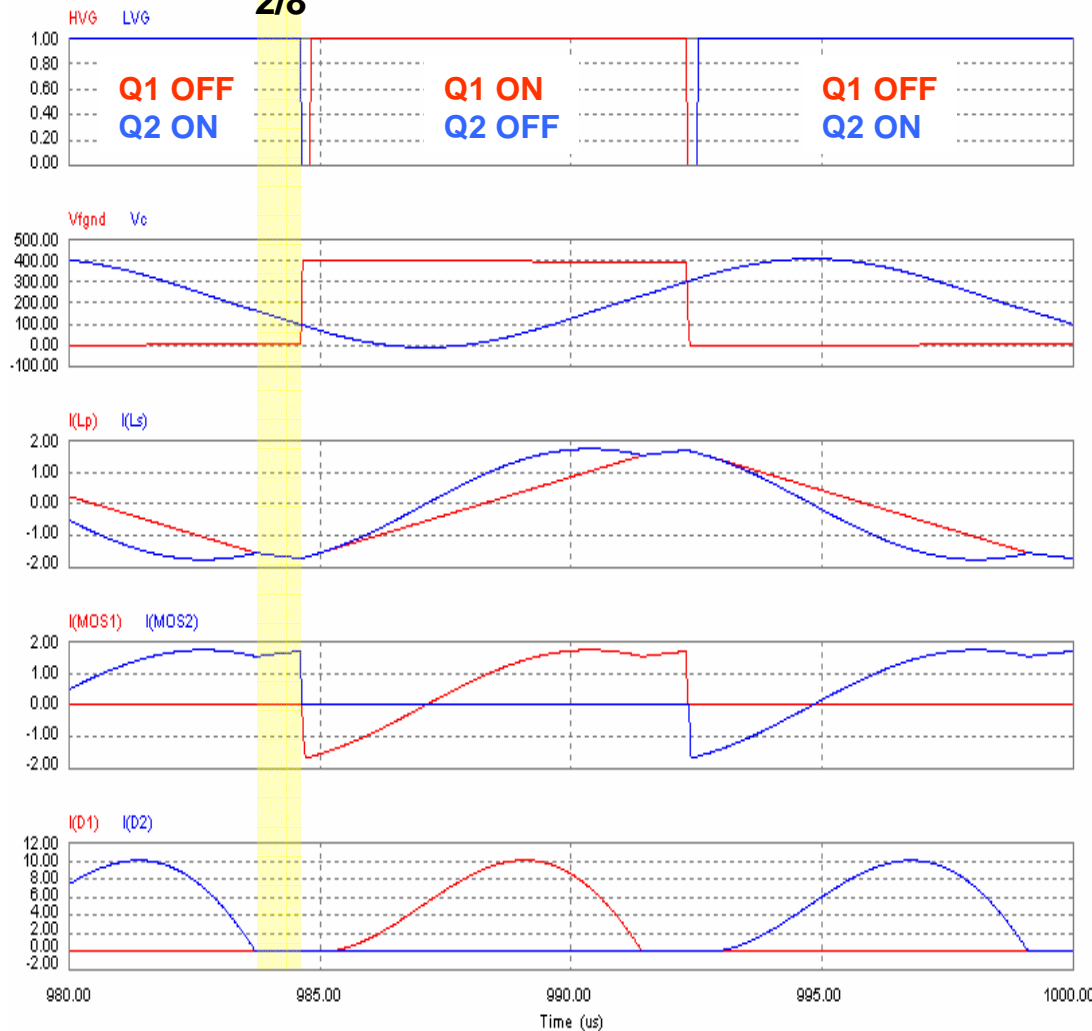


- Q1 is OFF, Q2 is ON
- D1 is OFF, D2 is ON; $V(D1) = -2 \cdot V_{out}$
- Lp is dynamically shorted: $V(Lp) = -n \cdot V_{out}$
- Cr resonates with Ls, f_{r1} appears
- Output energy comes from Cr and Ls
- Phase ends when $I(D2) = 0$

LLC Resonant Half-bridge

Operating Sequence below resonance (Phase 2/8)

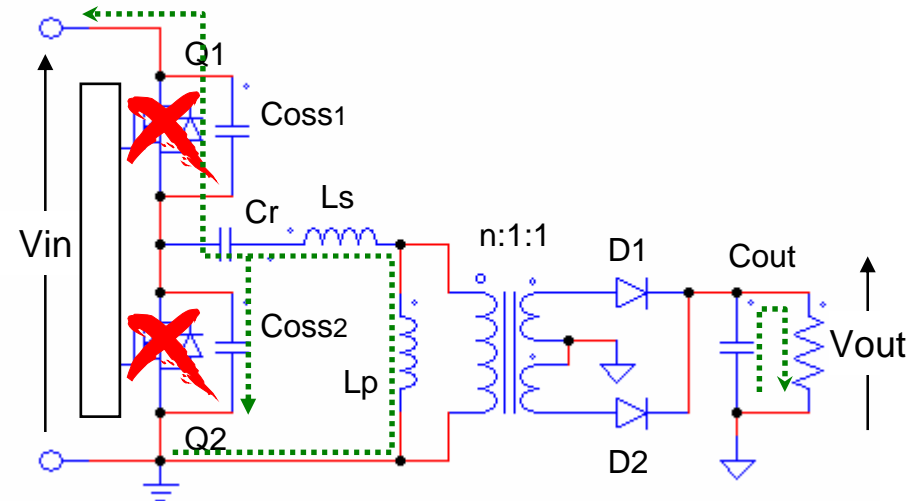
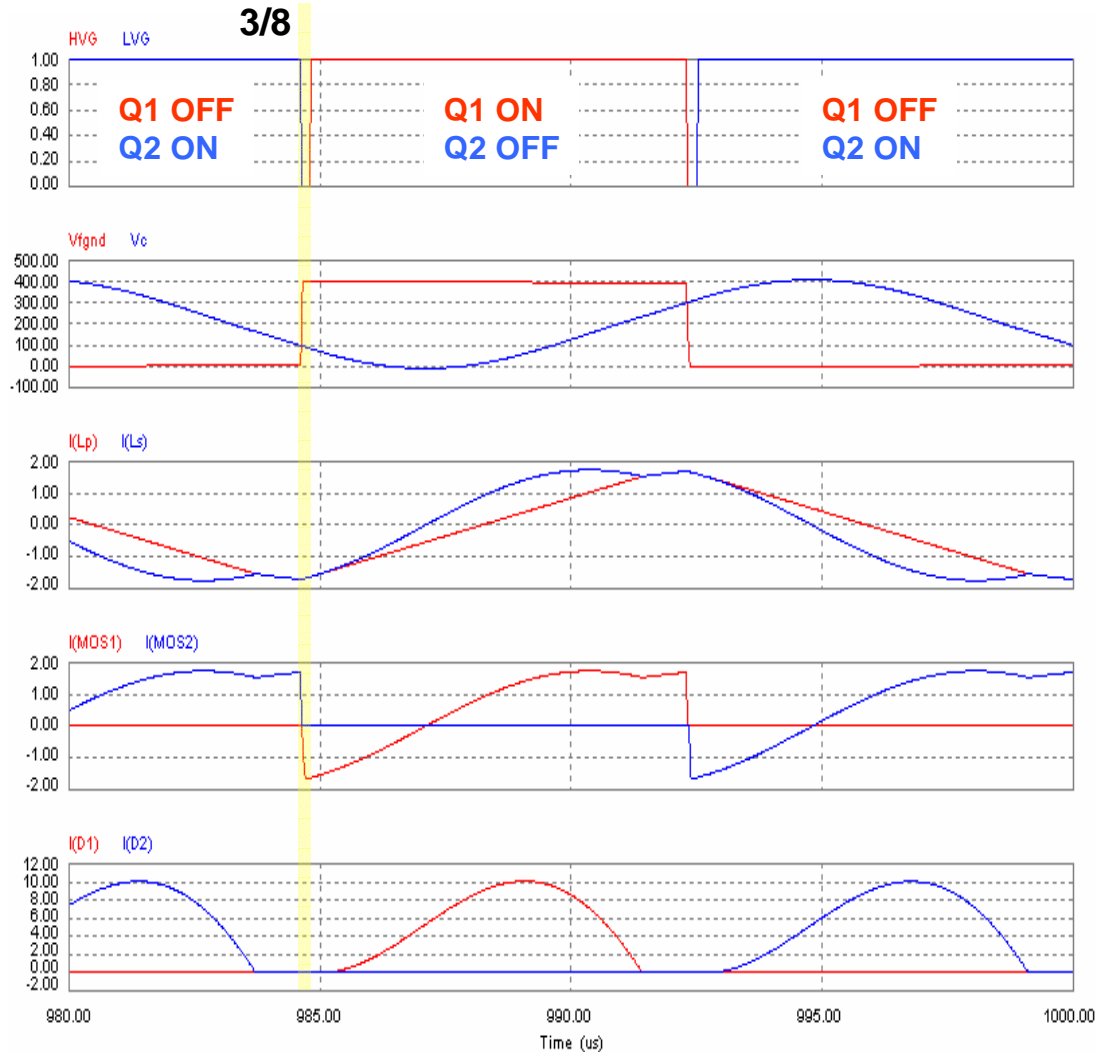
2/8



- Q2 is ON, Q1 is OFF
- D1 and D2 are OFF; $V(D1)=V(D2)=0$; transformer's secondary is open
- C_r resonates with L_s+L_p , f_{r2} appears
- Output energy comes from C_{out}
- Phase ends when Q2 is switched off

LLC Resonant Half-bridge

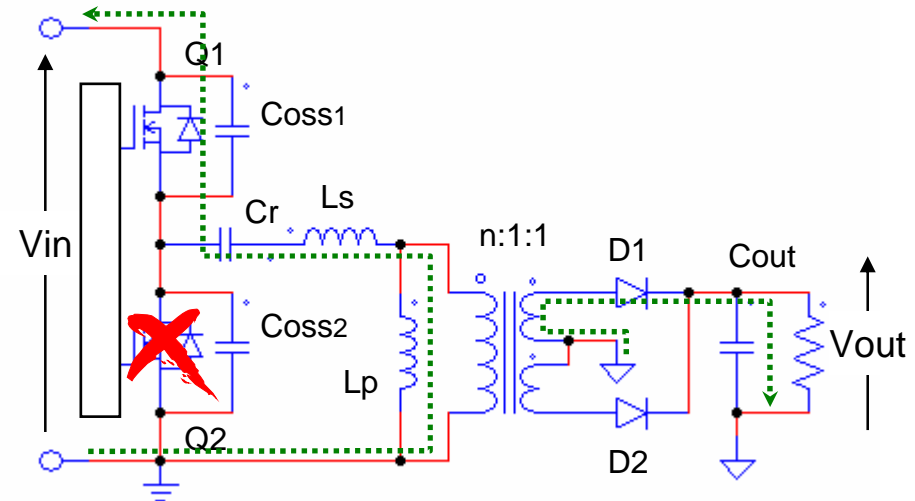
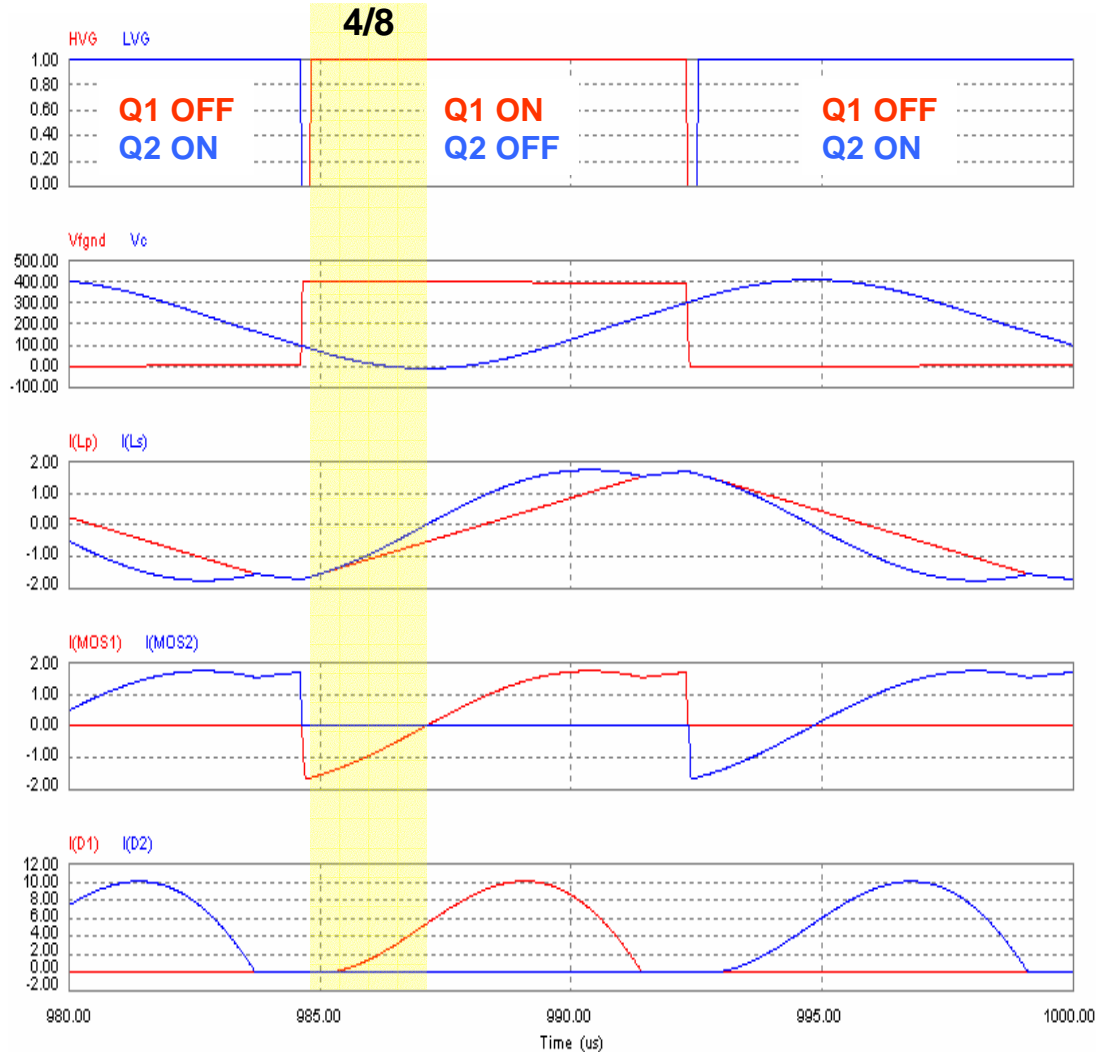
Operating Sequence below resonance (Phase 3/8)



- 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 $V(C_{OSS2})=V_{in}$; Q1's body diode starts conducting, energy goes back to V_{in}
- Phase ends when Q1 is switched on

LLC Resonant Half-bridge

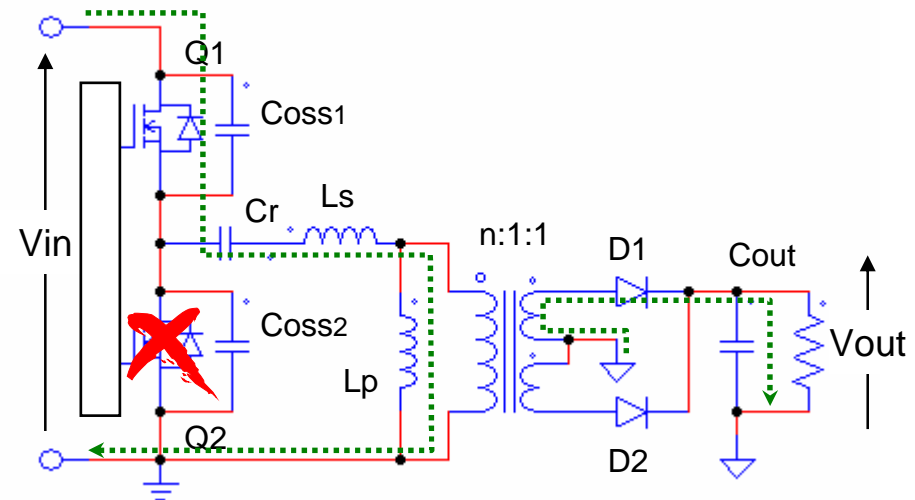
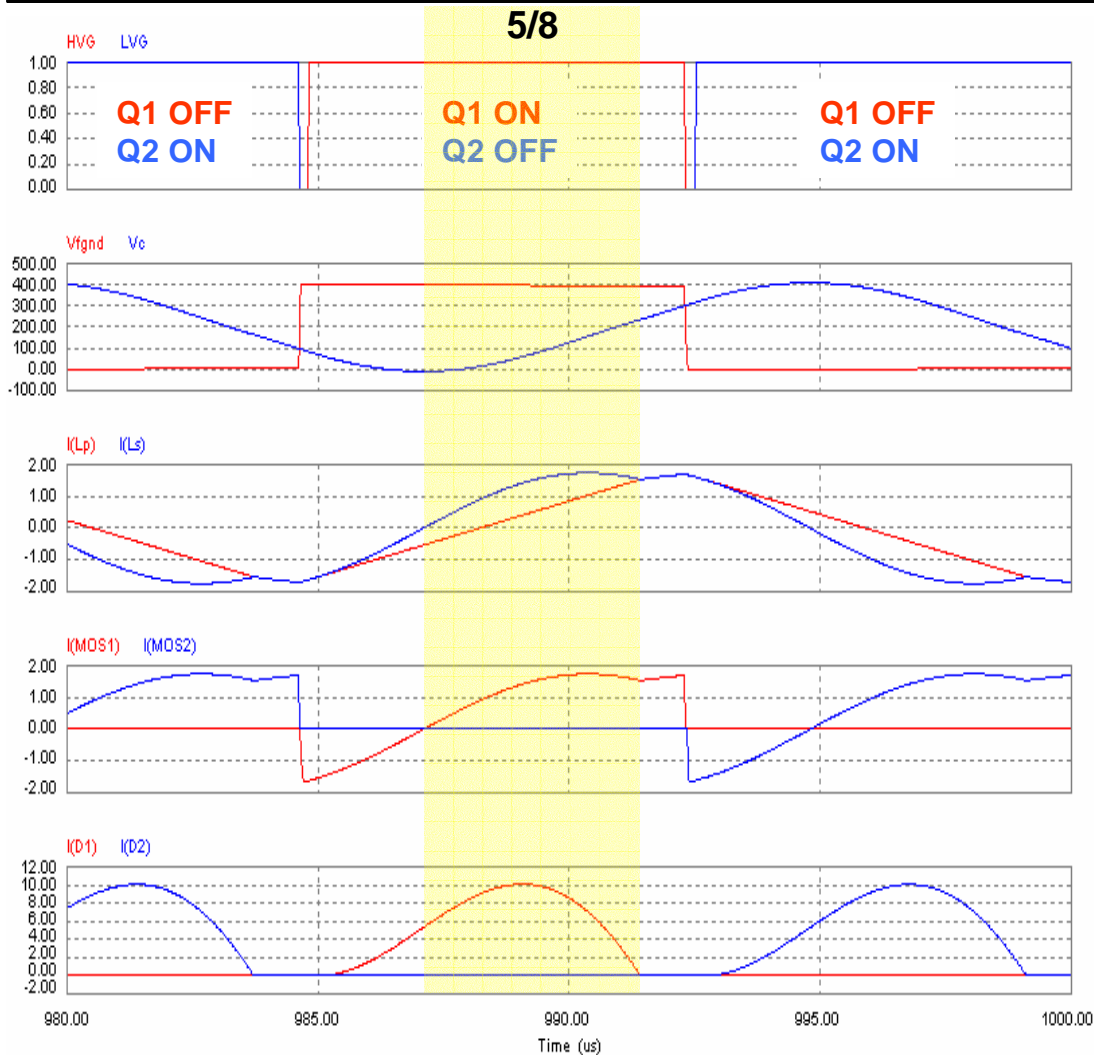
Operating Sequence below resonance (Phase 4/8)



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q1's $R_{DS(on)}$ back to V_{in} (Q1 is working in the 3rd quadrant)
- Energy is recirculating into V_{in}
- Phase ends when $I(L_s) = 0$

LLC Resonant Half-bridge

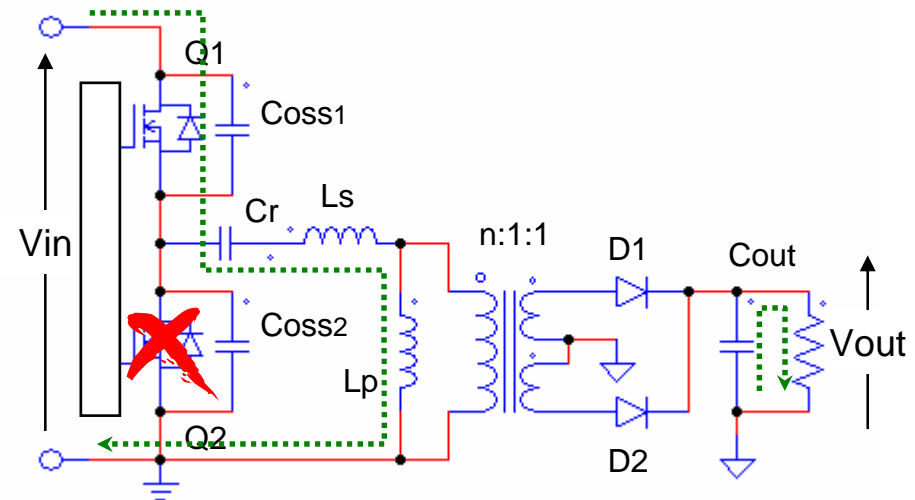
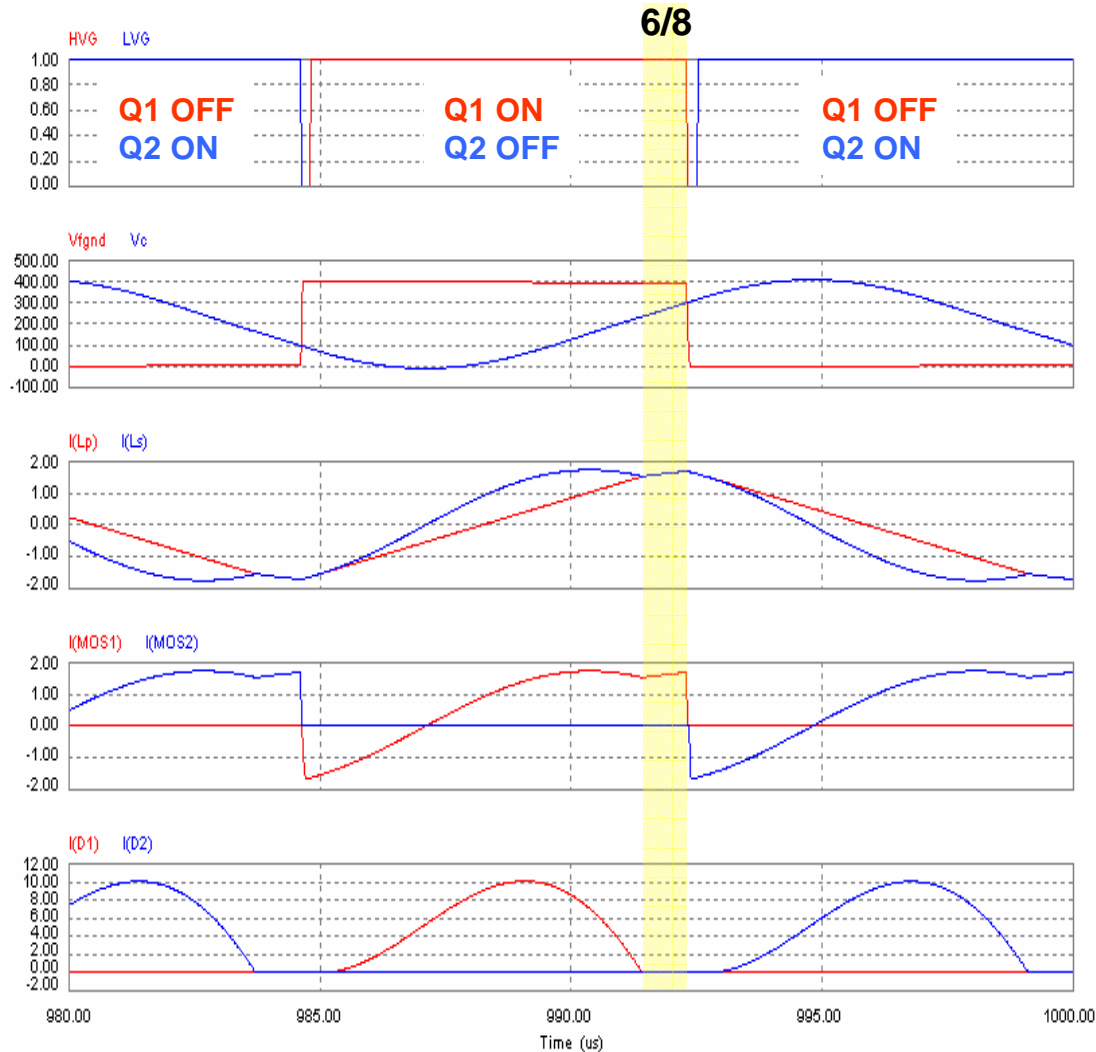
Operating Sequence below resonance (Phase 5/8)



- Q1 is ON, Q2 is OFF
- D1 is ON, D2 is OFF; $V(D2) = -2 \cdot V_{out}$
- L_p is dynamically shorted: $V(L_p) = n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q1's $R_{DS(on)}$ from V_{in} to ground
- Energy is taken from V_{in} and goes to V_{out}
- Phase ends when $I(D1) = 0$

LLC Resonant Half-bridge

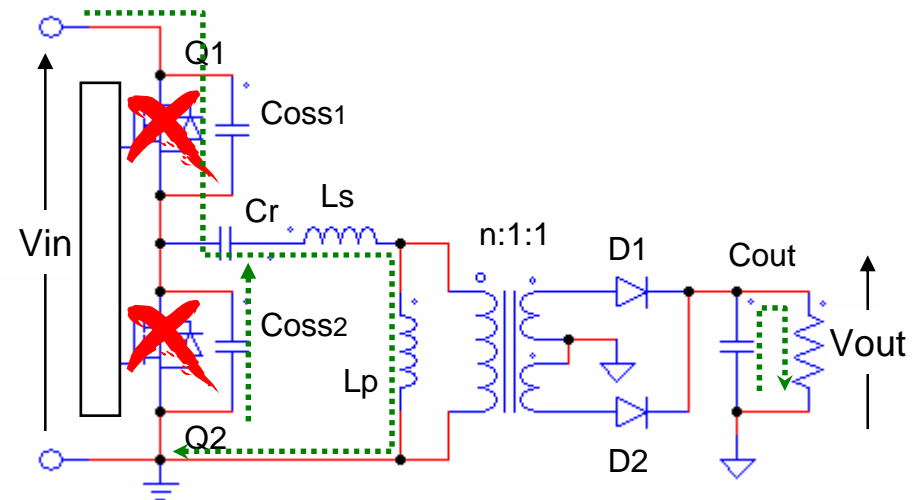
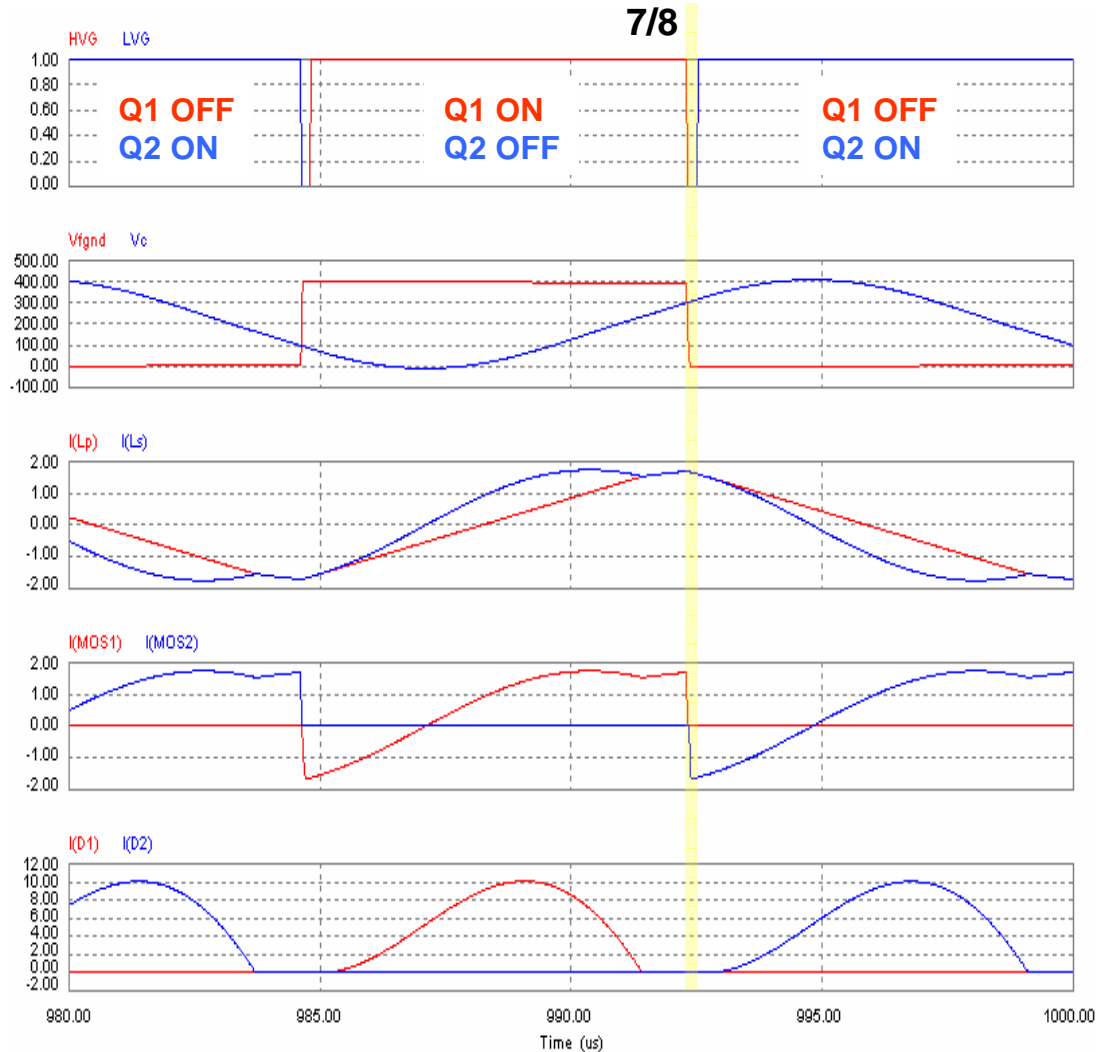
Operating Sequence below resonance (Phase 6/8)



- Q1 is ON, Q2 is OFF
- D1 and D2 are OFF; $V(D1)=V(D2)=0$; transformer's secondary is open
- C_r resonates with L_s+L_p , f_{r2} appears
- Output energy comes from C_{out}
- Phase ends when Q1 is switched off

LLC Resonant Half-bridge

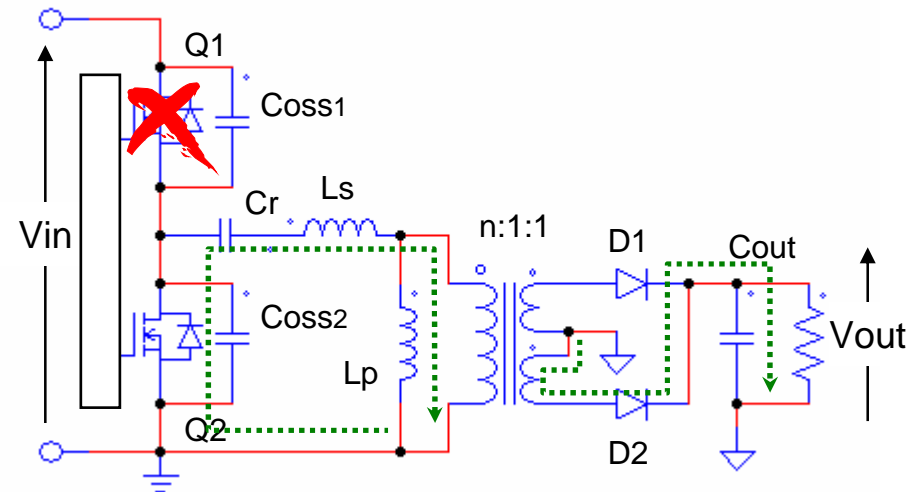
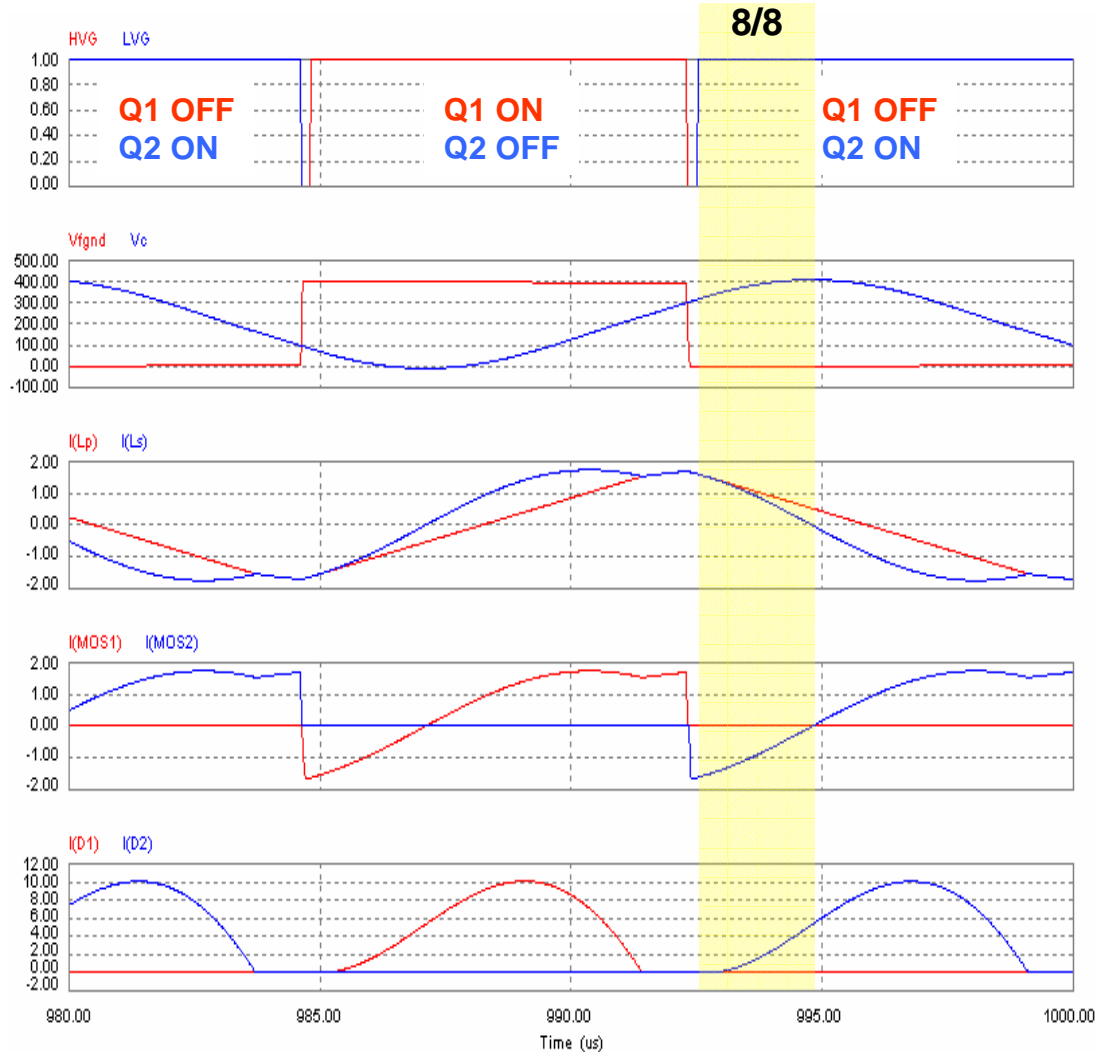
Operating Sequence below resonance (Phase 7/8)



- Q1 and Q2 are OFF (dead-time)
- D1 and D2 are OFF; $V(D1)=V(D2)=0$; transformer's secondary is open
- $I(L_s+L_p)$ charges C_{oss1} and discharges C_{oss2} , until $V(C_{oss2})=0$, then Q2's body diode starts conducting
- Output energy comes from C_{out}
- 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
- L_p is dynamically shorted: $V(L_p) = -n \cdot V_{out}$.
- C_r resonates with L_s , f_{r1} appears
- $I(L_s)$ flows through Q2's $R_{DS(on)}$ (Q2 is working in the 3rd quadrant)
- Output energy comes from C_r and L_s
- Phase ends when $I(L_s)=0$, 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:

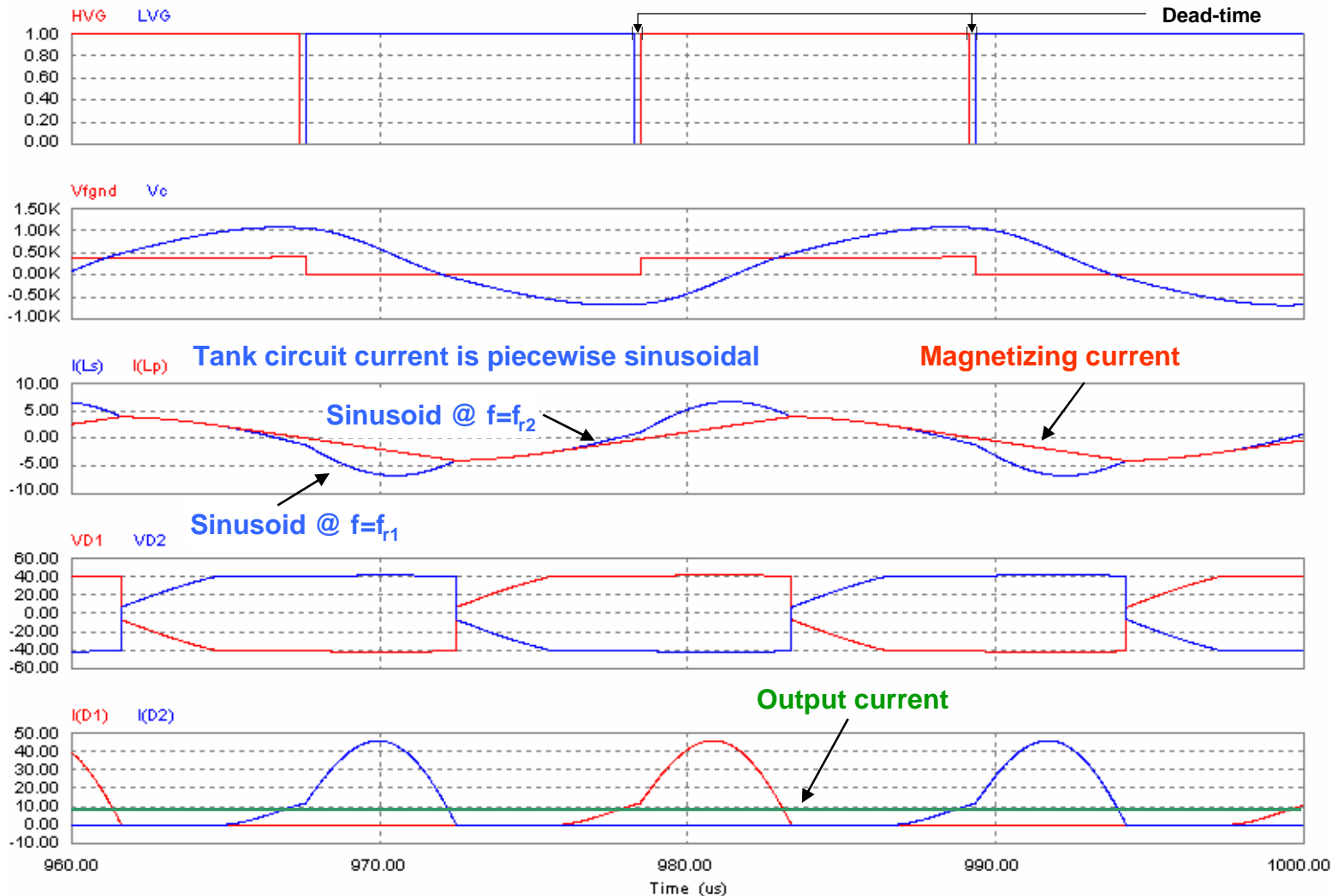
- Hard switching of Q1 & Q2: high switching losses at turn-on and very high capacitive losses at turn-off
- Body diode of Q1 & Q2 is reverse-recovered: high current spikes at turn-on, additional power dissipation; MOSFETs will easily blow up.
- High level of generated EMI
- Large and energetic negative 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!)

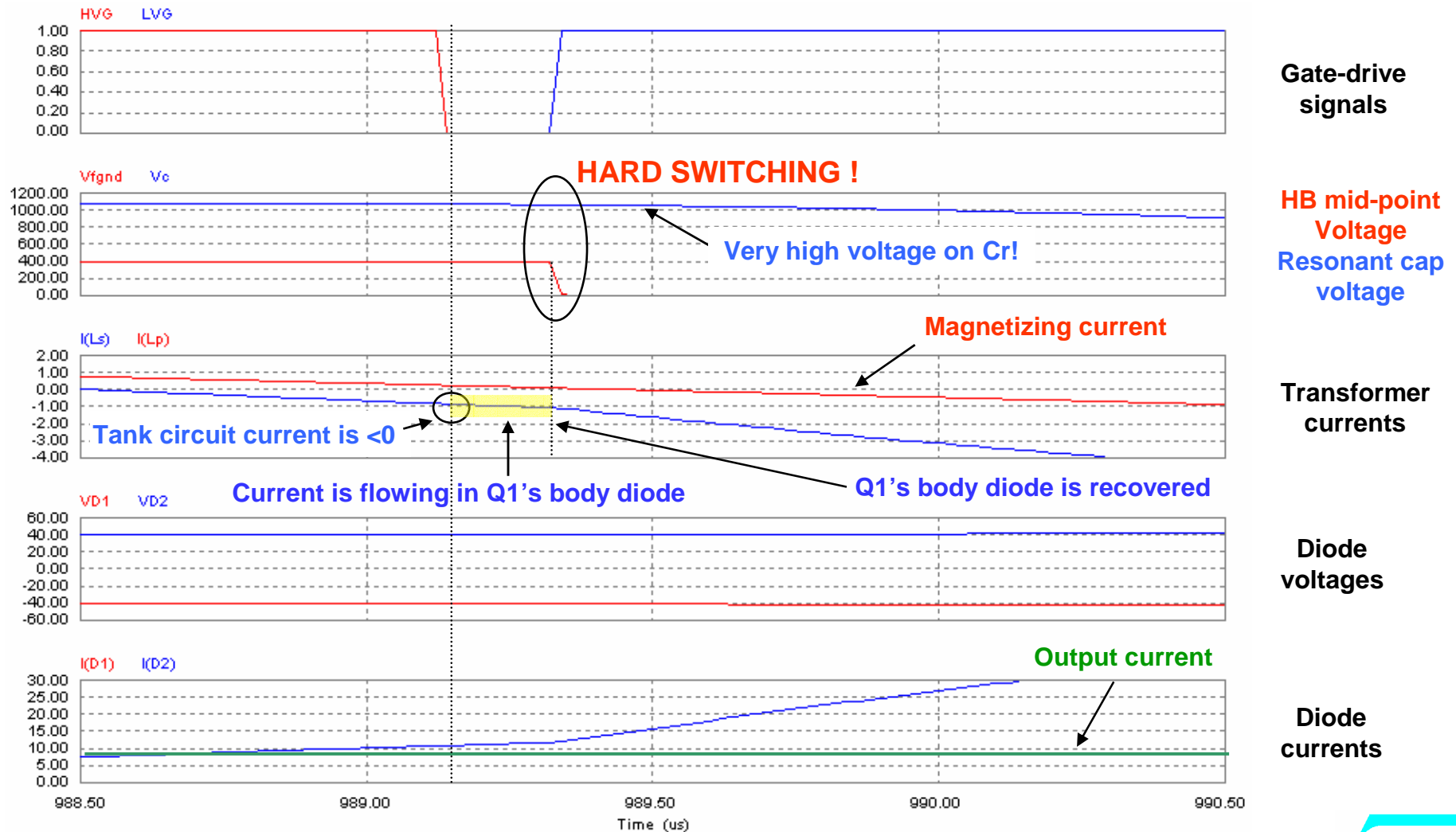
LLC Resonant Half-bridge

Waveforms in capacitive mode ($f_{sw} \sim f_{r2}$)



LLC Resonant Half-bridge

Switching details in capacitive mode ($f_{sw} \sim f_{r2}$)

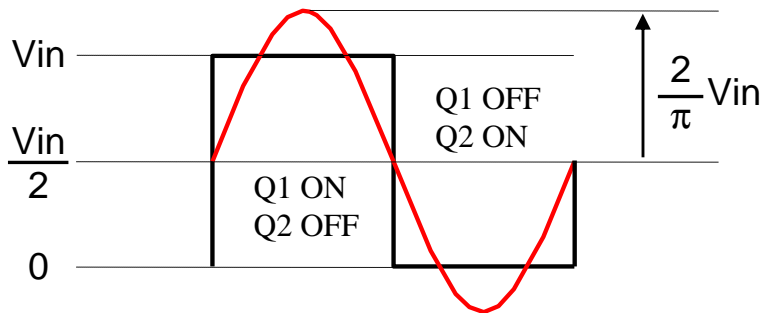
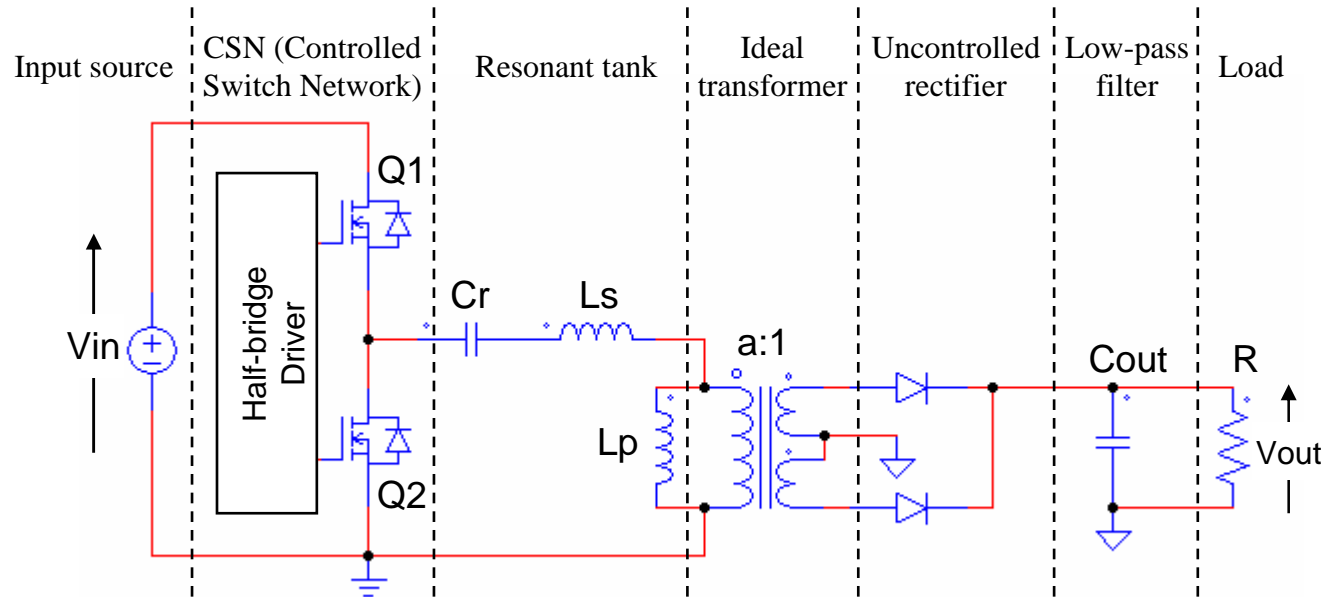


LLC Resonant Half-bridge

Approximate analysis with FHA approach: Basics

BASIC PRINCIPLES

- CSN provides a square wave voltage at a frequency f_{sw} , 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:

- C_r is both resonant and dc blocking capacitor
- Its ac voltage is superimposed on a dc component equal to $V_{in}/2$ (duty cycle is 50% for both Q1 and Q2)

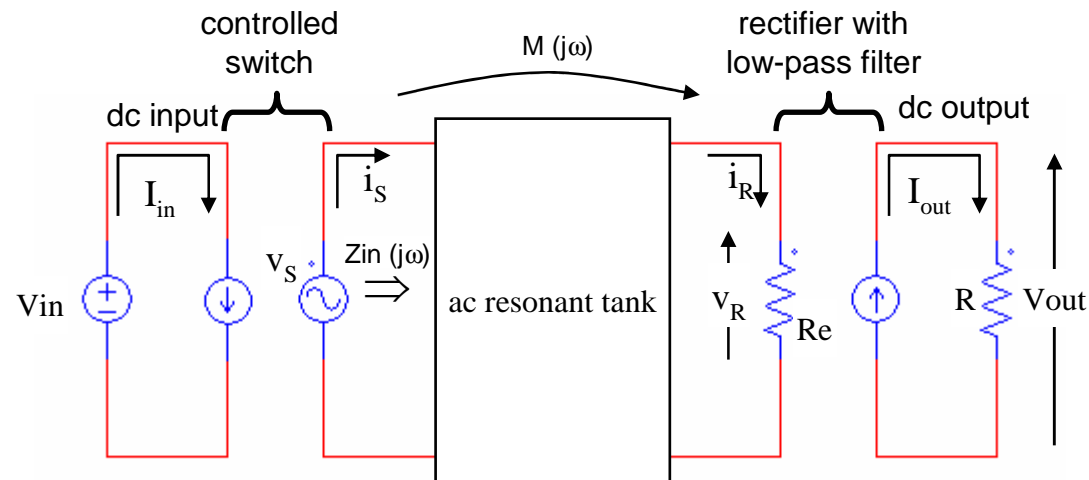
LLC Resonant Half-bridge

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 $Z_{in}(j\omega)$ and Forward Transfer Function $M(j\omega)$.
- It is possible to show that the complete conversion ratio V_{out}/V_{in} is:

$$\frac{V_{out}}{V_{in}} = \|M(j\omega)\|$$

- This result is valid for any resonant topology



$$v_s = \frac{2}{\pi} V_{in} \cdot \sin(2\pi \cdot f_s \cdot t)$$

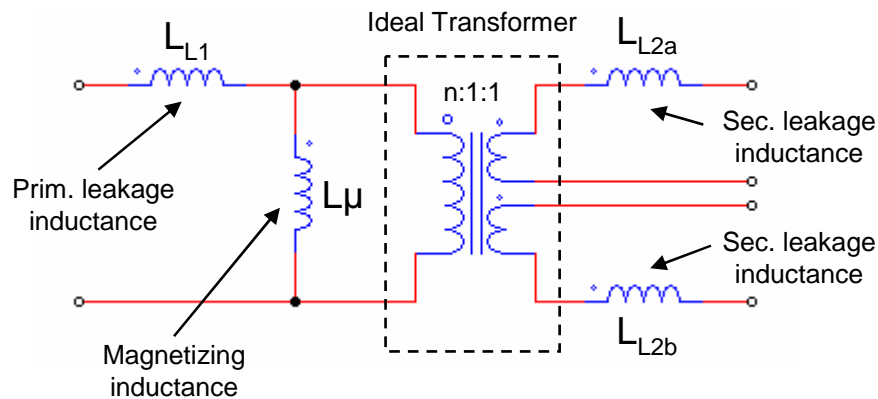
$$R_e = \frac{8}{\pi^2} a^2 R$$

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

$$I_{out} = \frac{2}{\pi} a \|i_R\|$$

LLC Resonant Half-bridge Transformer model (I)

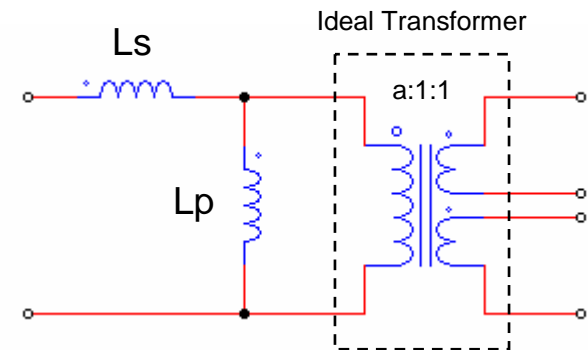
Physical model



- Results from the analysis of the magnetic structure (reluctance model approach)
- n is the actual primary-to-secondary turn ratio
- L_μ 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: $L_{L2a} = L_{L2b}$

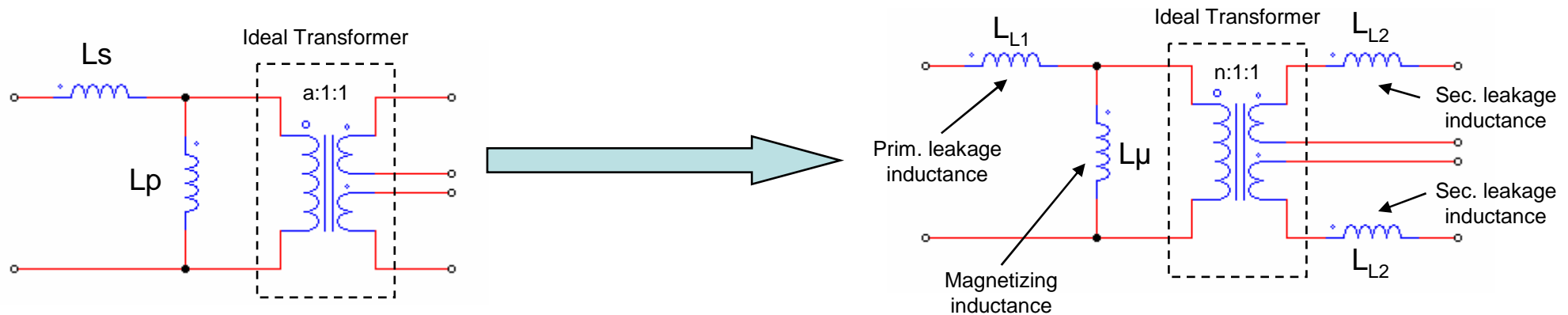
NOTE: $L_{L1} + L_\mu = L_s + L_p = L1$ primary winding inductance

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
- L_s is the primary inductance measured with all secondaries shorted out
- L_p is the difference between the primary inductance measured with secondaries open and L_s

LLC Resonant Half-bridge Transformer model (II)

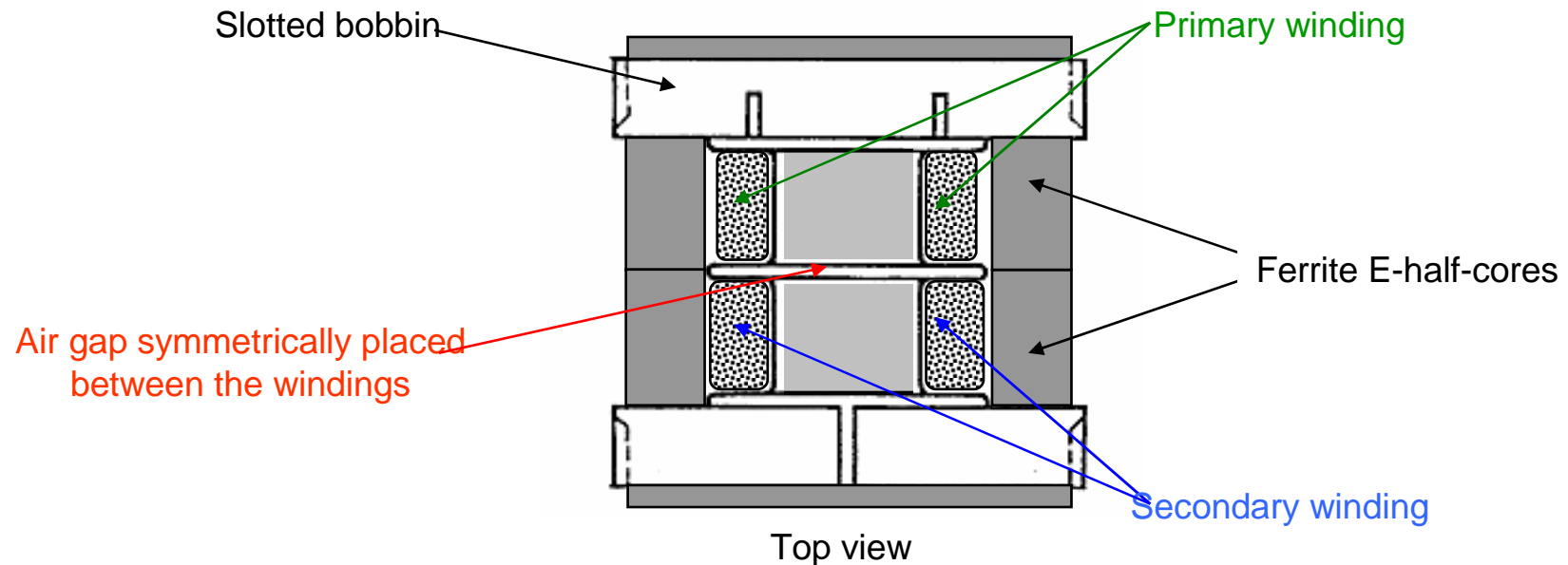


- We need to go from the APS model to the physical model to determine transformer specification
- Undetermined problem (4 unknowns, 3 conditions); one more condition needed (related to the physical magnetic structure)
- Only n is really missing: $L_1 = L_s + L_p = L_{L1} + L_\mu$ is known and measurable, L_s is measurable
- Magnetic circuit symmetry will be assumed: equal leakage flux linkage for both primary and secondary $\Rightarrow L_{L1} = n^2 \cdot L_{L2}$; then:

$$n = a \sqrt{\frac{L_p}{L_p + L_s}}$$

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 $L_1 = N_p^2 \cdot A_L$
- In this structure it is also possible to define a specific leakage inductance A_{Llk} such that $L_s = N_p^2 \cdot A_{Llk}$. A_{Llk} is a function of bobbin's geometry; it depends on air gap position but not on its thickness

LLC Resonant Half-bridge

Numerical results of ac analysis

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

■ Input Impedance:

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

■ 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:

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

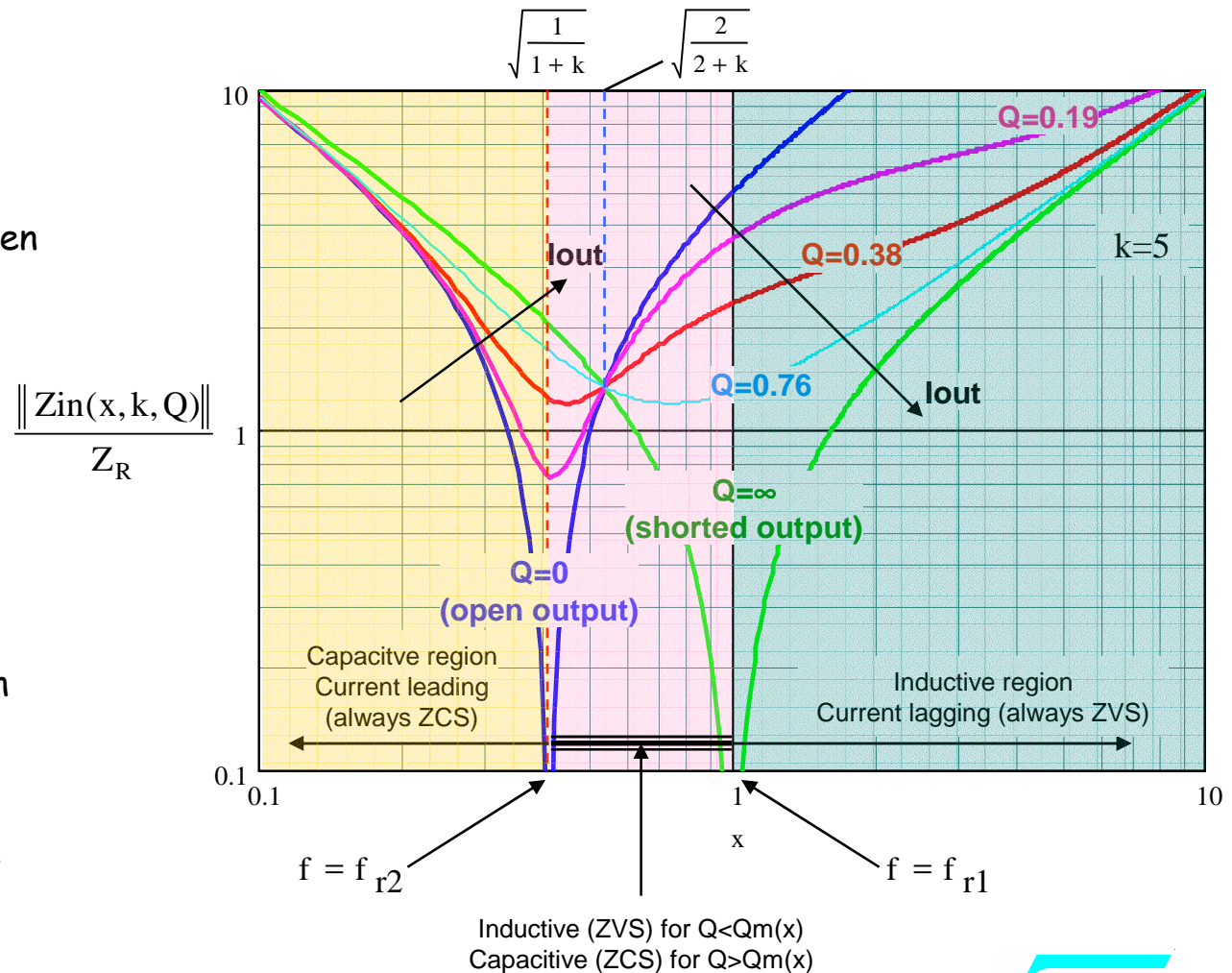
NOTES:

- 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 $Re=\infty$ (open load), $Q=\infty$ means $Re=0$ (short circuit); one can think of Q as proportional to I_{out}

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Resonant Tank Input Impedance $Z_{in}(j\omega)$

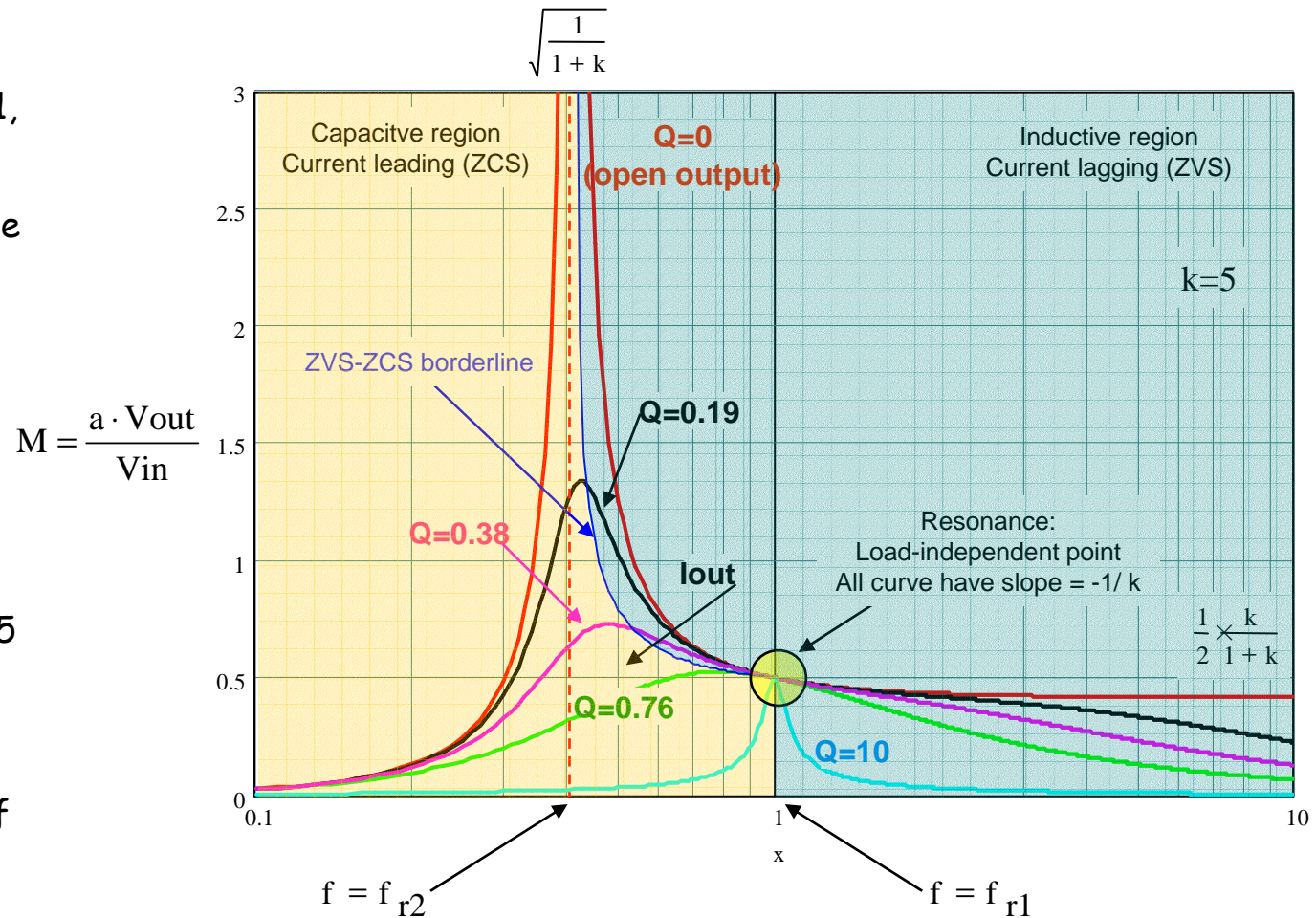
- Above resonance ($x > 1$) $Z_{in}(j\omega)$ is always inductive; current lags voltage, so when $v_s = 0$, i_s is still > 0 : ZVS
- Below f_{r2} ($x < \sqrt{\frac{1}{1+k}}$), $Z_{in}(j\omega)$ is always capacitive; current leads voltage, so when $v_s = 0$, i_s is already < 0 : ZCS
- Below the first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



LLC Resonant Half-bridge

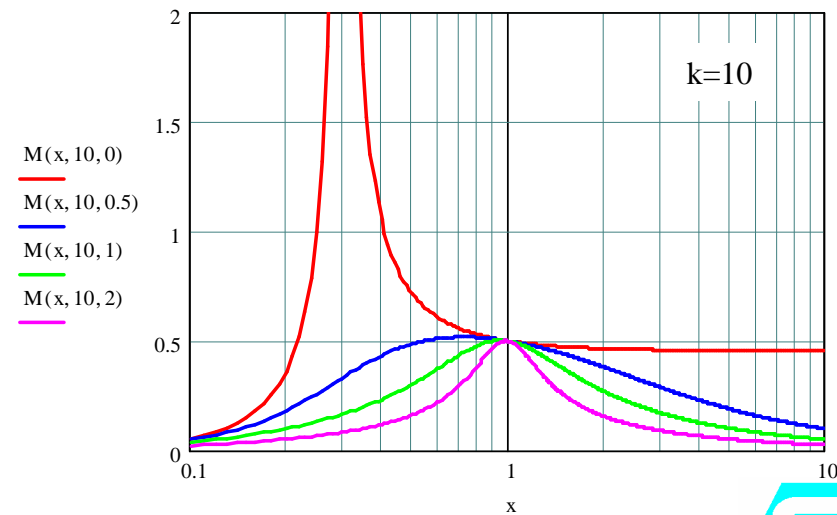
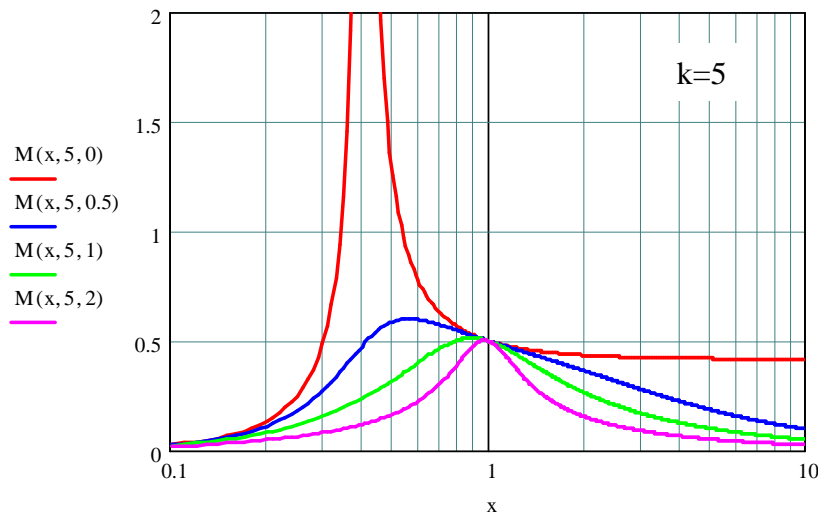
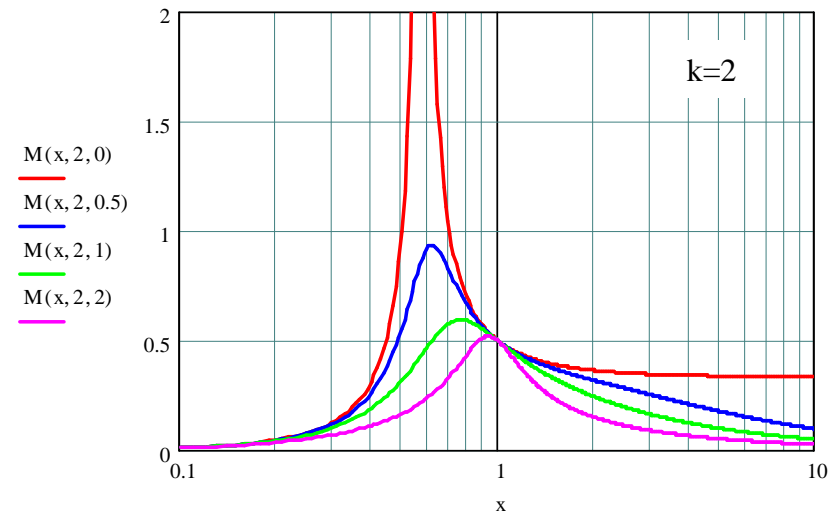
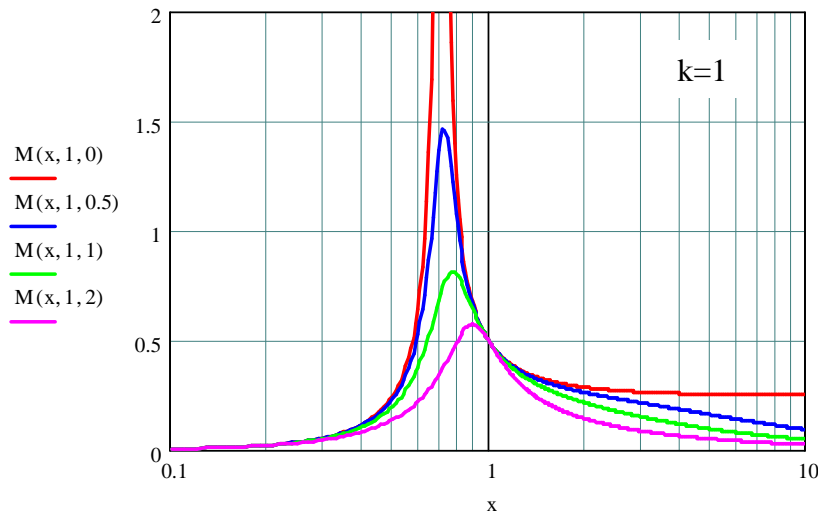
Voltage conversion ratio $||M(j\omega)||$

- 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 $x \rightarrow \infty$;
 $M \rightarrow \infty$ 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 $Q > Q_m$.



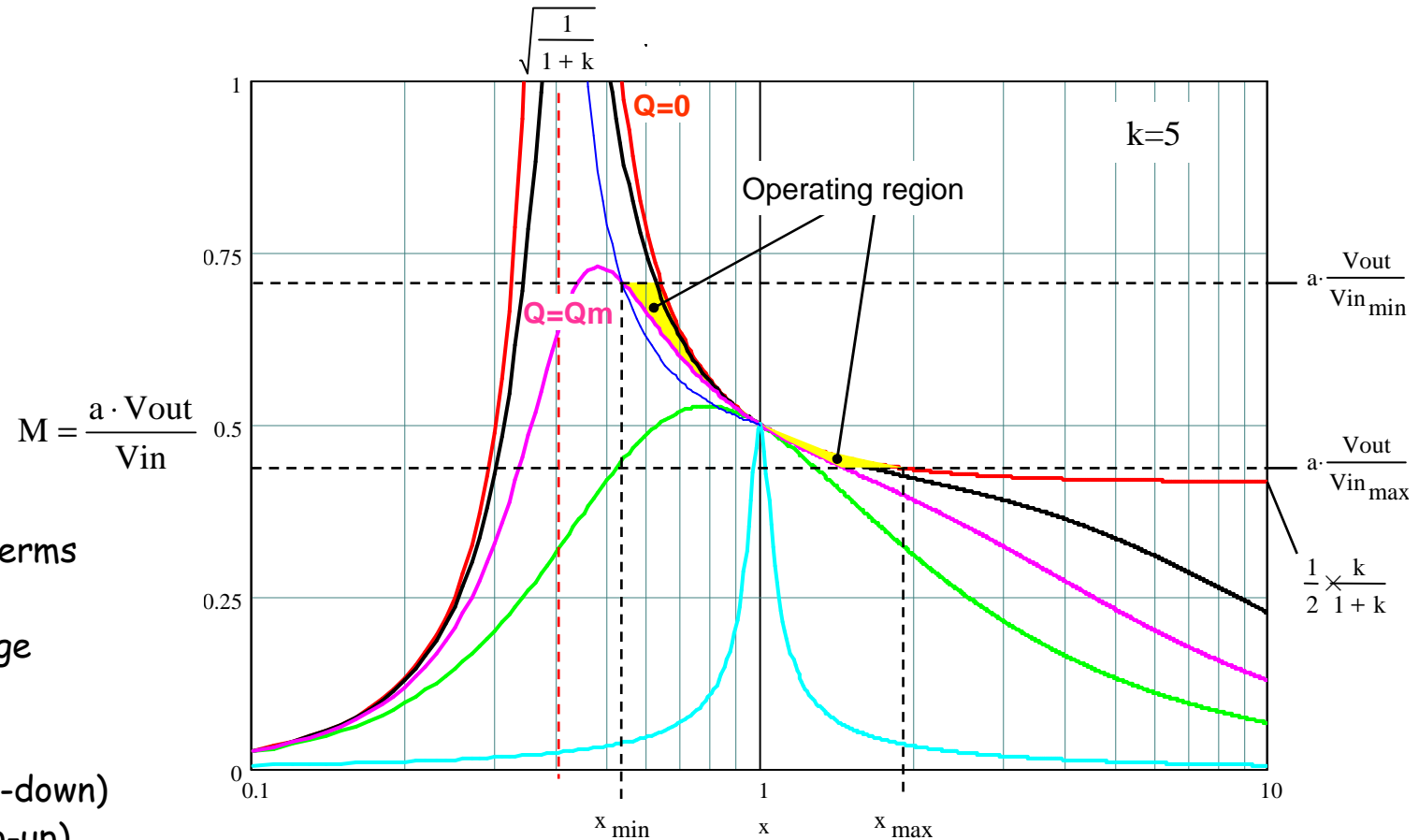
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Effect of k on $\|M(j\omega)\|$



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Operating region on $||M(j\omega)||$ diagrams



- M-axis can be rescaled in terms of V_{in} : V_{out} is regulated
- Given the input voltage range ($V_{in_{min}} \div V_{in_{max}}$), 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

- $Z_{in}(j\omega)$ analysis has shown that ZVS occurs for $x < 1$, provided $Q \leq Q_m$, i.e. $\text{Im}[Z_{in}(j\omega)] \geq 0$.
- If $Q = Q_m$ ($\text{Im}[Z_{in}(j\omega)] = 0$) 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 $Q \leq Q_Z < Q_m$.
- Mathematically, the ZVS condition is :

$$\frac{\text{Im}(Z_{in}(x, k, Q))}{\text{Re}(Z_{in}(x, k, Q))} \geq \frac{2 \cdot C_{oss} + C_{stray}}{\pi \cdot T_d} \cdot \frac{V_{in_{min}}^2}{P_{in_{max}}}$$

- C_{oss} is the MOSFET's output capacitance, C_{stray} 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

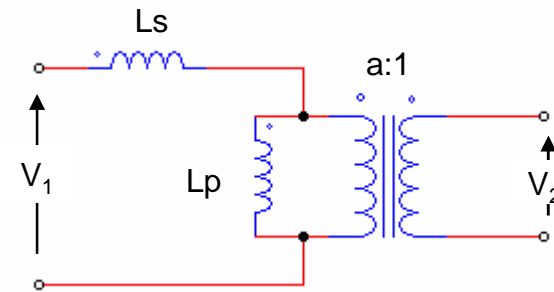
No-load issues: regulation

- LLC converter can regulate down to zero load, unlike the conventional LC series-resonant
- At a frequency $\gg f_{r1}$ Cr disappears and the output voltage is given by the inductive divider made up by L_s and L_p
- 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 :

$$a \cdot \frac{V_{out}}{V_{in_{max}}} > \frac{1}{2} \cdot \frac{k}{1+k}$$

- This is equivalent to the graphical constraint that the horizontal line $a \cdot V_{out}/V_{in_{max}}$ must cross the $Q=0$ curve

Equivalent schematic of LLC converter for $x \rightarrow \infty$



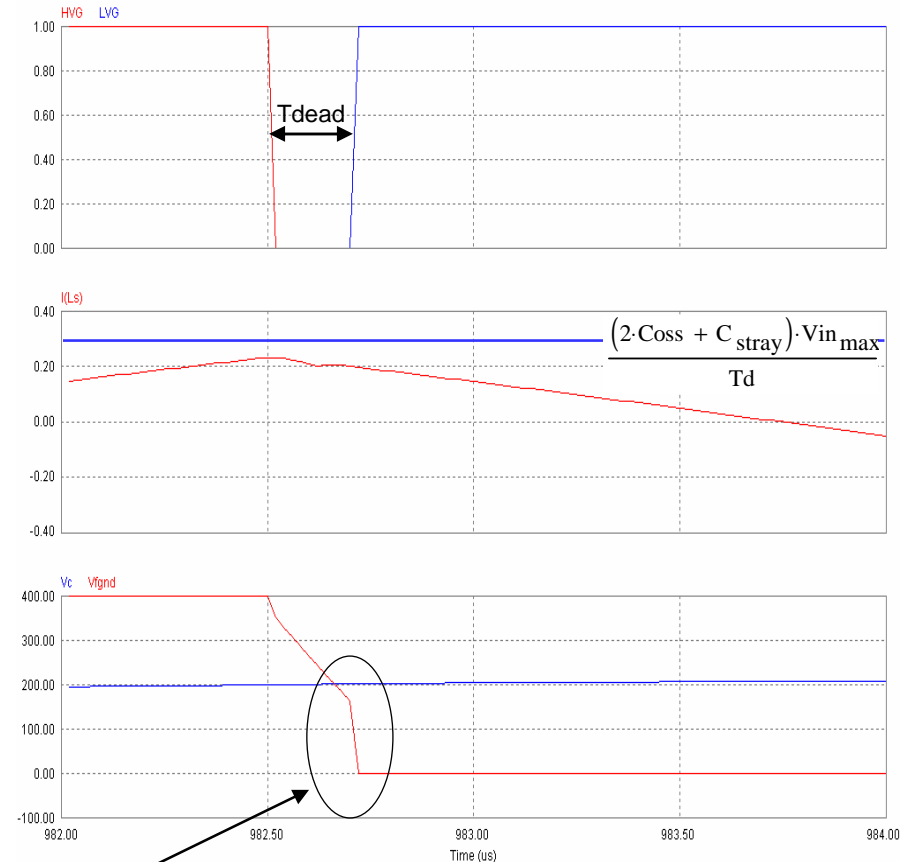
$$V_2 = V_1 \cdot \frac{1}{a} \cdot \frac{L_p}{L_s + L_p}$$

LLC Resonant Half-bridge

No-load issues: ZVS

- $Z_{in}(j\omega)$ 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 full load:

$$Q \leq \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{\max}} \cdot \frac{T_d}{\operatorname{Re}(2 \cdot C_{\text{oss}} + C_{\text{stray}})}$$

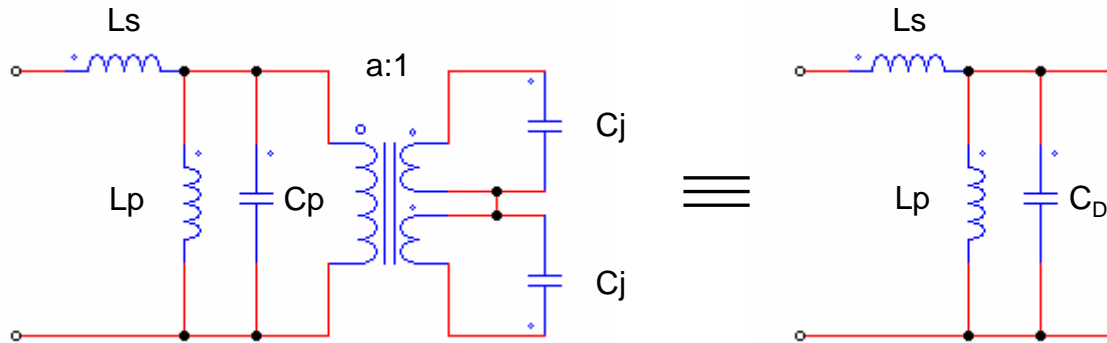


Hard Switching at no load

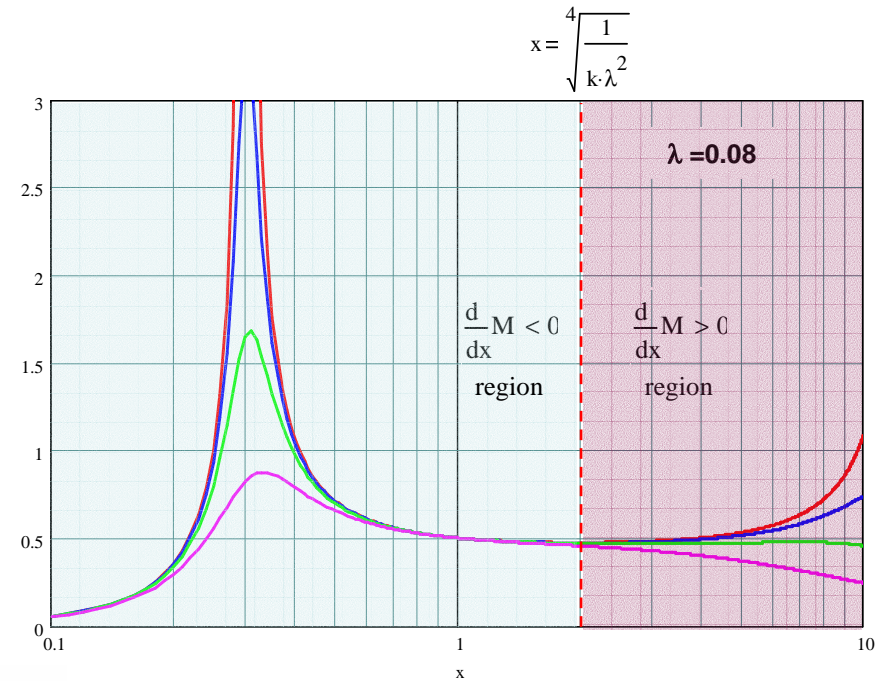
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No-load issues: Feedback inversion

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



$$M = \frac{a \cdot V_{out}}{V_{in}}$$



$$C_D = C_p + \frac{C_j}{a^2} \quad \lambda = \sqrt{\frac{C_D}{C_r}}$$

LLC Resonant Half-bridge

Design procedure. General criteria.

DESIGN SPECIFICATION

- Vin range, holdup included ($V_{in_{min}} \div V_{in_{max}}$)
- Nominal input voltage ($V_{in_{nom}}$)
- Regulated Output Voltage (V_{out})
- Maximum Output Power ($P_{out_{max}}$)
- 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 $P_{out_{max}}$

- 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 $a=1$:

$$M_{\min} = \frac{V_{\text{out}}}{V_{\text{in}_{\max}}} \quad M_{\max} = \frac{V_{\text{out}}}{V_{\text{in}_{\min}}} \quad M_{\text{nom}} = \frac{V_{\text{out}}}{V_{\text{in}_{\text{nom}}}}$$

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

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

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, $Q_{\max 1}$, to stay in the ZVS region at min. V_{in} and max. load:

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

LLC Resonant Half-bridge

Design procedure. Proposed algorithm (II).

6. Calculate the effective load resistance:

$$R_e = \frac{8}{\pi^2} \cdot a^2 \cdot R = \frac{8}{\pi^2} \cdot a^2 \cdot \frac{V_{out}^2}{P_{out\ max}}$$

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

$$Q_{max2} = \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{max}} \cdot \frac{T_d}{Re \cdot (2 \cdot C_{oss} + C_{stray})}$$

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:

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

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

$$Z_R = Re \cdot Q_S \quad C_s = \frac{1}{2 \cdot f_r \cdot Z_R \cdot \pi} \quad L_s = \frac{Z_R}{2 \cdot \pi \cdot f_r} \quad L_p = k \cdot L_s$$

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 threshold of the PFC pre-regulator
Nominal input voltage	400 Vdc	Nominal output voltage of PFC
Regulated output 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:

$$M_{\min} = \frac{V_{\text{out}}}{V_{\text{in}_{\max}}} = \frac{24}{450} = 0.053 \quad M_{\max} = \frac{V_{\text{out}}}{V_{\text{in}_{\min}}} = \frac{24}{320} = 0.075 \quad M_{\text{nom}} = \frac{V_{\text{out}}}{V_{\text{in}_{\text{nom}}}} = \frac{24}{400} = 0.06$$

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

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

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:

$$R_e = \frac{8}{\pi^2} \cdot a^2 \cdot R = \frac{8}{\pi^2} \cdot a^2 \cdot \frac{V_{out}^2}{P_{out\ max}} = 108.067\ \Omega$$

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

$$Q_{max2} = \frac{\pi}{4} \cdot \frac{1}{(1+k) \cdot x_{max}} \cdot \frac{T_d}{R_e \cdot (2 \cdot C_{oss} + C_{stray})} = 0.519$$

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:

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

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

$$Z_R = R_e \cdot Q_S = 38.472\ \Omega \quad C_S = \frac{1}{2 \cdot f_r \cdot Z_R \cdot \pi} = 46\ \text{nF} \quad L_S = \frac{Z_R}{2 \cdot \pi \cdot f_r} = 68\ \mu\text{H} \quad L_p = k \cdot L_S = 408\ \mu\text{H}$$

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 R_{Fmin} :

$$R_{Fmin} = \frac{1}{3 \cdot C_F \cdot f_{min}} = \frac{1}{3 \cdot 470 \cdot 10^{-12} \cdot 53.28 \cdot 10^3} = 13.3 \text{ k}\Omega$$

Calculate R_{Fmax} :

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

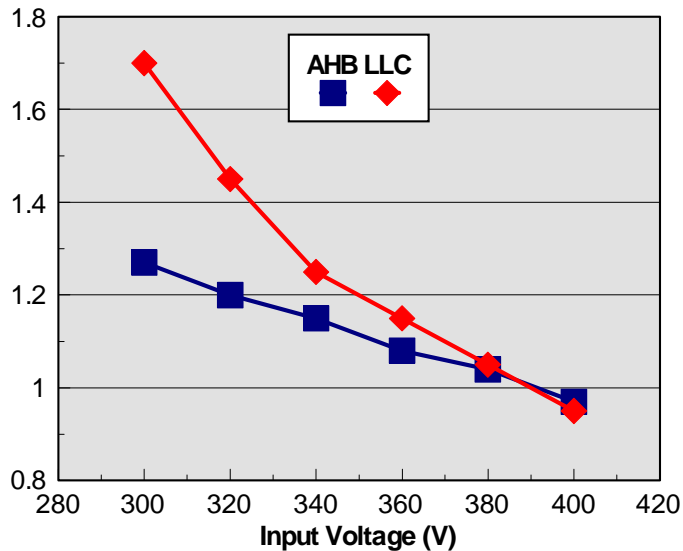
Calculate Soft-start components:

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

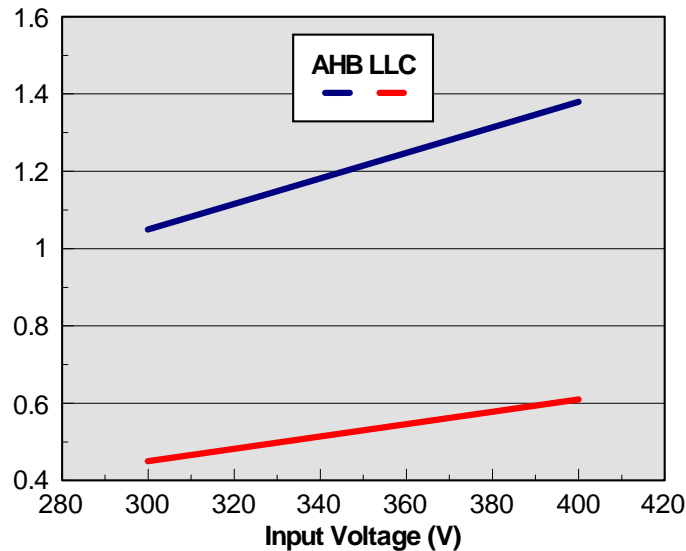
LLC Resonant Half-bridge

Comparison with ZVS Half-bridge (I)

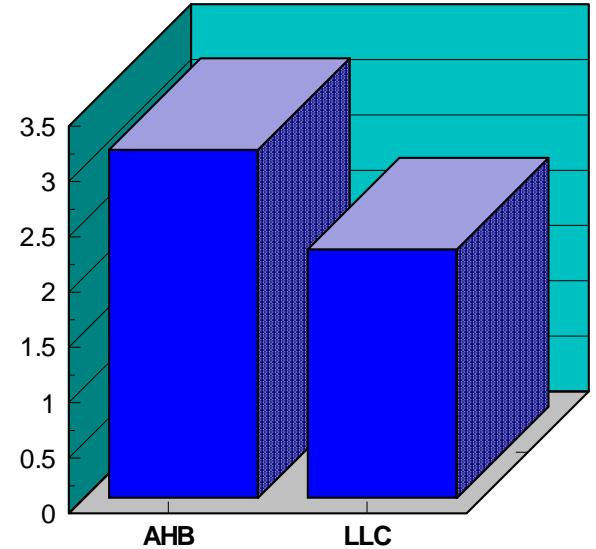
Primary Conduction Losses (W)



Primary Switching Losses (W)



Secondary Conduction Losses



ELECTRICAL SPECIFICATION

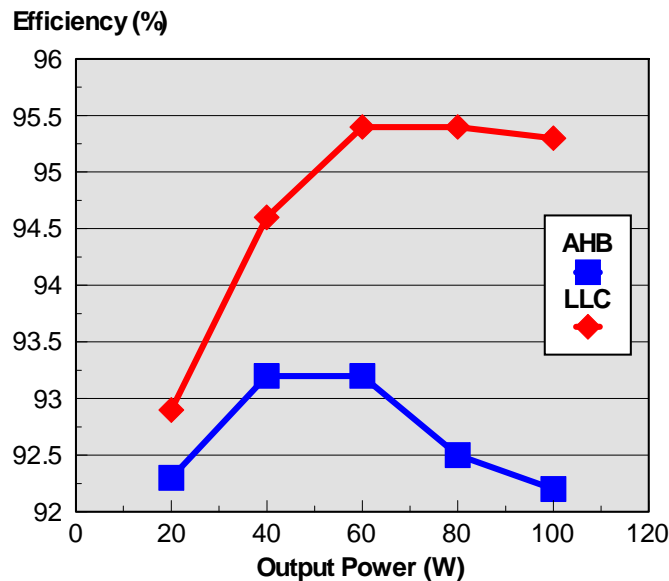
Input Voltage:	300 to 400(*) Vdc
Output voltage:	20 Vdc
Output power:	100 W
Switching frequency:	200 kHz

(*) 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

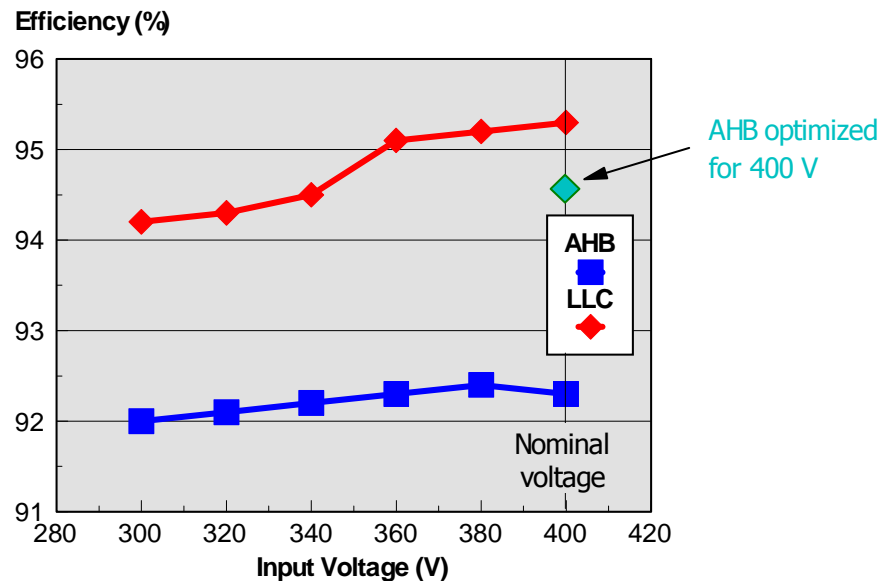
LLC Resonant Half-bridge

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 \Rightarrow higher $V_F \Rightarrow$ 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 ($2 \cdot V_{out}$) \Rightarrow lower $V_F \Rightarrow$ low conduction losses; ZCS \Rightarrow no recovery losses
- Operation can be optimized at nominal input voltage