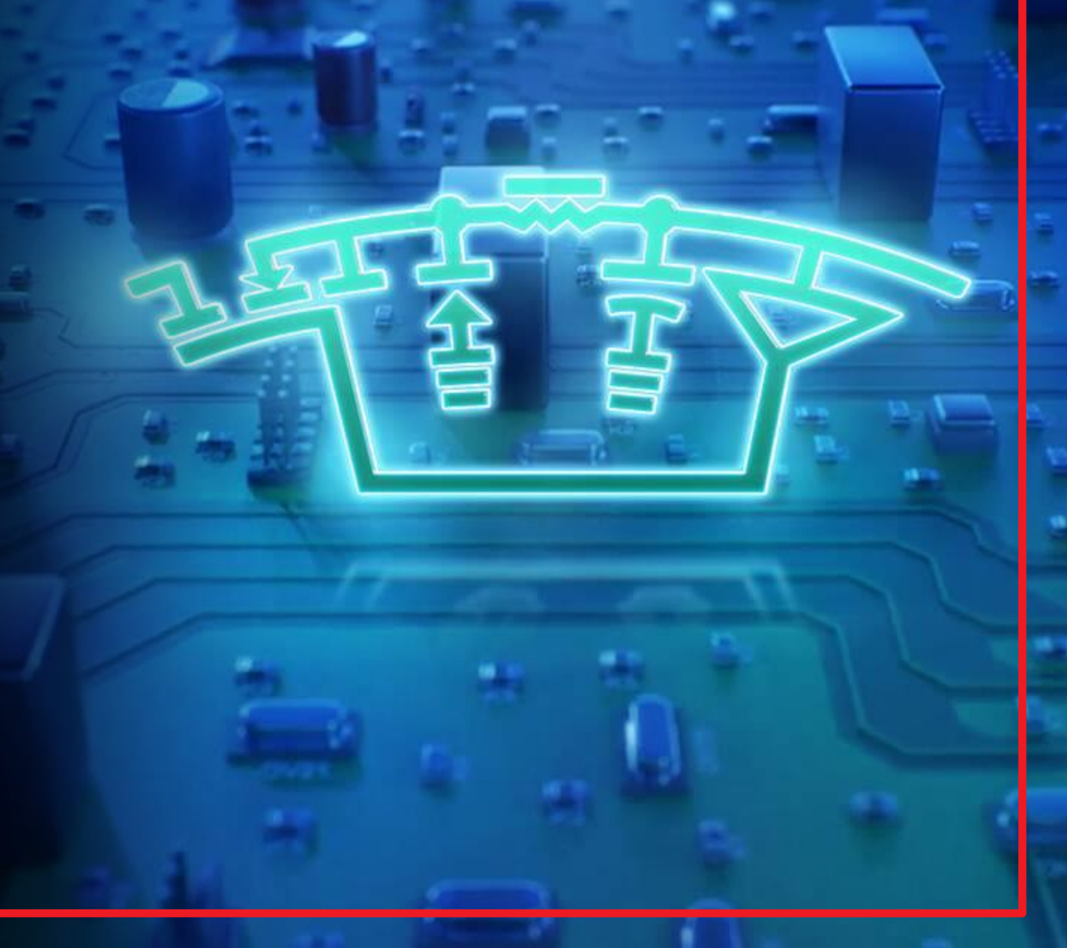
Texas Instruments

Power Supply Design Seminar

GaN-optimized transition-mode power factor correction



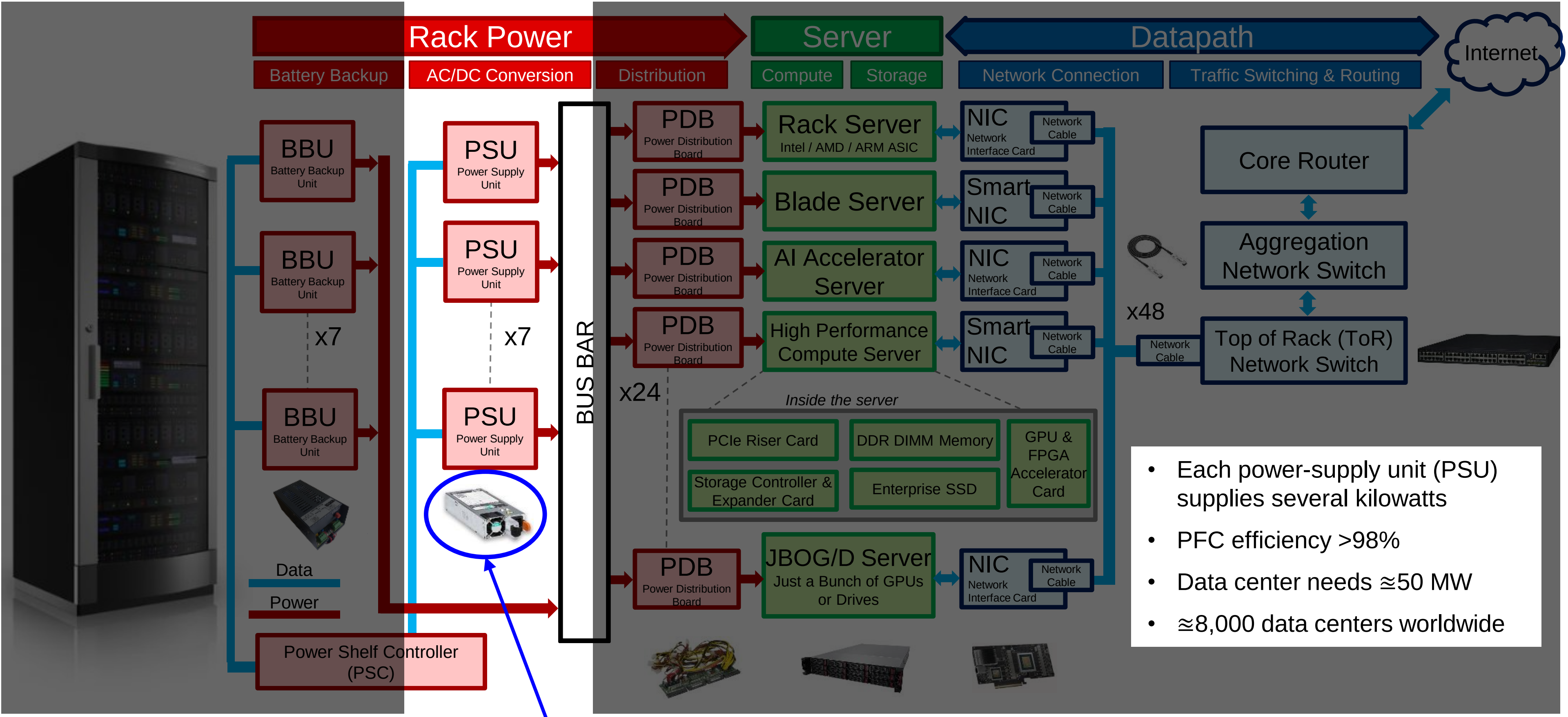
Author

Brent McDonald

Agenda

- Applications
- Boost converter
  - Topology review
  - Conduction modes
- Control methods
  - Constant on-time
  - Zero current detection (ZCD)
  - Zero voltage detection (ZVD)
- Experimental results
- Conclusions

Typical enterprise data center system



- Each power-supply unit (PSU) supplies several kilowatts
- PFC efficiency >98%
- Data center needs ≅50 MW
- ≅8,000 data centers worldwide

Power factor correction (PFC) circuit

Totem-pole PFC – using one boost converter for PFC

Positive half cycle

Negative half cycle

Control field-effect transistor (FET) "D"

- Can you control the input current with one boost converter?
- Yes, if you add the ability to reconfigure the circuit during each half cycle

Rectifier "1-D"

Totem-pole PFC

Positive half cycle

Negative half cycle

Control FET "D"

Synchronous rectifier "1-D"

Strengths

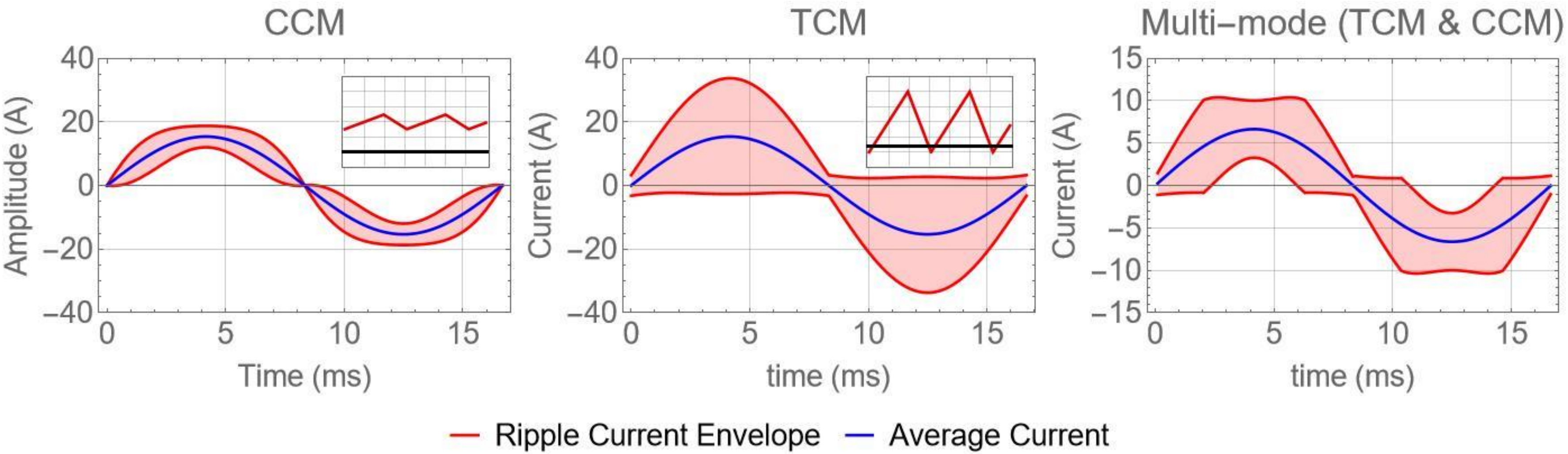
- Highest efficiency
- Minimizes conduction loss

Weaknesses

- Control complexity
- Usually requires wide band-gap switches
- Current sensing
- Common-mode electromagnetic interference (EMI)

CCM totem-pole PFC paper

PFC conduction modes



Continuous conduction mode (CCM)

- Hard switching and reverse recovery
- Lower conduction loss
- Small ripple current
- Simple control

Transition conduction mode (TCM)

- Zero voltage switching (ZVS)
- Higher conduction loss
- Large ripple
- Complex control

Multimode

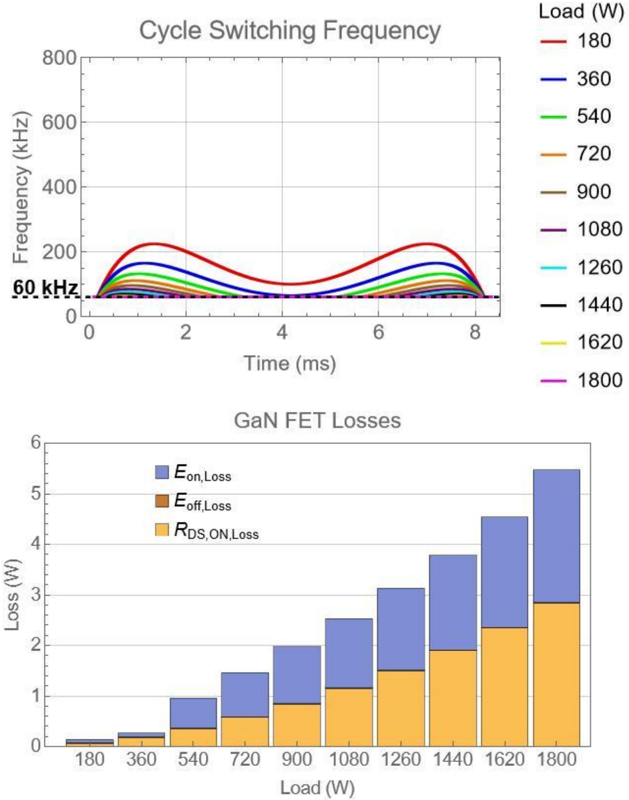
- Combination of CCM/TCM
- Attempts to get benefits of each
- Complex control

$\left\langle I_{L_g}(t) \right\rangle_{T_s}$ denotes the current in L_g averaged over each switching cycle

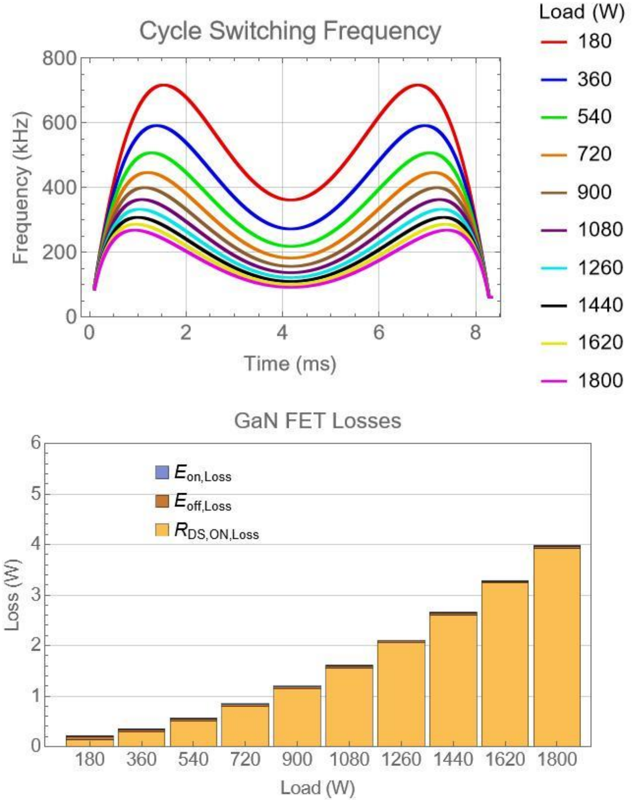
Conduction-mode impact on FET losses

Topology	CCM/TCM	TCM
Inductor	150 µH	25 µH
f_s range	60 kHz-250 kHz	75 kHz-750 kHz
FET loss	High	**Low**
Inductor volume	Big	**Small**
EMI filter size	**Small**	Big

CCM/TCM

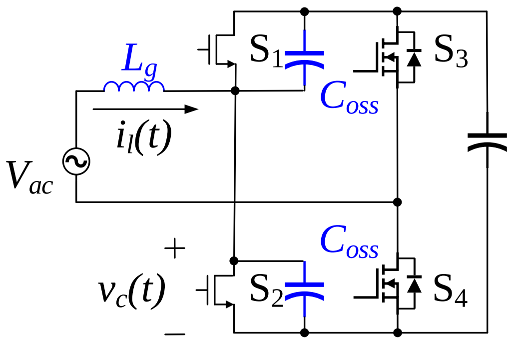


TCM

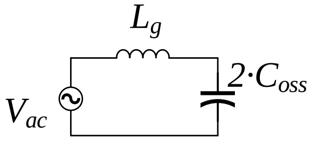


Control constraints

TCM converter



ZVS equivalent circuit



$$Z_0 = \sqrt{\frac{L_g}{2 \cdot C_{oss}}}$$

$$i_l(t) = 2 \cdot C_{oss} \cdot \frac{dv_c(t)}{dt}$$

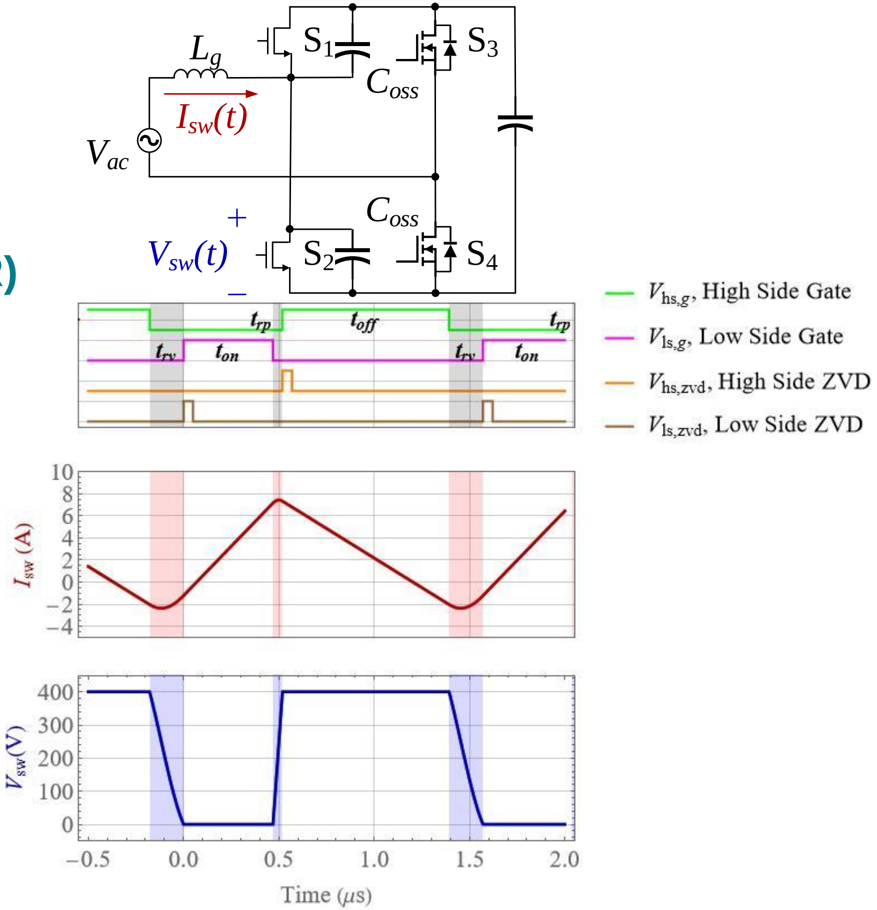
$$v_{ac}(t) - v_c(t) = L_g \frac{di_l(t)}{dt}$$

- PFC requirements
  - Condition No. 1: ZVS
    - S_1 achieves ZVS if $v_c(t) = v_{OUT}$ before turnon
    - S_2 achieves ZVS if $v_c(t) = 0$ before turnon
  - Condition No. 2: low total harmonic distortion (THD)
    - $v_{ac}(t) = \sqrt{2} \cdot v_{ac,rms} \cdot \sin(\omega \cdot t + \varphi)$
    - $\left\langle I_{L_g}(t) \right\rangle_{T_s} = \frac{v_{ac}(t)}{R_e}$, $R_e = \frac{v_{ac,rms}^2}{P_{out}}$
- Well-known solution to equivalent circuit
  - $v_c(t) = i_l(t_0) \cdot Z_0 \cdot \sin(\omega_0 \cdot t) + \left(v_c(t_0) - v_{ac}(t_0)\right) \cdot \cos(\omega_0 \cdot t)$
  - $i_l(t) = \frac{\left(v_{ac}(t_0) - v_c(t_0)\right)}{Z_0} \cdot \sin(\omega_0 \cdot t) + i_l(t_0) \cdot \cos(\omega_0 \cdot t)$
- Microcontroller solves for required timing

$\left\langle I_{L_g}(t) \right\rangle_{T_s}$ denotes the current in L_g averaged over each switching cycle

Control timing definitions

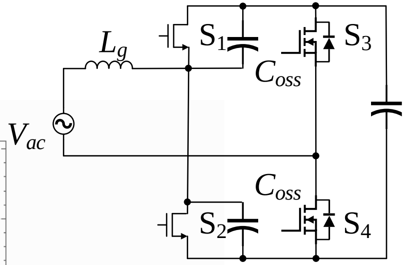
- Control variables
  - t_{on} – **on-time** of the **control FET**
  - t_{off} – **on-time** of the **synchronous rectifier (SR)**
  - t_{rp} – **dead time** between the **control FET turnoff** and **synchronous rectifier turnon**
  - t_{rv} – **dead time** between the **synchronous rectifier turnoff** and the **control FET turnon**
- Positive AC half cycle
  - S1 – synchronous rectifier
  - S2 – control FET
- Negative AC half cycle
  - S1 – control FET
  - S2 – synchronous rectifier

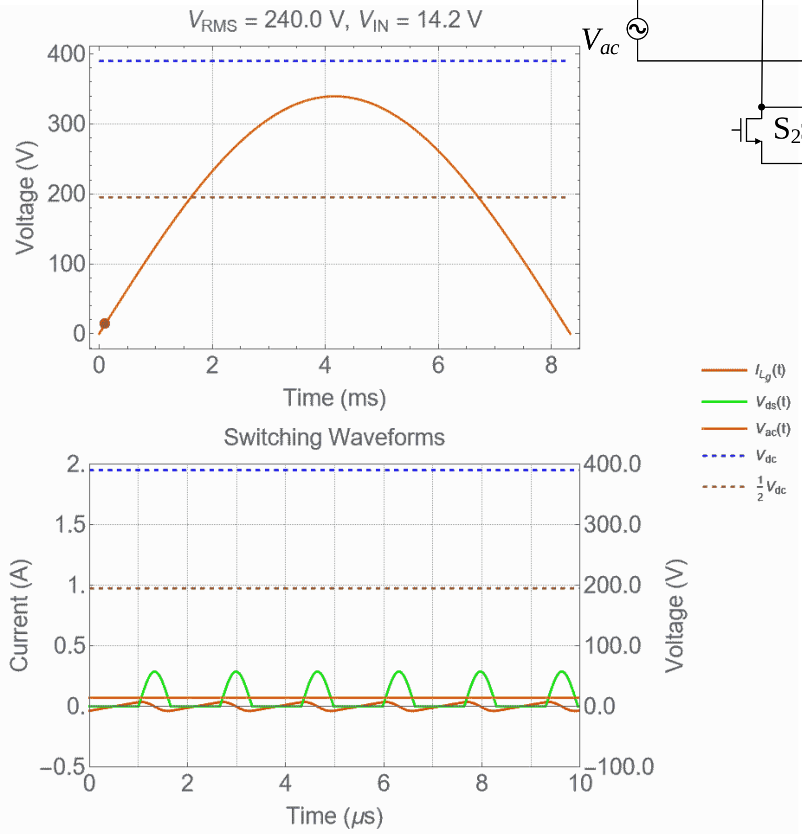


Transition-mode control – COT

- Constant on-time (COT) control
  - $\left\langle I_{L_g}(t) \right\rangle_{T_s} = \frac{V_{ac}(t)}{2 \cdot L_g} t_{on}$
- Operates on the discontinuous-conduction-mode (DCM)/CCM boundary
- Large switching frequency variation
- The inductor current will go negative every cycle
- ZVS
  - $V_{IN} < 1/2\ V_{OUT}$ – ZVS for all loads
  - $V_{IN} > 1/2\ V_{OUT}$ – loss of ZVS
- Low THD is challenging

$\left\langle I_{L_g}(t) \right\rangle_{T_s}$ denotes the current in L_g averaged over each switching cycle

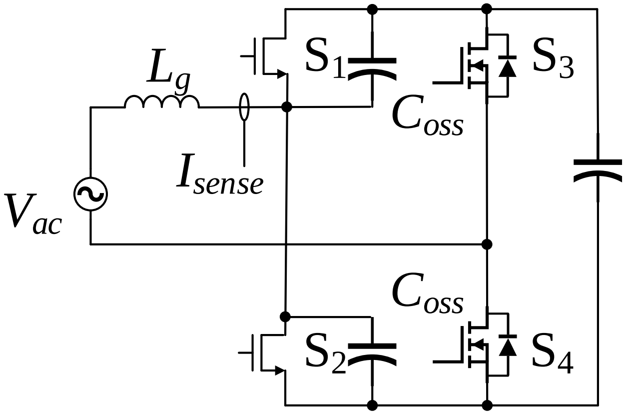


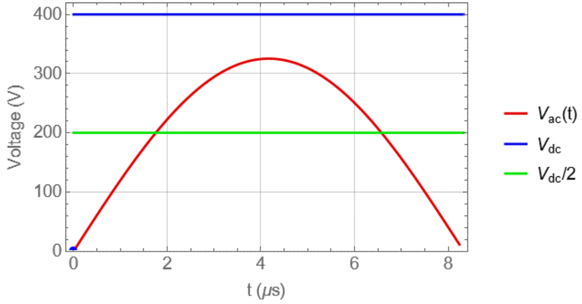


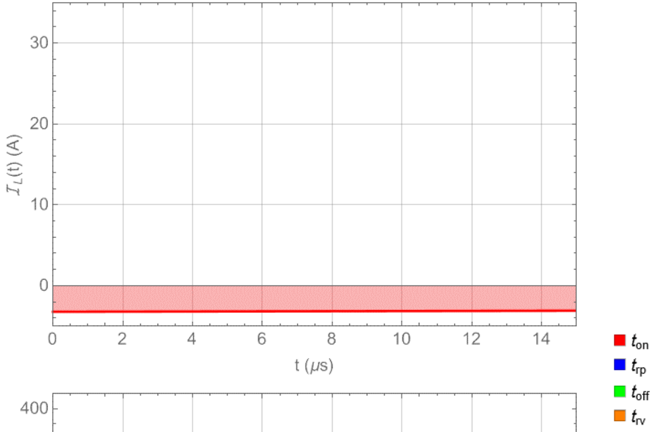
Note: Time base in zoomed plots is relative to: 0.1 ms.

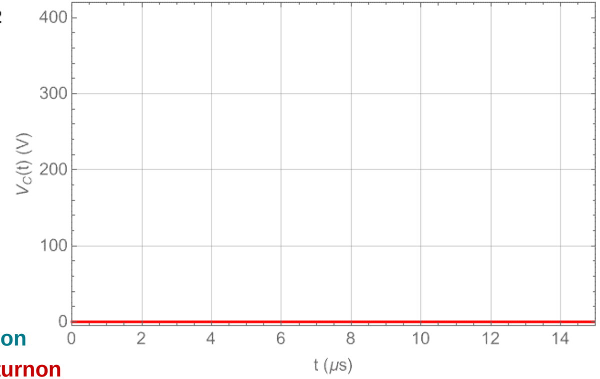
Transition-mode control – ZCD

- Solves the loss of ZVS issue for $V_{IN} > 1/2\ V_{OUT}$
- Requires:
  - Precise ZCD
  - Robust algorithm





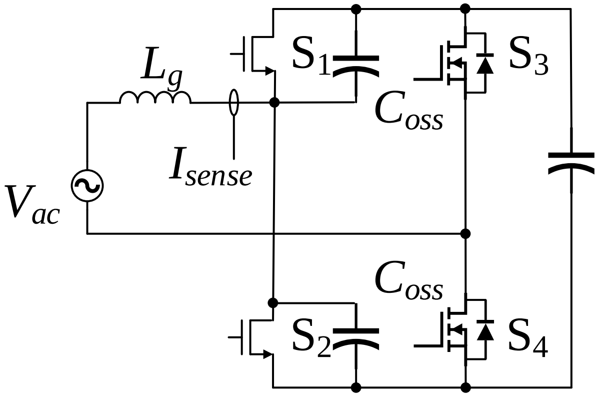


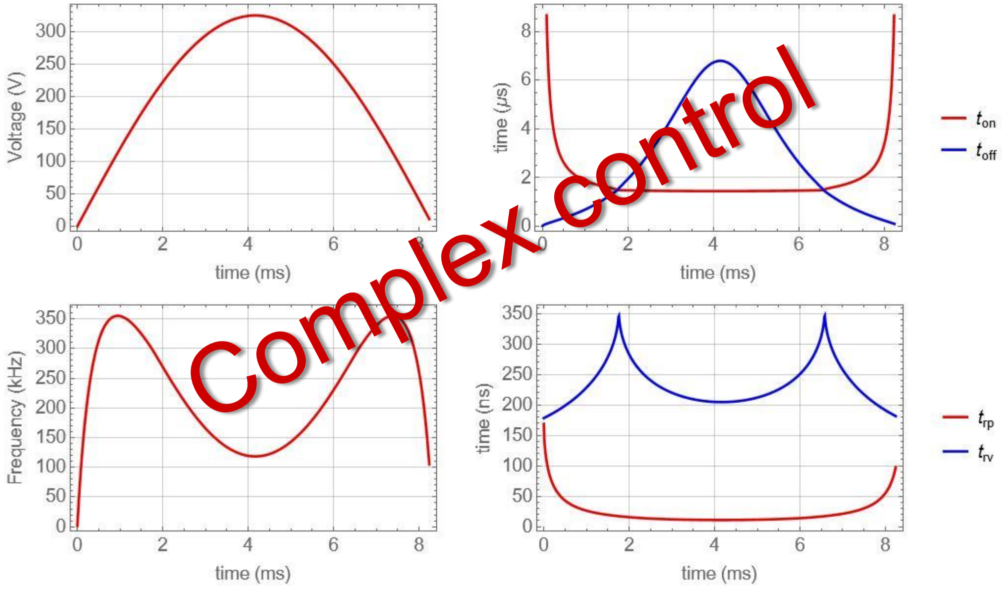


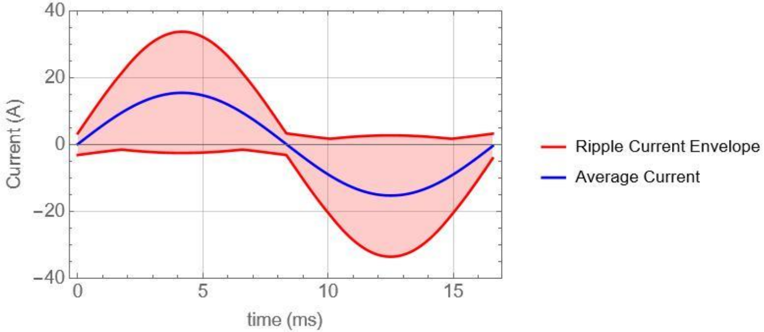
t_{on} – **on-time** of the **control FET**
t_{off} – **on-time** of the **SR**
t_{rp} – **dead time** between the **control FET turnoff** and **SR turnon**
t_{rv} – **dead time** between the **SR turnoff** and the **control FET turnon**

ZCD solution

- $V_{AC} < 1/2\ V_{DC}$ natural ZVS
- $V_{AC} > 1/2\ V_{DC}$ additional SR time required
- Exact timing solution is not available

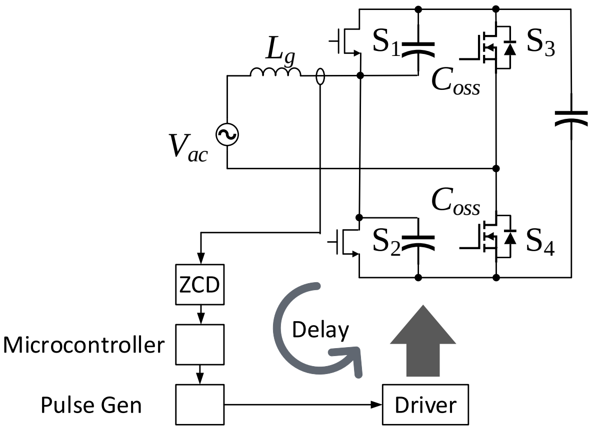


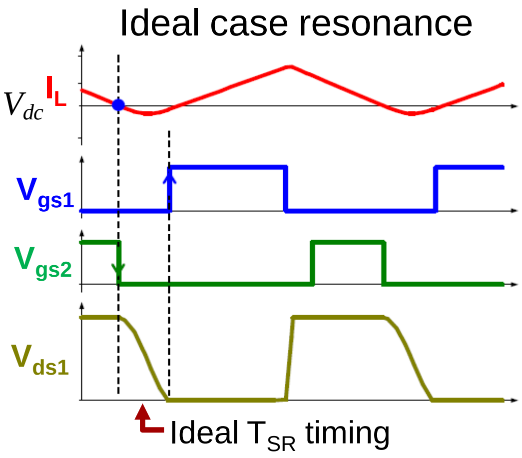


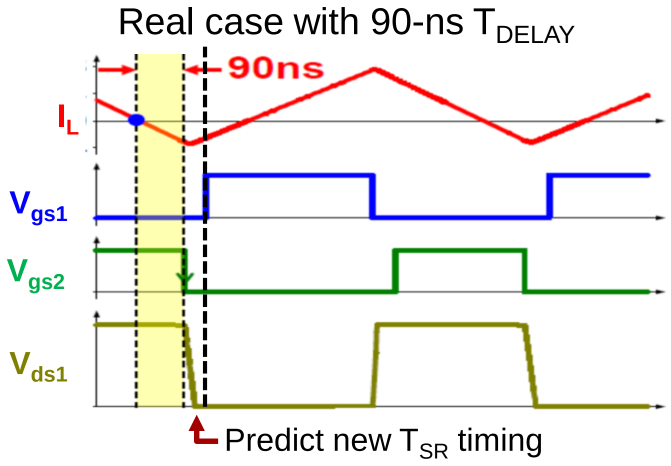


t_{on} – **on-time** of the **control FET**
t_{off} – **on-time** of the **SR**
t_{rp} – **dead time** between the **control FET turnoff** and **SR turnon**
t_{rv} – **dead time** between the **SR turnoff** and the **control FET turnon**

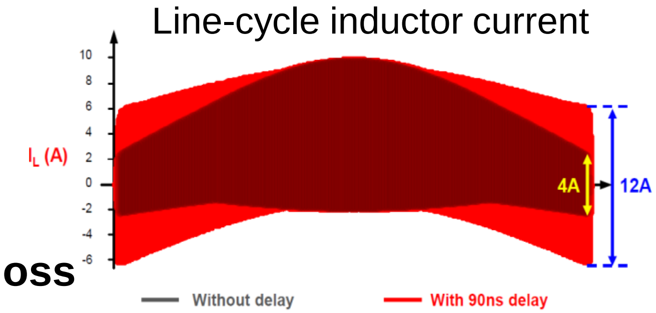
ZCD – timing challenge



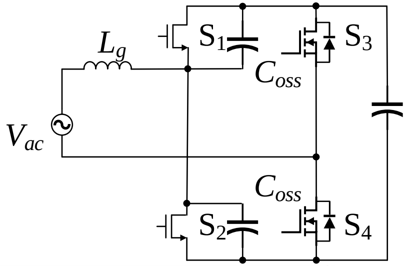




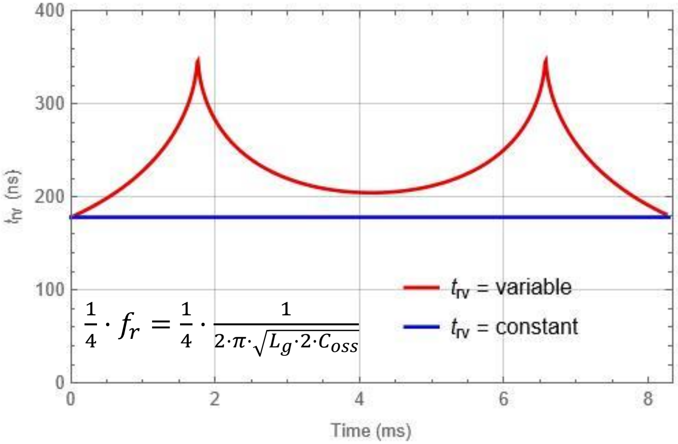
- Need accurate ZCD timing
  - Requires high bandwidth, low delay sensor
  - Delays limit response time
- Requires additional computation to compensate for delays
- **Results in increased THD and unnecessary conduction loss**



Path to solution: Step 1 – simplify timing

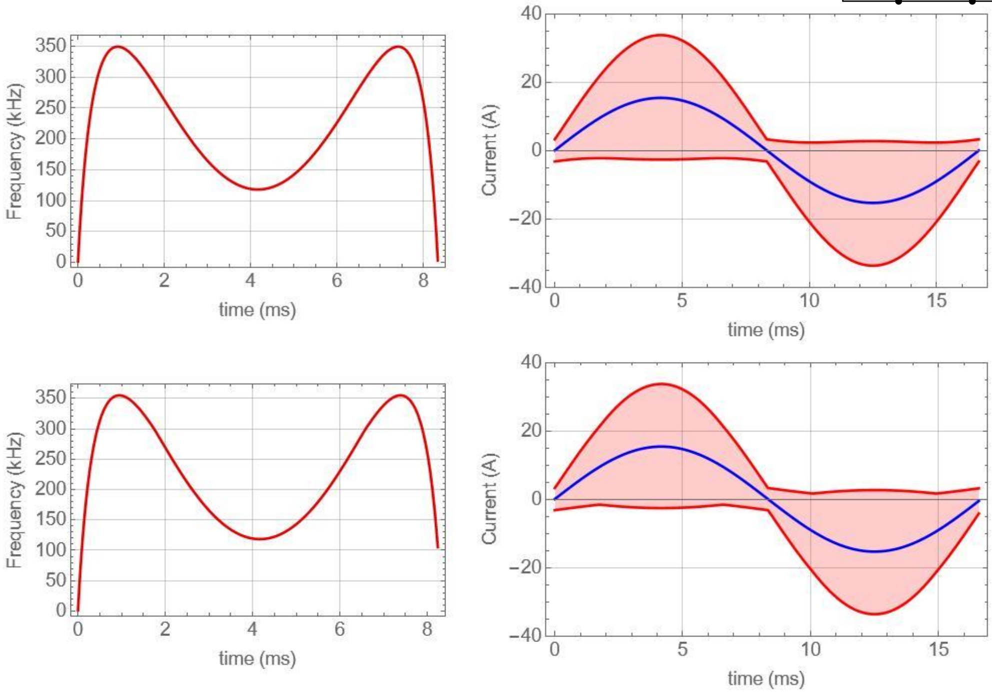


- Simplify by making t_{rv} a constant
- Frequency variation is similar
- Ripple current is similar



Constant t_{rv}

Variable t_{rv}



t_{on} – **on-time** of the **control FET**

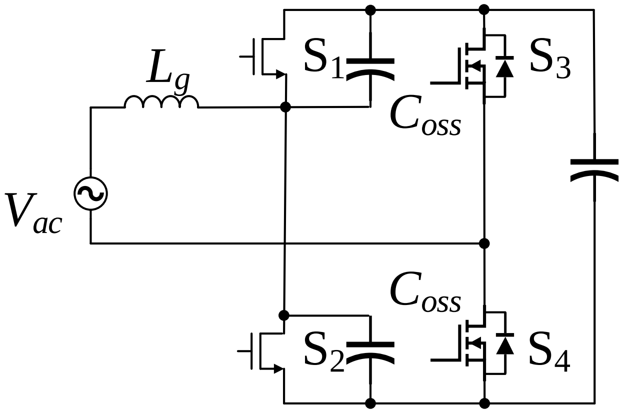
t_{off} – **on-time** of the **SR**

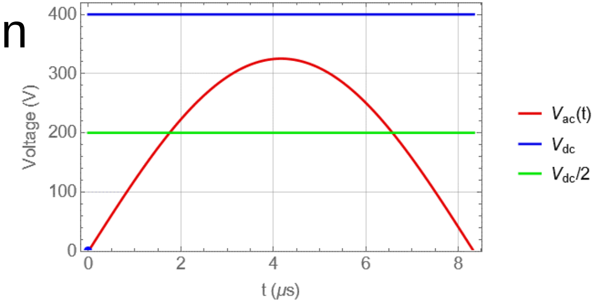
t_{rp} – **dead time** between the **control FET turnoff** and **SR turnon**

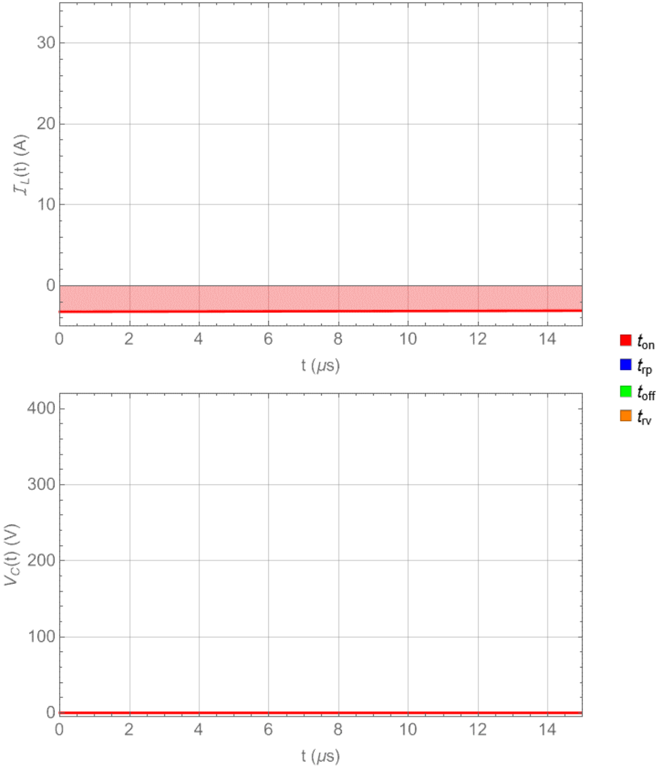
t_{rv} – **dead time** between the **SR turnoff** and the **control FET turnon**

TCM – constant t_{rv}

- No exact solution
- ZVD feedback
  - Eliminates another timing variable
  - Enables an exact solution







t_{on} – **on-time** of the **control FET**

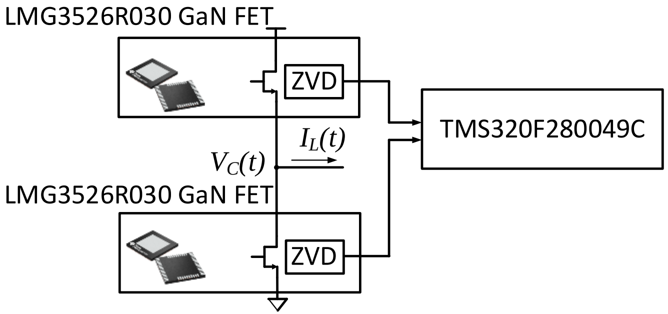
t_{off} – **on-time** of the **SR**

t_{rp} – **dead time** between the **control FET turnoff** and **SR turnon**

t_{rv} – **dead time** between the **SR turnoff** and the **control FET turnon**

Path to solution: Step 2 – ZVD feedback

- Status bit output indicating if turned on with ZVS
  - At 500 kHz, the gallium-nitride (GaN) switch achieves ZVS
  - At 1.3 MHz, the GaN switch loses ZVS

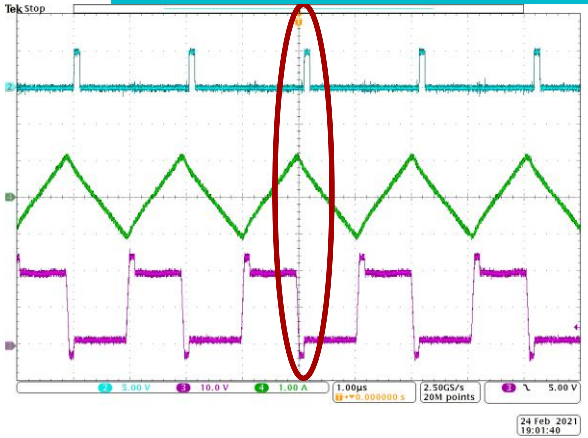


ZVD pulse indicates the achievement of ZVS in the device at turnon

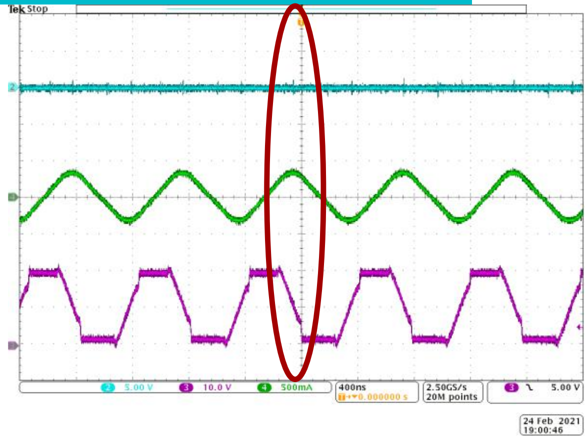
Low-side FET ZVD signal (5 V/div)

I_L (1 A/div)

V_{ds} (10 V/div)

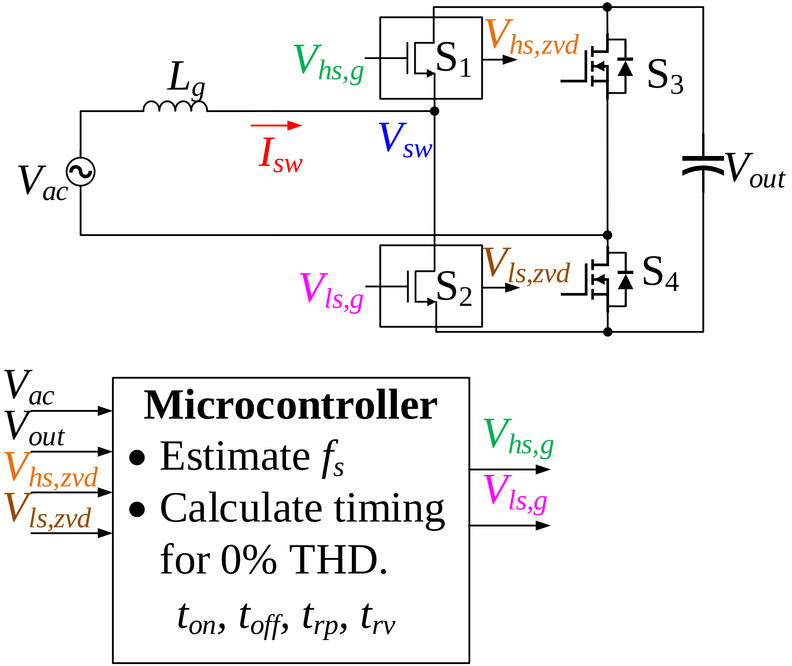


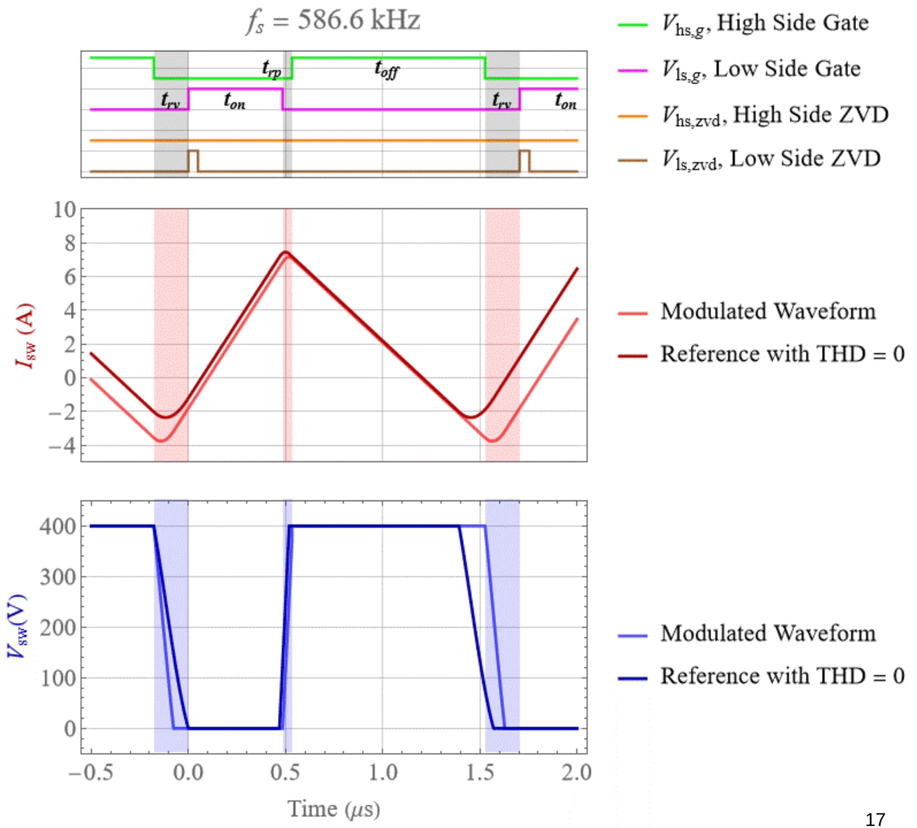
20 V and 500 kHz



20 V and 1.3 MHz

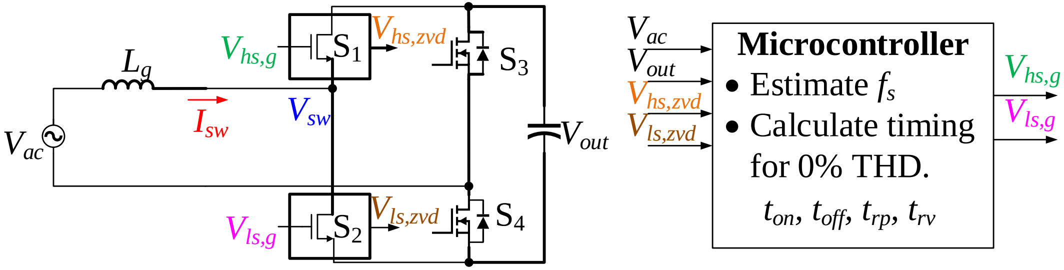
Exact solution: ZVD feedback and constant t_{rv}

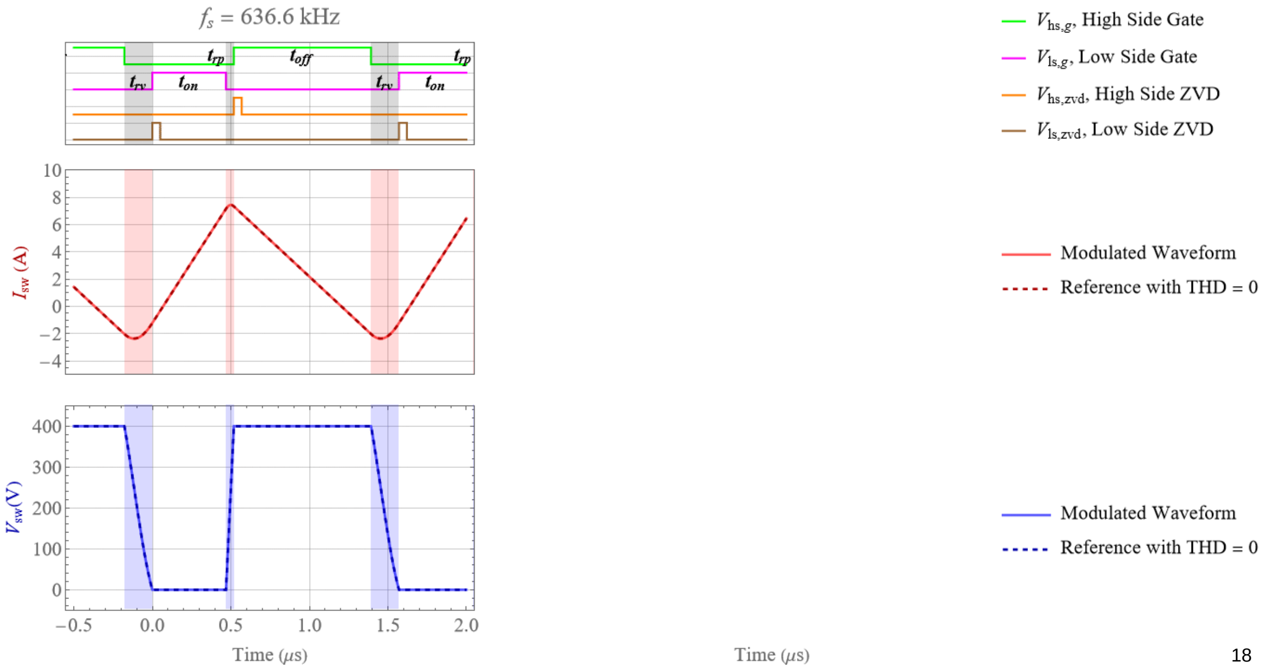




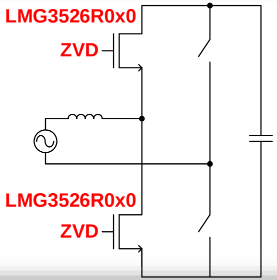
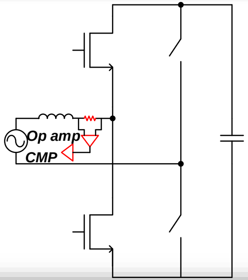
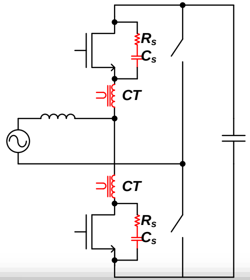
- Reduced control complexity
  - t_{rv} is a constant
  - ZVD feedback determines f_s
- Microcontroller now can force ZVS and unity power factor

Frequency dithering

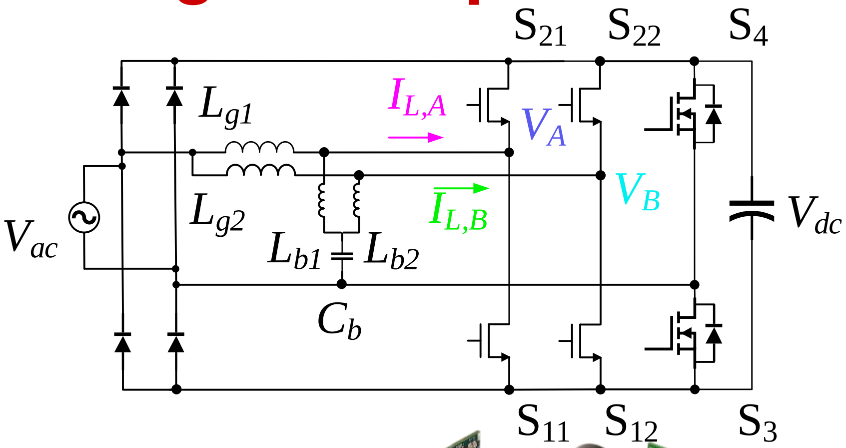


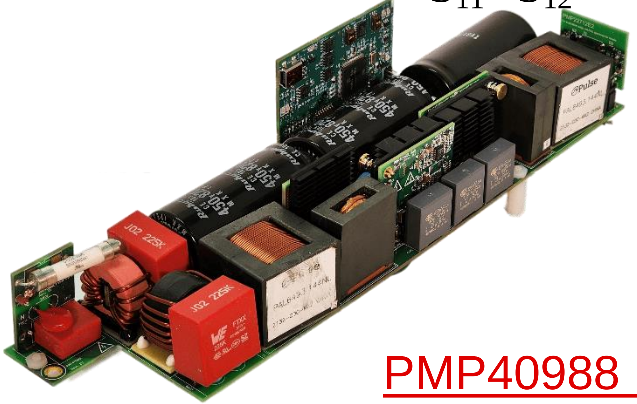


ZVD benefits and comparison to other solutions

	TI GaN ZVD feature LMG3526R0X0	Shunt resistor method	Current transformer method
Circuit diagram			
Periphery circuit	• One added channel in isolator	• One shunt resistor, • One high-bandwidth op amp • One fast comparator	• Two current transformers • Two comparators • Clamping circuits: two high-voltage capacitors, two resistors
Periphery circuit cost	**$**	$$$	$
Efficiency impact	**No impact**	Reduced efficiency caused by shunt loss	Reduced efficiency from current transformer and snubber circuit losses
Footprint size	**Almost no added footprint**	Large	Large
Control complexity	**Simple**	Complex	Complex

Design example – 5-kW PFC

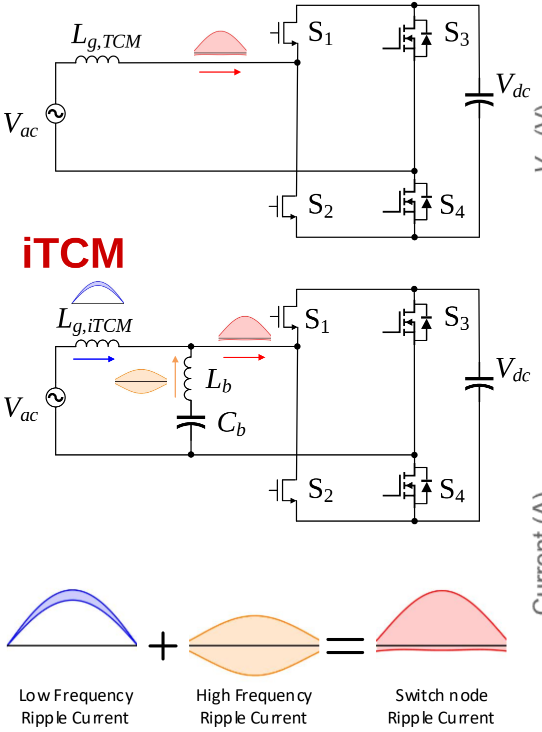


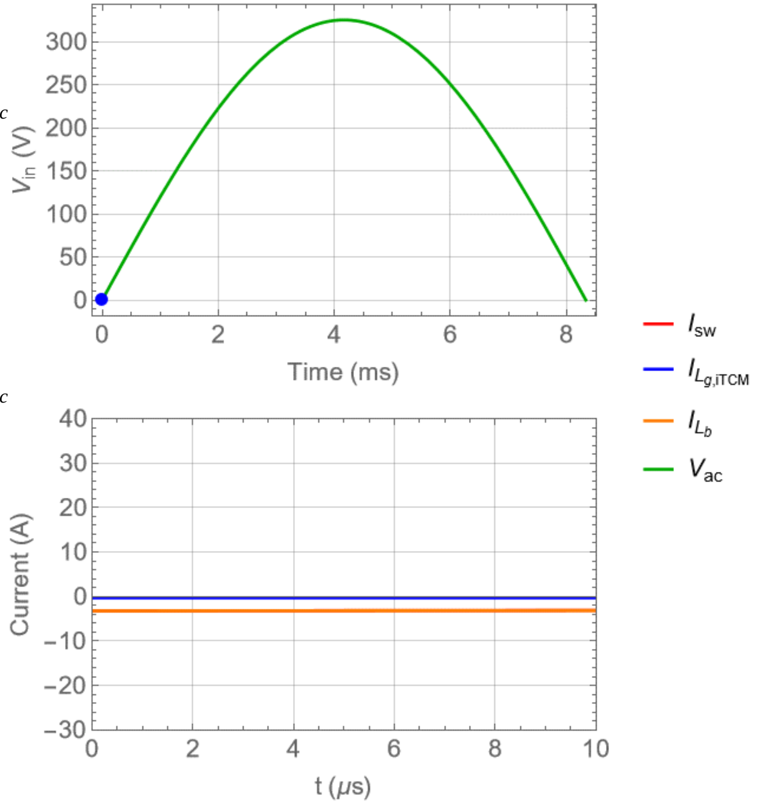


Parameters	Value
AC input	208 V-264 V
Line frequency	50-60 Hz
DC output	400 V
Maximum power	5 kW
Holdup time at full load	20 ms
L_g, low-frequency inductor	140 µH
L_b, high-frequency inductor	14 µH
C_b, high-frequency blocking capacitor	1.5 µF
THD	<5%
EMI	EN55022 Class A
Operating frequency	Variable, 75 kHz-1.2 MHz
Microcontroller	TI: TMS320F280049C
High-frequency GaN FETs (S_{11}, S_{12}, S_{22}, S_{21})	TI: LMG3526R030
Internal dimensions	38 mm × 65 mm × 263 mm
Power density	120 W/in^3

PMP40988 link

iTCM vs. TCM design

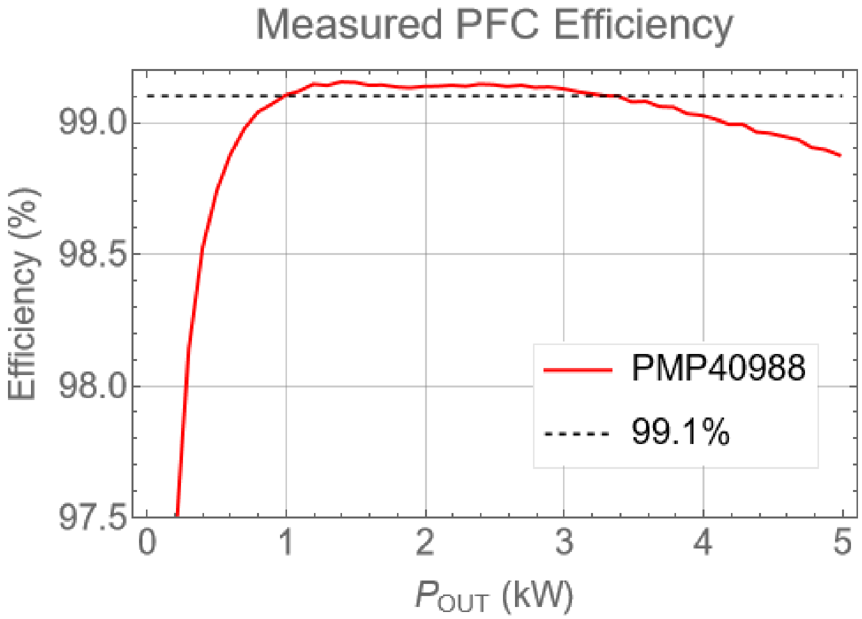


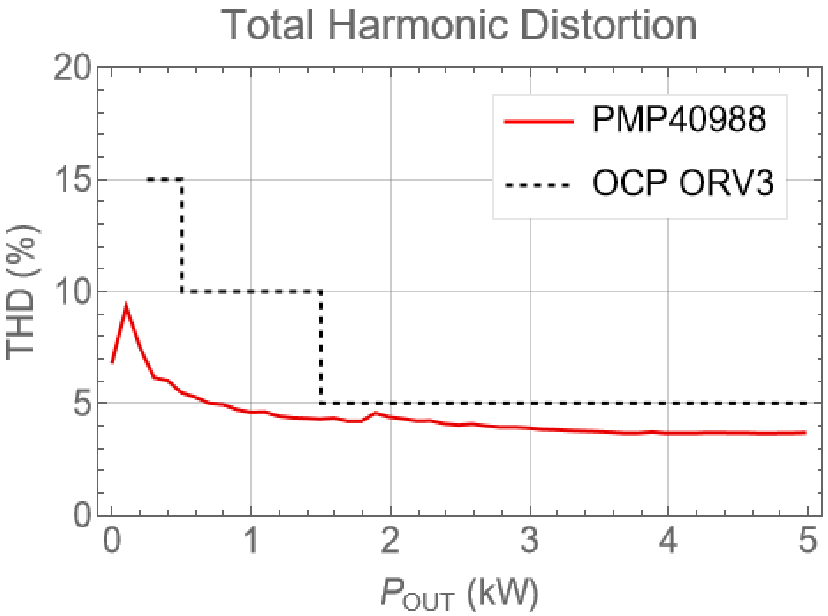


iTCM potential benefits

- Optimized inductors
  - L_b (ferrite) – reduced peak currents
  - $L_{g,iTCM}$ inductor (powder iron) – low ripple
    - $L_{g,TCM}$ is ferrite for high-frequency ripple
- Improved differential-mode EMI as high-frequency ripple bypasses input
  - Reduces EMI filter size
  - $L_{g,iTCM}$ forms part of differential-mode filter
- $L_{g,TCM} = L_{g,iTCM} \parallel L_b$

Efficiency and THD with phase shedding



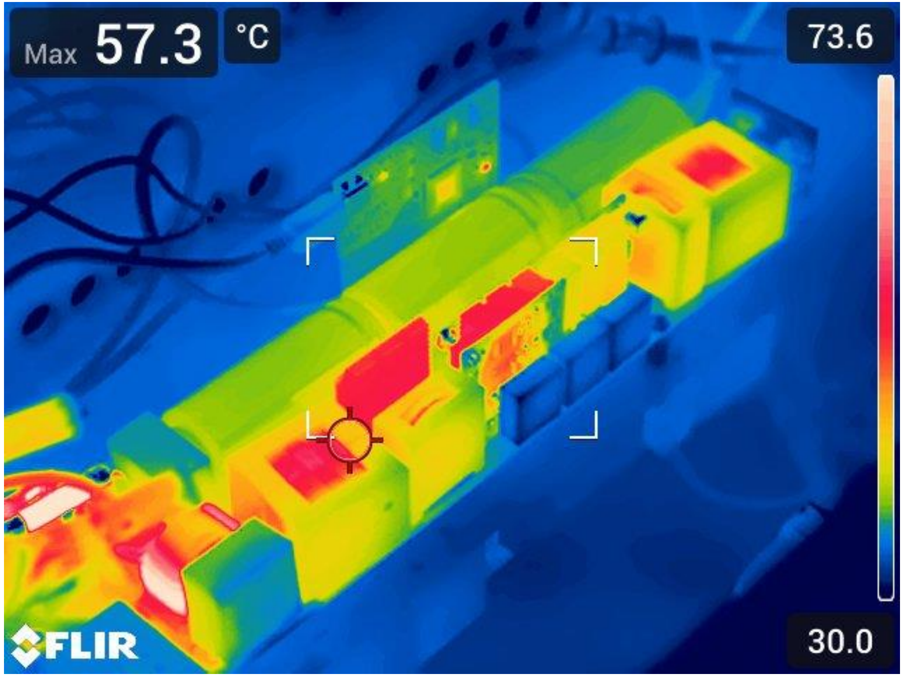


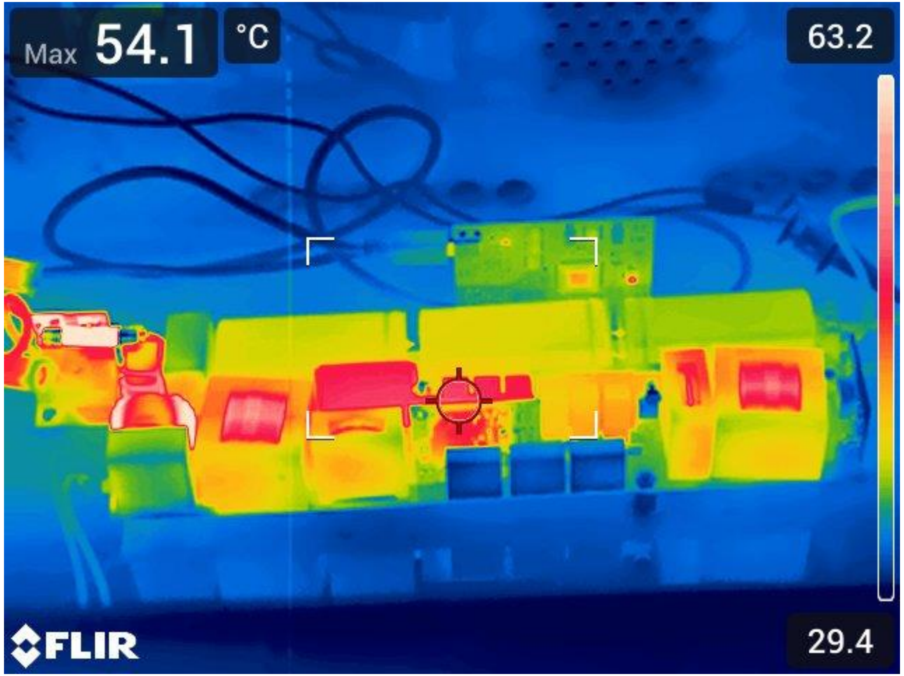
V_{IN}: 230 V
Phase shedding/additional threshold: 1.8 kW

Texas Instruments

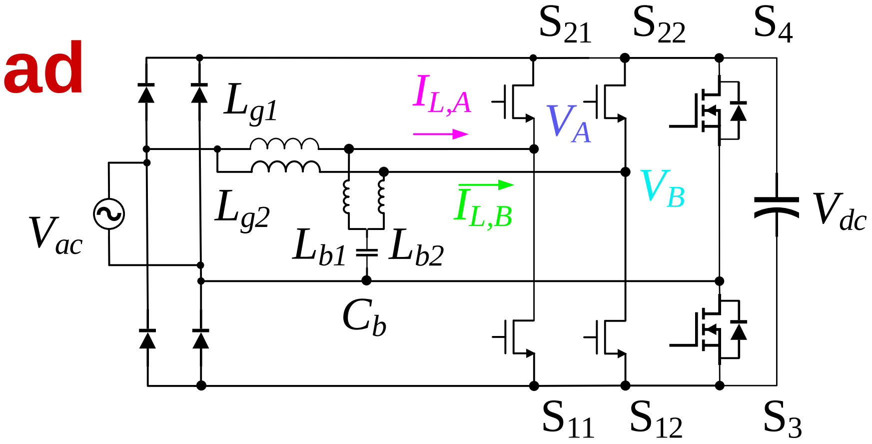
Full-load thermal scan

V_{IN} = 230 V_{AC}
V_{OUT} = 400 V
I_{OUT} = 12.5 A
38 CFM fan



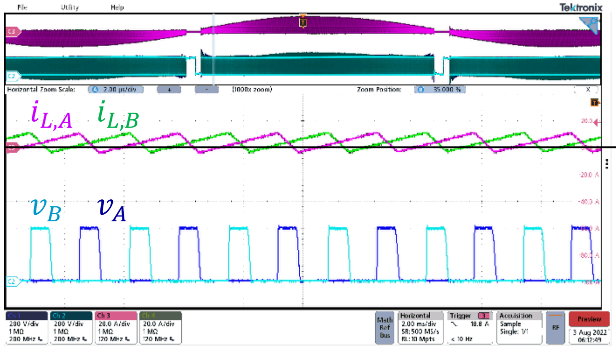


Experimental results – full load



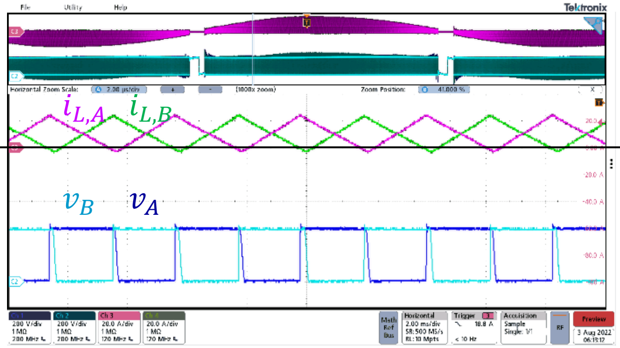
$V_{IN} = 230$ VRMS $V_{OUT} = 400$ V P = 5 kW

$V_{IN} \ll VOUT/2$



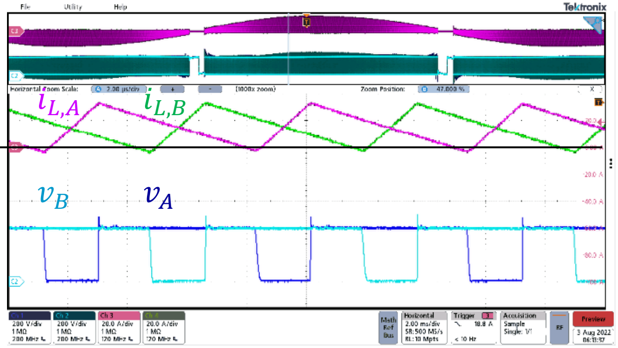
200 V/div, 20 A/div, 2 µs/div

$V_{IN} = V_{OUT}/2$



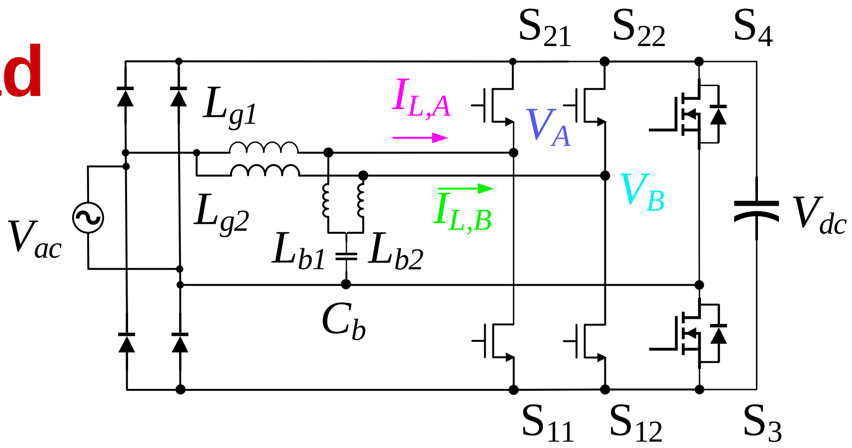
200 V/div, 20 A/div, 2 µs/div

$V_{IN} \gg V_{OUT}/2$



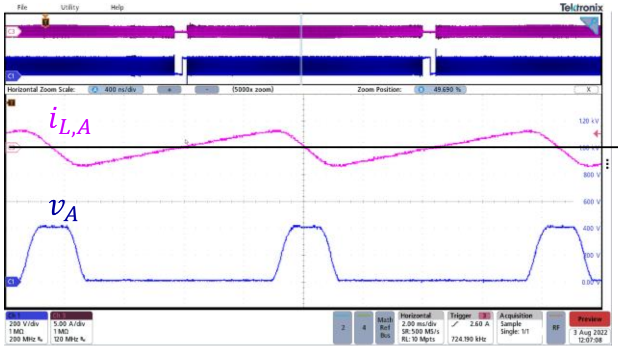
200 V/div, 20 A/div, 2 µs/div

Experimental results – no load



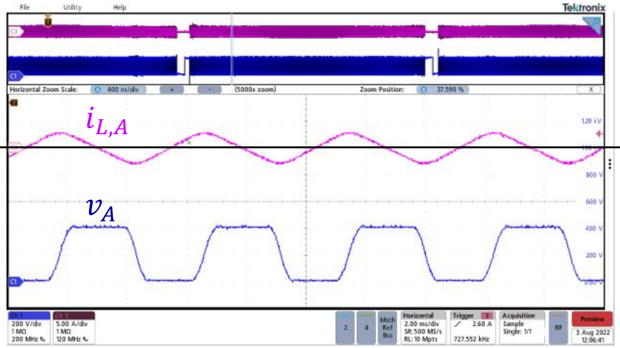
$V_{IN} = 230$ VRMS $\quad V_{OUT} = 400$ V $\quad P = 0$ kW

$V_{IN} \ll VOUT/2$



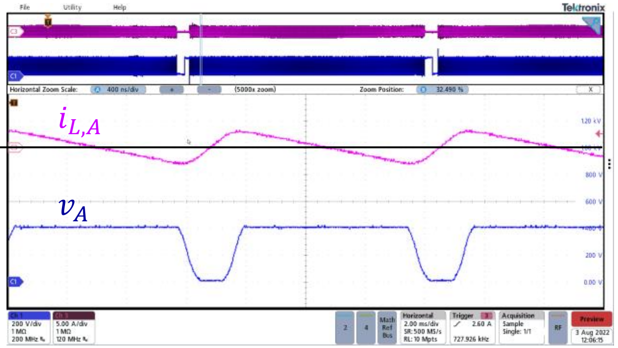
200 V/div, 5 A/div, 400 ns/div

$V_{IN} = VOUT/2$



200 V/div, 5 A/div, 400 ns/div

$V_{IN} \gg VOUT/2$



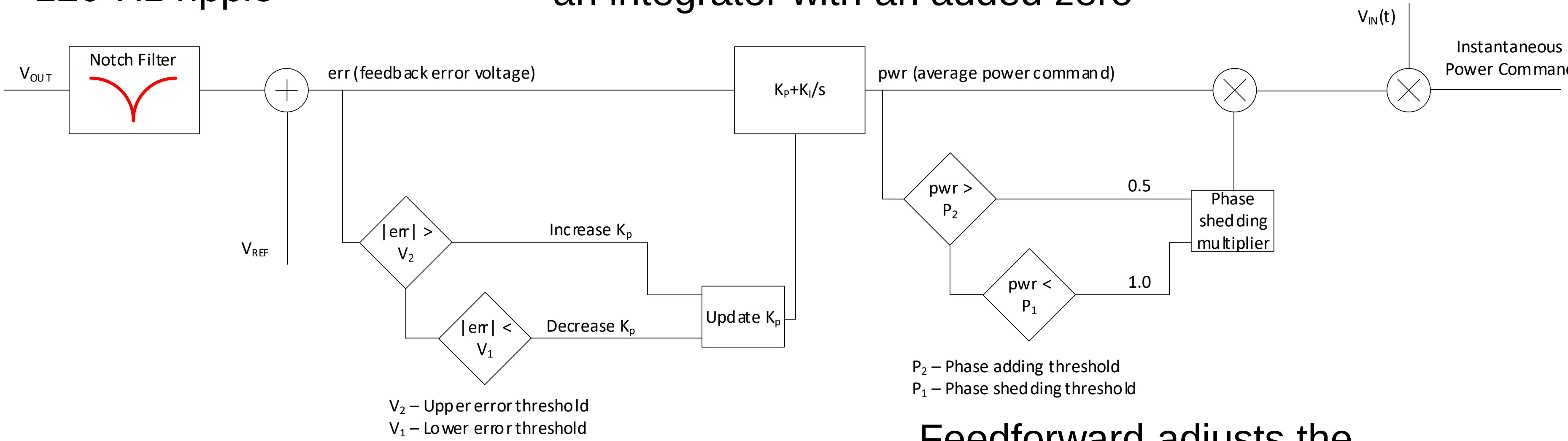
200 V/div, 5 A/div, 400 ns/div

Texas Instruments

Voltage-loop compensator

Notch filter removes 120-Hz ripple

Standard proportional integral controller equivalent to an integrator with an added zero

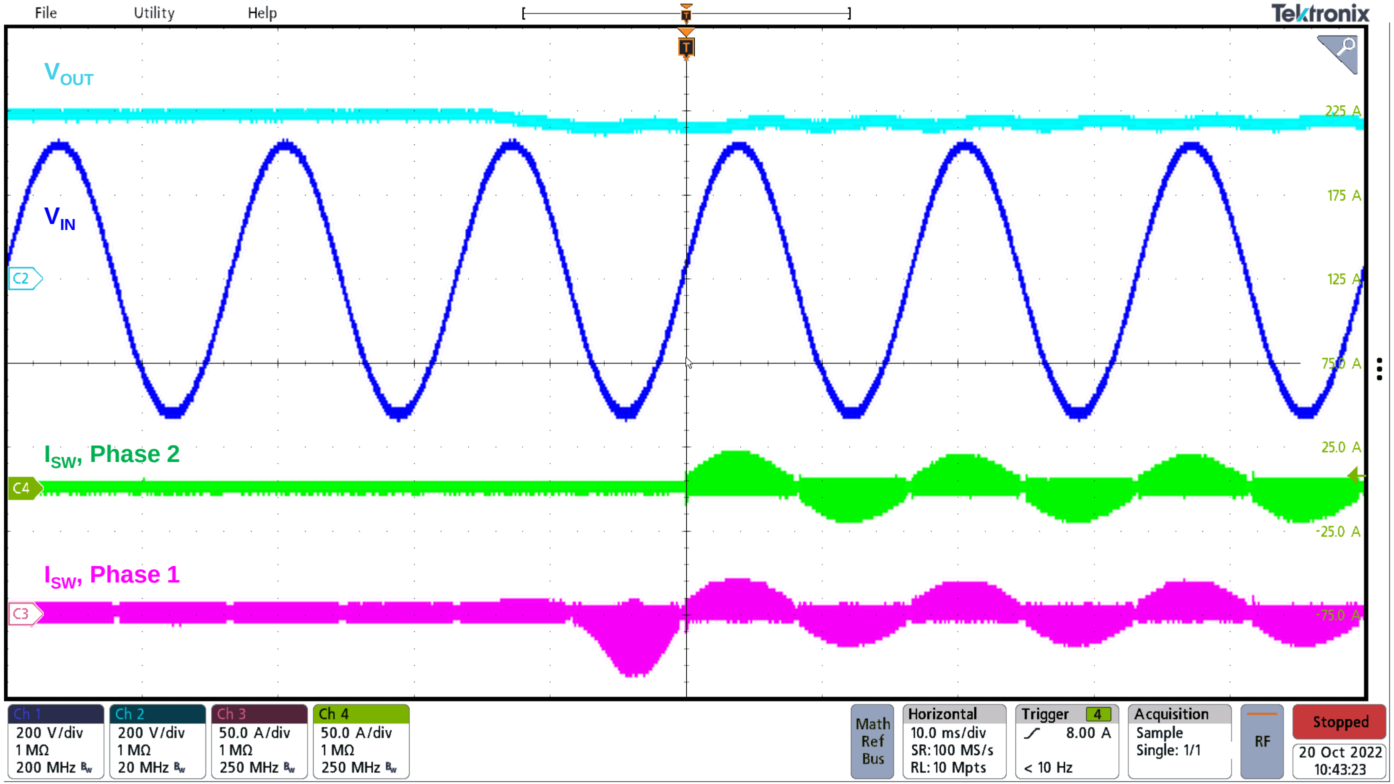


Dynamically change K_p to enable faster transient response when the output is far from its target

Feedforward adjusts the power command to each phase depending on how many phases are running

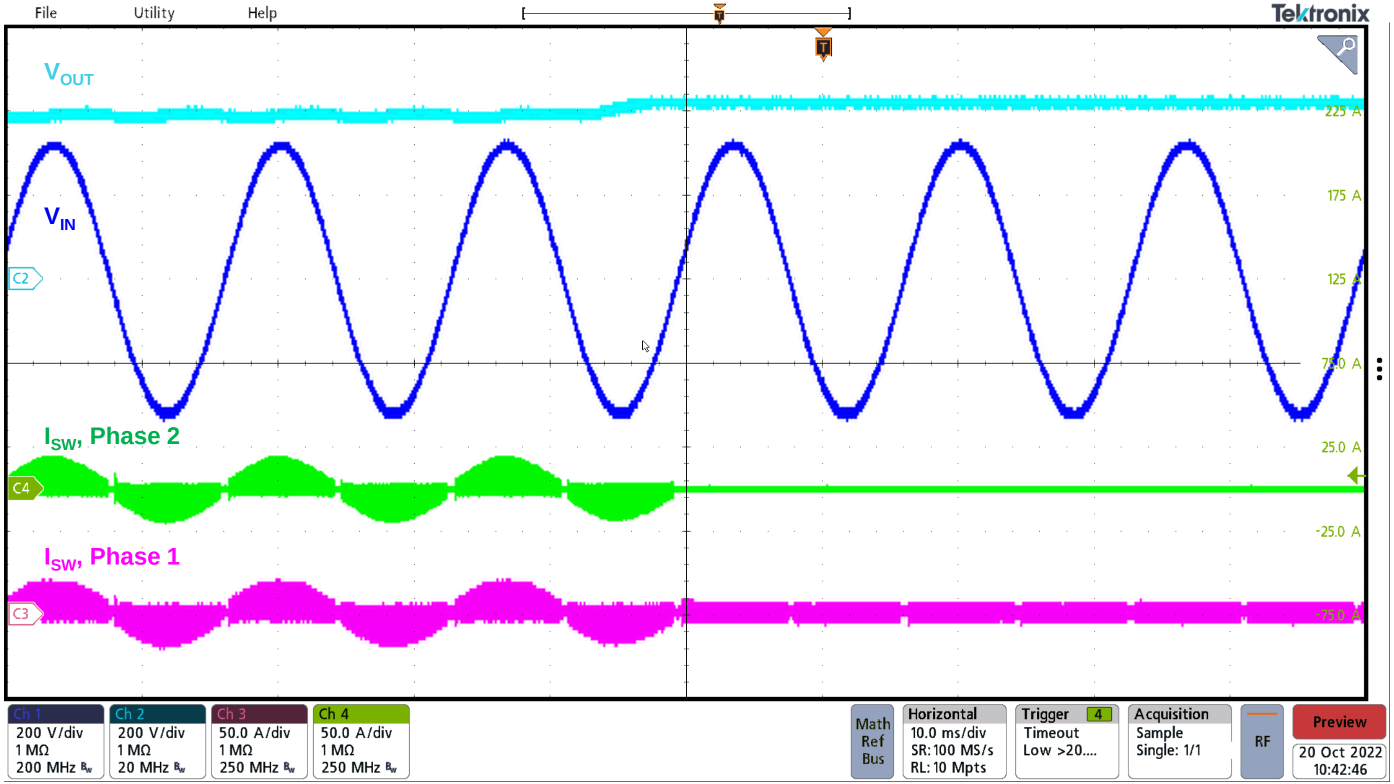
Load transient: 40 W → 2.5 kW

V_{IN} = 230 V_{AC}
V_{OUT} = 400 V
I_{OUT} = 0.1 A to 6.25 A



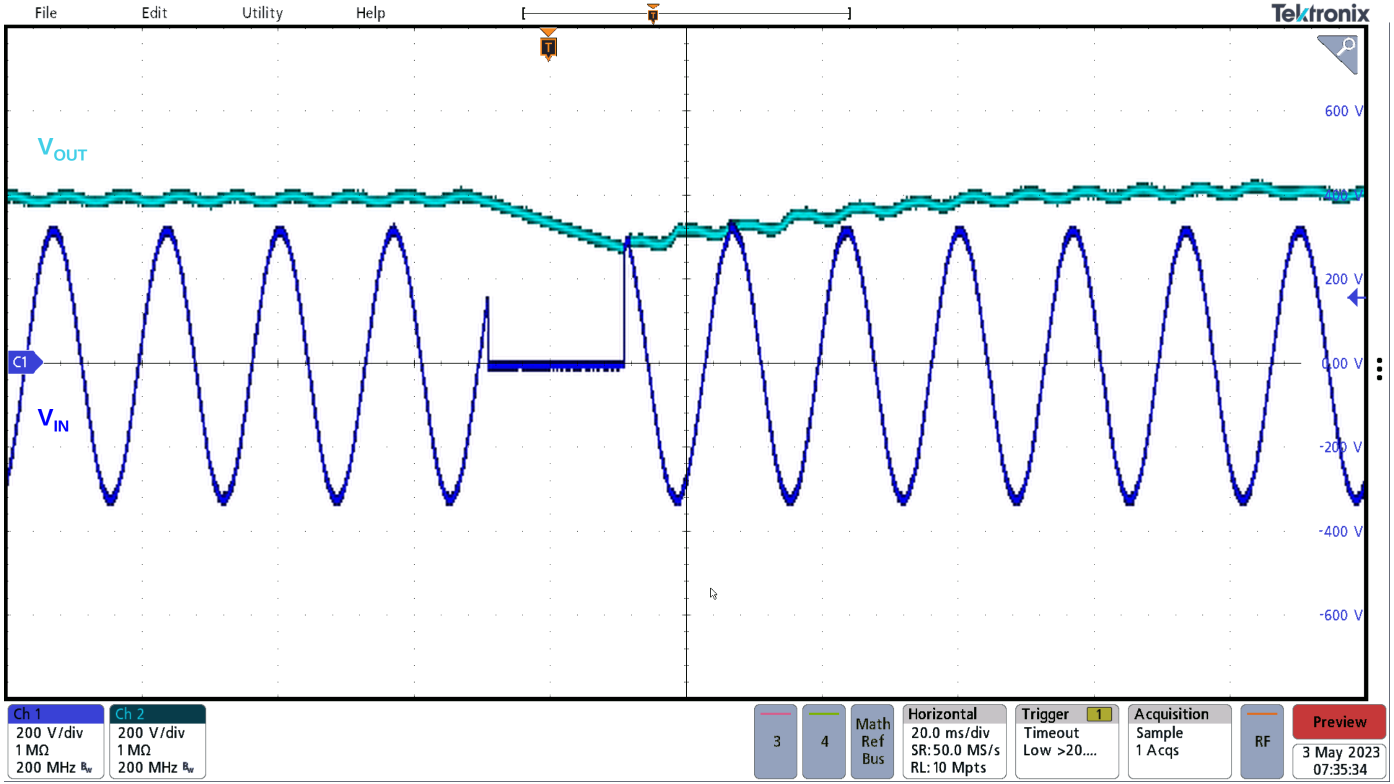
Load transient: 2.5 kW → 40 W

V_{IN} = 230 V_{AC}
V_{OUT} = 400 V
I_{OUT} = 6.25 A to 0.1 A



AC dropout and restore

V_{IN} = 230 V_{AC}
V_{OUT} = 400 V
I_{OUT} = 12.5 A
Dropout = 20 ms
Phase = 30 degrees



Texas Instruments

Summary and conclusions

- A computationally simple TCM PFC control:
  - Achieves ZVS across the full line and load range
  - Achieves best-in-class THD
  - Requires no control current sensor
- A two-phase interleaved solution using variable frequency and ideal interleaving
  - Efficiency >99.1%
  - THD <5%
- The use of a new ZVD-enabled GaN FET
- ZVD enables the use of a cost-effective C2000™ microcontroller

References

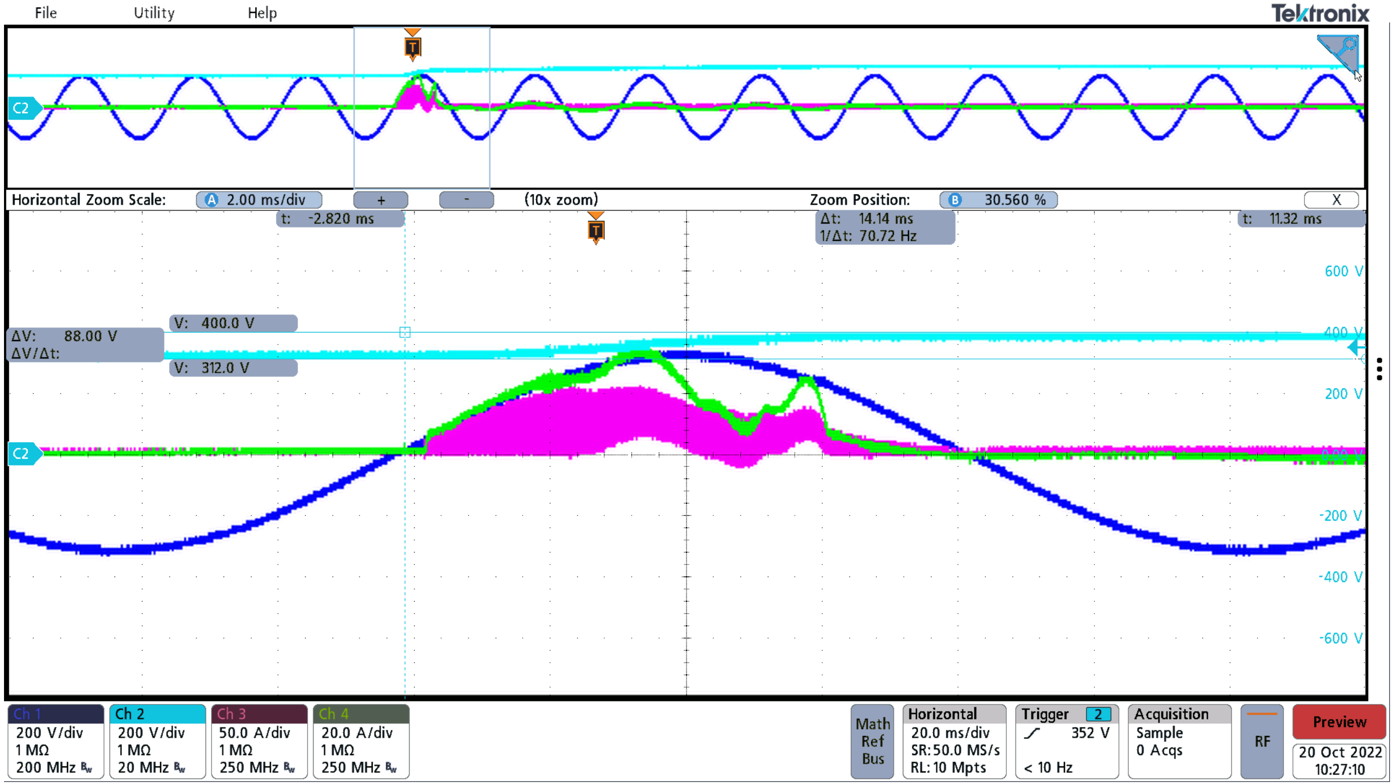
- Fernandes, Ryan, and Olivier Trescases. “A Multimode 1-MHz PFC Front End with Digital Peak Current Modulation.” Published in IEEE Transactions on Power Electronics 31, no. 8 (August 2016): pp. 5694-5708. doi: 10.1109/TPEL.2015.2499194.
- Lim, Shu Fan, and Ashwin M. Khambadkone. “A Multimode Digital Control Scheme for Boost PFC with Higher Efficiency and Power Factor at Light Load.” Published in 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Feb. 5-9, 2012, pp. 291-298. doi: 10.1109/APEC.2012.6165833.
- Rothmund, Daniel, Dominik Bortis, Jonas Huber, Davide Biadene, and Johann W. Kolar. “10kV SiC-Based Bidirectional Soft-Switching Single-Phase AC/DC Converter Concept for Medium-Voltage Solid-State Transformers.” Published in 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), April 17-20, 2017, pp. 1-8. doi: 10.1109/PEDG.2017.7972488.
- Liu, Zhengyang. 2017. “Characterization and Application of Wide-Band-Gap Devices for High Frequency Power Conversion.” Ph.D. dissertation, Virginia Polytechnic Institute and State University. http://hdl.handle.net/10919/77959.

Backup

Startup

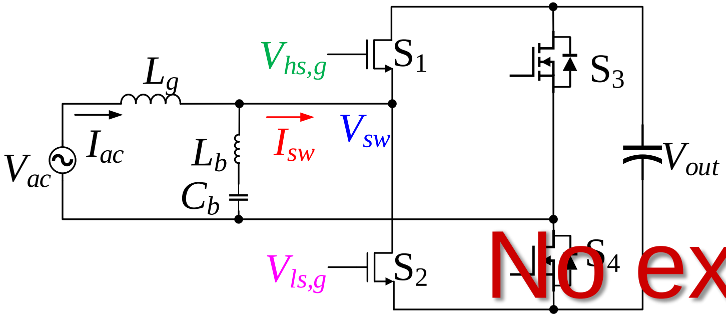
V_{IN} = 230 V_{AC}
V_{OUT} = 400 V
I_{OUT} = 0 A

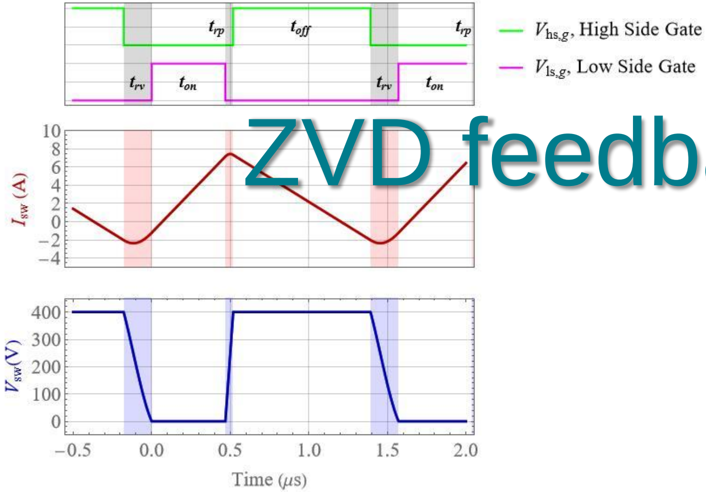
CH1 – V_{IN}
CH2 – V_{OUT}
CH3 – I_{SW}, master
CH4 – I_{IN}

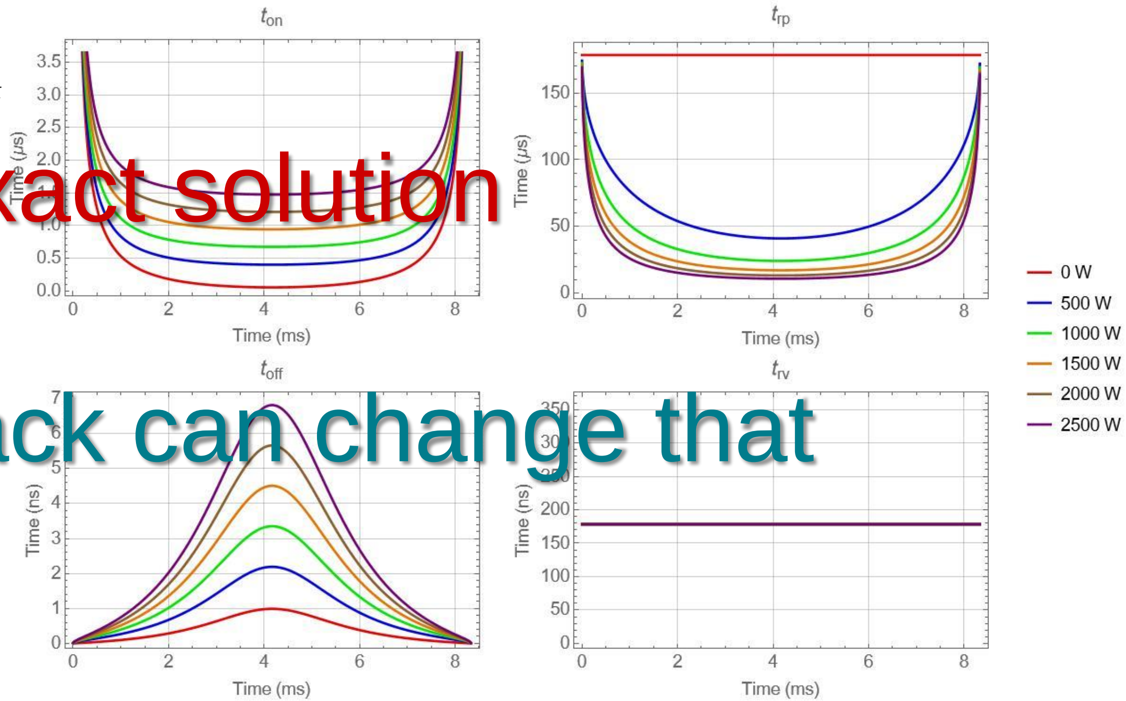


Complete timing solution

t_{on} – **on-time** of the **control FET**
t_{off} – **on-time** of the **SR**
t_{rp} – **dead time** between the **control FET turnoff** and **SR turnon**
t_{rv} – **dead time** between the **SR turnoff** and the **control FET turnon**







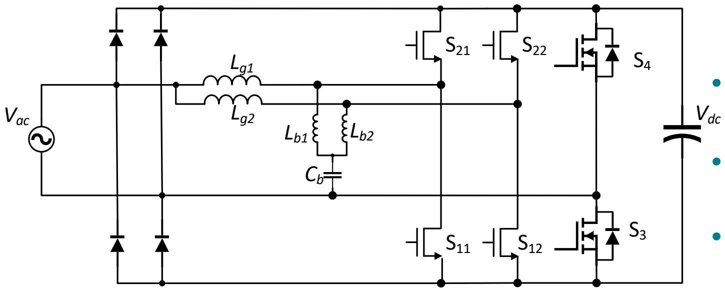
No exact solution

ZVD feedback can change that

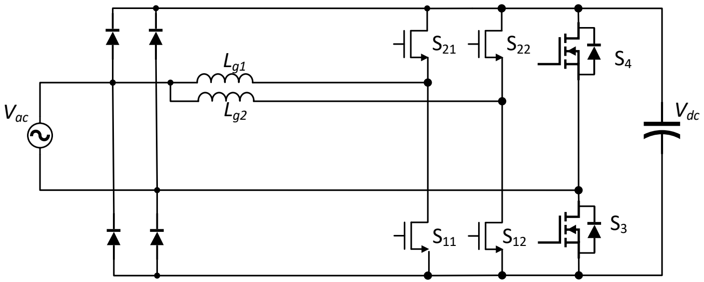
iTCM and TCM design equations

$V_{g,\text{peak}}$	$230\sqrt{2}$
V_{out}	400
f_{min}	75 000
P	5000
I_{ZVS}	4
r	0.2
d	0.25

$L_{g,\text{TCM}} = \frac{V_{g,\text{peak}}^2 (V_{\text{out}} - V_{g,\text{peak}})}{2 f_{\text{min}} V_{\text{out}} (I_{\text{zvs}} V_{g,\text{peak}} + 2P)}$	11.6604×10^{-6}
$L_{g,\text{iTCM}} = \frac{V_{g,\text{peak}}^2 (V_{\text{out}} - V_{g,\text{peak}})}{2 P r f_{\text{min}} V_{\text{out}}}$	131.775×10^{-6}
$L_{b,\text{iTCM}} = \frac{V_{g,\text{peak}}^2 (V_{g,\text{peak}} - V_{\text{out}})}{2 f_{\text{min}} V_{\text{out}} (P(r-2) - I_{\text{zvs}} V_{g,\text{peak}})}$	12.7924×10^{-6}
$C_{b,\text{iTCM}} = \frac{V_{\text{out}} (I_{\text{zvs}} V_{g,\text{peak}} - P(r-2))}{2\pi^2 d f_{\text{min}} V_{g,\text{peak}}^2 (V_{\text{out}} - V_{g,\text{peak}})}$	1.40808×10^{-6}



- $L_{g,iTCM} = \frac{V_{g,peak}^2 \cdot (V_{out} - V_{g,peak})}{2 \cdot P \cdot r \cdot V_{out} \cdot f_{min}}$
- $L_{b,iTCM} = \frac{V_{g,peak}^2 \cdot (V_{g,peak} - V_{out})}{2 \cdot V_{out} \cdot f_{min} \cdot (P \cdot (r-2) - I_{zvs} \cdot V_{g,peak})}$
- $C_{b,iTCM} = \frac{V_{out} \cdot (I_{zvs} \cdot V_{g,peak} - P \cdot (r-2))}{2 \cdot \pi^2 \cdot d \cdot f_{min} \cdot V_{g,peak}^2 \cdot (V_{out} - V_{g,peak})}$



- $L_{g,TCM} = \frac{V_{g,peak}^2 \cdot (V_{out} - V_{g,peak})}{2 \cdot V_{out} \cdot f_{min} \cdot (I_{zvs} \cdot V_{g,peak} + 2 \cdot P)}$

- $I_{sw,pk}$ – peak current in the switch
- I_{avg} – cycle-by-cycle average inductor current
- $\Delta I_{L_{g,<i>TCM}}$ – delta I in the inductor
- D – duty cycle
- I_{zvs} – current required for ZVS
- V_{out} – output voltage
- $V_{g,peak}$ – peak AC input voltage
- f_{min} – minimum desired switching frequency
- P – output power
- r – ripple current ratio
- d – impedance ratio