High VOLT Interactive

Where power supply design meets collaboration

Maximizing efficiency of your LLC power stage: design, magnetics and component selection

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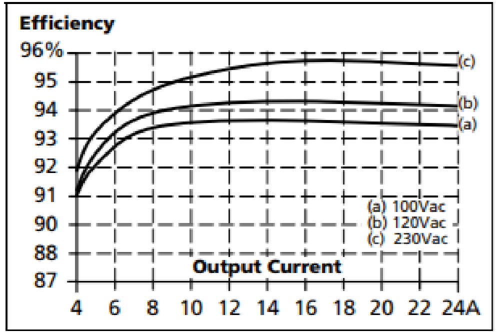
What will I get out of this session?

- In this session we will look at the design considerations for developing high efficiency LLC converters
- Reference design examples based on TI's LLC and SR controllers

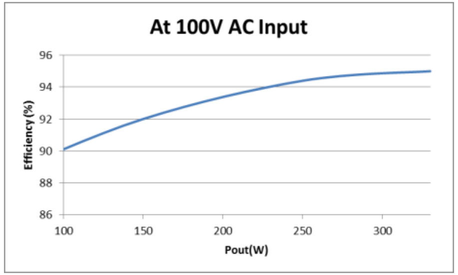
- Part numbers mentioned:
  - UCC25630x
  - UCC24612
  - UCC24624
- Reference designs mentioned:
  - TIDA-01494 (Industrial AC/DC)
  - TIDA-01501 (PC PSU AC/DC)
  - TIDA-010015 (Industrial AC/DC, TV PSU)
  - TIDA-01495 (PC PSU AC/DC)
  - TIDA-01557 (PC PSU AC/DC)

Industrial AC/DC, D_{IN} rail



~97% efficiency DC/DC stage

Next gen gaming PC adaptor

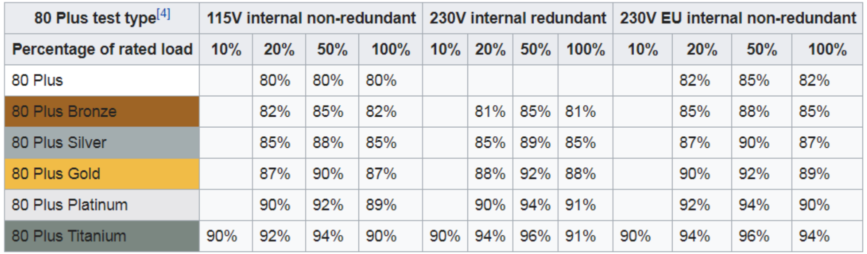


160x75x35 cm

~97% efficiency at 90V AC input

Server PSU

>98% efficiency from PFC stage

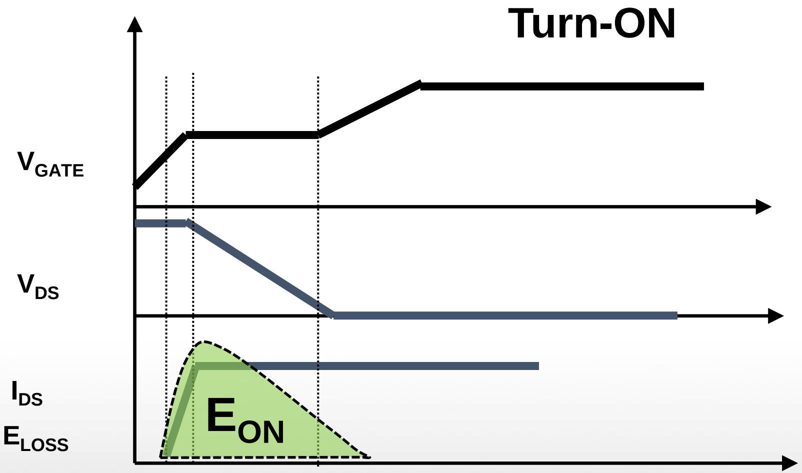


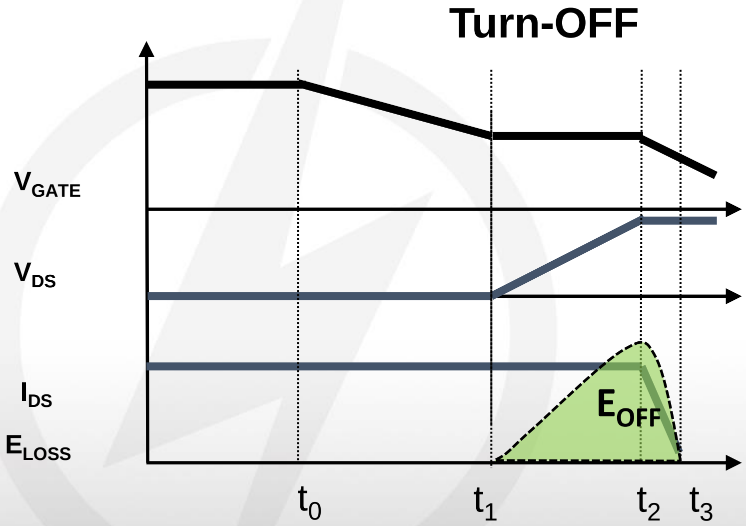
80 Plus test type[4]	115V internal non-redundant				230V internal redundant				230V EU internal non-redundant			
Percentage of rated load	10%	20%	50%	100%	10%	20%	50%	100%	10%	20%	50%	100%
80 Plus		80%	80%	80%						82%	85%	82%
80 Plus Bronze		82%	85%	82%		81%	85%	81%		85%	88%	85%
80 Plus Silver		85%	88%	85%		85%	89%	85%		87%	90%	87%
80 Plus Gold		87%	90%	87%		88%	92%	88%		90%	92%	89%
80 Plus Platinum		90%	92%	89%		90%	94%	91%		92%	94%	90%
80 Plus Titanium	90%	92%	94%	90%	90%	94%	96%	91%	90%	94%	96%	94%

Overall peak efficiency >96%

Apart from using bridgeless PFC
need >97.5% peak efficiency DC/DC stage

Switching losses





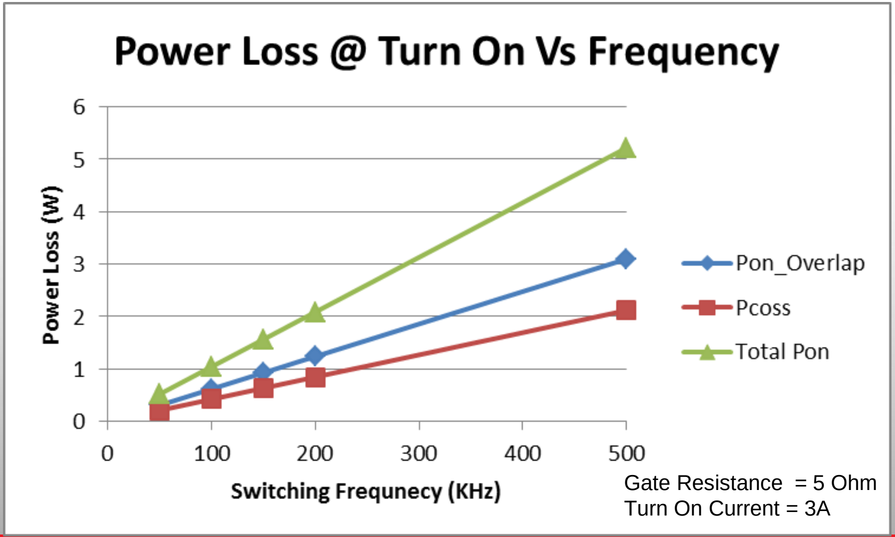
In hard-switched converters

- Current & voltage overlap @ turn-on & turn-off
- Results in significant switching losses
- Limits switching frequencies, power density
- Increased EMI issues

- Additional losses due to output capacitance (C_{oss})
- In half-bridge configurations, reverse recovery (Q_{rr}) losses can also be present

Why soft switching?

- As the demand for higher power density in power supplies increases:
    - Need to increase switching frequency
    - Hence need to reduce losses associated with switching
- An example: using a state of the art SJ MOSFET in a 400W power supply IPB60R180C7



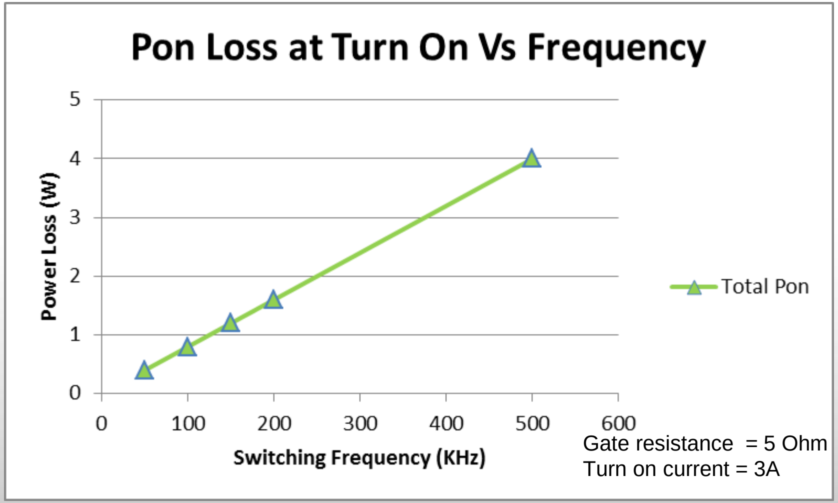
Gate Resistance = 5 Ohm
Turn On Current = 3A

- For a hard switched half bridge converter operating @ 200KHz
- Pon losses 2x2.1W = 4.2W
- A soft switched converter will have >1% efficiency improvement in this example.
- And the EMI signature?

Data taken comparing CCM PFC with SiC diode

If I use GaN, do I need to worry about switching loss?

- Let’s look at a popular GaN in the market

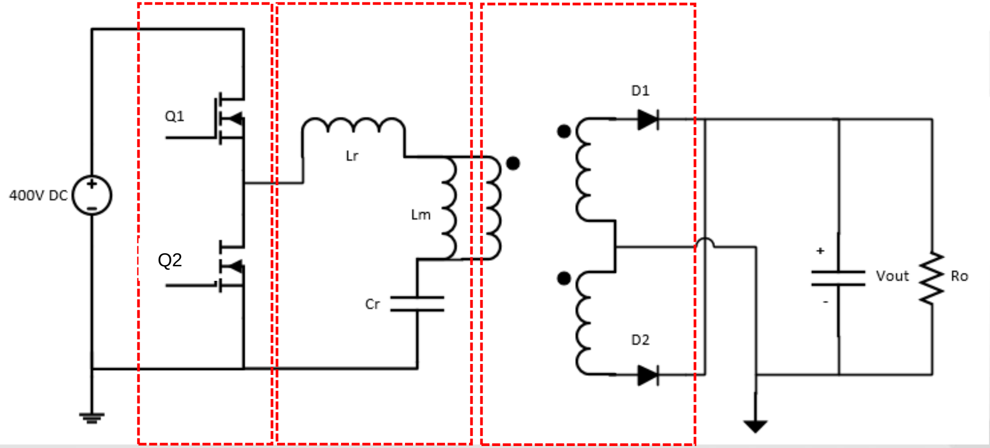


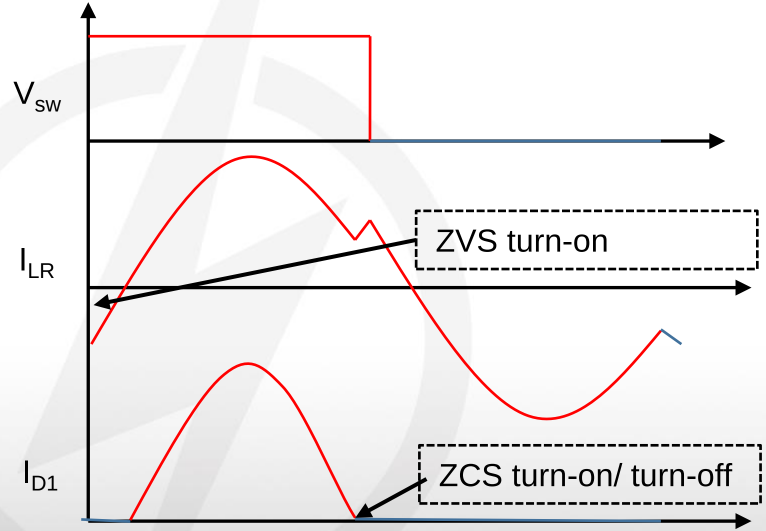
Gate resistance = 5 Ohm
Turn on current = 3A

- Compared to the latest generation SJ MOSFET, under hard switching:
  - GaN has lower turn-off losses
  - Turn-on losses are almost similar
- Higher dv/dt also results in more EMI concerns.

Soft switched topologies are even more important for exploiting GaN

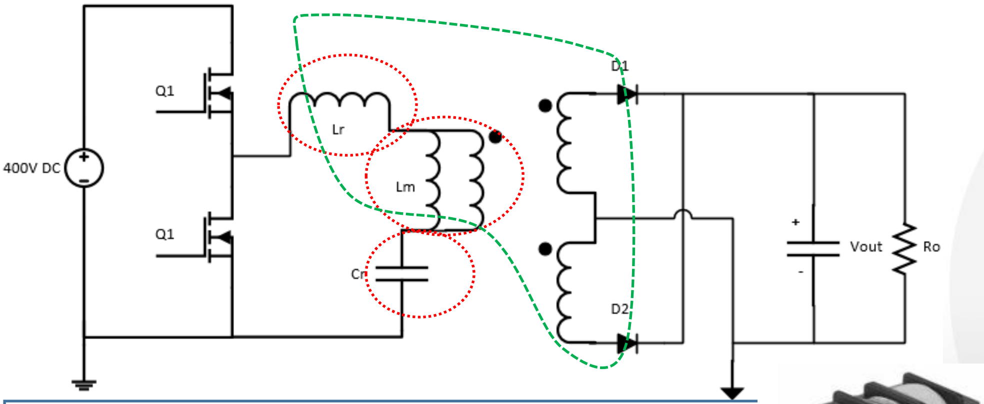
Resonant converters





- The switch network on the primary applies a square wave to the resonant tank
- The resonant tank’s fundamental frequency is close the frequency of the square wave
- The rectifier on the secondary side applies a rectified and filtered sinusoidal current to the load

LLC resonant converter



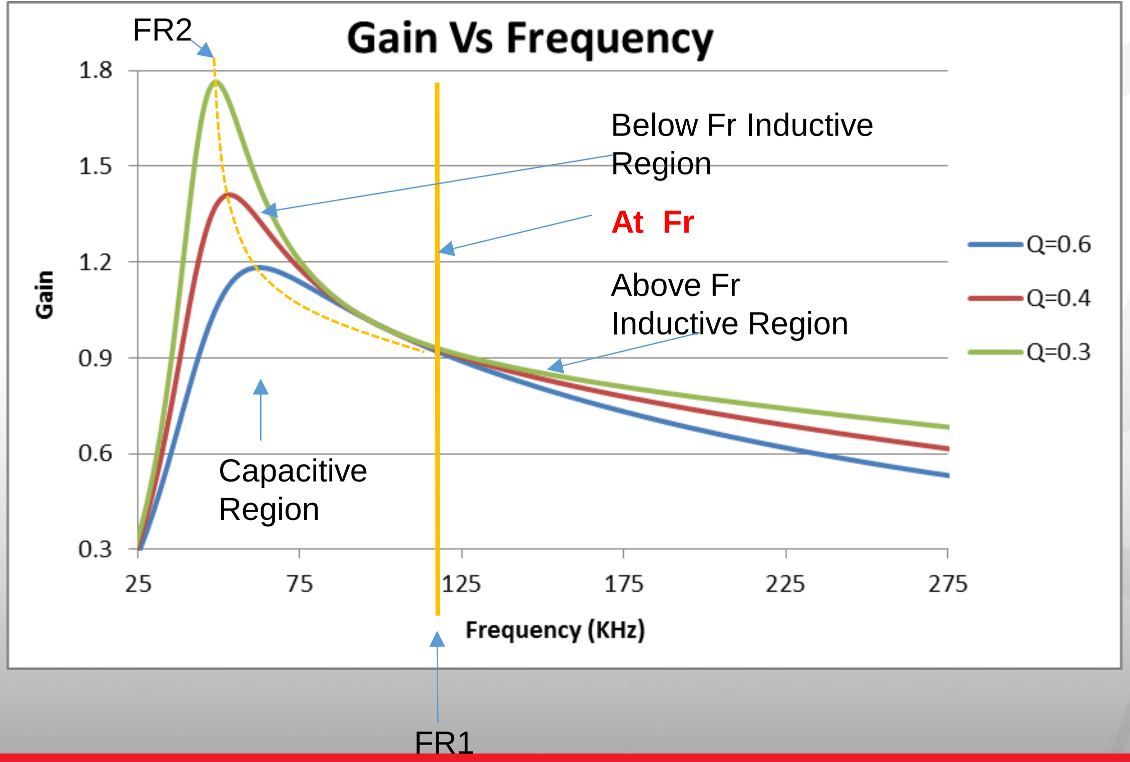
The Lr , Lm & Cr form the resonant tank

Using integrated magnetics, it’s possible to implement $Lr\ (leakage\ inducatnce)$ & $Lm\ (magnetizing\ inductance)$ using the same transformer core

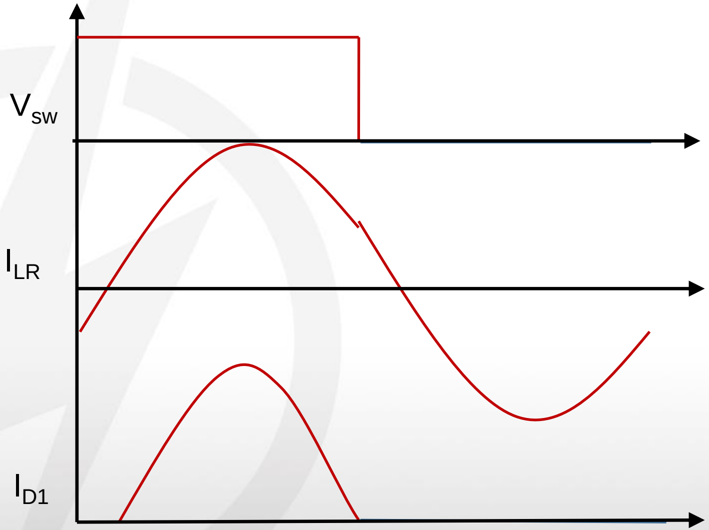
Advantages of LLC converters

- The low magnetizing inductance enables ZVS even at no load (higher magnetizing current)
- LLC converters can regulate output voltage even under no load conditions
- Can be designed to operate in a narrow frequency range over a wide output load range

The gain curve

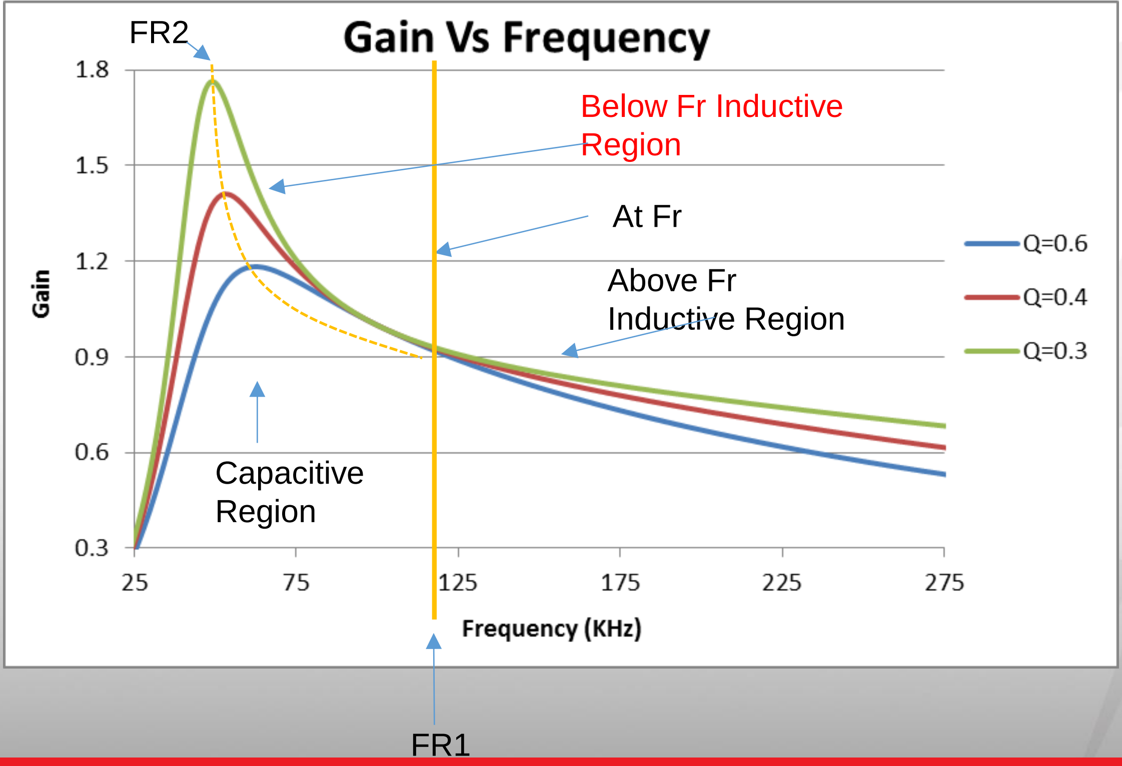


At resonance Fr

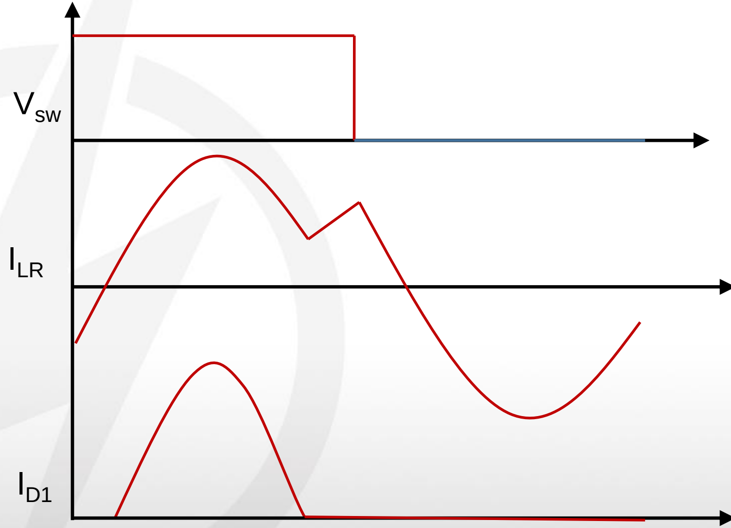


- Lowest RMS currents
- Unity gain point
- ZVS for HV MOSFET & ZCS for SR MOSFET

The gain curve

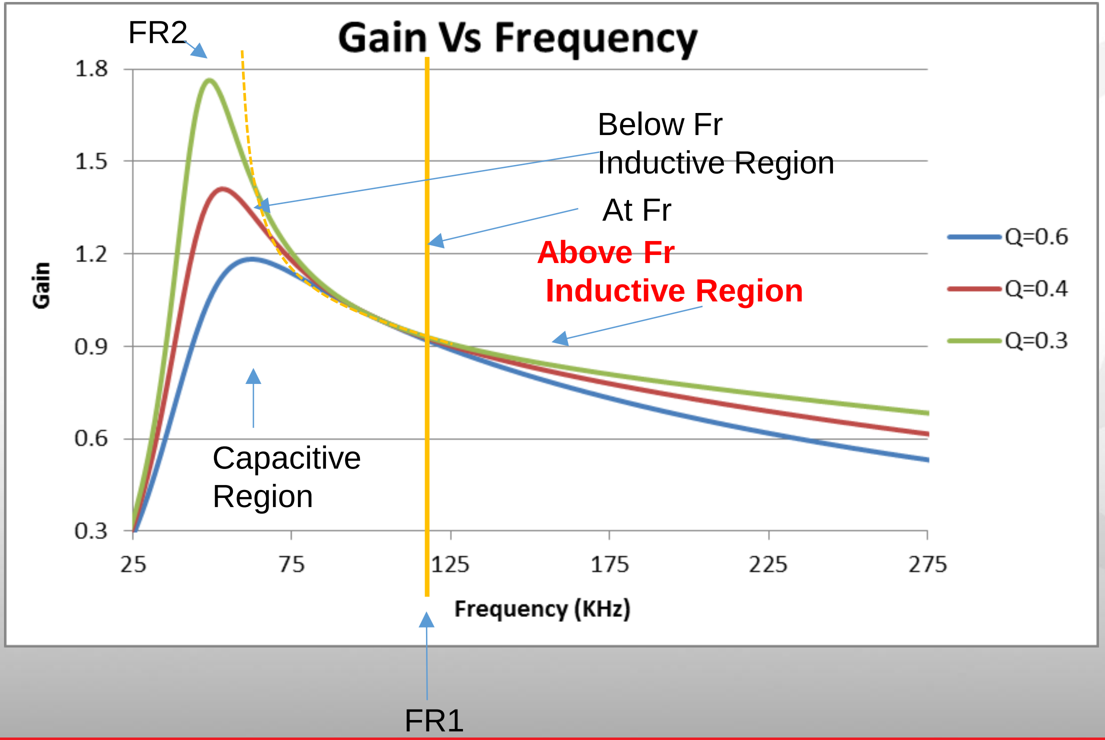


Below Fr Inductive region

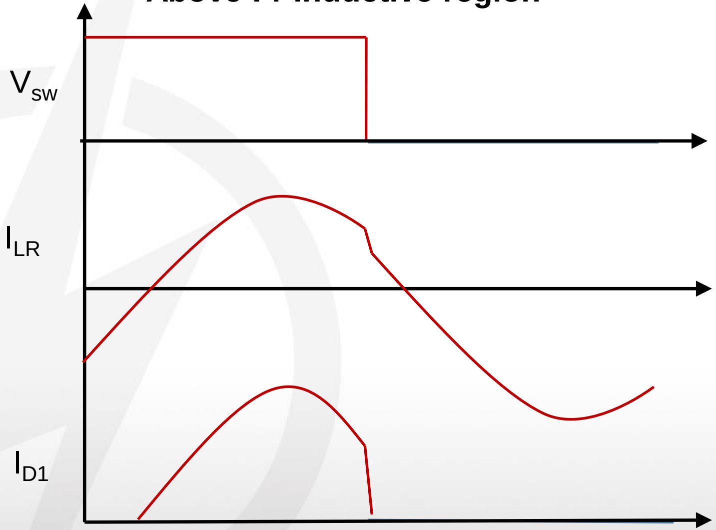


- Higher RMS currents
- Can get high gain
- ZVS for HV MOSFET & ZCS for SR MOSFET

The gain curve



Above Fr inductive region



- Frequency Increases to operate at light load
- ZVS for HV MOSFET
- High di/dt on SR MOSFET at turn-off results in Q_{rr} losses

Design procedure

- As an example we look at a 500W HB-LLC design
- The key design input parameters are given below

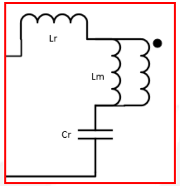
Parameter	Value
Output voltage & current	24V, 21A
Nominal input voltage	390V
Minimum input voltage*	310V
Full load efficiency @ nominal input	96.5%

- The minimum input voltage is EE dependent
  - In industrial, server PSU, it could be based on holdup time
  - In TV power supplies, it might need to operate even from 90VDC (standby load conditions)

Dimensioning the Resonant Tank

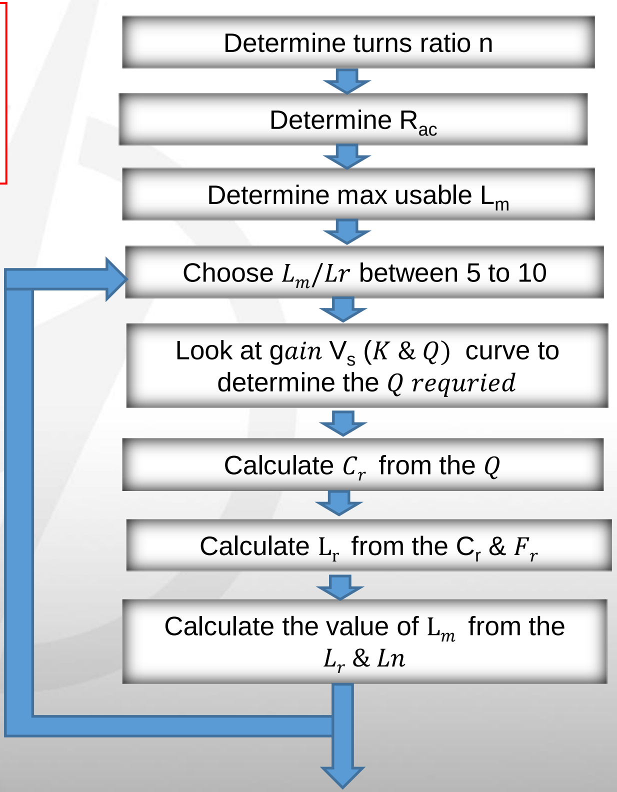
Resonant tank components are very critical for high efficiency:

- High L_m reduces circulating current, hence reduces conduction losses
- But high L_m reduces the available energy at light load to create ZVS condition
- Ratio of $\left(\frac{L_m}{L_r}\right) = L_n$ & Q of the tank determines the M_{max}
- Q is determined by L_r & C_r



If L_m is very high

- Multiple parameters affect the choice
- How do we start?



Determine turns ratio n

Determine R_{ac}

Determine max usable L_m

Choose L_m/Lr between 5 to 10

Look at gain V_s $(K$ & $Q)$ curve to determine the Q $requried$

Calculate C_r from the Q

Calculate L_r from the C_r & F_r

Calculate the value of L_m from the L_r & Ln

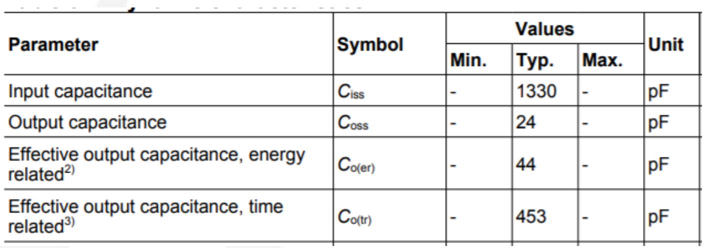
Effect of magnetizing inductance on dead time

- Magnetizing inductance (L_m) determines the dead time (T_d) required to achieve ZVS
- As L_m increases the T_d increases
- As L_m increases, primary RMS currents (I_{rms}) decrease up to a certain point

$$L_m \le \left(\frac{Td}{Fr * 16 * Coss_{eq}}\right) = 274uH$$

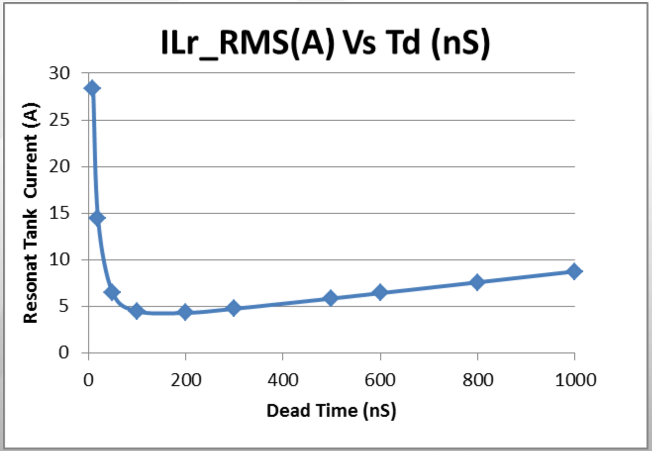
Fr	**100kHz**
T_d	**200nS**

A similar converter designed with LMG3410 $70m\Omega$ Rdson results in Max $L_m = 398\mu H$, ~60% reduction in conduction losses



Parameter	Symbol	Values			Unit
		Min.	Typ.	Max.	
Input capacitance	C_{iss}	-	1330	-	pF
Output capacitance	C_{oss}	-	24	-	pF
Effective output capacitance, energy related[2]	$C_{o(er)}$	-	44	-	pF
Effective output capacitance, time related[3]	$C_{o(tr)}$	-	453	-	pF

MOSFET with $R_{dson} = \sim 150m\Omega$



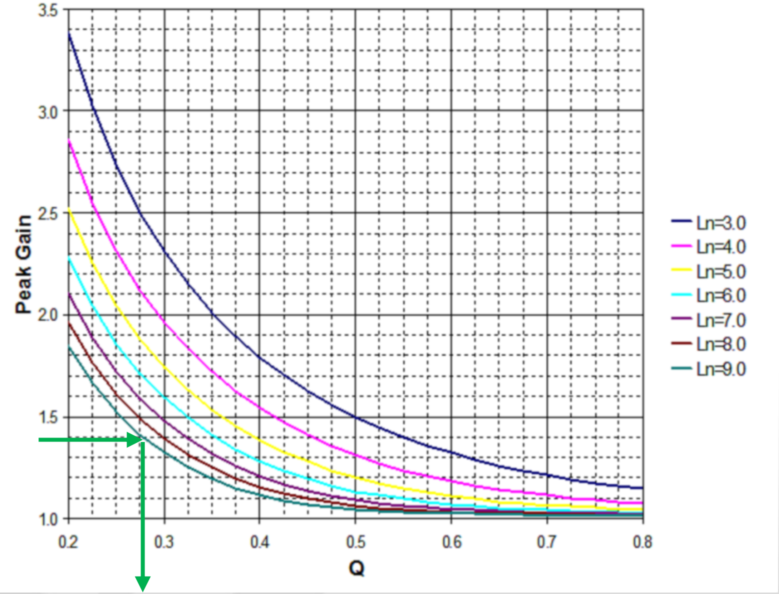
- LLC tank max gain: $Mmax$

  Tank gain at V_{innom}, $Mnom = 0.95$

  $$M_{max} = Mnom * \left(\frac{Vin_{nom}}{Vin_{min}}\right) = \frac{390}{310} = 1.19$$

  - High value of L_n results in lower losses
- Find required Q to get peak gain $110\%\ of\ Mmax = 1.31$
- Calculate the value of the C_r , L_r & L_m from this
- $C_r = \frac{1}{2\pi * Fr * Q * Rac} \cong 94nF$
- $L_r = \frac{1}{(2\pi * Fr)^2 * Cr} = 27\mu\text{H}$
- $L_m = Ln * Lr = 243\mu H$

Lower than max Lm



Choosing $L_n = 9, Q = 0.275$

Component selection & losses: HV MOSFET

Conduction loss

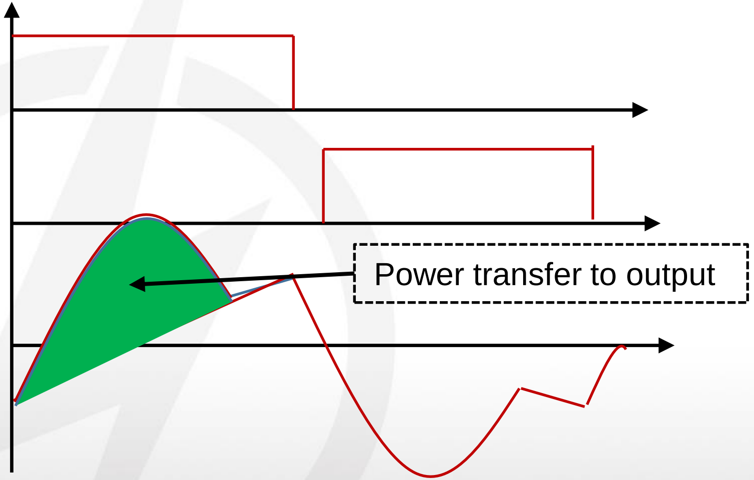
Resonant inductor current has 2 components:

- Load current carried by the HV MOSFET $Ipri_{\mathrm{ref}}$
- Resonant tank magnetizing current I_{lm}

$$Ipri_{ref} = \frac{\pi}{2\sqrt{2}}\left(\frac{I_{out}}{N}\right) = 3.04\ A$$

$$I_{lm} = \left(\frac{N*Vout}{4*Fsw*Lm}\right) = 2.013\ A$$

$$I_{lr} = \sqrt{Ipri_{ref}^{2} + Ilm^{2}} = 3.64\ A$$



$$IHV_{rms} = Ilr/\sqrt{2} = 2.57\ A$$

$$IPD60R145CFD7\ R_{dson} = 145m\Omega$$

$$PCond_{HV} = IHV_{rms}^{2} * Rds = 0.957\ W$$

Component selection & losses: HV MOSFET

Switching loss: turn-off

At full load, converter operates mostly closer to Fr

$$IHV_{toff} = Ilm = 1.89\ A$$

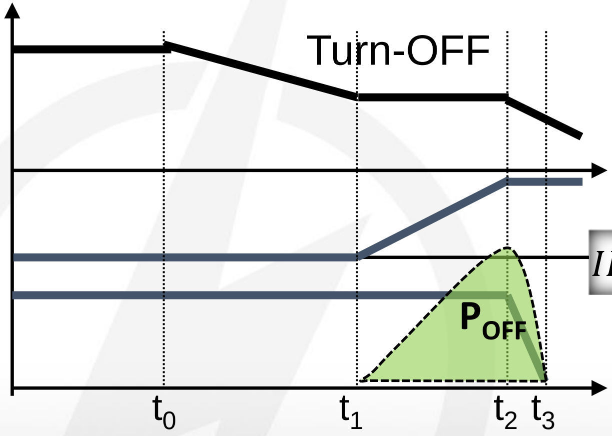
$$t_{off} = t_2 + t_3$$

$$t_{off} = (Qgd/Vds) * Rgate * \left(\frac{V_{ds} - Vpl}{V_{pl}}\right) + Ciss * Rgate * Ln * \left(\frac{V_{pl}}{V_{th}}\right)$$

$$t_{off} = 14.1nS$$

$$E_{off} = 0.5 * Vds * IHV_{toff} * toff = 5.35\mu J$$

$$\boxed{PSw_{HV} = Fsw\ * Eoff = 0.535W}$$



$IPD60R145CFD7$

Symbol	Parameter	Value
C_{iss}	Input capacitance	$1060\ pf$
C_{rss}	Reverse transfer capacitance	$2.2pF$
R_{gate}	Gate resistance	5Ω
Q_{gd}	Miller charge	$12nF$
V_{pl}	Miller plateau voltage	$5.5V$
V_{th}	Threshold voltage	$3V$

Component selection & losses: SR MOSFET

Using CSD19501KCS, UCC24612

$$ISR_{rms} = Iout * \frac{\pi}{4} = 16.4\ A$$

$$Pcond_{SR} = ISRV_{rms}^{2} * Rds_{on} = 1.4W$$

$$Pdiode_{SR} = Fsw * ISR_{turnoff} * Vf * Tdiode$$
$$= 0.18W$$

$$PSRV_{sw} = Fsw * Qg * Vdrive = 34mW$$

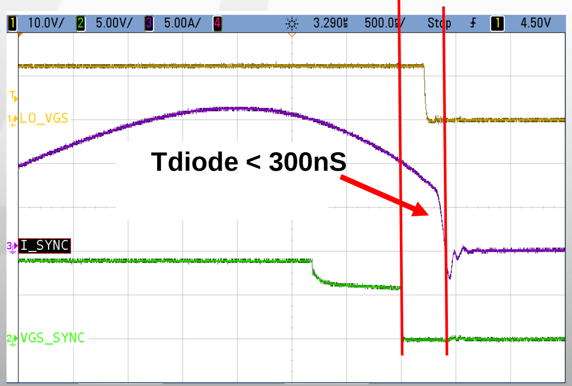
$$PSR_{tot} = 1.63\ \mathrm{W}$$

Reduces losses by **3W** on each leg compared with Schottky diode based rectifier

Below Fr operation

Tdiode = 350nS

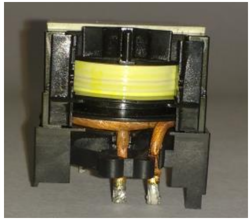
Reliable above Fr operation



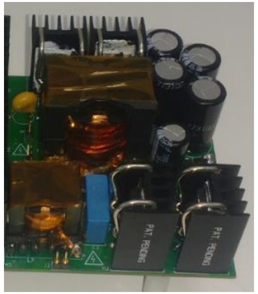
Tdiode < 300nS

Magnetics design : transformer

Integrated magnetics:
Use single magnetic structure to implement resonant inductor and transformer



Discrete magnetics:
Use two separate magnetic structure



- Occupies less space
- Requires special (split) bobbin, but cheaper if manufacturing quantity is high
- Less core losses, increases efficiency at light load
- Increased “AC resistance” due to proximity effect. Higher conduction loss.

- Slightly more expensive
- Occupies more space
- Huge reduction in “proximity” effect. Reduces “AC resistance” conduction loss significantly.
- For high output current applications, integrated magnetics reduce conduction losses
- More core choices for high performance applications

Magnetics design : transformer

Calculating number of turns:

Secondary turns: N_s

$$N_s = \frac{V_{out}}{2 * Fres * \Delta B * Ae} = 3\ turns$$

Primary turns: N_p

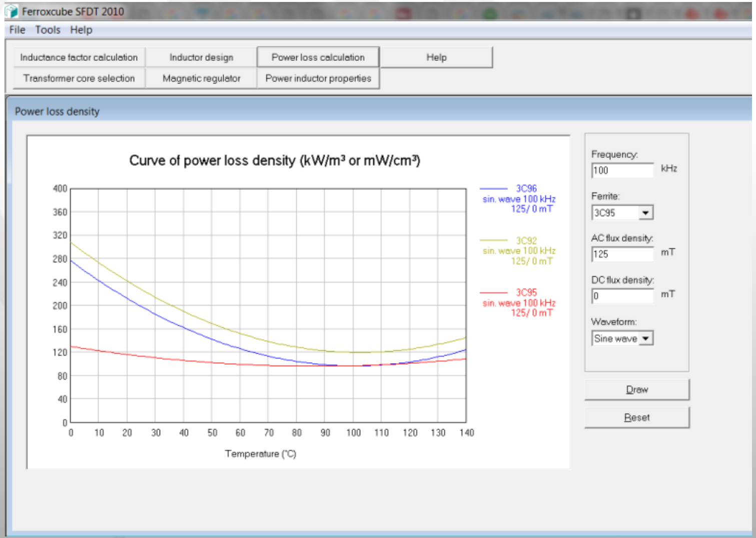
$$N_p = 7.67 * Ns = 23\ turns$$

Use the operating points $Fres$ & ΔB to estimate the core loss before choosing

$$Ptrans_{FE} = \frac{120KW}{m^3} * Ve = 1.5\ W$$

$$\boxed{Ptrans_{FE} = 1.5\ W}$$

Symbol	Parameter	Value
$Core\ geometry$		$PQ3230$
A_e	Effective area	$162mm^2$
A_n	Window area	$99mm^2$
V_e	Effective volume	$12500mm^3$
MLT	Mean length of turn	$66.7mm^2$



Frequency: 100 kHz

Ferrite: 3C95

AC flux density: 125 mT

DC flux density: 0 mT

Waveform: Sine wave

Magnetics design : transformer

- Take bobbin fill factor (K): 30%
- Equal division for primary and secondary

Symbol	Parameter	Value
A_n	Window area	$99mm^2$
MLT	Mean length of turn	$66.7mm$
N_p		23
N_s		3

Secondary Winding Loss:

$$Lwire_{sec} = MLT * Ns = 200\ mm$$

$$Awire_{sec} = \frac{\frac{K}{2} * An}{2 * Ns} = 2.22\ mm^2$$

$$Rac_{sec} = 1.5 * \ Rdcsec = \ _{CU} * \frac{Lwire_{sec}}{Awire_{sec}} = \ 1.66\ m\Omega$$

$$Ptranssec_{cu} = 2 * ILV_{rms}^2 * Rdcs_{ec}\ = 1342\ mW$$

$$Ptrans_{cu} = 2.02\ W$$

Primary Winding Loss:

$$Lwire_{pri} = MLT * Np = 1518\ mm$$

$$Awire_{sec} = \frac{\frac{K}{2} * An}{N_p} = 0.65mm^2$$

$$Rac_{pri} = 1.5 * \ R_{dcpri} = \rho_{CU} * \frac{Lwire_{pri}}{Awire_{pri}} = \ 43.76\ m\Omega$$

$$Ptranspri_{cu} = Ilr_{rms}^2 * Rdcp_{ri}\ = 680\ mW$$

Magnetics design : resonant inductor

$Ilr_{pk} = 1.414 * Ilr = 4.55A$

$L_r = 17\ \mu H$

With $B_{pk} = 0.16$ at Ilr_{pk}

Calculate resonant inductor turns:

$$N_r = \frac{L_r * Ilr_{pk}}{B_{pk} * Ae} = 12.2\ \ turns$$

Core losses:

Following the same procedure as the transformer
Estimate core loss from Ferroxcube tool

$$Pres_{FE} = 250\left(\frac{KW}{m^3}\right) * Ve = 0.71\ W$$

$$\boxed{Total\ Pres = 1.014\ W}$$

Symbol	Parameter	Value
Core geometry		*PQ2020*
A_e	Effective area	$62.9mm^2$
A_n	Window area	$36mm^2$
V_e	Effective volume	$2850mm^3$
MLT	Mean length of turn	$44mm$

Conduction losses:

Assuming (K) 30% fill factor, AC resistance factor 2.7

$Lwire_{sec} = MLT * Nr = 528\ mm$

$$Awire_{res} = \frac{K * An}{N_r} = 0.9\ mm^2$$

$Proximity\ effect$
$from\ 2\ layer\ winding$

$$Rdc_{res} = 1.5 * \rho_{CU} * \frac{Lwire_{sec}}{Awire_{sec}} = \ \ 16.7\ m\Omega$$

$$Pres_{cu} = Ilr^2 * Rdc_{res}\ \ = 0.33W$$

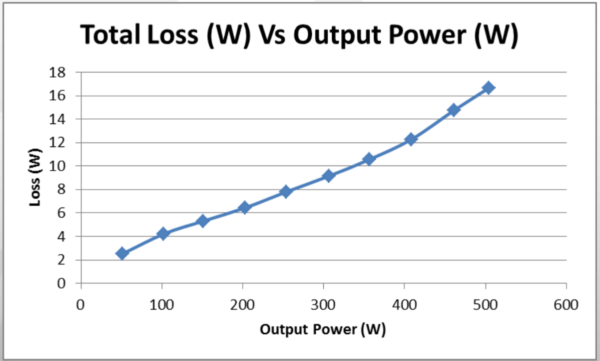
Total losses

Component	Loss/ Pc (W)	Total loss(W)
HV MOSFET	1.759	3.568
SR MOSFET	1.63	3.26
LLC transformer		3.52
Resonant inductor		1.014
Total		11.36

Using GaN Rdson 70mΩ, very low Eoff, can reduce loss by 1.8W

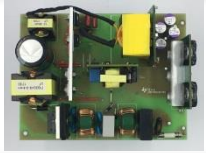
Using SR driver which minimizes dead time increasing efficiency

- The estimated losses above do not include losses from resonant capacitor, output filter components or transformer termination losses
- Overall, the losses for this design will be up to 16W



Actual data for TIDA – 010015

80 PLUS® platinum, 93% efficiency, super transient, 450W AC/DC - single-layer PCB TI Design: TIDA-01501

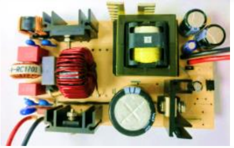


Leading transient performance (half duty-cycle response for line transient & dynamic load)
Meets 80 PLUS Platinum specs peak efficiency 92.4% @ 115V_{AC}, 94.0% @ 230V_{AC}
Single layer PCB design to achieve low solution cost
UCC28180, UCC256301, UCC24612

24V, 480W nominal 720W peak, >93.5% efficient, robust AC/DC industrial power supply TI Design: TIDA-01494

- Meet 80 PLUS Platinum overall efficiency >93.5% with peak efficiency > 94% at 230V_{AC}
- ZCS avoidance in the LLC stage, enabling wider input voltage range operation and robustness
- Peak output power of up to **720W for a short duration of 3 seconds**
- UCC28180, UCC256301, UCC24612

93% efficiency, 200W, fast transient, desktop PC PSU reference design TI Design: TIDA-01557



No load <0.1W; >50% at 0.25W; > 79% at 2W;>81% at 4W
Meet 80 PLUS Platinum spec peak efficiency 93% @ 230V_{AC}
Output OCP, OVP, short-circuit protection, OTP with single layer PCB
UCC28056, UCC256301, UCC24612

480W, thin profile (<17 mm), 94% efficiency, fast transient response AC/DC TI Design: TIDA-01495

Thin profile <17 mm with small PCB form factor of 185 x 110 mm

PFC phase shedding and advanced burst mode in the LLC enables high efficiency at light load conditions

Peak efficiency of 94.1% @ 230 V_{AC}, light load efficiency >85% (230 V_{AC}) at 5% load

UCC28063, UCC256303, UCC24612

94.5% efficiency, 500W industrial AC/DC with <250mW standby

Peak efficiency 95% @ 230V_{AC} and 93.5% @ 115V_{AC}

PFC phase shedding, burst mode in the PFC, LLC enables high efficiency at light load conditions

Peak efficiency 95% @ 230V_{AC} and 93.5% @ 115V_{AC}

UCC28064, UCC256303, UCC24612

Conclusions & key takeaway

- Resonant converters are a preferred topology for high efficiency isolated DC/DC
- With GaN switches finding more of a commercial usage, soft switched topologies remain relevant
- We looked at ways to estimate losses in the major components of an LLC converter , which can be used to make optimized design choices
- Multiple TI Designs developed based on TI's latest generation LLC and SR controllers developed to act as a quick start reference for industrial/consumer AC-DC applications