Control Methods of LLC Converters

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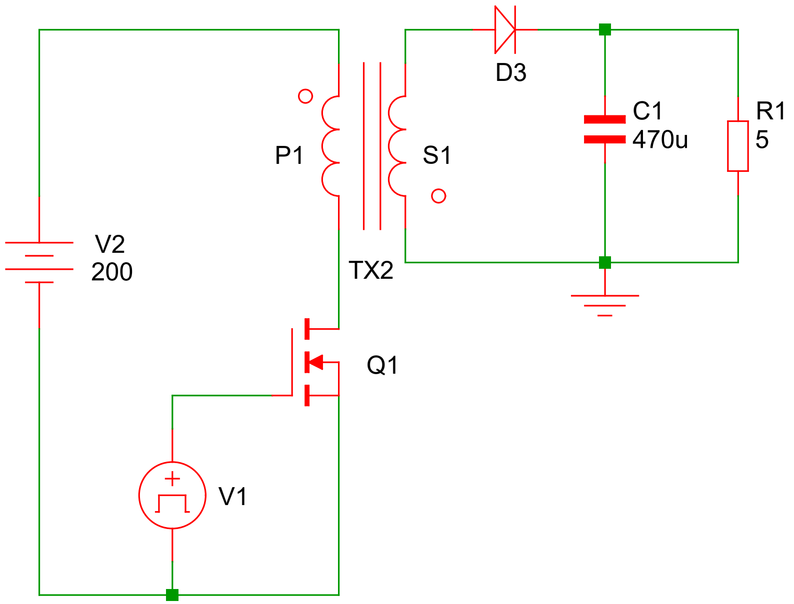
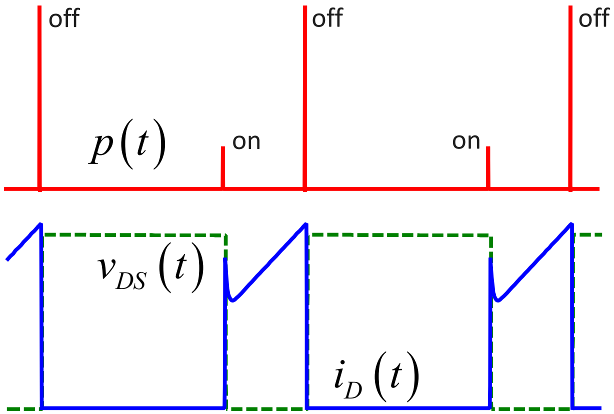
Agenda

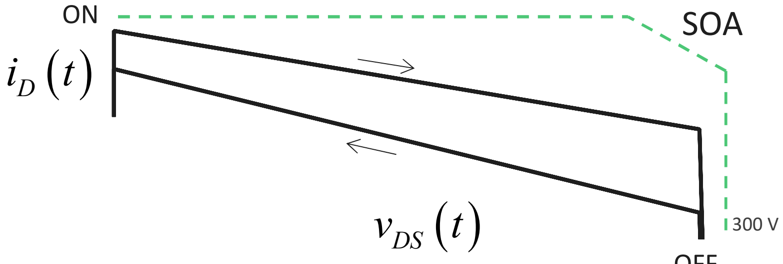
- Hard and Soft Switching
- What is an LLC Converter?
- Controlling the Switching Frequency
- Closing the Loop
- Charge-Controlled Operation I
- Charge-Controlled Operation II
- Current-Mode Control
- Time-Shift Control
- An Overview of Available LLC Controllers

Hard-Switching Operations without Parasitics

- A switching circuit without parasitics operates safely within maximum ratings





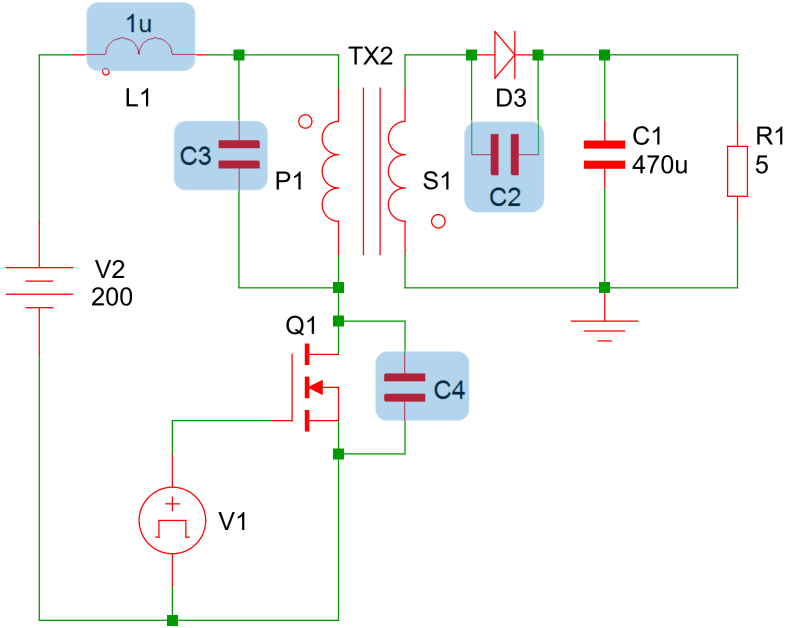


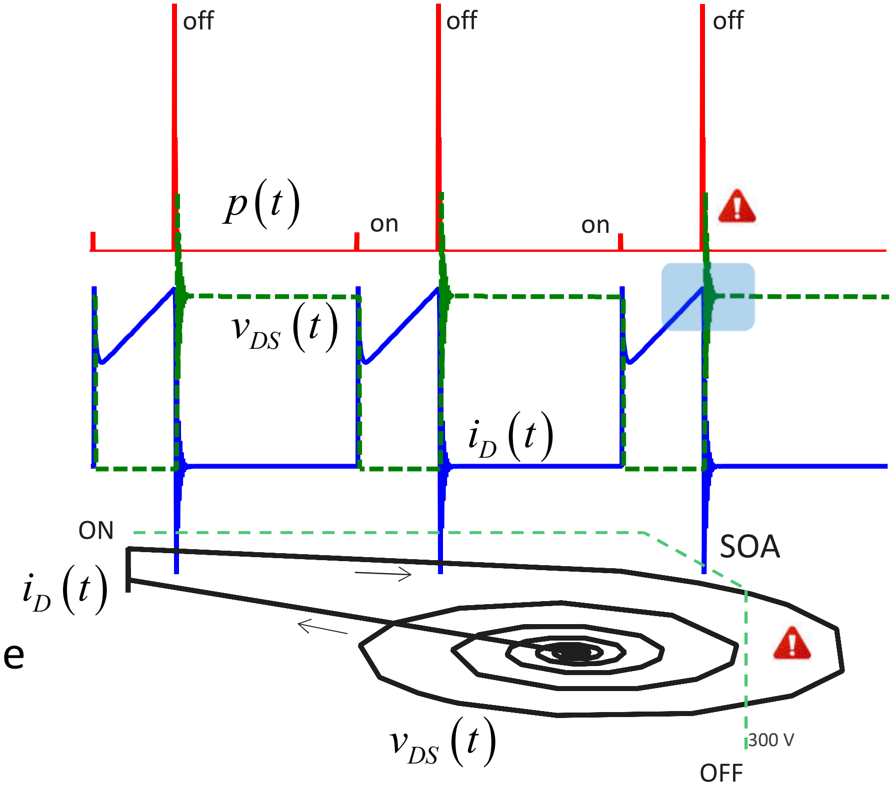
SOA: safe operating area

- Overlap between current and voltage is minimum and keeps switching losses low

Parasitics degrade Switching Performance

- Parasitics add oscillatory phenomena and safe limits can be violated

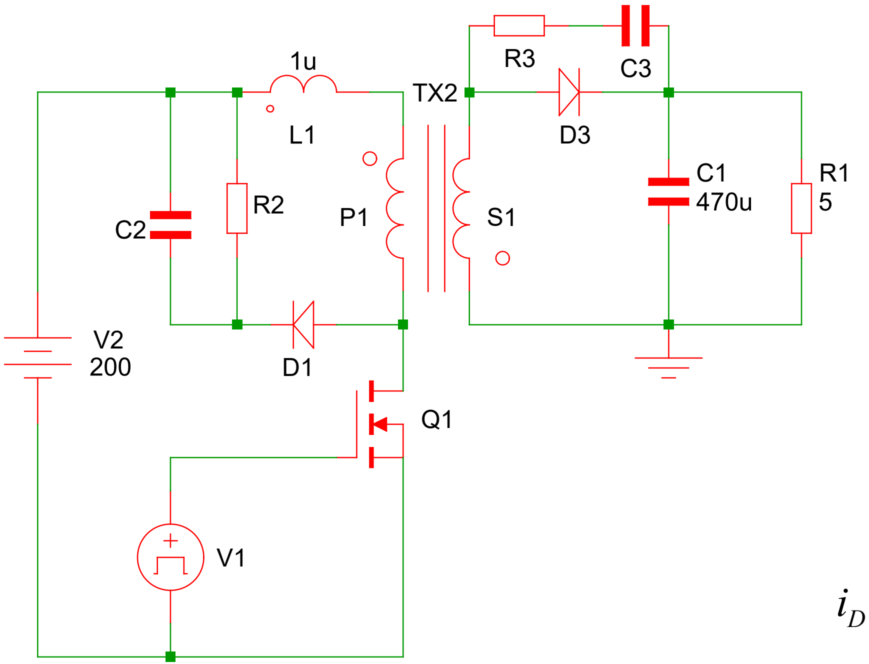


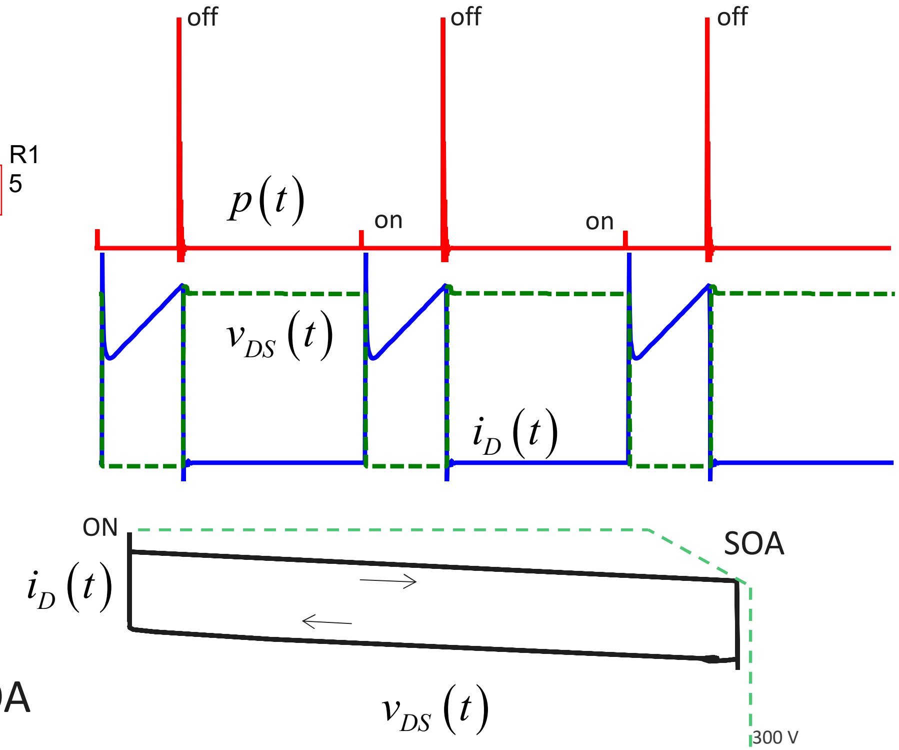


- Leakage inductance brings the v_{DS} outside of the safe operating area
- Switching losses scale up with frequency

Voltage Excursion must be Clamped

- Dampers and snubbers efficiently calm down oscillations

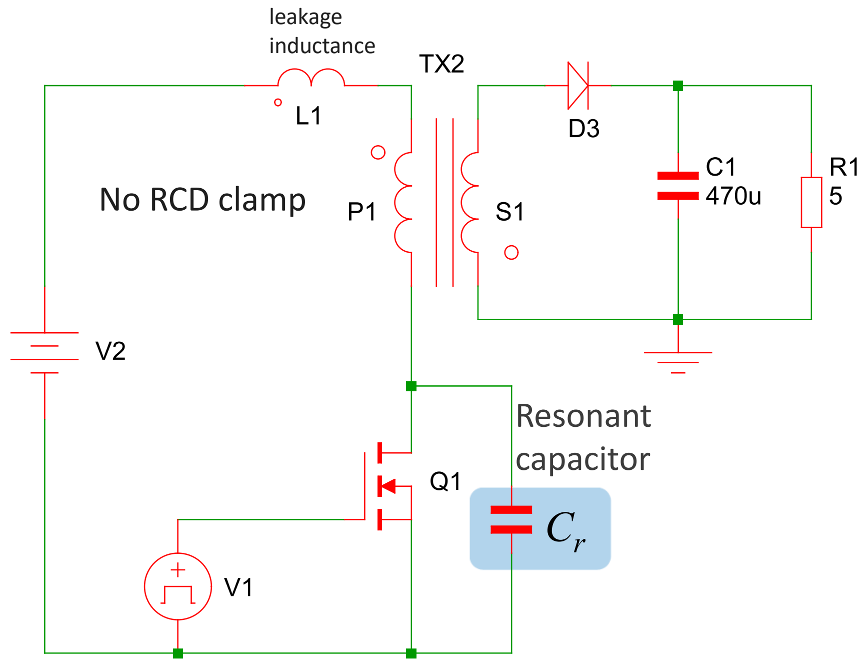


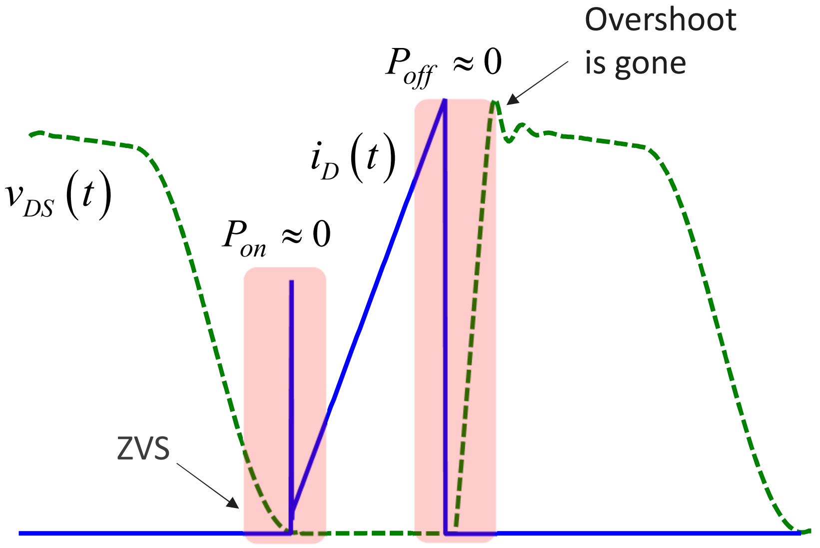


- The voltage excursion is back into the SOA
  - Power dissipation is still there with dampers

Resonant Waveforms Smooth Switching Events

- Quasi-resonance operation brings near-zero-voltage transition

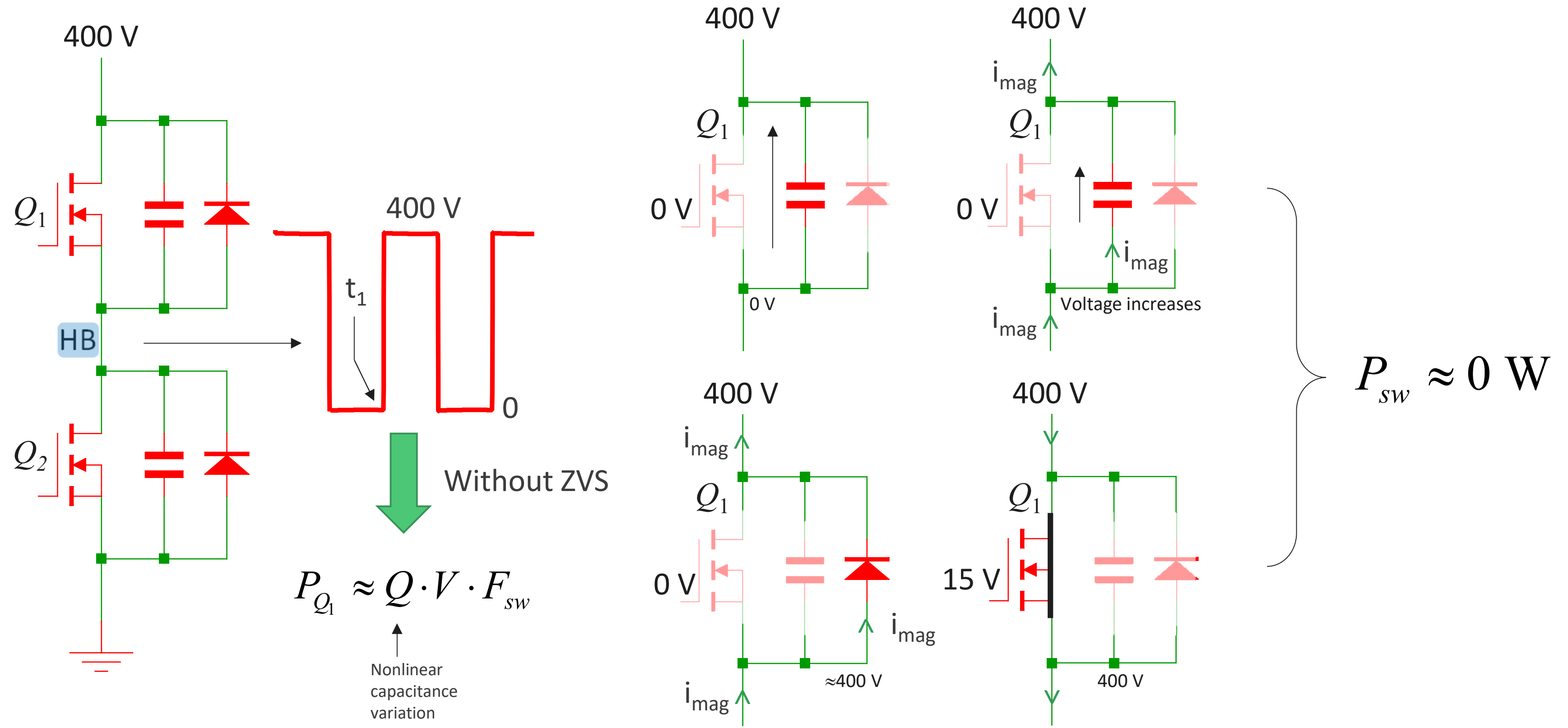




- Capacitor C_r ensures a slowly-rising $v_{DS}(t)$ at turn off
- ✓ The overlap I-V has disappeared, and turn-off loss is 0 W
- The oscillation involving L_m ensures C_r discharge to 0 V
- ✓ Zero-voltage switching cancels turn-on loss

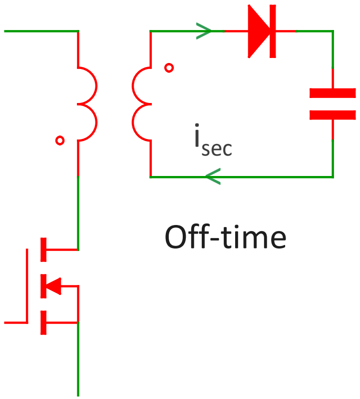
Soft Switching Definitions – ZVS

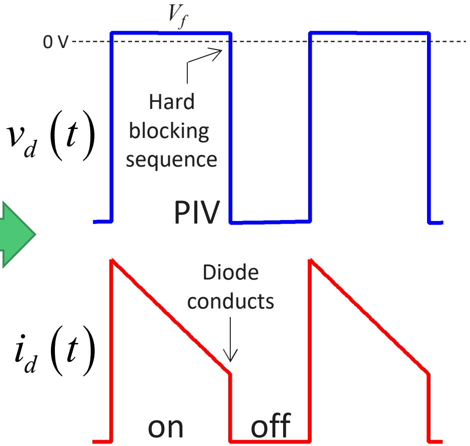
- Zero-voltage switching or ZVS implies a switch turned on with 0 V across its terminals

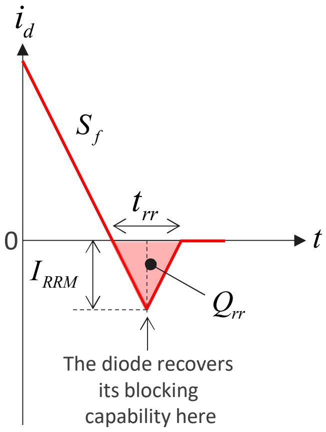


Soft Switching Definitions – ZCS

- Reverse recovery occurs when the diode is hard-blocked by a negative voltage

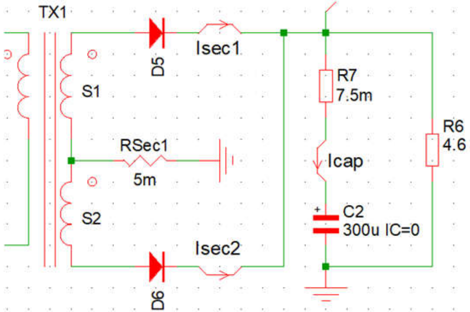


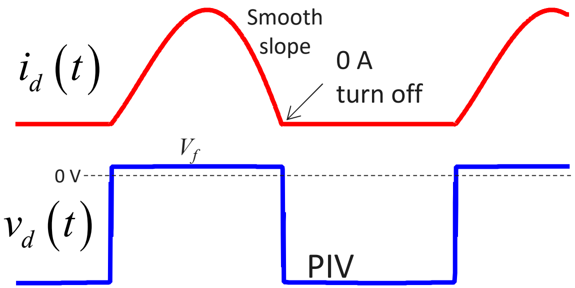




$$P_d = F_{sw} \cdot \mathrm{PIV} \cdot Q_{rr}$$

- Zero-current switching or ZCS implies a turn-off mechanism initiated at zero current





$$P_{sw} \approx 0 \text{ W}$$

PIV: peak inverse voltage

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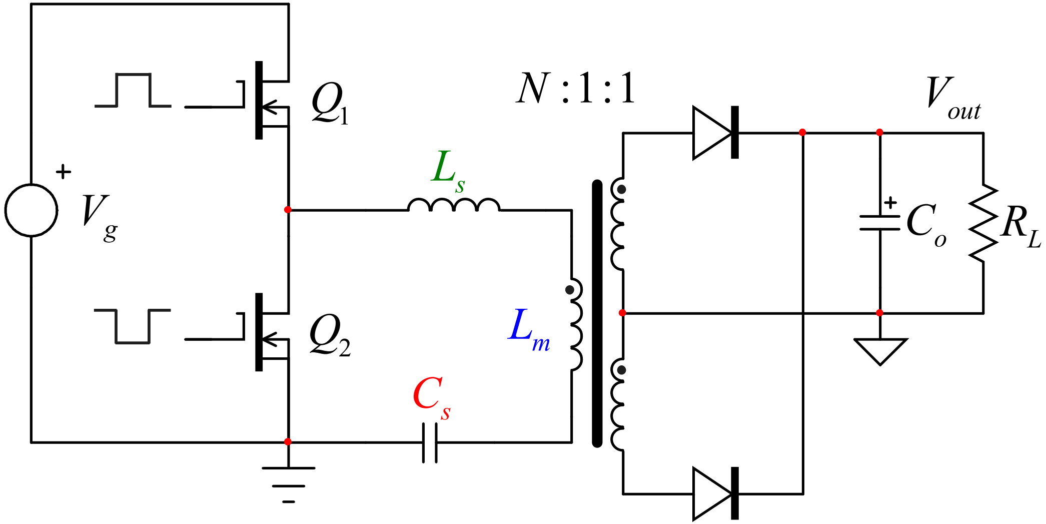
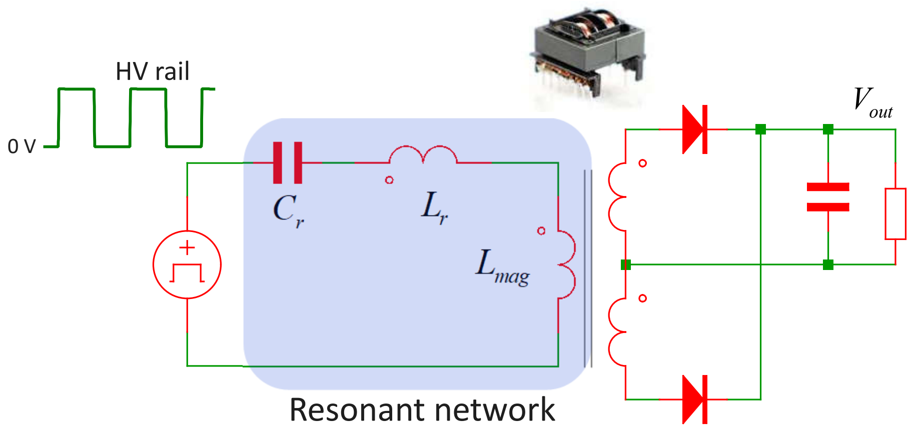
What is an LLC Converter?

- The LLC converter is a member of the series-resonant converters family
  - The magnetizing inductance L_m is part of the resonating elements (L)
  - The transformer leakage inductance or an extra inductor forms the term L_s (L)
  - A series capacitor C_s is inserted to form the complete resonant converter (C)



The Benefits of the LLC Converter

- The LLC converter offers soft-switching conditions in normal-load conditions
- ✓ Zero-voltage switching (ZVS) for the switches in the primary side
- ✓ Zero-current switching (ZCS) for the secondary-side diodes
- It can operate at high switching frequency to build compact converters
- ✓ Perfect for flat-panel displays like LCD TVs, game stations, servers power supplies

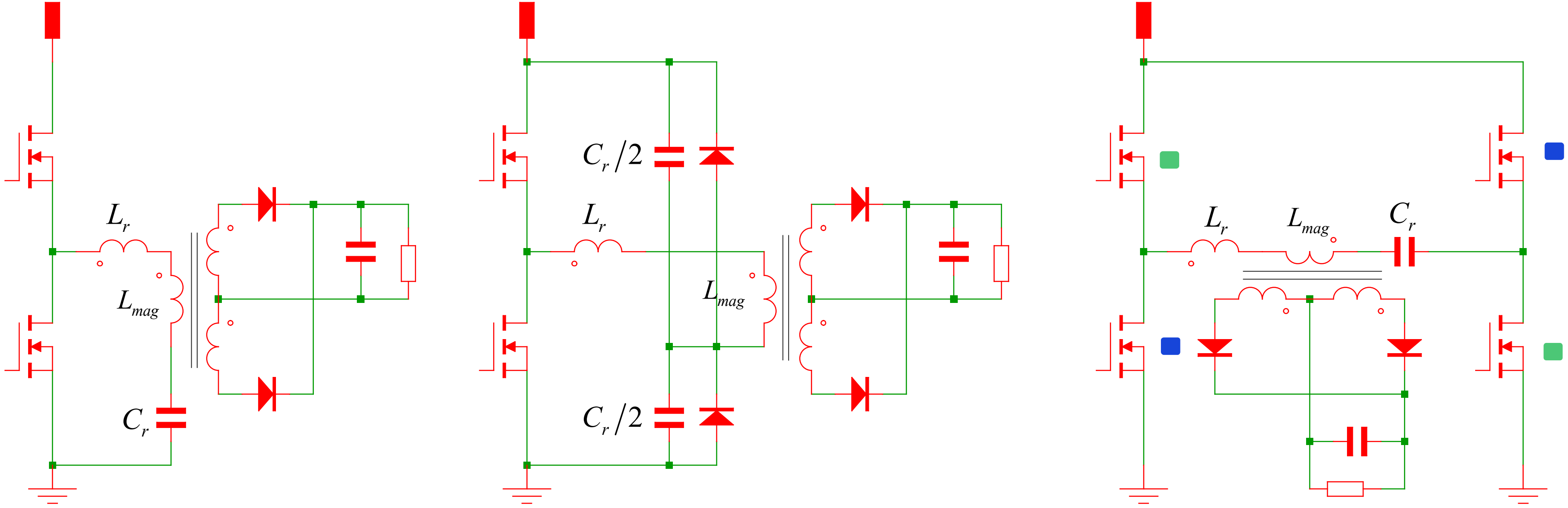


✓ Three energy-storing elements, C_r, L_r and the transformer magnetizing inductance L_{mag}

✓ Components count is limited especially if integrated magnetics is adopted

Different Configurations for the LLC - Primary

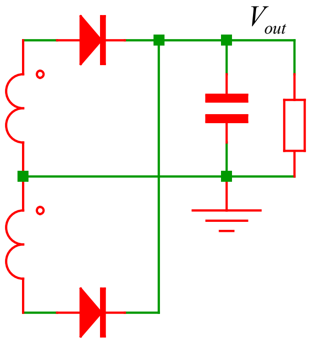
- The LLC converter can be operated in half- or full-bridge configuration



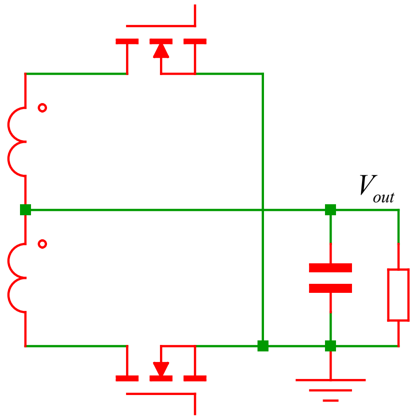
- Power up to 600 W
- Robust version with clamp diodes
  - ✓ Lower input ripple current
  - ✓ Half rms current in a capacitor
- Power beyond 1 kW
  - ✓ Diagonal conduction

Different Configurations for the LLC - Secondary

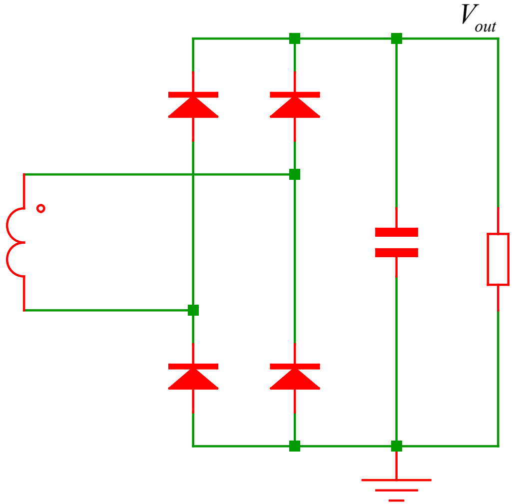
- A full-bridge rectifier requires diodes with a lower breakdown voltage



- Two separate windings
- BV > $2V_{out}$
- Secondary leakage brings current imbalance



- Synchronous rectification



- One single winding
- BV > V_{out}
- No current imbalance

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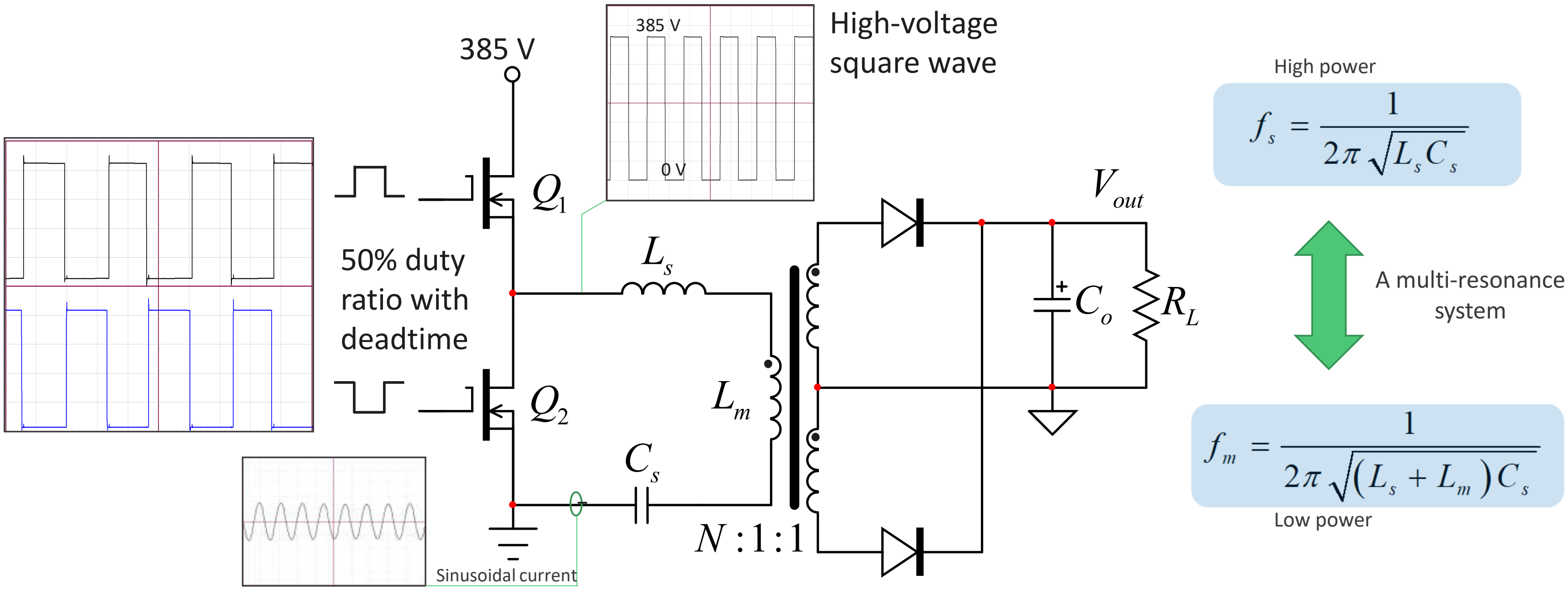
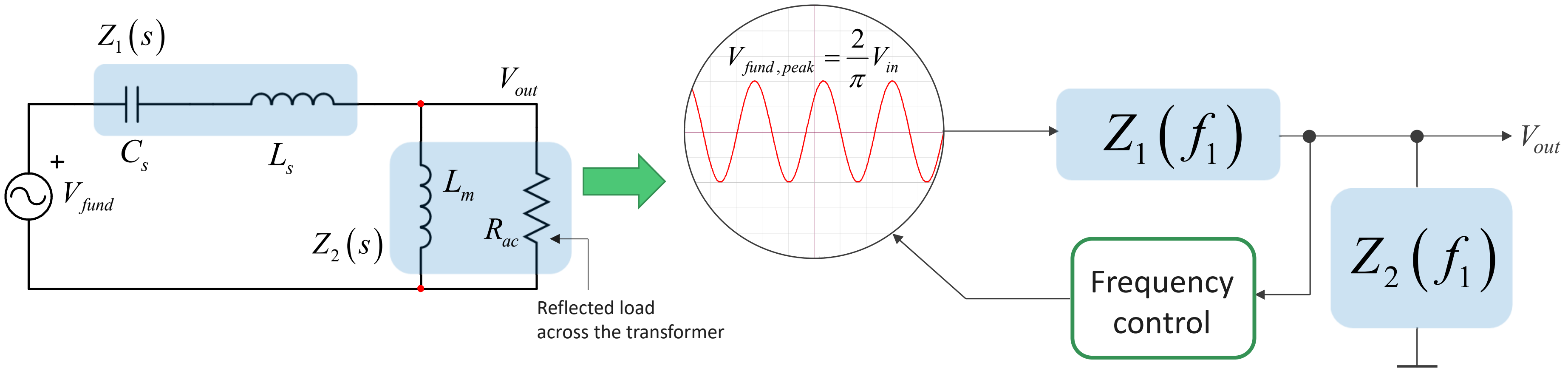
Voltage-Mode Control

- An LLC converter is typically operated from a 50% high-voltage square waveform
  - The power flow is then adjusted by varying the switching frequency
  - Soft-switching on MOSFETs and diodes depends on frequency with respect to f_s



The Resonance varies with the Output Power

- The LLC converter is a multi-resonance converter depending on operating conditions
  - In heavy-load condition, L_s dominates the resonant tank as L_m is shunted by R_{ac}
  - In lighter-load operations, L_m and L_s together set the resonant frequency



- The converter is modeled using the first harmonic approximation or FHA

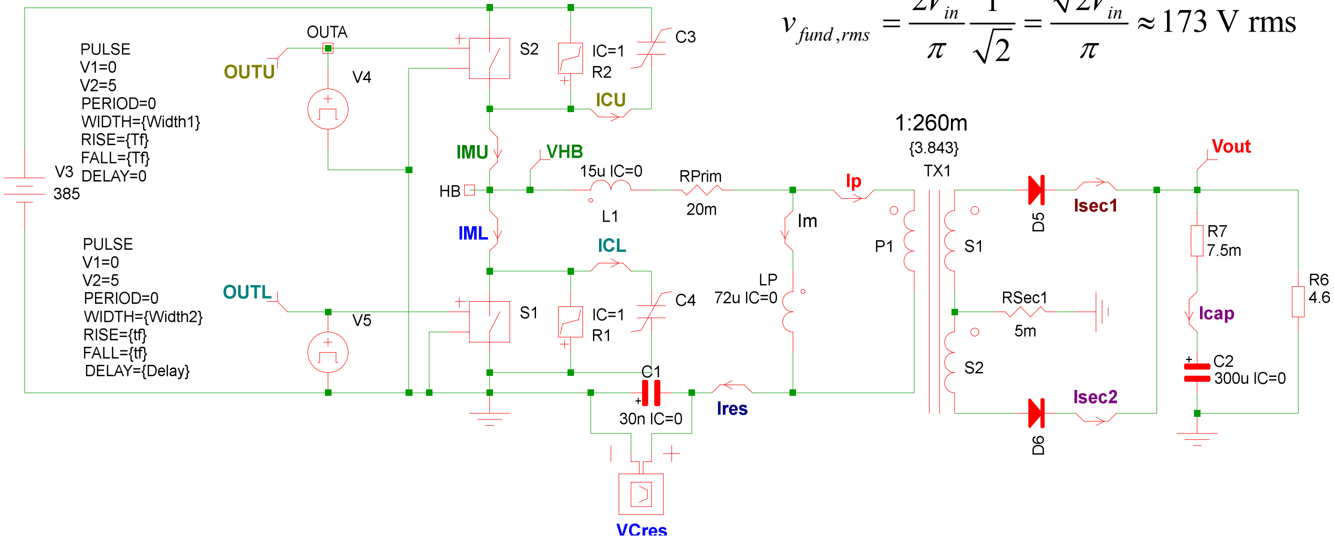
Output Voltage of an LLC Converter

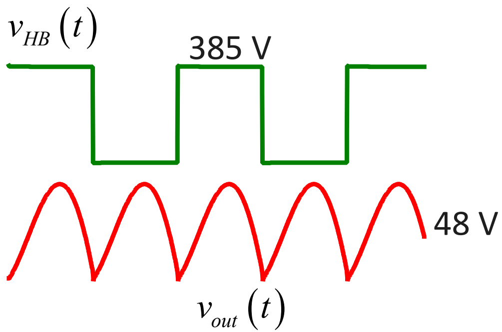
- The equivalent network is fed by the square-wave fundamental value according to FHA
- ✓ Determine the output voltage with the transfer function of the 3rd-order network

$$H_{m1}(s) := \frac{1}{N_{ps}} \cdot \frac{\frac{L_3}{L_2} \cdot \left(\frac{s}{\omega_s}\right)^2}{1 + s \cdot \frac{L_3}{R_1} + \left(\frac{s}{\omega_m}\right)^2 + s^3 \cdot \frac{L_3}{L_2 \cdot Q_1 \cdot \omega_s^{\ 3}}}$$

$$V_{out} := V_{fund} \cdot \left| H_{ref}(i \cdot 2\pi \cdot F_{sw}) \right| = 45.19774V$$

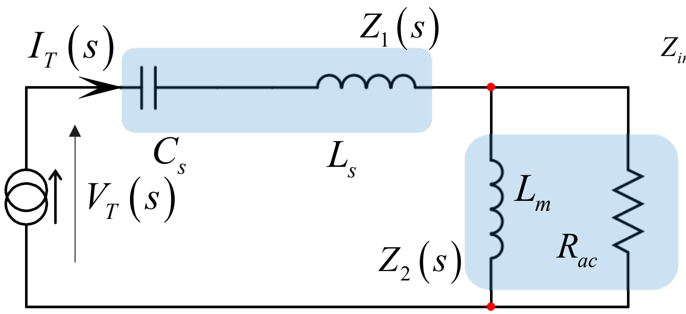
$$v_{fund,rms} = \frac{2V_{in}}{\pi} \frac{1}{\sqrt{2}} = \frac{\sqrt{2}V_{in}}{\pi} \approx 173 \text{ V rms}$$



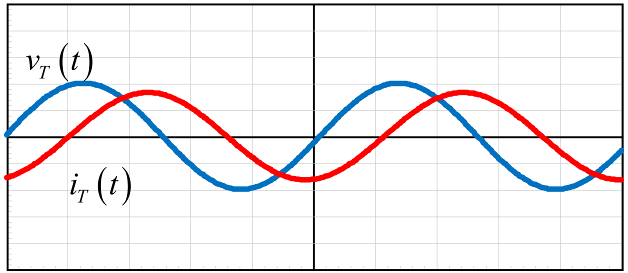


A Complex Input Impedance

- The impedance offered by the network to the half-bridge shows two main zones:
  - A capacitive region: $F_T < F_{\min}$
  - An inductive region: $F_T > F_{\min}$

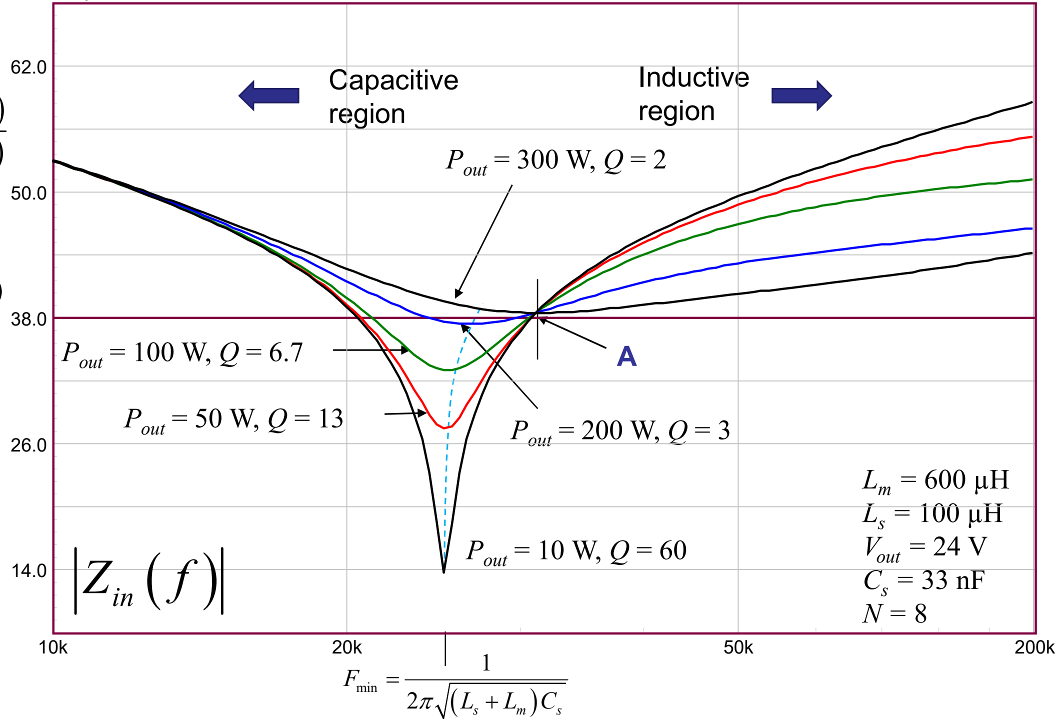


$$Z_{in}(s) = \frac{V_T(s)}{I_T(s)}$$



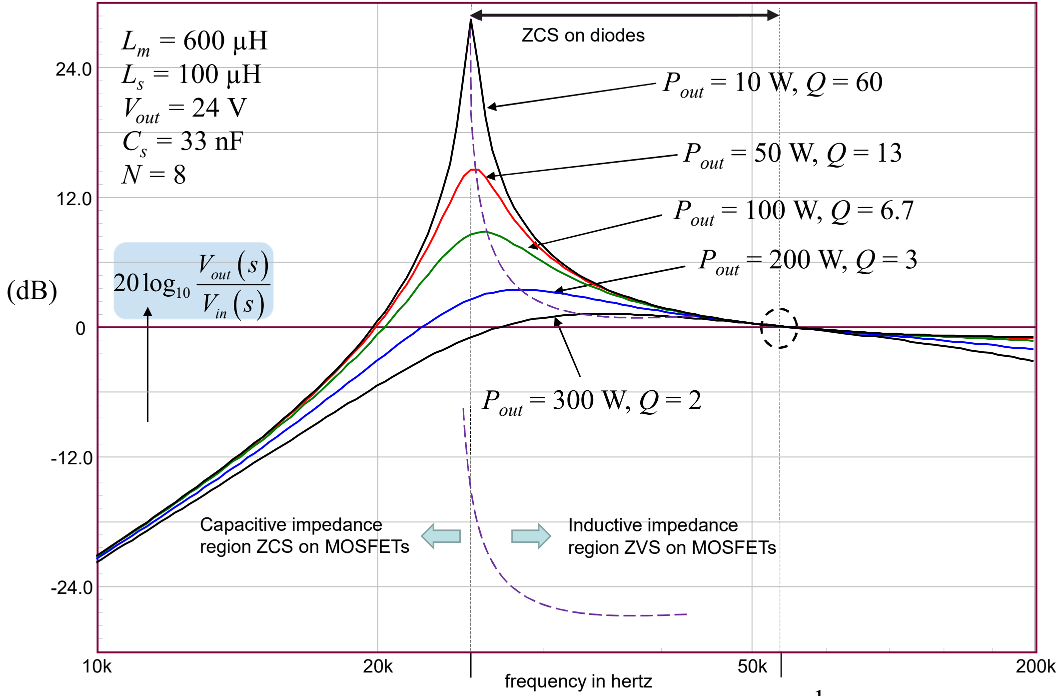
Voltage and current in the inductive region

Impedance of the series resonant network



Where to Operate the Converter?

- Plotting the dc transfer characteristic of the LLC network reveals several points

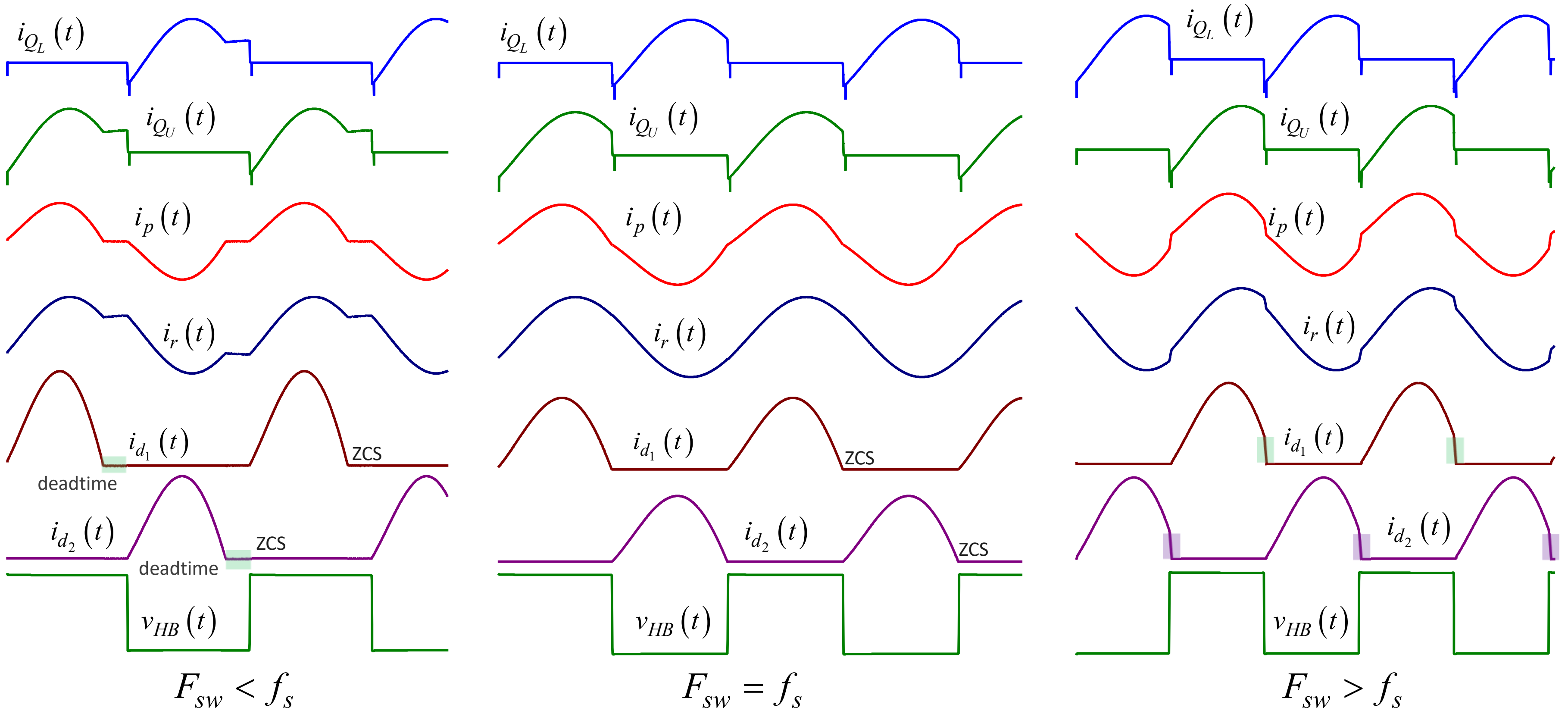


$$F_{min} = \frac{1}{2\pi\sqrt{(L_s + L_m)C_s}} \qquad F_o = \frac{1}{2\pi\sqrt{L_s C_s}}$$

- ✓ As load current decreases, L_m enters the picture and brings a second peak
- ✓ An impedance plot shows so-called ***capacitive*** and ***inductive*** regions
- ✓ The inductive region brings ZVS on power MOSFETs and ZCS on output diodes
- ✓ ZCS on MOSFETs is occurring in the capacitive region but the control law changes!

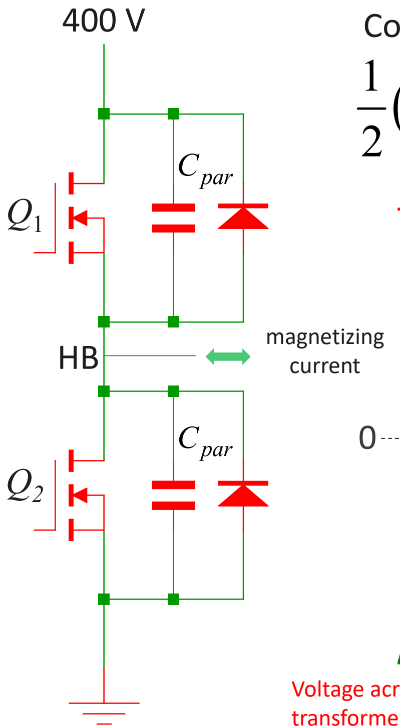
Observing Waveforms tells us the Operating Region

- Resonating current i_r is a perfect sinewave when LLC operates at resonant frequency



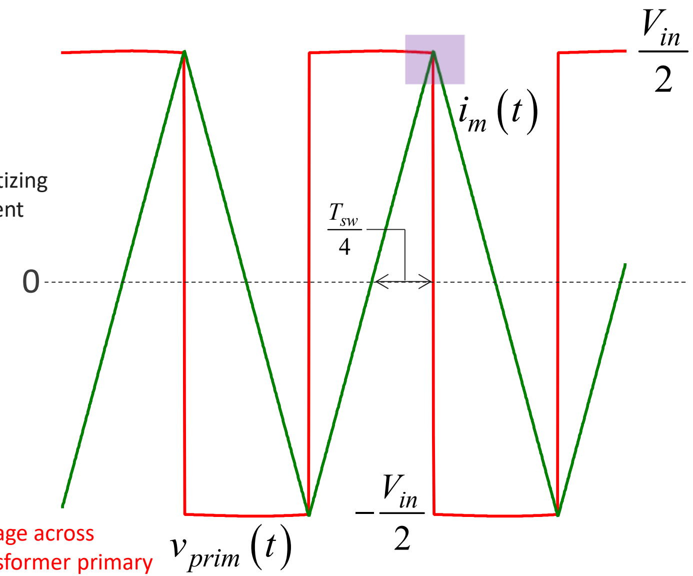
Ensuring Zero-Voltage Switching

- The deadtime duration must be sufficiently long to discharge parasitics
- ✓ Select primary inductance so that magnetizing current ensures ZVS at the highest F_{sw}



Condition for ZVS:

$$\frac{1}{2}\left(L_m + L_r\right)I_{m,peak}^2 \geq \frac{1}{2}\left(2C_{par}\right)V_{in}^2$$



$$t_{DT} = \frac{V_{in} \cdot 2C_{par}}{I_m}$$

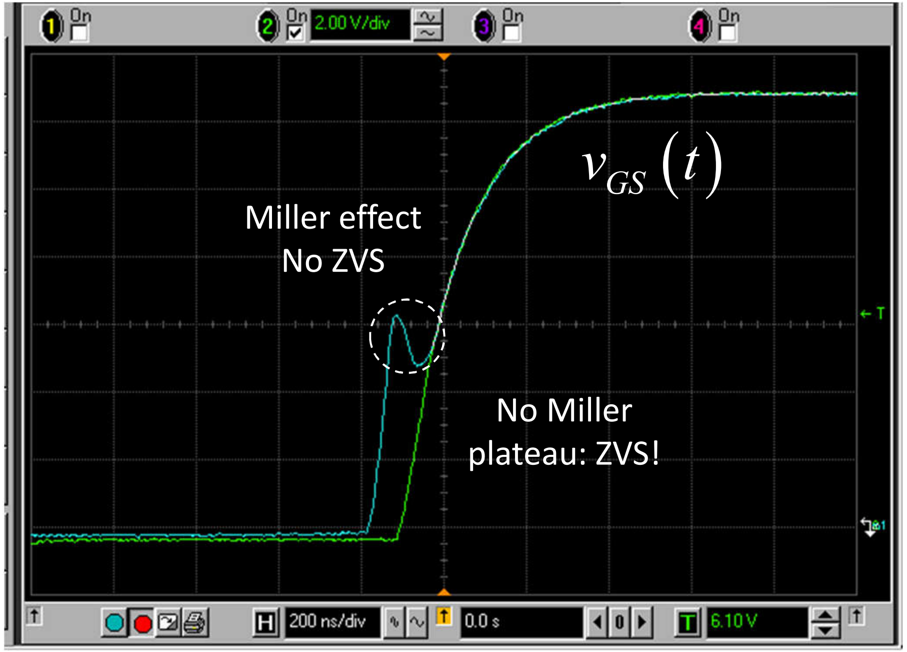
$$I_m \approx \frac{V_{in}}{2L_m}\frac{1}{4F_{sw}}$$

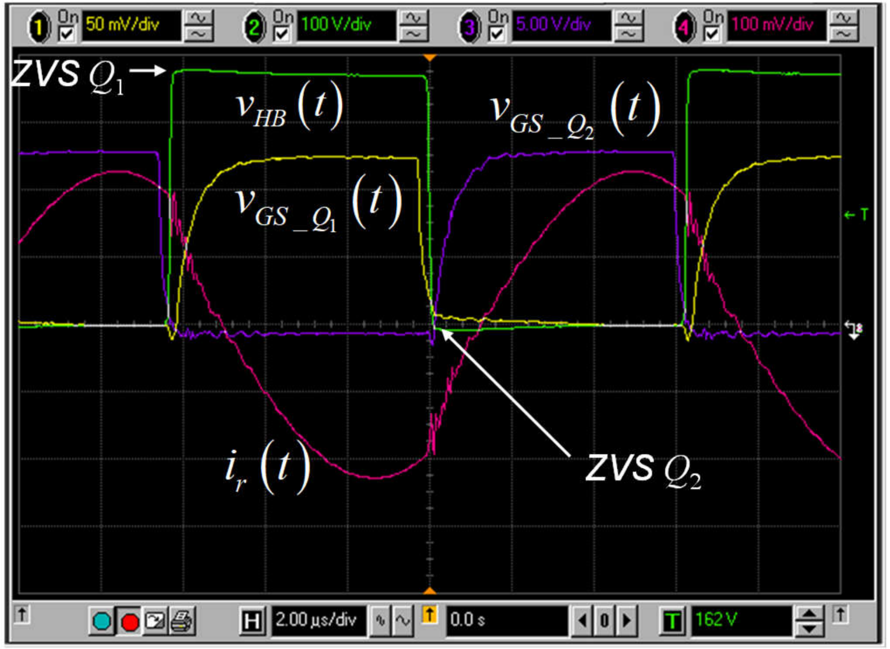
$$t_{DT} = V_{in} \cdot 2C_{par} \cdot \frac{8L_m F_{sw}}{V_{in}}$$

$$t_{DT} \geq 16 \cdot C_{par} L_m F_{sw}$$

The Right DeadTime for ZVS Conditions

- Calibrate deadtime to minimize body diode conduction time whilst ensuring ZVS

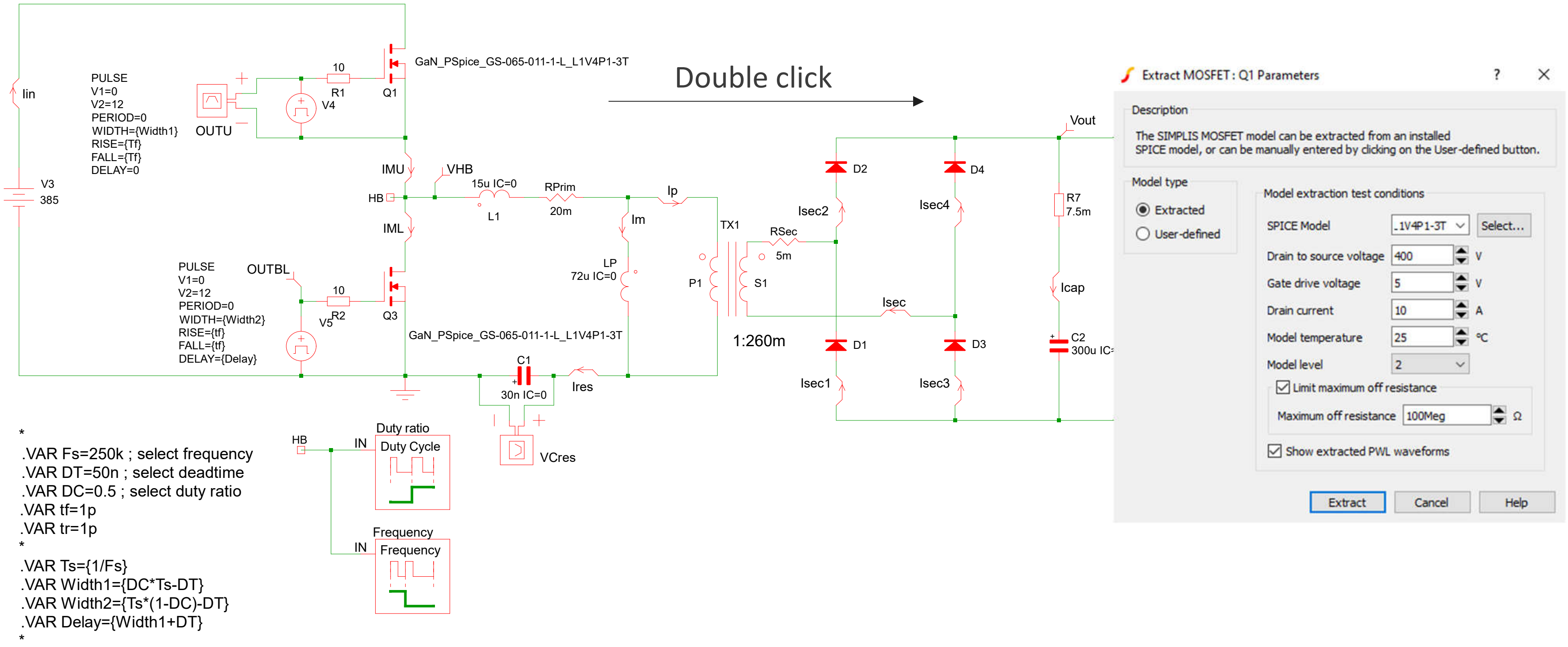




ZVS gets rid of the Miller plateau and further minimizes drive losses

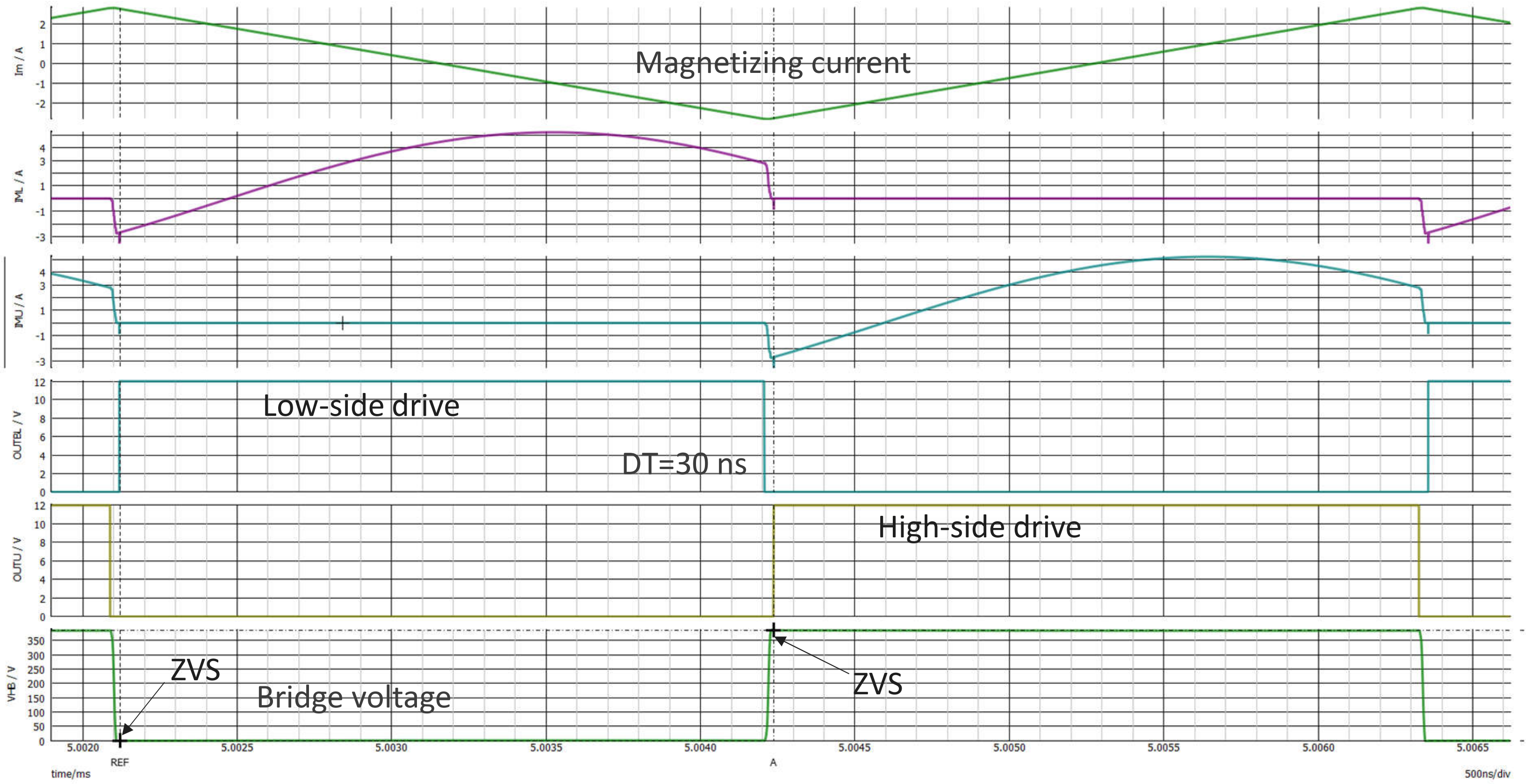
SIMPLIS can simulate GaN Transistors

- Adding GaN transistors to the schematic capture is an easy process



Simulation confirms ZVS with a Reduced Dead Time

- A smaller C_{oss} for the GaN leads to a lower magnetizing current for improved efficiency



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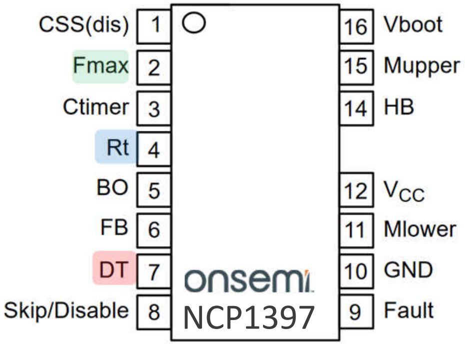
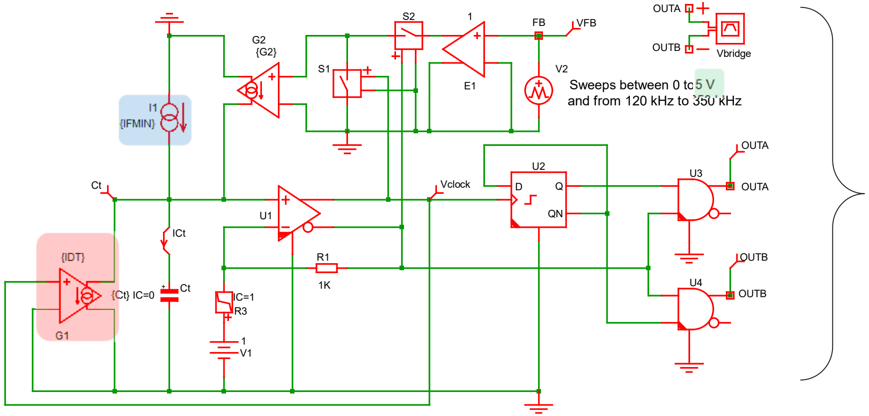
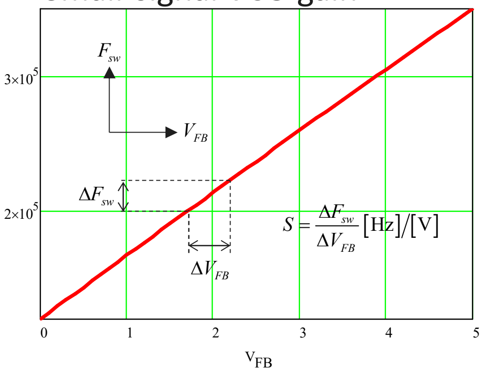
Controlling the LLC Converter

- We have seen that changing the switching frequency affects the output power
  - If a regulation loop drives a voltage-controlled oscillator (VCO), output power is adjusted
  - The frequency varies from a min value (high power) to a maximum high value (light load)





Small-signal VCO gain



- A dead time is set to avoid shoot-through currents but also ensures ZVS operation

Transfer Function in Voltage-Mode Control

- There is no averaged model for the LLC because energy is transported by fundamental

➢ The control-to-output transfer function complicates proper compensation:

✓ The transfer function is a 3-pole system for $F_{sw} \neq F_o$ – dominant LF pole, one pole pair

✓ The transfer function becomes a 2-pole system when $F_{sw} \approx F_o$

$$H(s) \approx K_{vf} \frac{1+\frac{s}{\omega_z}}{\left[1+\frac{s}{Q\omega_o}+\left(\frac{s}{\omega_o}\right)^2\right]\left(1+\frac{s}{\omega_p}\right)}$$

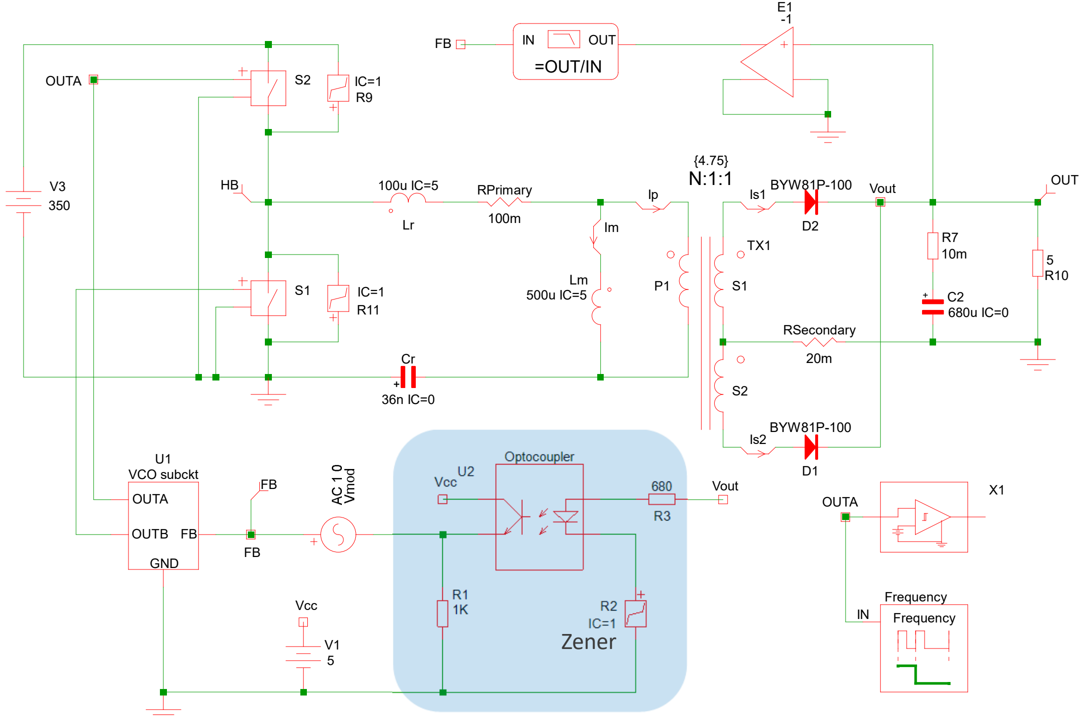
- K_{vf} is a gain proportional to slope at the considered operating point on the voltage curve
- The quality factor Q and the double-pole beat frequency vary with operating conditions
- The low-frequency pole ω_p is linked to the output capacitance and also moves with operating conditions
- The output capacitor and its ESR contribute the zero ω_z

➡ Compensating the LLC operated in voltage-mode is not a dinner party!

J. Jang et al., *Dynamic Analysis and Control Design of Optocoupler-Isolated LLC Series Resonant Converters with Wide Input and Load Variations*, 2009 IEEE Energy Conversion Congress and Exposition

Simulating the LLC Converter

- A program like SIMPLIS lends itself perfectly for assessing the ac response of the LLC



Bias point setting

- A very simple setup is sufficient to obtain the transfer function
- The operating point is automatically set depending on V_{in} and P_{out}
- Frequency is recorded to see where the LLC stands at a given operating point.

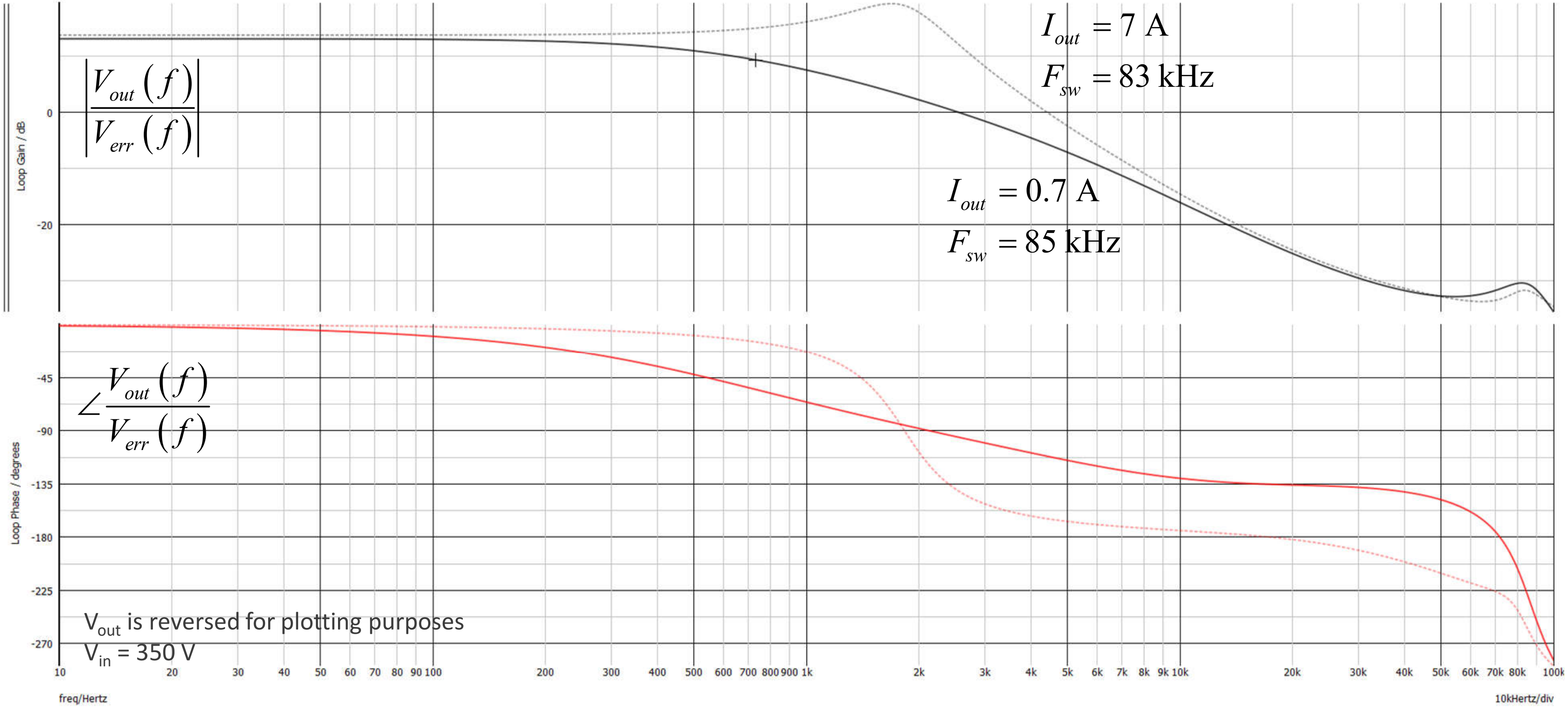
$L_r := 100\mu H \qquad L_m := 500\mu H \qquad C_r := 36nF$

$$f_o := \frac{1}{2\cdot\pi\cdot\sqrt{L_r\cdot C_r}} = 83.882kHz$$

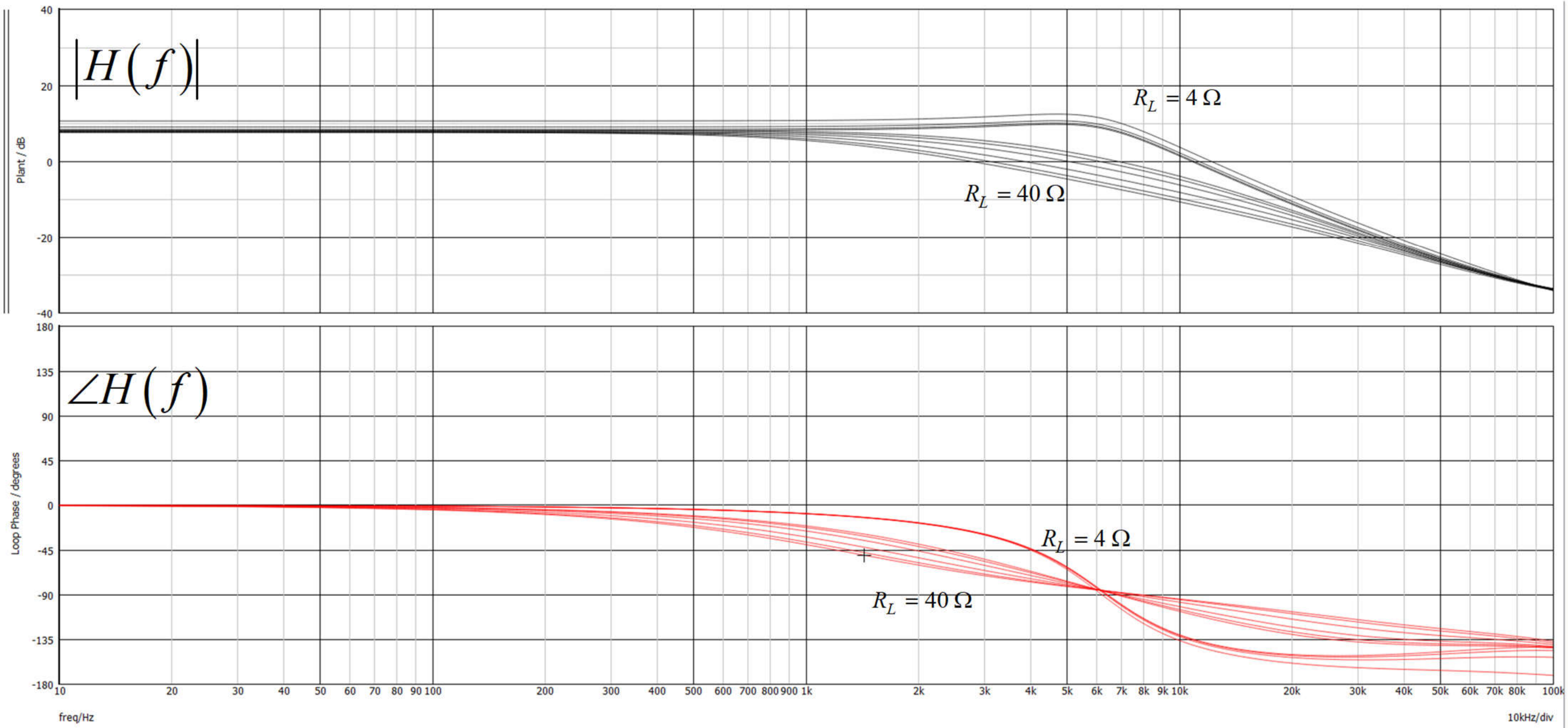
$$f_{o2} := \frac{1}{2\cdot\pi\cdot\sqrt{(L_r + L_m)\cdot C_r}} = 34.245kHz$$

Various Small-Signal Responses

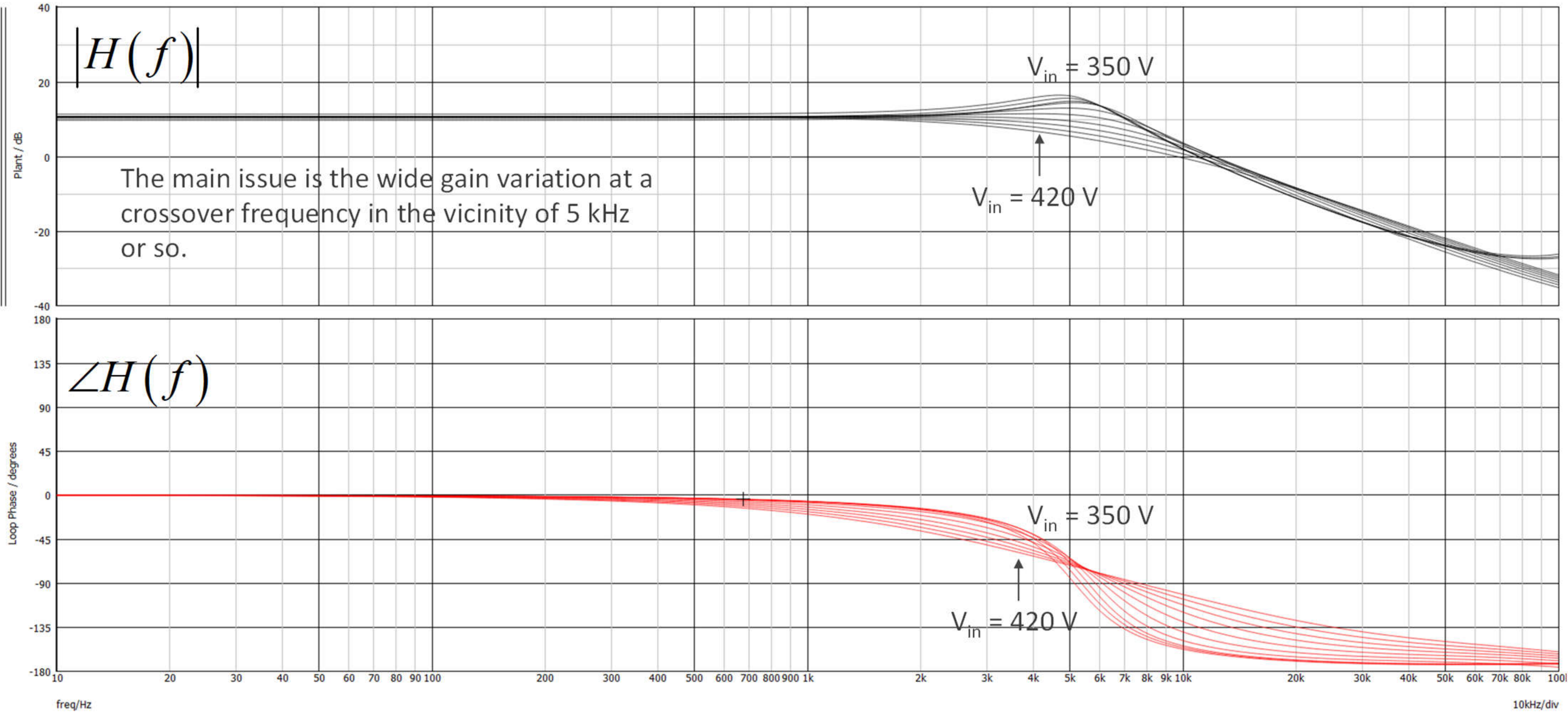
- At a 350-V input voltage with two different loads, the shape changes considerably



Control-to-Output Transfer Function – Variable Load



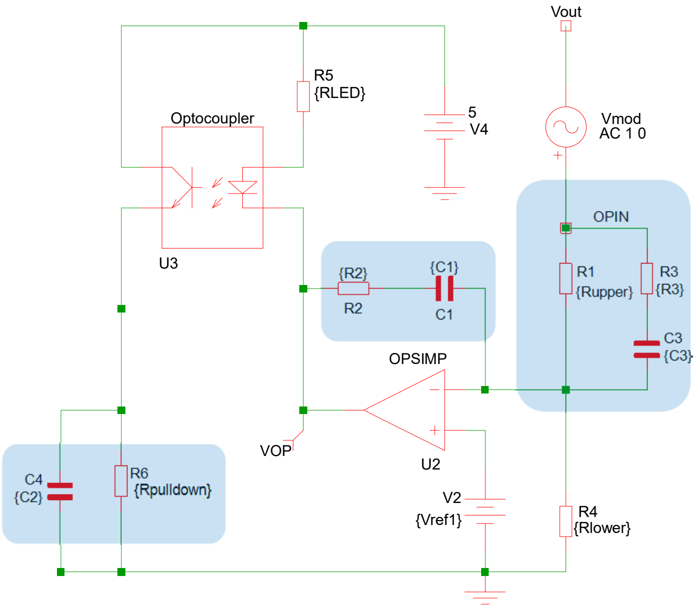
Control-to-Output Transfer Function – Variable Input



The main issue is the wide gain variation at a crossover frequency in the vicinity of 5 kHz or so.

A Type 3 for Compensation

- Considering the deep phase lag, a type 3 compensator is needed
- The resonant peak occurs below 2 kHz implying a crossover at 4-5 kHz



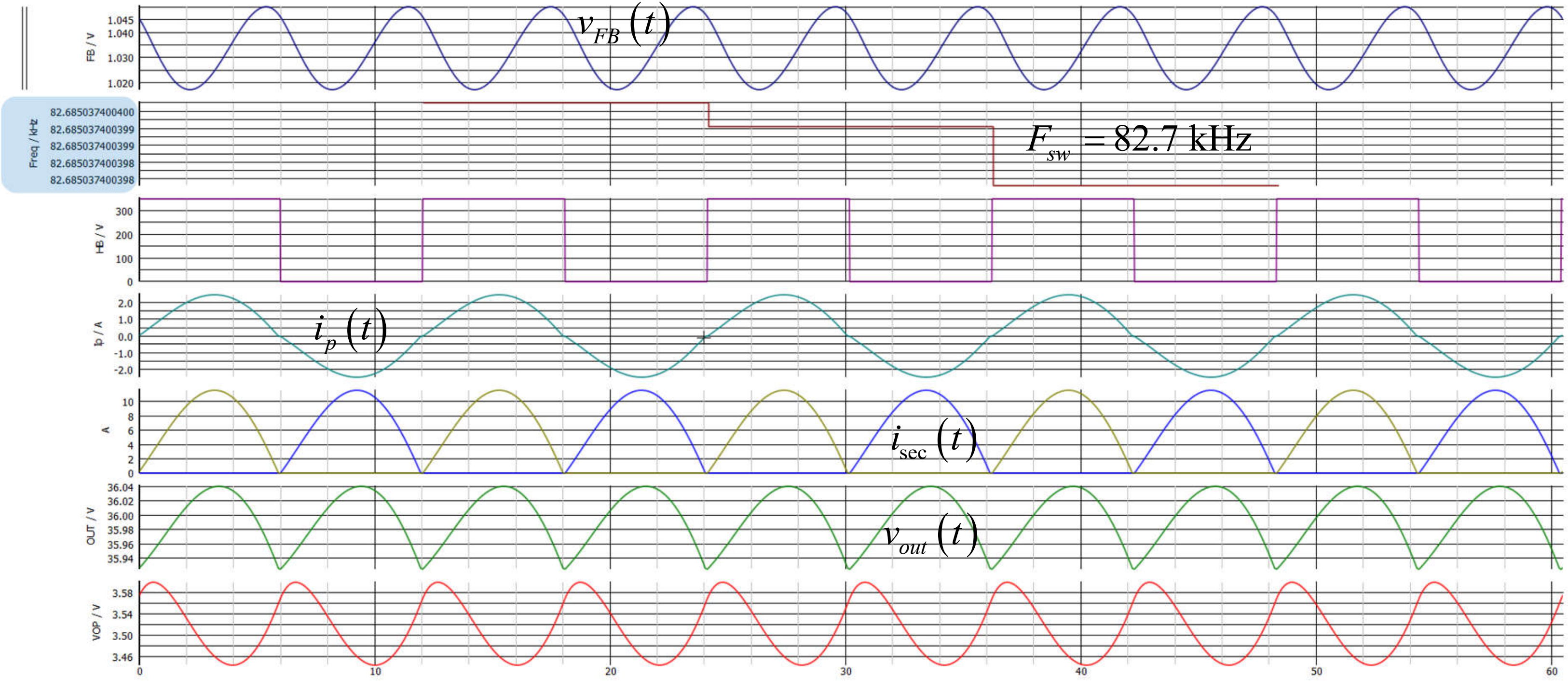
In the netlist

```
*
* Rupper = 9500
* Rlower = 2500
* R2 = 650.530552995995
* R3 = 174.134419551935
* C1 = 4.07756772168279e-07
* C2 = 3.15387865941603e-08
* C3 = 1.82795501890341e-08
* Boost = 110
* Fz1 = 600
* Fz2 = 900
* Fp1 = 8357.24400717011
* Fp2 = 50000
*
```

- SIMPLIS automates the poles-zeroes positions and components values

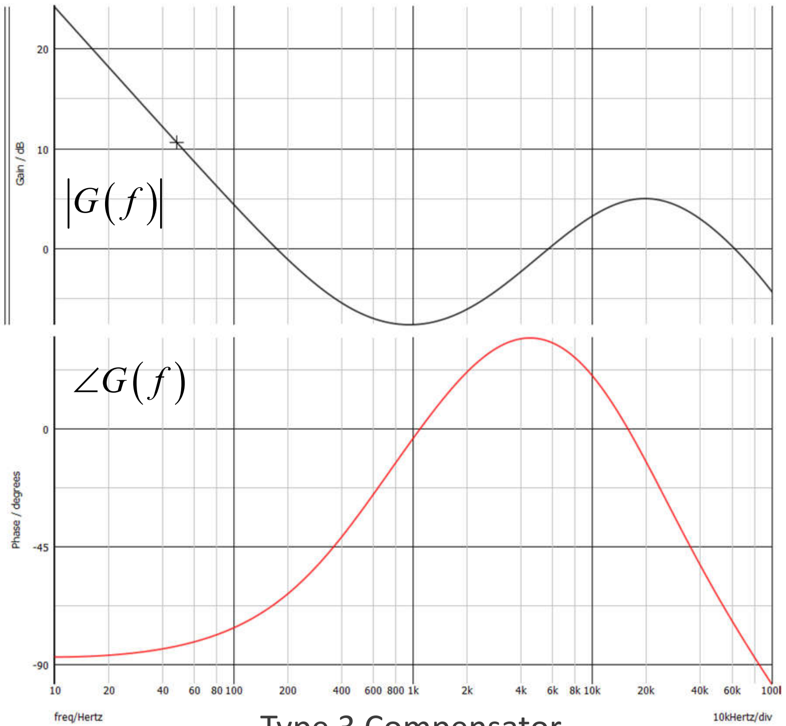
Always Check the Operating Point!

- The operating point will tell you if the converter regulates correctly
- It is important to check this point otherwise the ac analysis can be useless

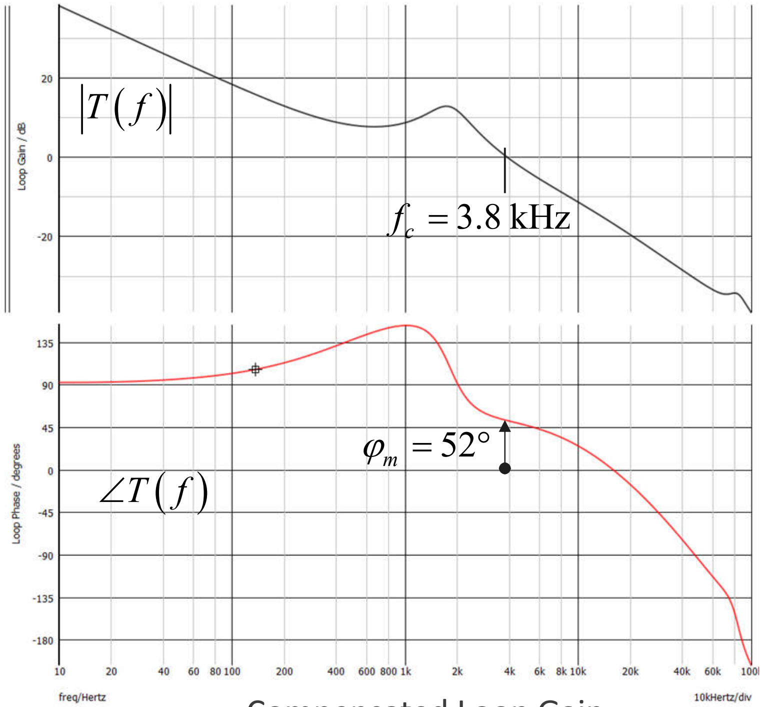


Good Compensation at a 350-V Input Voltage

- The simulation reveals a good loop gain meeting the wanted crossover and phase margin



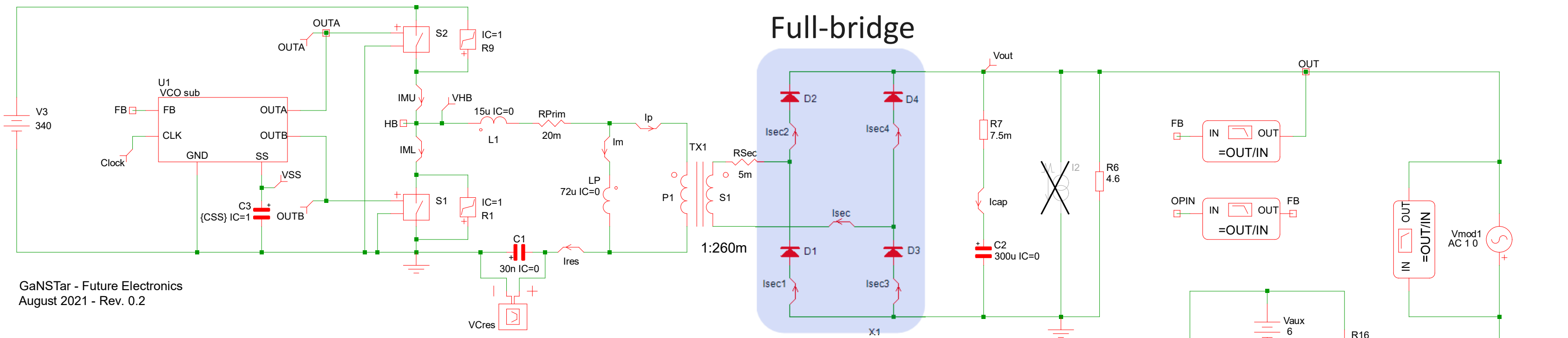
Type 3 Compensator

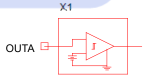


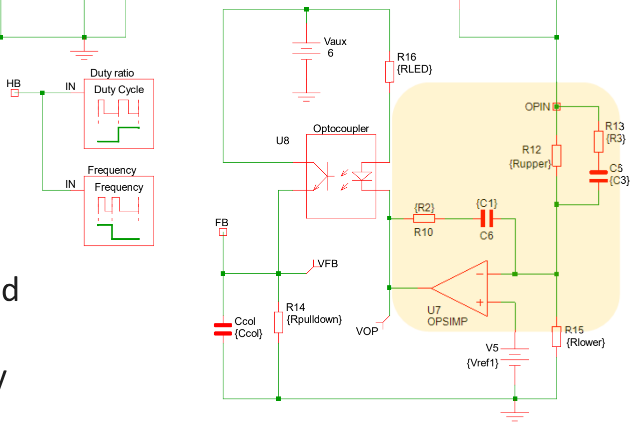
Compensated Loop Gain

Simulating the Entire Converter

- The simulation reveals a good loop gain meeting the wanted crossover and phase margin







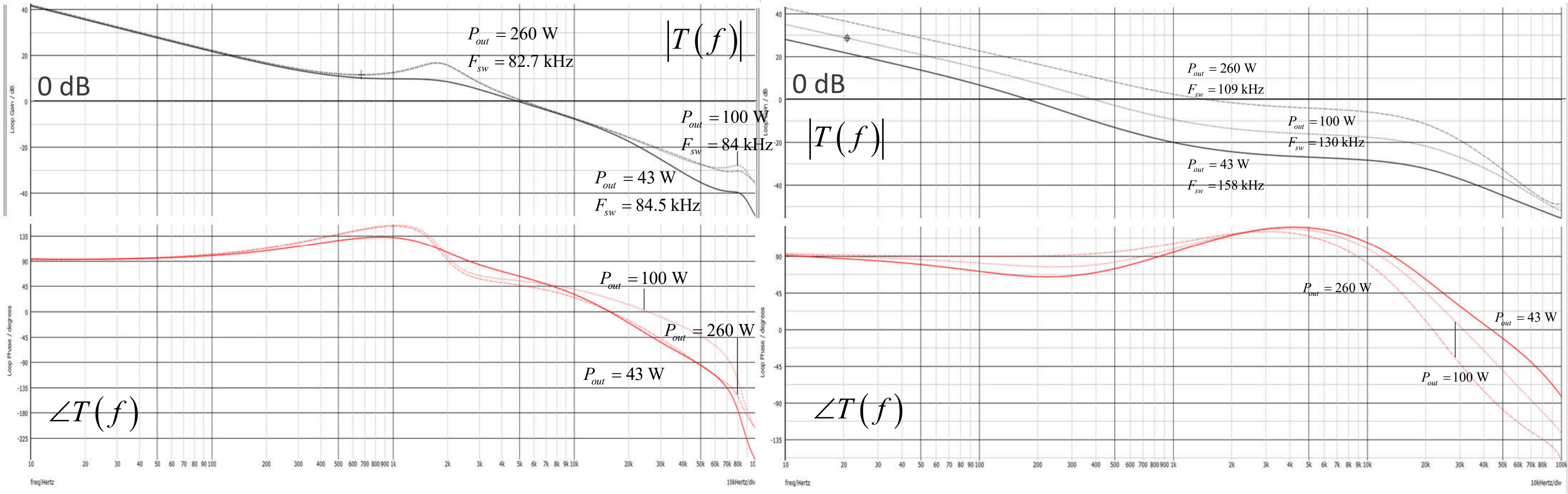

```
*
 .GLOBALVAR Fsw=380k * the LLC network will see half this min freq. value for VFB = 0 *
 .GLOBALVAR DT=50n * this is clock pulse width for DT generation *
.GLOBALVAR Ct=10p
 .GLOBALVAR Vswing=2.01 * Timing capacitor final swing *
 .GLOBALVAR IFMIN=Ct*Vswing/((1/Fsw)-DT) * charging current when VFB = 0 V *
 .GLOBALVAR IDT=-(IFMIN-Ct*Vswing/DT)/5
.GLOBALVAR CSS=22n
*
```

- All the compensation parameters are automatically calculated

✓ Easy to change strategy and see the effects

Large Variations of Loop Gain

- Changing operating conditions affect crossover and phase margin

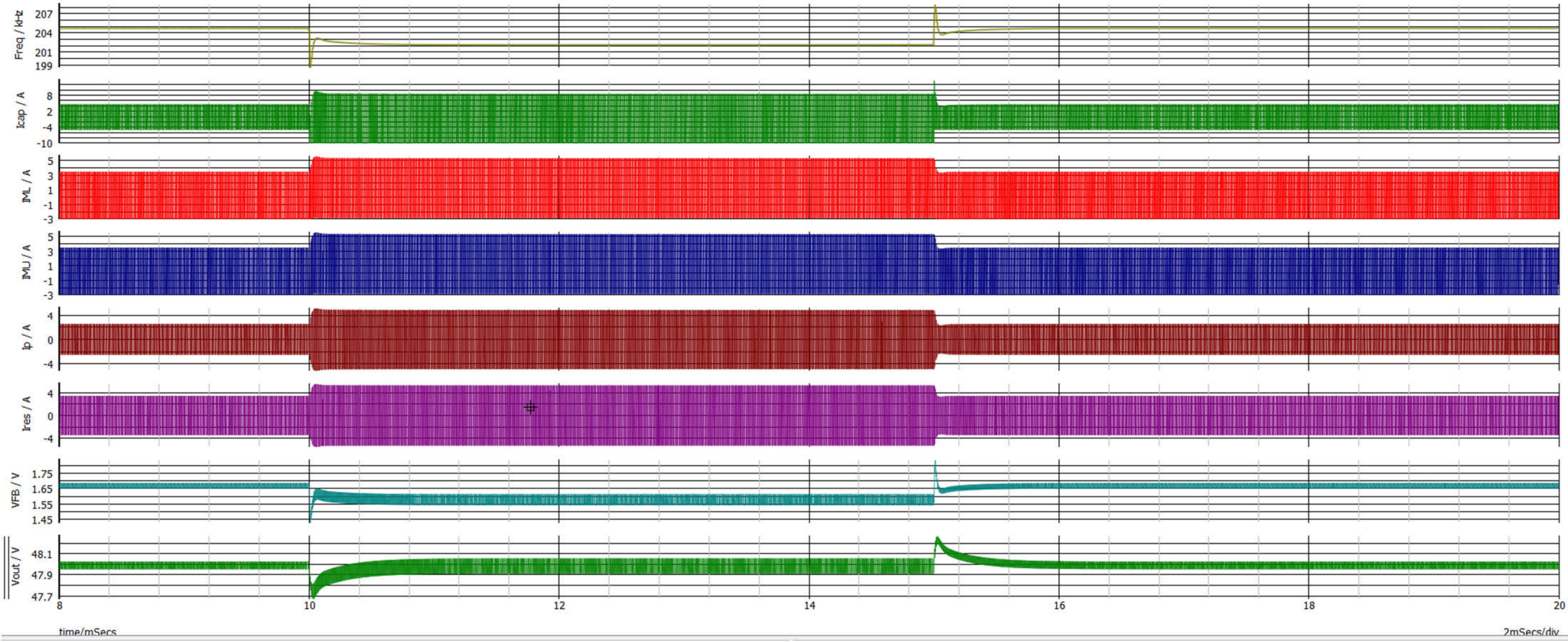


Low-line operations, V_{in} = 350 V dc

High-line operations, V_{in} = 420 V dc

- At low line, frequency variations are moderate, operations close to resonance
- At high line, frequency variations are large, operations above resonance

Closed-Loop Operation with Analogue Compensation



Transient response at V_{in} = 340 V and P_{out} stepped from 240 W to 480 W with a 1-A/µs slope

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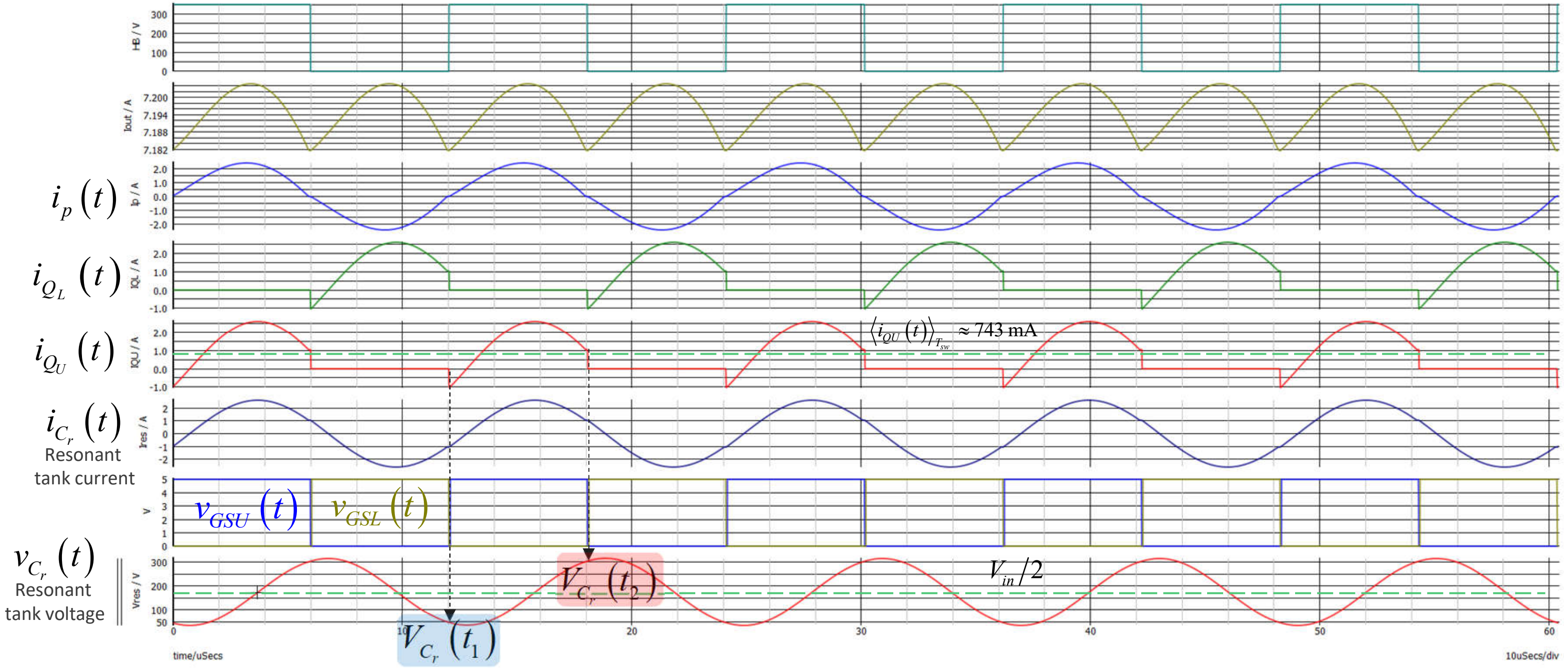
Charge Control Operations

- The voltage across the resonant capacitor is the integral of the resonant tank current



$$Q_{net} = Q_{neg} + Q_{pos}$$

$$Q_{net} = C_s\left[V_{C_r}(t_1) - V_{C_r}(t_2)\right]$$

$$P_{in} = Q_{net} F_{sw} V_{in}$$

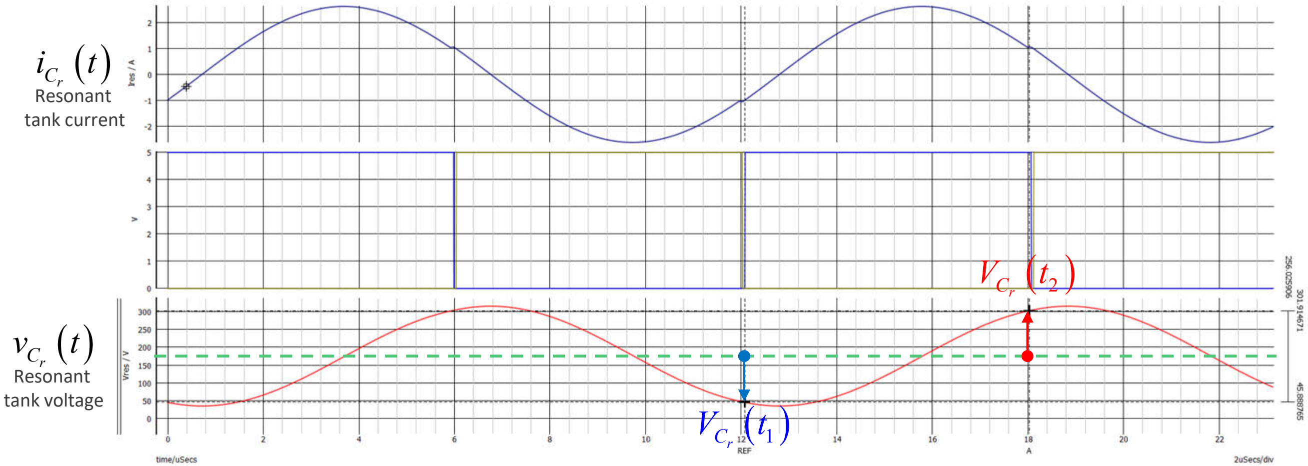
➢ The net electric quantity can be calculated from the capacitor voltage at t_1 and t_2

✓ $P_{in} = 36n \times (302 - 46) \times 83k \times 350 \approx 268$ W

Z. Hu et al., *Bang-Bang Charge Control for LLC Resonant Converters*, IEEE Transactions on Power Electronics, 2015, Vol. 30, Issue 2

Adjusting the Output Power

- In a half-bridge topology, the average voltage across the resonating capacitor is $\frac{V_{in}}{2}$
  - Owing to symmetry of the waveform, we can define the two voltages



$$\frac{V_{in}}{2} - V_{C_r}(t_1) = V_{C_r}(t_2) - \frac{V_{in}}{2}$$

$$V_{C_r}(t_1) + V_{C_r}(t_2) = V_{in}$$

- The feedback loop can set the peak voltage and deduce the valley voltage

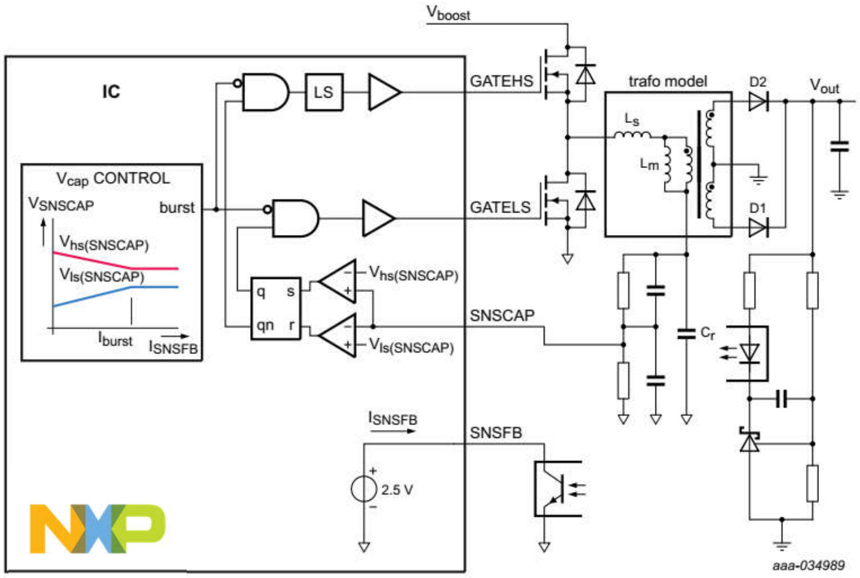
$$V_{C_r}(t_1) = k_{sen} V_{in} - V_{C_r}(t_2)$$

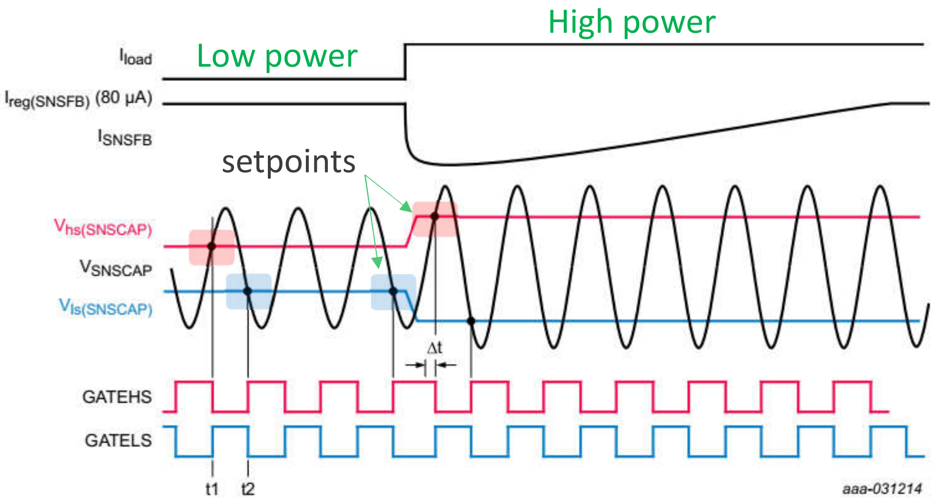
valley — $V_{C_r}(t_1)$; peak — $V_{C_r}(t_2)$

Practical Implementation with TEA2017

FUTURE ELECTRONICS

- NXP's combo controller implements a proprietary bang-bang charge control scheme

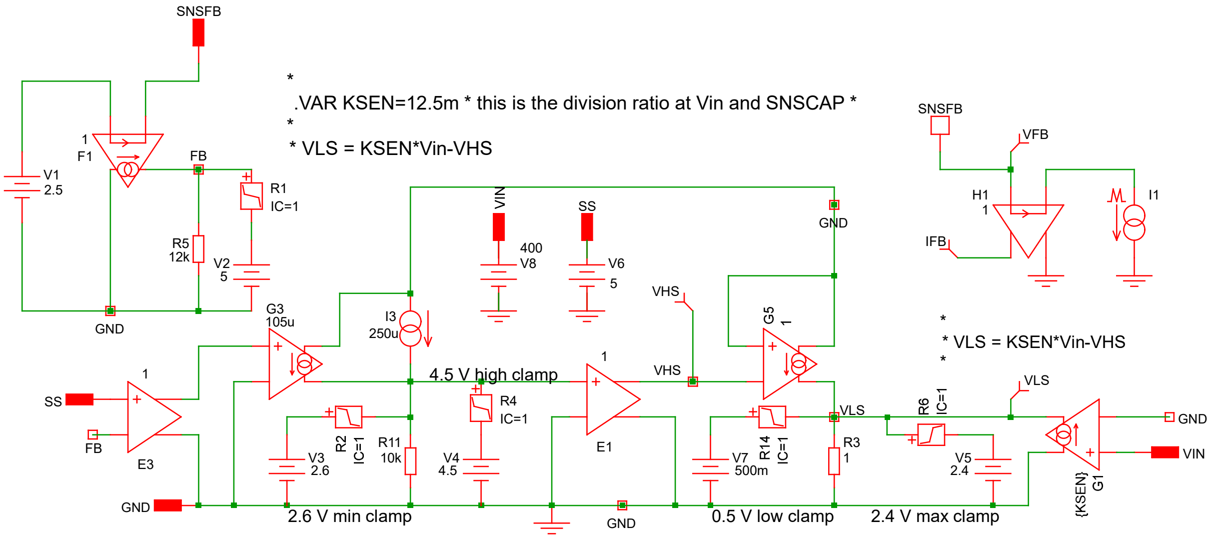


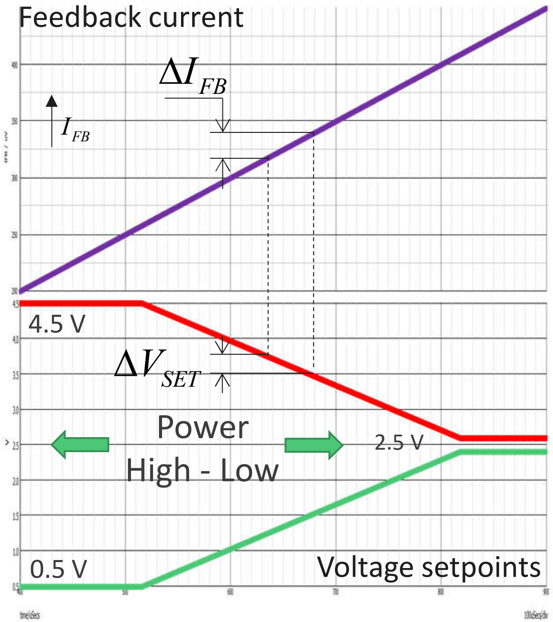


- Absorbing current from the feedback pin adjusts resonating peak voltage setpoints
- The optocoupler *average* current is regulated at 80 µA for best standby power

Modeling the Modulator Section

- A SIMPLIS model helps understand how setpoints are modulated in values





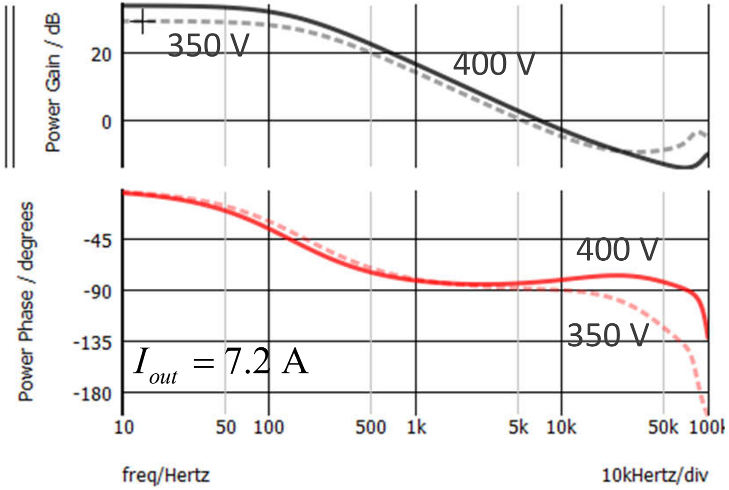
- The modulator imposes a small-signal gain

$$G = \frac{\Delta V_{SET}}{\Delta I_{FB}}$$

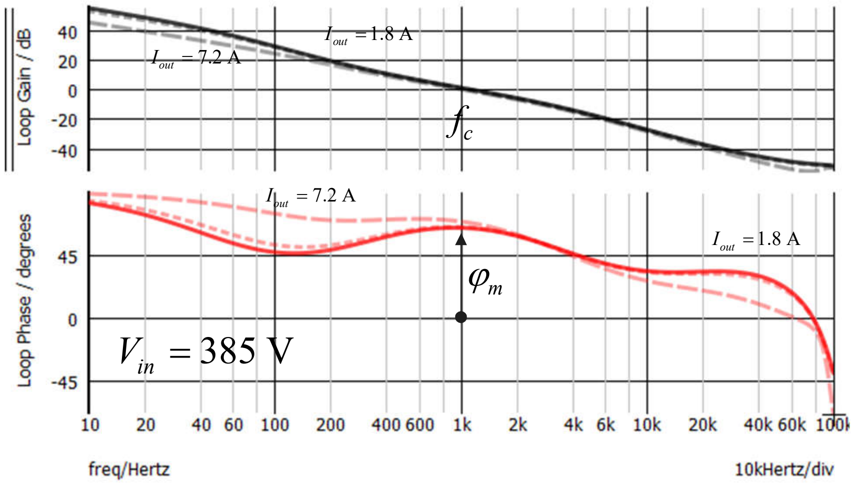
An Easier-to-Compensate Converter

- The charge control scheme simplifies the control-to-output transfer function

$$\frac{V_{out}(s)}{V_{thH}(s)} = H_0 \frac{1}{1+\frac{s}{\omega_p}} \qquad H_0 = \frac{V_{in} C_r F_{sw} k_{sen} R_L}{V_{out}} \qquad \omega_p = \frac{1}{C_{out} R_L} \qquad \omega_z = \frac{1}{r_C C_{out}}$$



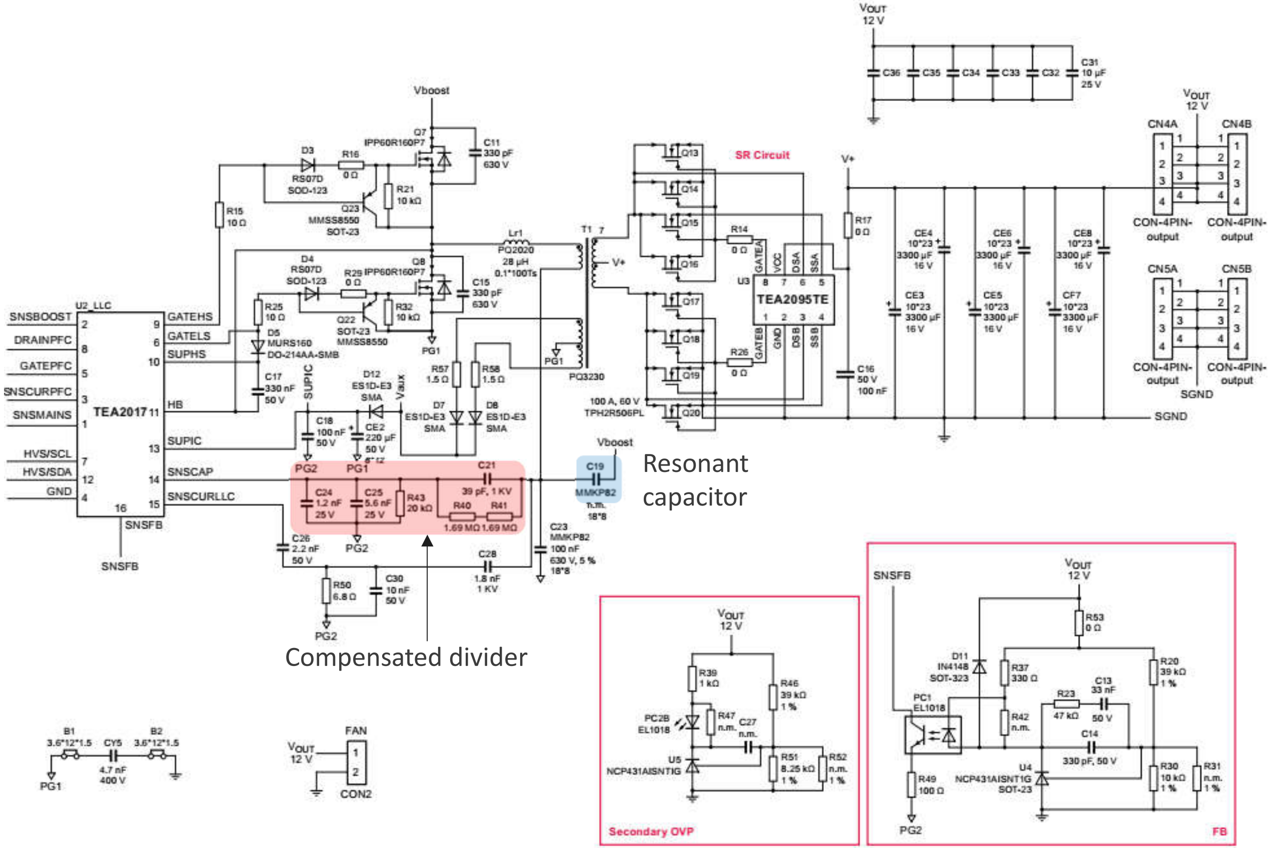
Power stage, different input voltages



Loop gain at different output currents

A 12-V/50-A Demonstration Board

- Typical application of the TEA2017 in a 600-W demonstration board – UM11613



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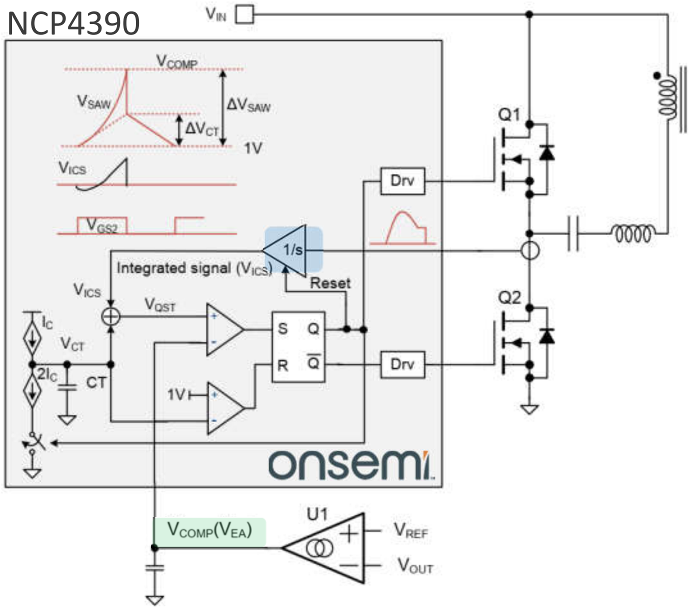
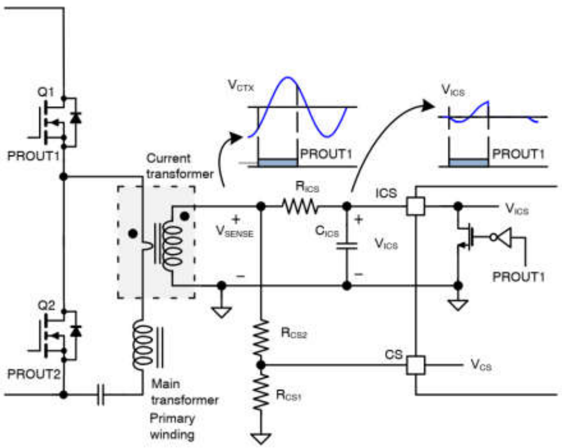
Integrating the Primary Current

- Fairchild – now onsemi – patented a technique based on charge control
  - The resonating current is integrated and supplemented with an artificial ramp
  - The resulting waveform is then classically compared with the error voltage

NCP4390



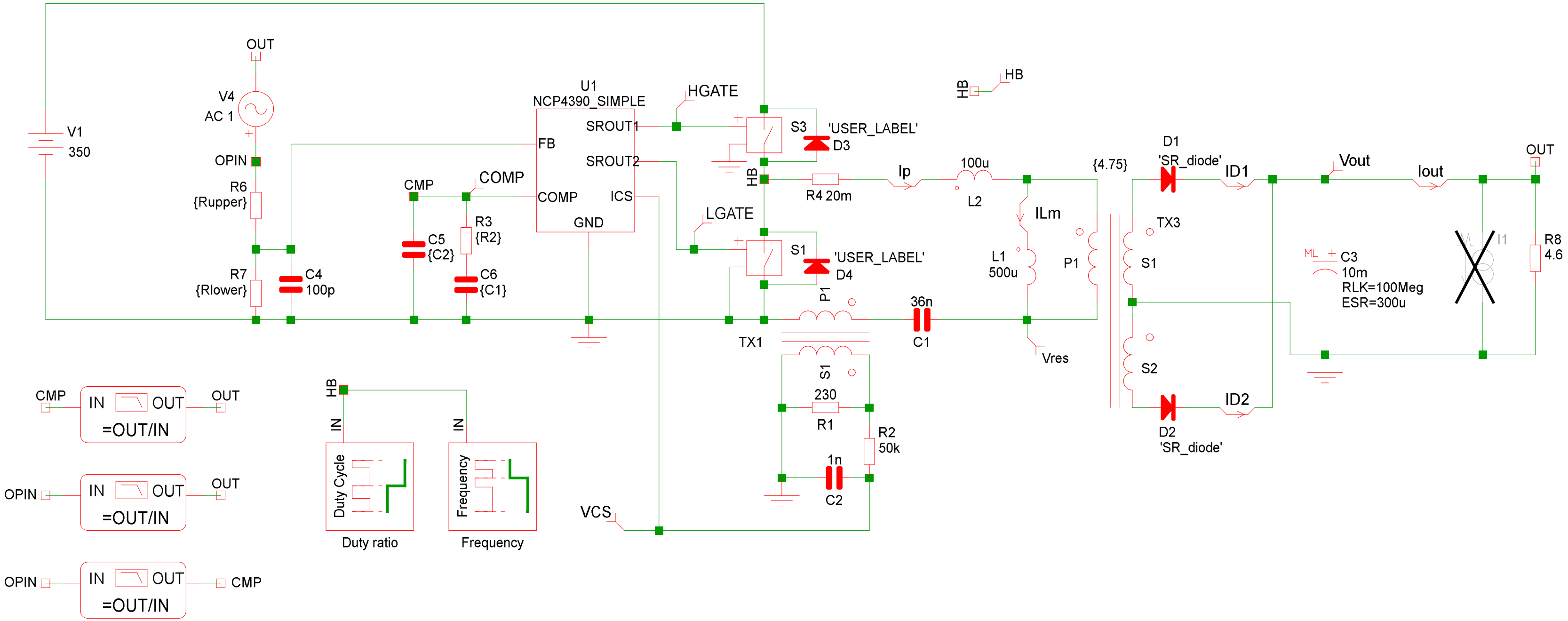


A current transformer provides the current information

https://www.onsemi.com/products/power-management/ac-dc-power-conversion/offline-controllers/ncp4390

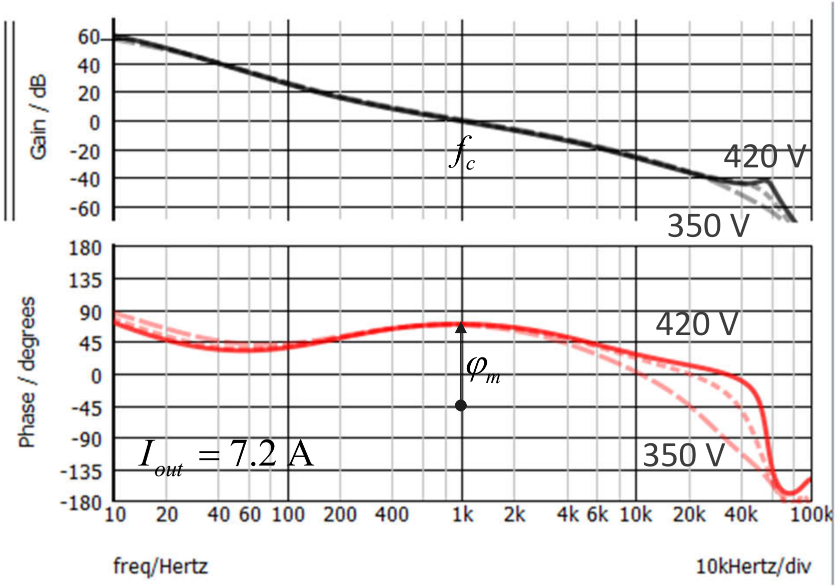
Checking the Frequency Response

- It is possible to run a SIMPLIS simulation with the same LLC converter
- The converter is stabilized to crossover at 1 kHz with a 70° phase margin

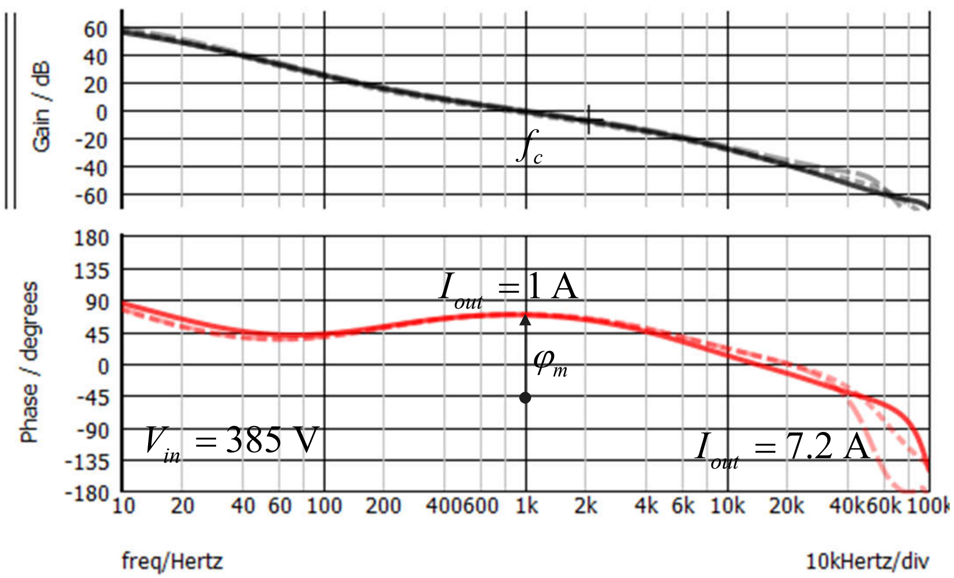


An Easier-to-Compensate Converter

- The frequency response, regardless of the input voltage or the load does not change
  - Phase margin is comfortable and obtained with a simple type 2 compensator



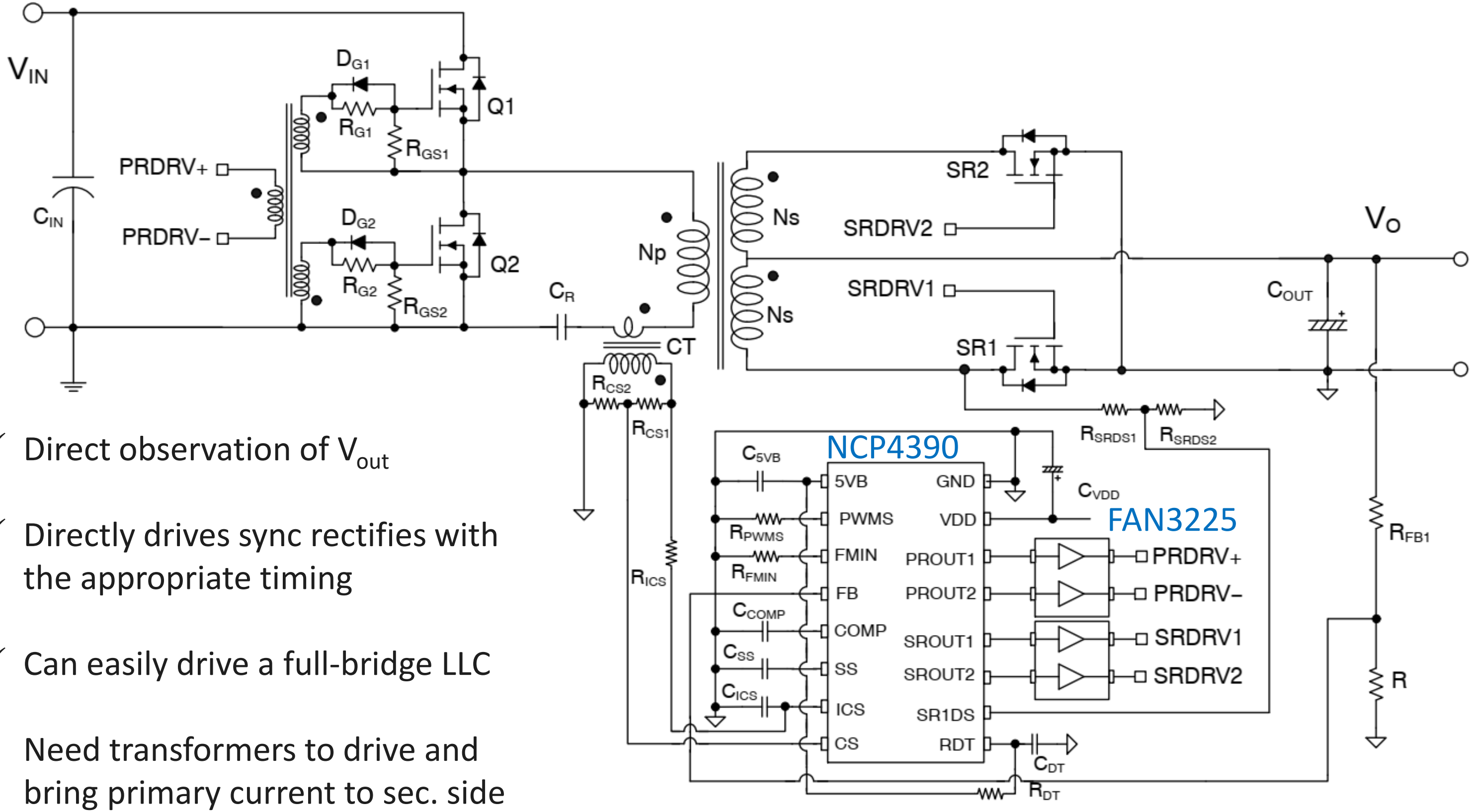
Loop gain, different input voltages



Loop gain, different output currents

High-Power Half- or Full-Bridge Control

- The controller is located in the secondary side for easier synchronous rectifiers control



- ✓ Direct observation of V_{out}
- ✓ Directly drives sync rectifies with the appropriate timing
- ✓ Can easily drive a full-bridge LLC
- Need transformers to drive and bring primary current to sec. side

https://www.onsemi.com/pub/collateral/evbum2726-d.pdf

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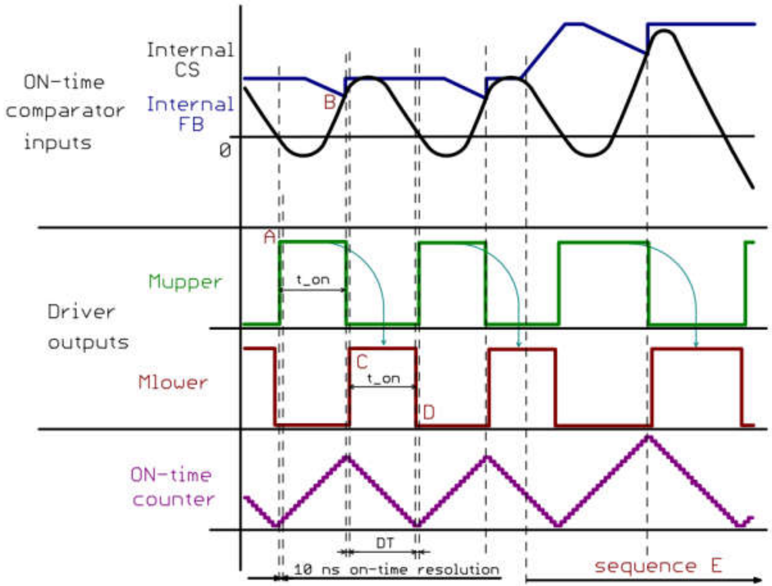
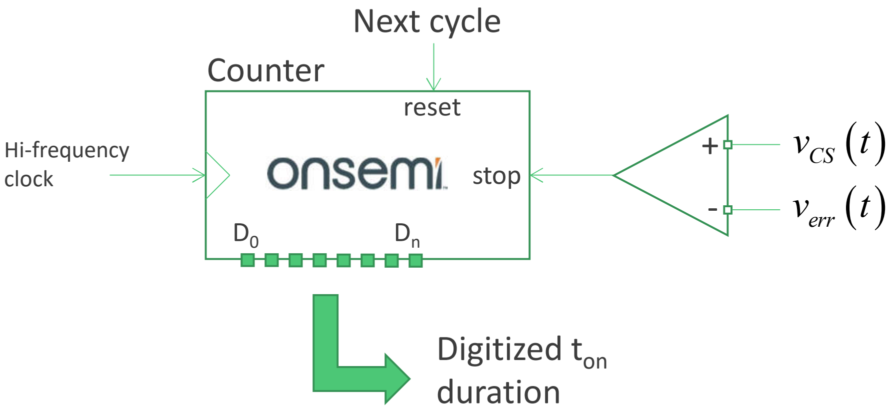
Current-Mode Control Operations

- The NCP13992 observes the resonating current integrated by capacitor C_r
- A cycle-by-cycle control adjusts the on-time to meet the peak current setpoint
- ➢ A digital core mirrors the on-time with a 10-ns resolution to drive the low-side switch





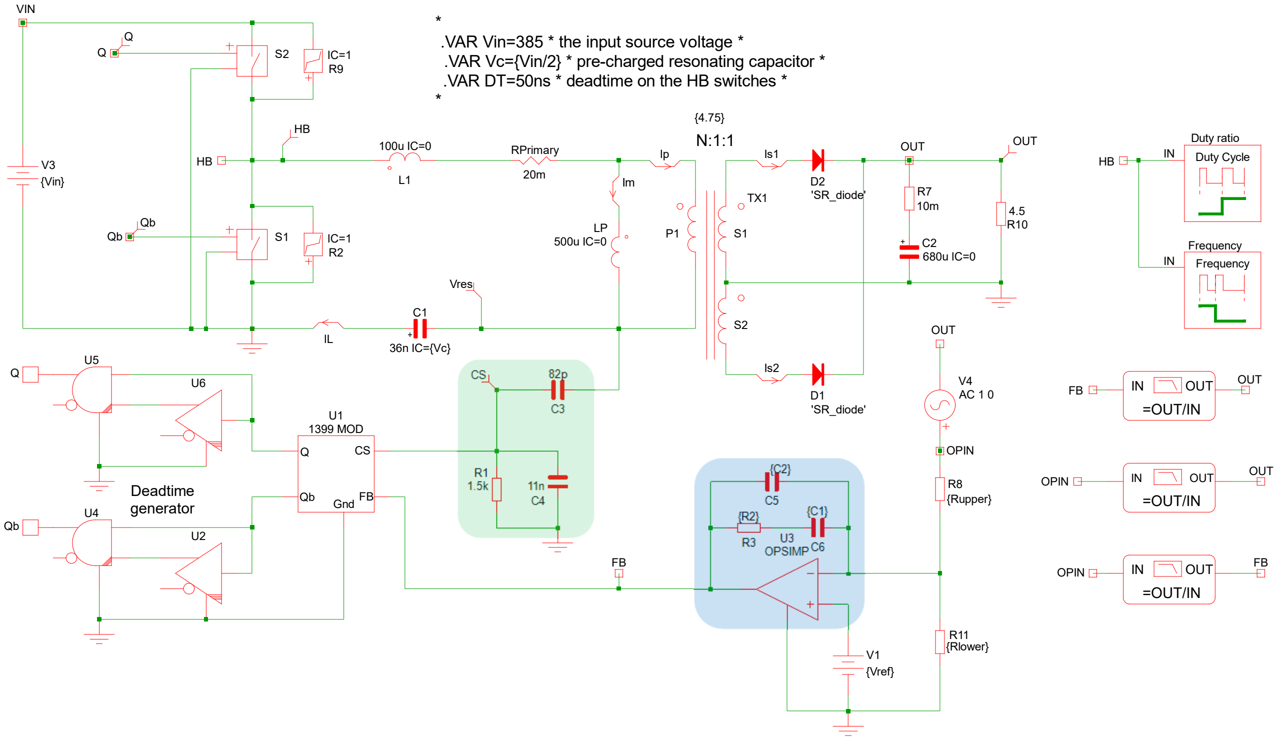
A digital core replicates t_{on} for an exact 50% operation

https://www.onsemi.com/products/power-management/ac-dc-power-conversion/offline-controllers/ncp1399

Ac Response of the Current-Mode-Controlled LLC

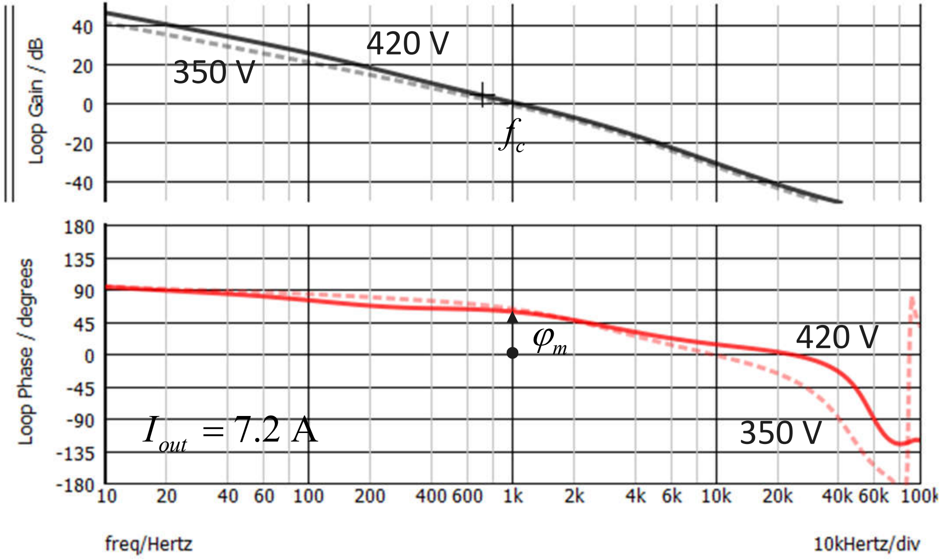
- It is possible to emulate the on-time replication via an analogue subcircuit
  - Symmetry between timings is obtained with a simple capacitor-based ramp generator

- A type 2 compensator is sufficient
- Current reading requires a simple capacitive divider

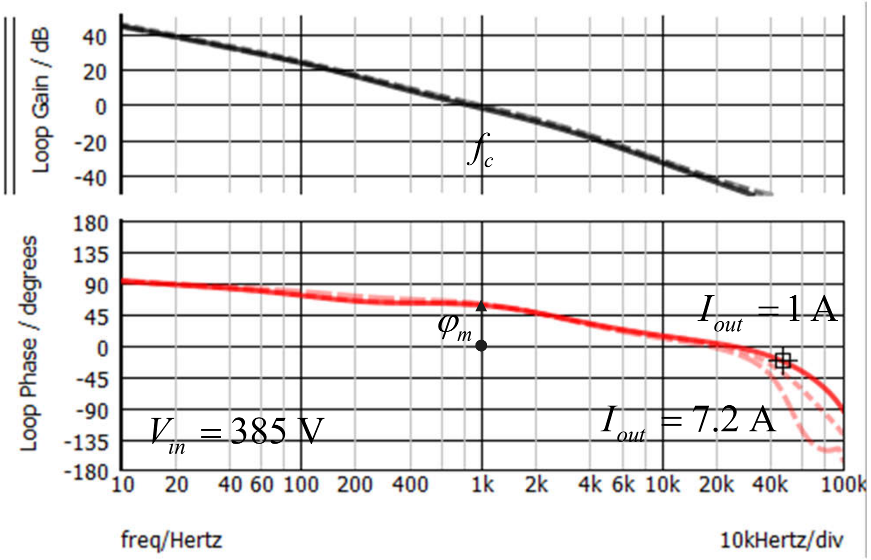


A Stable Response across all Operating Conditions

- The converter is compensated for a 1-kHz crossover frequency with a 60° phase margin
- Despite line and load variations, the loop gain remains similar



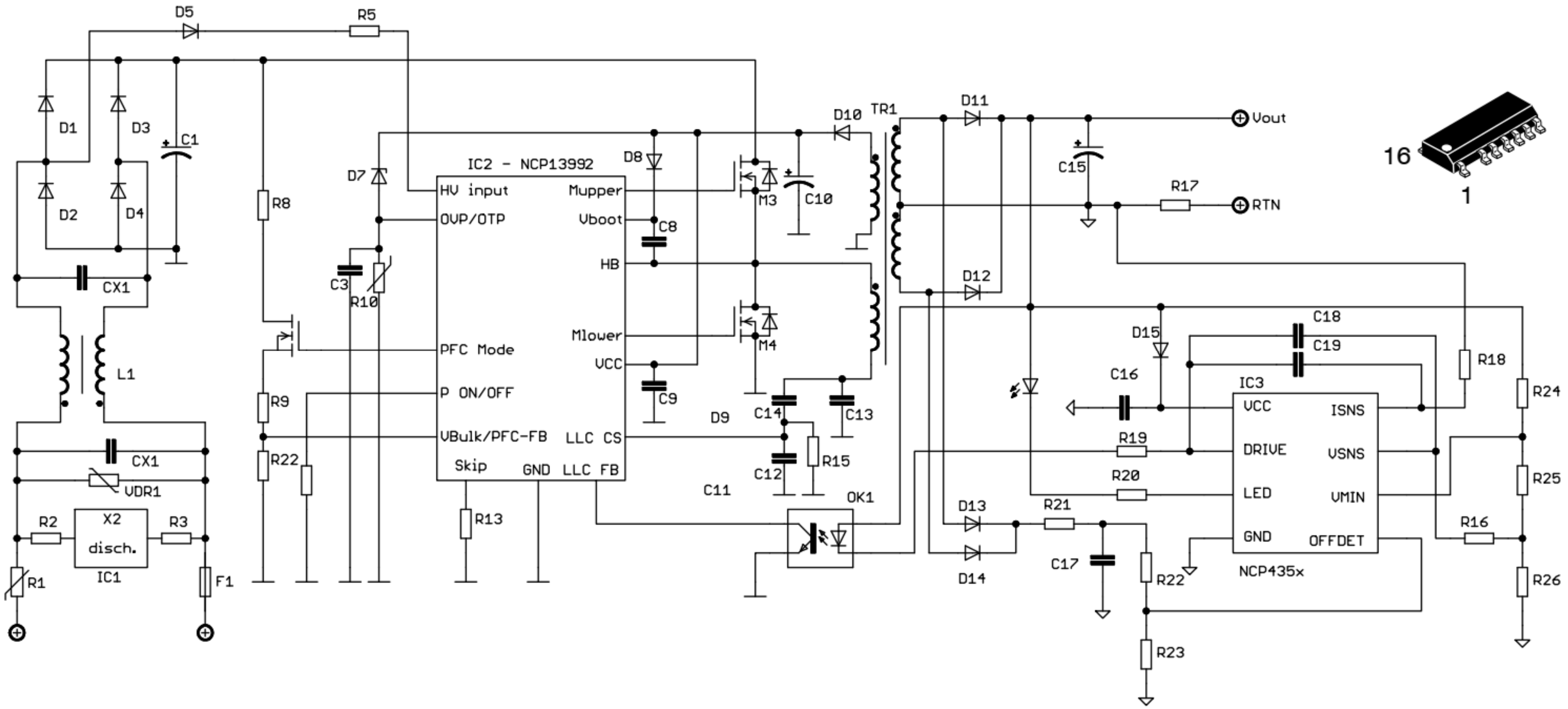
Loop gain, different input voltages



Loop gain, different output currents

Typical Application Schematic of NCP13992

- The part observes the resonating current via a capacitive differentiator on pin CS



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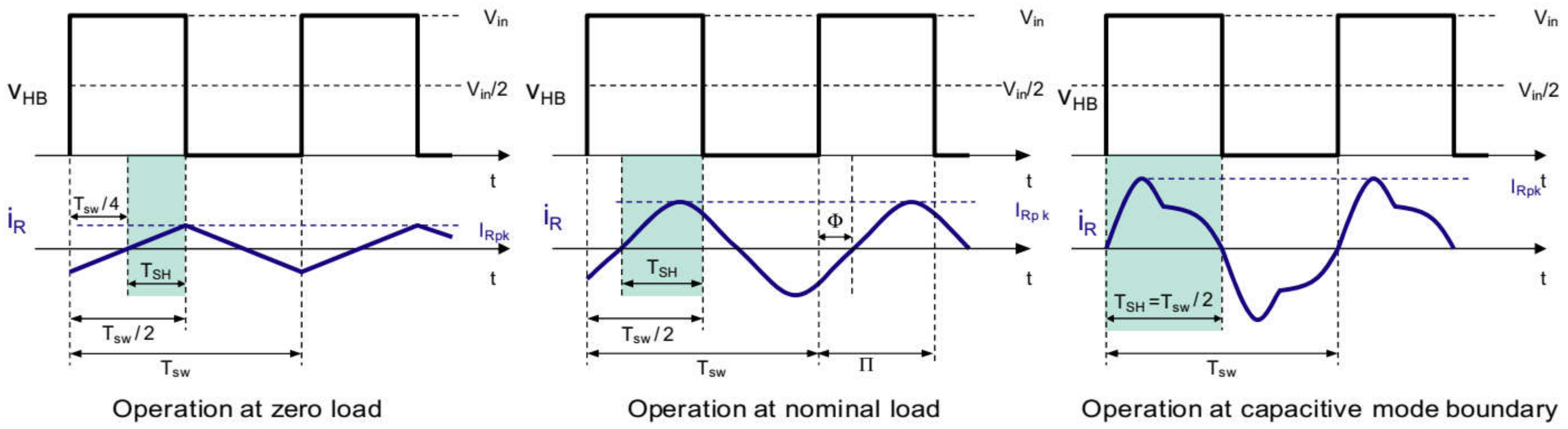
Time-Shift Control of LLC Converters

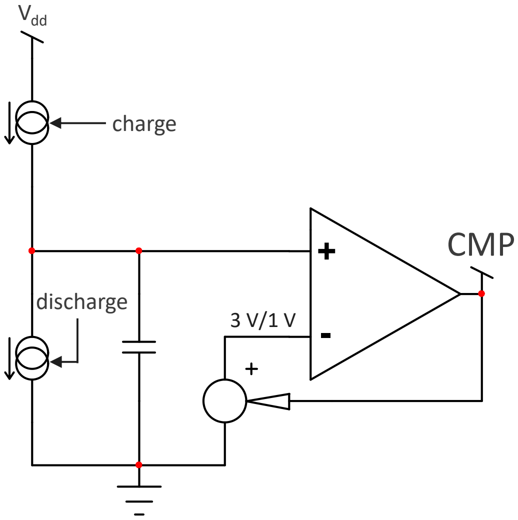
- The controller inserts a pause before the 0-A crossing point of the resonating current
  - For ZVS operations, the resonant current lags the half-bridge voltage
  - The feedback loop modulates the delay and adjusts the output power



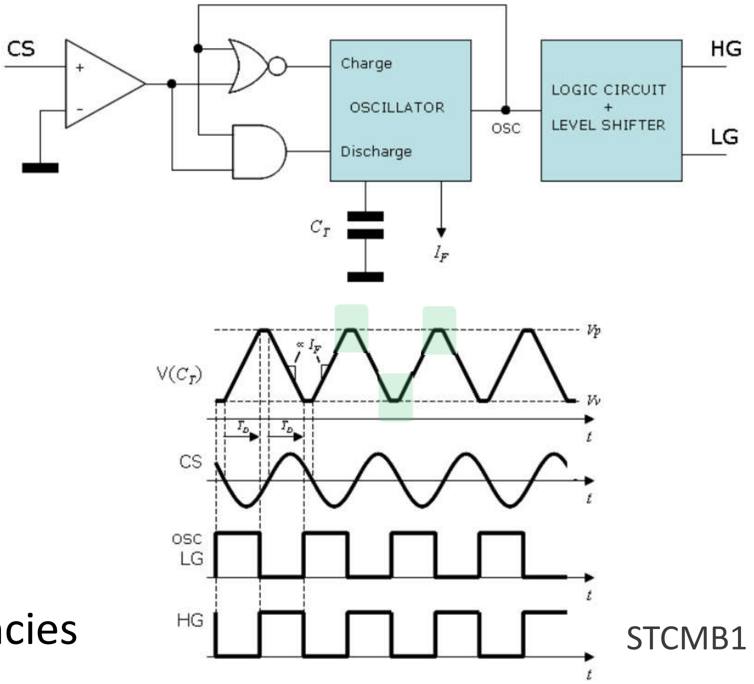
C. Adragna et al., *Digital Implementation and Performance Evaluation of Time-Shift-Controlled LLC Resonant Half-Bridge Converter*, Applied Power Electronics Conference, Fort Worth, 2014

Modifying the Frequency Modulator

- It is possible to insert a delay by pausing the charge/discharge current
- The pause duration depends on the resonating current approaching the 0-A point



Add extra logic gates



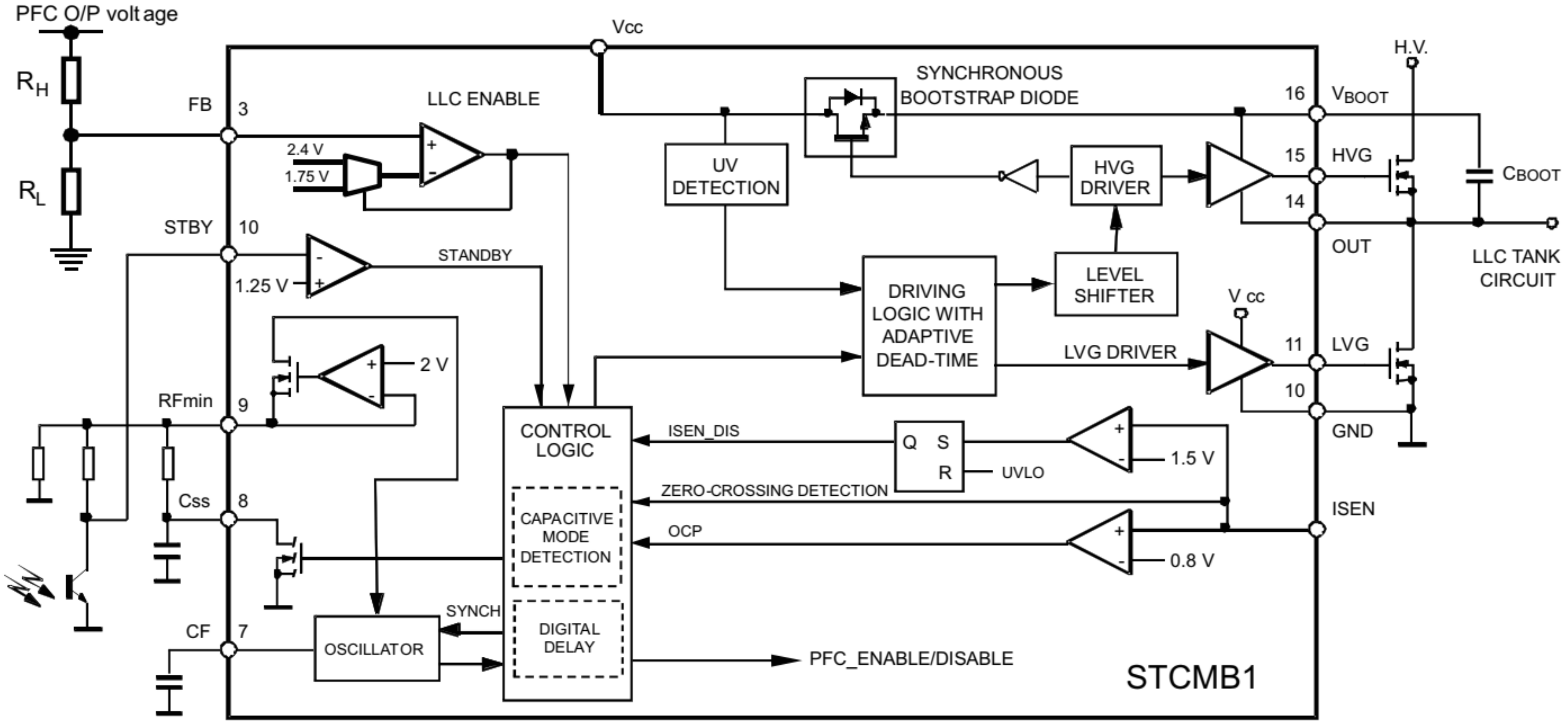
STCMB1

✓ 50% duty ratio naturally guaranteed

✓ Need to set the min/max switching frequencies

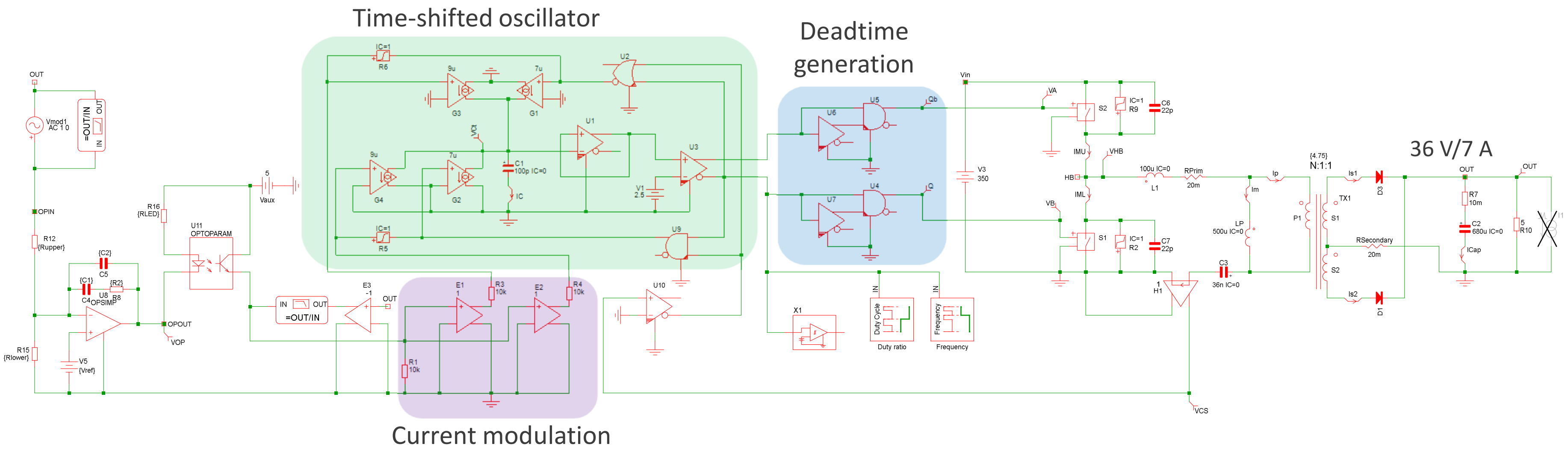
Internal Circuitry for the Half-Bridge Driver

- The STCMB1 features automatic dead-time management for ZVS operation



SIMPLIS Simulation of the Time-Shifted-Controlled LLC

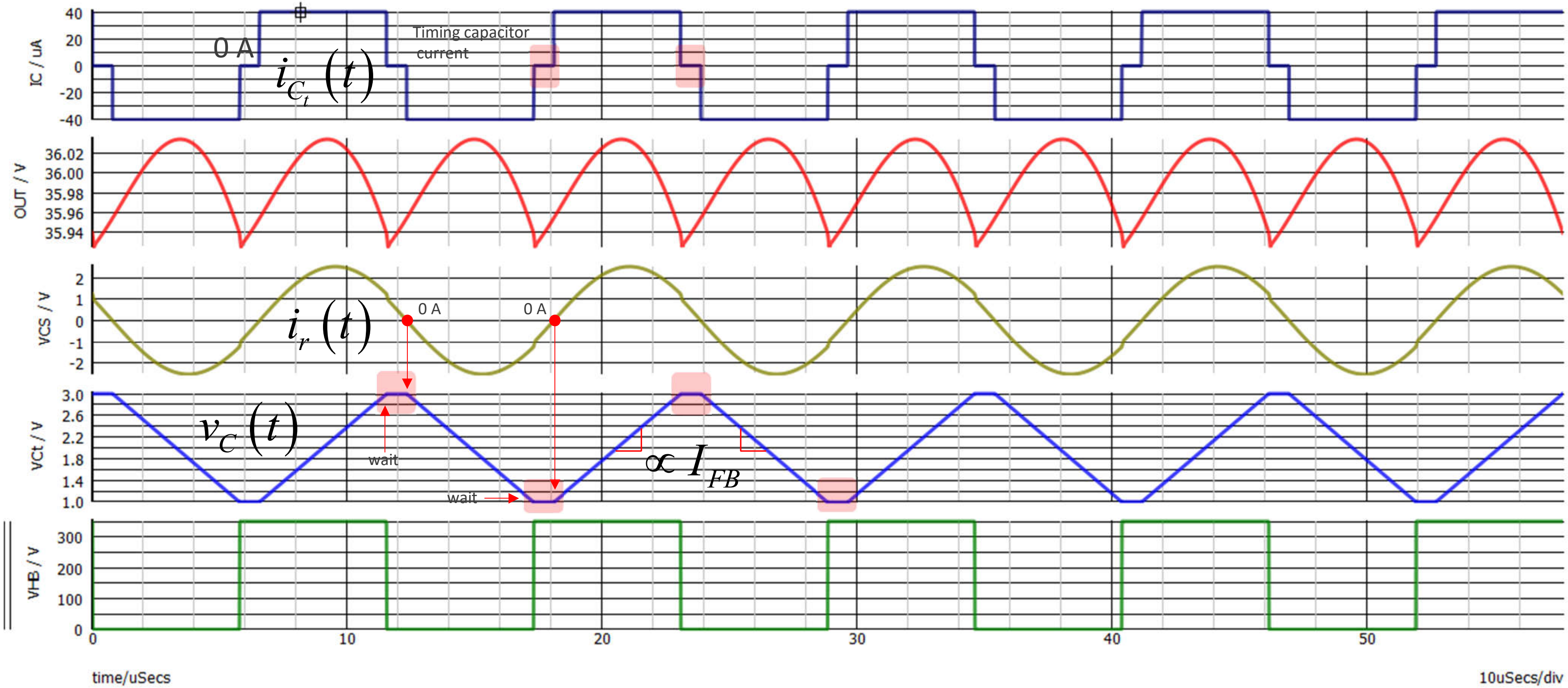
- A delay is inserted by modulating the charge/discharge current of the timing capacitor
- The feedback current modulates the delay and the switching frequency indirectly



- ✓ A simple type 2 compensator is enough to stabilize the converter
- ✓ Current sensing can be implemented via a simple resistance or a capacitive divider

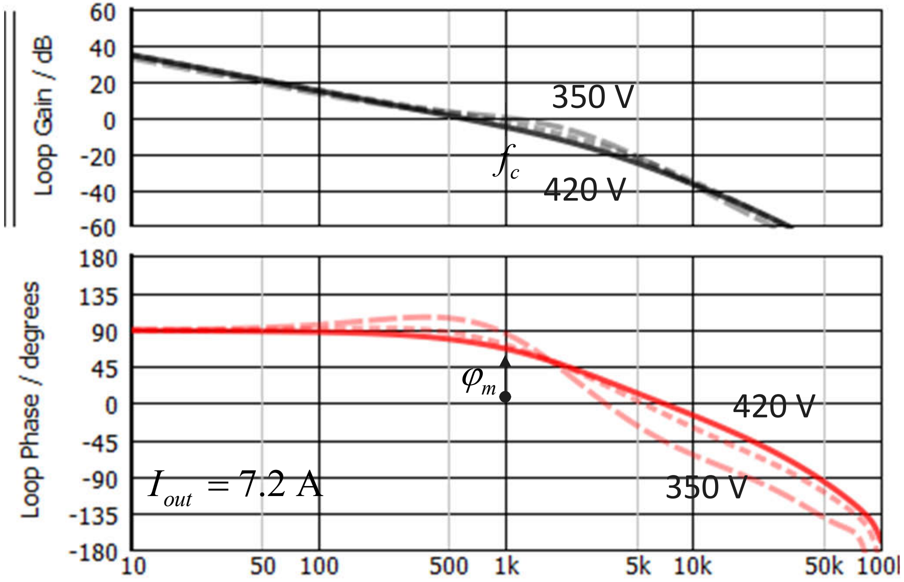
Typical Operating Waveforms

- The pause in the charge/discharge process is clearly visible in this 36-V LLC converter

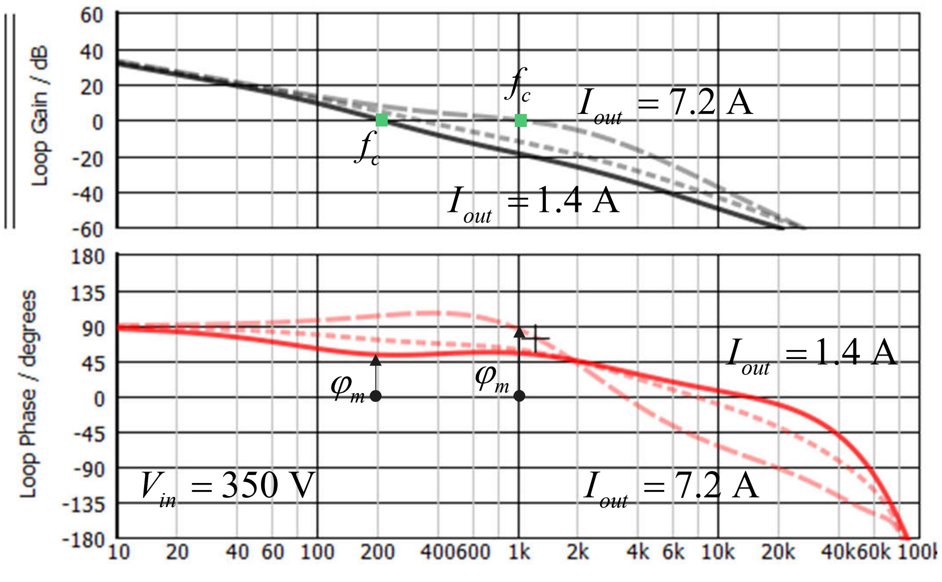


Time-Shift-Controlled Compensated LLC Converter

- The converter is compensated for a 1-kHz crossover frequency with a 60° phase margin
- The response is stable at various conditions but shows some variability in crossover



Loop gain, different input voltages

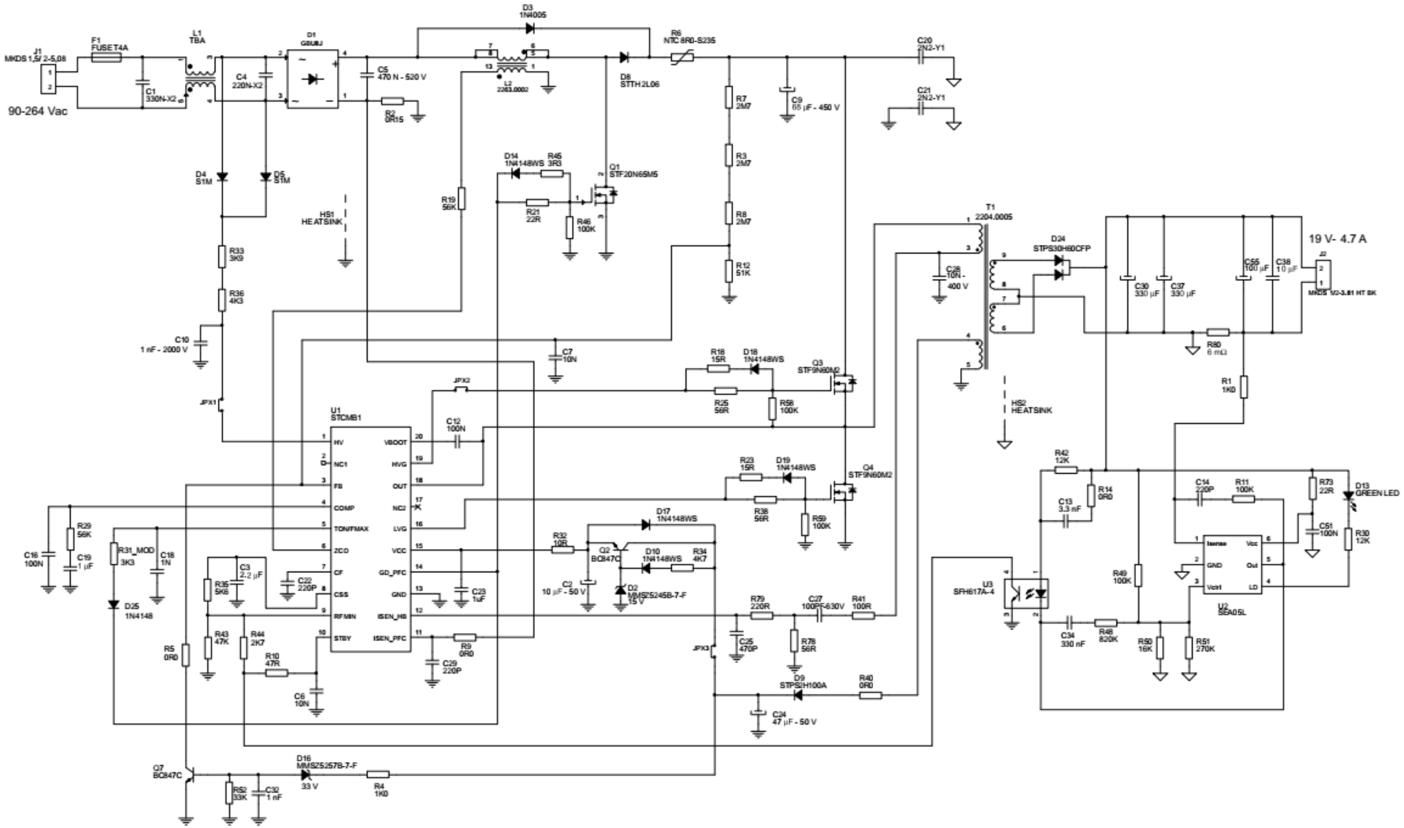


Loop gain, different output currents

FUTURE ELECTRONICS

Combining LLC Control and PFC in a Combo Chip

- The controller includes a PFC and the time-shift control section



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FUTURE ELECTRONICS

An Overview of Commercially-Available LLC Controllers

Part-Number	High-Voltage Drivers	Variable-Frequency Control	Charge Control	Current-Mode Control	Time-Shifted Control	Combo LLC+PFC	Package	Brand
NCP13992	√	—	—	√	—	—	SO-16	onsemi
NCP4390	—	—	√	—	—	—	SO-16	onsemi
TEA2017	√	—	√	—	—	√	SO-16	NXP
TEA19161	√	—	√	—	—	—	SO-16	NXP
STCMB1	√	—	—	—	√	√	SO-20W	ST life.augmented
L6699	√	√	—	—	—	—	SO-16	ST life.augmented
HR1002A	√	√	—	—	—	—	SO-16	MPS
HR1211	√	—	—	√	—	√	SO-20	MPS
ICE2HS01G	—	√	—	—	—	—	SO-20	infineon
IRS27951	√	√	—	—	—	—	SO-8	infineon

Conclusion

- An LLC converter operated in variable-frequency mode exhibits a complicated ac response
- It is difficult and perilous to maintain a safe phase margin depending on conditions
  - ➢ Crossover frequency is constrained to modest values
- The charge-controlled LLC converter offers a simpler and predictable ac response
- A simple type 2 compensator is enough to ensure reliable operations
  - ➢ High crossover frequencies become possible with good margins
- Variations around this theme exist and bear different names
- Current-mode control also exists and offers interesting characteristics
- Time-shifted-controlled LLC brings a different scheme and simplifies compensation