LLC Converter Operating Principles and Optimization for Transient Response

High Voltage Power
High Voltage Controllers
Agenda

• LLC Converters: Topology Benefits and Example Applications

• Basic Operating Principle

• LLC Power Stage Design Example

• Direct Frequency Control vs Hybrid Hysteretic Control

• Transient Response Considerations

• Test Results
LLC Topology Benefits

- Soft switching over entire load range
- Reduced EMI signature (sinusoidal primary current)
- Efficiency of ~93% to 96% realizable
- Easy Magnetics integration
ZVS Switching

• Zero volt switching achievable when there is enough circulating current in the LLC power stage

• At gate turn-off, circulating current discharges the switch node capacitance

• Switch node must fully discharge during the dead time before the next gate turn-on

• ZVS greatly reduces switching losses and minimizes EMI
LLC Common Applications

• Common Design Characteristics
  – Narrow, High voltage input
    • PFC input (~400V)
    • Low line input (85V to 120V)
    • High line input (190V to 265V)
  – Output Power
    • 100W to 1kW
    • High Efficiency Desired (~93% to 96%)

• Common Applications
  – OLED/LED TV
  – All-In-One (AIO) Power
  – AC Adapter
  – Projector

~100W – 1000W
Example Application

- UCC28056 + UCC25630x
- Single Phase Transition Mode
  PFC + LLC
- Up to 300W
- System architecture minimizes number of high voltage dividers
  - maximizes efficiency across entire load range
Example Application

- UCC28064 + UCC25630x
- Interleaved Transition Mode PFC + LLC
- Greater than 300W
- Low profile designs
- High light load efficiency via phase shedding
PFC + LLC System Level Considerations

**UCC28056**
- 75W to 300W
- Very low standby power
- Enables systems to meet energy standards while keeping PFC on during standby
  - Greatly simplifies power architecture
- No AUX winding required for zero cross detection

**UCC28064**
- 300W to 700W
- Reduced current ripple – higher system reliability
- User adjustable phase management and burst mode threshold to achieve low standby power
- Soft burst-on and burst-off avoids audible noise
LLC Operating Principle
LLC Operating Principle

- Lr, Cr, Lp and reflected RL forms an impedance divider

- Complex Gain Equation

- Gain varies by varying frequency.

- LLC operates at a fixed 50% duty cycle
LLC Operating Principle

- Lr, Cr, Lp and reflected RL forms an impedance divider

- Gain varies by varying frequency

- Q1 and Q2 always operating at 50% duty cycle

- Regulation achieved by modulating switching frequency

\[
\begin{align*}
Z_1 &= 2\pi F \times L_r + \frac{1}{2\pi F \times C_r} \\
Z_2 &= \frac{2\pi F \times L_m \times R_e}{2\pi F \times L_r + R_e} \\
V_{OUT} &= \frac{Z_2}{Z_1 + Z_2} = \frac{V_{IN}}{2n}
\end{align*}
\]
LLC Operating Principle

State | Q1 | Q2 | Q3 | Q4
--- | --- | --- | --- | ---
1 | ON | OFF | OFF | ON
2 | ON | OFF | ON | OFF
3 | ON | OFF | OFF | OFF
4 | OFF | ON | OFF | ON
5 | OFF | ON | ON | OFF
6 | OFF | ON | OFF | OFF
LLC Operating Principle: At Resonance

- When switching frequency is equal to resonant frequency of LLC tank:
  - Two possible states
  - Power stage gain equal to 1

Mode State Sequence: 1→5

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LLC Operating Principle: Below Resonance

- When switching frequency is less than resonant frequency of LLC tank:
  - Four possible states
  - Power stage gain > 1

Mode State Sequence: 1→3→5→6

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LLC Operating Principle: Above Resonance

- When switching frequency is greater than resonant frequency of LLC tank:
  - Four possible states
  - Power stage gain < 1

Mode State Sequence: 1 → 4 → 5 → 2
LLC Design Example
LLC Power Stage Design Example

- Input Voltage Range: 340V to 410V
- Output Voltage: 12V
- Total Output Power: 120W
- Switching Frequency
  - Total Range: 50kHz to 160kHz
  - Resonant Frequency: 100kHz
- Diode Rectification
LLC Power Stage: First Harmonic Approximation

- LLC power stage analysis is difficult
  - No easy analytical solution
- First harmonic approximation is common design approach
  - Assumes only the first harmonic of the switching waveform is significant
  - Reasonably accurate close to resonant frequency
  - Increasingly inaccurate as operating point moves away from resonant frequency
LLC Stage: Gain Characteristic

- \( Q = \frac{\sqrt{L/R}}{C_{R}} \)
- Resonant Tank peak gain increases as \( Q \) decreases – ie. as load decreases
- \( \frac{\Delta G}{\Delta F} \) slope changes as switching frequency crosses from Inductive to Capacitive region – AVOID this
  - Loss of ZVS and control law reversal!
- ZVS is possible in Inductive regions
  - Possible ≠ Guaranteed
- Operate in Inductive regions
LLC Power Stage Design Example: Transformer Turns Ratio and LLC Gain

- Determine Transformer Primary:Secondary Turns Ratio

  \[ n = \frac{V_{\text{IN nominal}}/2}{V_{\text{out}}} = \frac{390/2}{12} = 16.25 \]

  - Turns ratio selected as 16

- Determine LLC power stage gain range

  \[ M_{g, \text{min}} = n \frac{V_{\text{out}}+V_{f, \text{diode}}}{V_{\text{IN max}}/2} = 16 \frac{12+0.5}{410/2} = 0.976 \]

  \[ M_{g, \text{max}} = n \frac{V_{\text{out}}+V_{f, \text{diode}}+V_{\text{loss}}}{V_{\text{IN min}}/2} = 16 \frac{12+0.5+0.5}{340/2} = 1.224 \]
LLC Power Stage Design Example: LLC Tank Parameters

- Calculate equivalent load resistance $R_e$
  \[ R_e = \frac{8 \times n^2}{\pi^2} \times \frac{V_{out}}{I_{out}} = \frac{8 \times 16^2}{\pi^2} \times \frac{12}{10} = 249 \Omega \]

- Select ratio of magnetizing Inductance to resonant inductance: $L_n$
  \[ L_n = \frac{L_m}{L_r} \]

- Select Quality Factor: $Q_e$
  \[ Q_e = \frac{\sqrt{L_r/C_r}}{R_e} \]

- Goal is to select $L_n$ and $Q_e$ from graph so that attainable gain is $> M_{g_{\text{max}}}$
  - $L_n$ of 13.5 and $Q_e$ of 0.15 selected

- Graph can be obtained from UCC25630x Calculator:
LLC Power Stage Design Example: LLC Tank Parameters

- Select resonant capacitance: \( C_r \)
  \[ C_r = \frac{1}{2\pi Q_e \times F_{res} \times R_e} = \frac{1}{2\pi \times 0.15 \times 100kHz \times 249\Omega} = 42.6nF \]
  - Use \( C_r = 44nF \)

- Select resonant inductance: \( L_r \)
  \[ L_r = \frac{1}{(2\pi F_{res})^2 \times C_r} = \frac{1}{(2\pi \times 100kHz)^2 \times 44nF} = 57.58\mu H \]
  - Use \( L_r = 61.5\mu H \)

- Select magnetizing inductance: \( L_m \)
  \[ L_m = L_n \times L_r = 13.5 \times 61.5\mu H = 830.25\mu H \]
  - Use 830\mu H

- Double check actual component values satisfy \( M_g_{peak} > M_g_{max} \)
  - Having some margin of \( M_g_{peak} > M_g_{max} \) is needed

FHA Calculation

\[ \text{Gain}(f_n, Q) = \left| \frac{L_n f_n^2}{L_n f_n^2 + (f_n^2 - 1)(1 + j f_n \cdot L_n \cdot Q)} \right| \]
LLC Power Stage Design Example: Primary side MOSFETs

- Select Primary Side MOSFET' based on primary side resonant current and voltage stress
  - Primary RMS current: \( I_{oe} = \frac{\pi}{2\sqrt{2}} \times \frac{I_{out}}{n} = \frac{\pi}{2\sqrt{2}} \times \frac{1.1\times10^4}{16} = 0.764 \) A
  - RMS magnetizing current: \( I_m = \frac{2\sqrt{2}}{\pi} \times \frac{n \times V_{out}}{2\pi F_{min} \times L_m} = \frac{2\sqrt{2}}{\pi} \times \frac{16 \times 12}{2\pi 50 kHz \times 830 \mu H} = 0.659 \) A
  - Total resonant Current: \( I_r = \sqrt{I_{oe}^2 + I_m^2} = \sqrt{(0.764 A)^2 + (0.659 A)^2} = 1.01 \) A
  - Choose MOSFET with current rating 1.1 times the total resonant current
  
  - Max voltage stress each MOSFET sees is equal to the input voltage
    - Choose MOSFET rated to 1.5 times the max input voltage
LLC Power Stage Design Example: Resonant Inductor

- Resonant inductor spec
  - Resonant inductance can either be implemented as discrete, external inductor or as the leakage inductance of the transformer (saves space)

  - For external resonant inductor, the maximum AC voltage across inductor is $V_{LR} = 2\pi F_{min} L_R I_R = 19.6V$

  - Complete Spec:
    - Inductance: 61.5µH
    - Rated Current: 1.1A
    - Terminal AC Voltage Rating: 20V
    - Frequency Range: 50kHz to 111kHz
LLC Power Stage Design Example: Transformer

- Calculate secondary side currents
  - $I_{oes} = n \times I_{oe} = 16 \times 0.764 \, A = 12.218 \, A$
  - Current in each secondary winding:
    - $I_{ws} = \frac{\sqrt{2} \times I_{oes}}{2} = \frac{\sqrt{2} \times 12.218}{2} = 8.639 \, A$

- Total Transformer Spec
  - Turns Ratio Primary : Secondary = 32 : 2
  - Primary Magnetizing Inductance: 830µH
  - Primary Winding Current: 1.1 A
  - Secondary Winding Current: 8.639 A
  - Switching Frequency Range: 50kHz to 111kHz
LLC Power Stage Design Example: Resonant Capacitor

• Calculate AC voltage on resonant capacitor
  \[ V_{CR,AC} = \frac{I_r}{2\pi f_{min} C_r} = \frac{1.1 A}{2\pi \times 50 kHz \times 44 nH} = 72.5 V \]

• Calculate peak resonant capacitor voltage
  \[ V_{CR,peak} = \frac{V_{in, max}}{2} + \sqrt{2} V_{CR,AC} = \frac{410 V}{2} + \sqrt{2} \times 72.5 V = 307.5 V \]

• Total resonant capacitor spec
  – Peak Voltage: 308V
  – Rated Current: 1.1A
  – Low dissipation factor preferred to limit temperature rise in the resonant capacitor
LLC Power Stage Design Example: Rectifier Diodes

- Calculate half-wave average current
  \[ I_{ws} = \frac{\sqrt{2} \times I_{oes}}{\pi} = \frac{\sqrt{2} \times 12.218}{\pi} = 5.503 \, A \]

- Calculate required voltage stress rating for each diode
  \[ V_{DB} = 1.2 \times \frac{V_{IN\,max}}{n} = 1.2 \times \frac{410}{16} = 30.75V \]
LLC Power Stage Design Example: Output Capacitance

- **Required Capacitor RMS Current Rating**
  \[
  I_{Cout} = \sqrt{\left(\frac{\pi}{2\sqrt{2}}I_{out}\right)^2 - I_{out}^2} = \sqrt{\left(\frac{\pi}{2\sqrt{2}} 10\right)^2 - 10^2} = 4.84\ A
  \]

- **Max ESR**
  - Determined by maximum allowable ripple voltage at steady state
  \[
  ESR_{\text{max}} = \frac{V_{\text{out}(pk-pk)}}{2I_{\text{out}}} = \frac{0.3V}{\pi/2 \times 10} = 19\ m\Omega
  \]

- Larger ESR results in more heat, reduced capacitor lifetime and larger output ripple
LLC Design Considerations
Why is Narrow Input Voltage Preferred?

- Min and Max input voltage determines necessary gain range
- Larger input voltage range results in larger required power stage gain range
- Operating point move further away from resonant frequency
  - Poor efficiency!
- FHA becomes less reliable
- Greater possibility for converter to operate in capacitive region and zero current switching
  - Avoid this
ZCS Avoidance

• ZCS leads to conduction of body diode in primary side MOSFETs
  – Large $dI/dt$ spike
  – Greater stress on primary side MOSFETs and probability of damage greatly increases

• Gain-Frequency relationship becomes inversed

$\Delta G/\Delta F$ is positive
$\Delta G/\Delta F$ is negative

Capacitive

Inductive_1

Inductive_2
ZCS Avoidance

- UCC25630x algorithm incorporates ZCS avoidance
- Polarity of the inductor current is sensed at gate turn off edge
- ZCS is detected if at HS or LS turn off edge, the direction of the resonant current (Ipolarity) is not correct
- HS or LS switch will not be turned on until the next slew is detected on primary side switch node.
- $V_{COMP}$ will be rapidly ramped down until there a complete switching cycle without a near ZCS event is detected.
Direct Frequency Control vs Hybrid Hysteretic Control
Direct Frequency Control (DFC)

- Analogous to voltage mode control
- Limited bandwidth and slow transient response
- Complex power stage transfer function
Direct Frequency Control (DFC)

- Power stage transfer function difficult to express analytically

- Compensation strategy is typically begin with integrator and increase bandwidth if enough phase margin is available
Hybrid Hysteretic Control (HHC)

- Charge control with added frequency compensation ramp
- Analogous to current mode control with added slope compensation
- 1st order power stage transfer function
- Higher bandwidth and fast transient response
Hybrid Hysteretic Control (HHC)

• HHC operating principle

• Gate turn off thresholds (VTH and VTL) are derived from feedback

• Gate turn off determined by comparing VCR to VTH and VTL

• Gate turn on determined by adaptive dead time circuit
Hybrid Hysteretic Control (HHC)

• Current sources on/off control synchronous to gate signal turn off edge

• Inherent negative feedback for low side and high side gate signal balance

• Automatically maintain the bias voltage at 3V – no need for extra resistor dividers

• Current sources are turned off during burst off period – reduce standby power consumption
Hybrid Hysteretic Control (HHC)

- ~1st order system
- Able to achieve higher bandwidth

- Frequency control - HHC
Hybrid Hysteretic Control (HHC)

- Optocoupler collector voltage regulated at a constant voltage

- No extra pole introduced due to the optocoupler parasitic capacitor
  - Higher loop bandwidth and fast transient

- Small bias current (82uA) is used to limit the optocoupler current at light load
  - Low standby power consumption
HHC: Burst Mode Control

- Advanced burst mode
  - Converter operates at the operating point with the highest efficiency during the burst period
  - Burst mode threshold tunable through external resistors

Efficiency vs. load for different $V_{IN}$ with different BM threshold setting

UCC25630x: $I_{res}$ stays at optimal efficiency operation condition in every switching cycle

Conventional solution: $I_{res}$ is not optimized
HHC: Burst Mode Control

- Burst mode allows system to turn on for a minimal of 15 switching pulses and turn off for a longer time to improve the light load efficiency – **Low standby power consumption**
- The higher value of $V_{comp}$ and burst mode threshold (BMT) is used to compare with VCR for pulse generating guarantee a fast transient from light load/no load to full load – **Fast transient**
HHC: Burst Mode Control

- Fast exit from burst mode without large $V_{OUT}$ dip
  - No need for secondary side wake up circuit

Load step between 0.5% load and full load. $V_{OUT}$ dip is ~100 mV
**HHC Benefits**

**Fast Transient Response**
- HHC simply plant to ~1\(^{st}\) order system, allowing for a higher system bandwidth
- Innovated feedback chain removes extra pole introduced by the optocoupler parasitic capacitor
- Burst mode implementation allow the system to get out of burst mode fast, to guarantee for a fast transient from light load to heavy load

**Low Standby Power Consumption**
- Slope compensation remove the need for extra resistors to maintain the dc bias voltage on VCR
- Low optocoupler bias current helps to achieve a low standby power consumption on feedback loop
- Burst mode improve the light load efficiency by turning off the switching for certain period
LLC Transient Response
Load Transient Response

• Performance metric describing the power supply’s response to sudden change in load current

• Factors to consider
  – Max output voltage deviation
  – Time needed for output voltage to return to regulation set point
  – Settling time behavior
Load Transient Response

• Transient response dependent on converter bandwidth and phase margin

• Approximation of delay between transient event and converter response from bode plot
  \[ t_p = \frac{1}{4 \times f_c} \]
  - \( f_c \) is crossover frequency
  - \( T_p \) is time from start of transient event to valley of output voltage dip
  - Approximation does not include slew rate or ESR considerations
Load Transient Response

- UCC25630-1EVM crossover frequency: 6kHz

- Approximation of delay between transient event and converter response:
  \[ t_p = \frac{1}{4 \times f_c} = \frac{1}{4 \times 6\text{kHz}} = 50\mu s \]
Load Transient Response

- Converter is unable to instantaneously react to transient event

- After the transient event but before converter responds, charge is transferred from output capacitance to the load, resulting in output voltage droop

- Maximum droop in output voltage dependent on closed loop output impedance, load step and slew rate
Load Transient Response

- Maximum voltage droop can be approximated from total output capacitance and ESR

\[
\Delta V_{out} = \frac{\Delta I_{Load\ Step} \times \Delta t_p}{C_{out}} + \Delta I_{Load\ Step} \times R_{ESR}
\]

- \[\Delta V_{out} = \frac{10 \text{ A} \times 50 \mu s}{1968 \ \mu F} + 10 \text{ A} \times 1.75 m\Omega = 272 \text{ mV}\]
Load Transient Response

- Phase margin describes stability of the power converter
- Determines the output voltage settling time and settling behavior
- Insufficient phase margin results in underdamped response and oscillation in output voltage
- >45° phase margin a must, >60° phase margin preferred

Phase Margin=20°  Phase Margin=67°
Compensation Goals

• Target higher bandwidth for faster transient response

• Maintain at least >45° phase margin at crossover frequency

• >10dB gain margin
Isolated Compensation

• Type II

\[ F_Z = \frac{1}{2\pi C_{28}(R_{22} + R_{25})} \]

\[ \frac{V_r(s)}{V_o(s)} = \frac{1 + sC_{28}(R_{25} + R_{22})}{sC_{28}R_{25}} \]

• R22 used to adjust mid-band gain of the feedback network
Test Results: UCC25630x EVM

- Input voltage: 340 Vdc – 410 Vdc
- Output voltage: 12 Vdc
- Output current (rated): 10A
- Resonant frequency: 96kHz
Test Results: Typical Waveforms

Full Load (10A)

- Resonant Cap Voltage
- Low side gate pulses

Light Load (0.1A)

- Output Voltage (AC coupling)
- Low side gate pulses
Test Results: Transient Response

No Load to Full Load

Output Voltage (AC coupling)

Load current

ΔV ~ 0.3V

Full Load to No Load

Output Voltage (AC coupling)

Load current
Transient Response DFC vs HHC: 12V Supply

**Legacy: Direct Frequency Control**

- Output Voltage (AC coupling): $\Delta V \sim 1V$
- Load current
- Low side gate

**TI: Hybrid Hysteretic Control**

- Output Voltage (AC coupling): $\Delta V \sim 0.1V$
- Load current
- Low side gate
Transient Response: Competitor #1 vs UCC25630x

**Competitor #1**
- CH1: LO
- CH2: Vout
- CH3: Iout
- CH4: HO-HS

10.8% Vout dip from no load to full load

**TI: UCC25630x**
- CH1: Vout
- CH2: LO
- CH3: HO-HS
- CH4: Iout

1.25% Vout dip from no load to full load
Transient Response: Competitor #2 vs UCC25630x

Competitor #2 using DFC Control

TI: UCC25630x

Vout dip: 600mV

Vout dip: 250mV
Transient Response: Competitor #3 vs UCC25630x

Competitor #3 using DFC Control

TI: UCC25630x

Vout dip: 740mV

Vout dip: 244mV
System Level Benefits to Improved Transient Response

• Tighter regulation of output voltage is realizable without needing additional output capacitance

• Output capacitance can be significantly reduced and meet the same transient response performance as direct frequency control
Light Load Power Consumption (UCC25630-1EVM)

38.2 mW no load power consumption
Standby Power: Competitor #2 vs UCC25630x

**Competitor #1**
Standby Power

**TI: UCC25630x**
Standby Power
UCC28056 + UCC25630x Standby Power

- PMP21251 170W transition mode PFC + LLC design
- **70mW** no load standby power at 115Vac
- **89mW** no load standby power at 230Vac
Standby Power System Level Benefits

• Enables designs to meet modern energy standards such as DOE Level VI and CoC Tier II

• PFC does not need to be disabled at light load to meet efficiency goals

• Keeping PFC ‘always on’ simplifies power supply architecture and provides faster response from standby to full load
Retrofitting UCC25630x into Gaming Station
Gaming: Transient Response

- Test Condition: VinAC=115V, Vout=12V, Iout step from 0A to 10A
- Transient performance is 10x better with UCC25630x
PS4: Startup

- Test Condition: VinAC=115V, Vout=12V, Iout=5A
PS4: Load Regulation

- Test Condition: VinAC=115V, Vout=12V, Iout=10A
Summary

• LLC is an excellent topology choice for designs with narrow, high voltage input and requires high efficiency across entire load range.

• First harmonic approximation forms the foundation of the LLC design flow

• Hybrid hysteretic control offers improved transient performance, reducing the required output capacitance to meet a given output voltage regulation requirement