LLC design guide: 3300 W converter

Simplified algorithm based on FHA and vector method

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About this document

Scope and purpose

This application note will review the basics of the LLC multi-resonant converter and describe a new vector method based on first harmonic approximation (FHA) that will provide a simple algorithm to design the resonant tank system for the LLC converter. It will dissect the **3300 W LLC demo board** and explain the designer's choices. The starting design is based on the FHA optimum solution. The designer's choices will be analyzed, along with their impact on LLC performance. Both designs will use the same transformer transfer ratio. LTspice® simulation is used to calculate actual values of the RMS current and compare two different LLC parameter setups.

Intended audience

This document is intended for design engineers who wish to develop a deeper understanding of the operation of LLC converters and their design.

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1 Introduction

The multi-resonant LLC converter has several desirable features, such as high efficiency, low EMI, and high power density. Design of a resonant converter is a challenging task and requires more effort to achieve design optimization compared to design for PWM converters. Current state-of-the-art LLC design methods are based on calculus and graphs and use a time-consuming iterative procedure. This document aims to simplify this task and make it easier to optimally design the LLC converter. It provides an overview of LLC converter operation and a new design method based on vector analysis. This new method enables a simple algorithm to calculate key component values of the LLC converter based on given requirements.

1.1 Overview of the LLC resonant converter

Figure 1 shows a basic half-bridge (HB) LLC converter with a center-tap rectifier. In a simplistic discussion, the switching bridge generates a square wave form to excite the LLC resonant tank, which will output a resonant sinusoidal current that gets scaled and rectified by the transformer and rectifier circuit. The output capacitor filters the rectified AC current and delivers a DC voltage for the output.

This is a frequency-controlled topology. The frequency operating range is selected such that input impedance of the converter always stays inductive, and the current lags behind the voltage. This enables zero-voltage switching (ZVS) on the primary side and zero-current switching (ZCS) on the secondary side, which practically eliminates turn-on losses and minimizes turn-off losses. Using the LLC converter in the correct operating mode is key to realizing these benefits. As an example, be careful with buck mode. Buck operation mode, when the LLC operates above the resonant tank frequency, reduces RMS current but will incur non-ZCS losses on the secondary side.

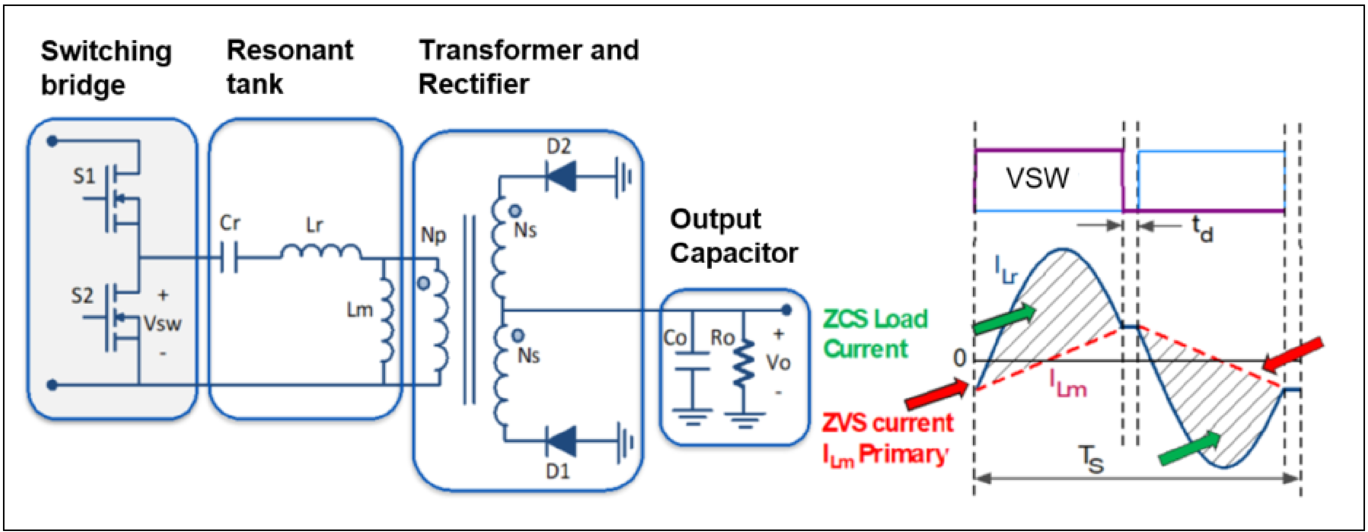

Figure 1 Principal schematic of a HB LLC converter

1.2 First harmonic approximation

The LLC converter is a non-linear topology that combines a linear network (resonant tank and transformer) with active switches (MOSFETs) and passive switches (diodes). The non-linear nature of the switching topology prevents simple and effective methods of the linear AC circuit analysis from being directly applied in this case. Averaging methods common in pulse-width modulation (PWM) topologies are not directly applicable either, because operating switching frequency is very close to the resonant frequency. However, harmonic analysis shows that the first harmonic represents LLC current very well. This is used to simplify the topology schematic, generate a linear circuit schematic (FHA model) and enable the use of linear circuit analysis methods.

2 Design-oriented analysis

Design is the reverse of analysis: one starts with the specification, which is the answer to analysis, and then must work the analysis backward to find the starting point, which is the circuit configuration and the element values. The intentional form of all equations should follow the idea that it is simple to move from analysis to design, and vice versa.

Our objective is power conversion from high-voltage (HV) input to low-voltage (LV) input using the LLC converter with a transformer. The key objectives are efficiency and density. The diagram below shows the process.

Topology: LLC converter
Purpose: transfer power P with efficiency η
from input voltage (V_{inmin}, V_{in}) to output voltage V_{out}
operating in two modes and frequency ranges

1. boost mode (f_o, f_r) and
2. buck mode (f_r, f_{max})

ANALYSIS

Properties/parameters:
Transformer transfer ratio n
Equivalent AC load: R_{ac}
Resonant tank L_r, C_r
Transformer magnetizing inductance L_m
MOSFET switches ($R_{DS(on)}$, $C_{o(tr)}$, Q_{gs})

Performance/specifications:
Transfer function or gain $G_{(\omega)}$, ω = 2*π*f
Borderline operating frequency f_o
LLC gain at borderline frequency $G_{(fo)}$
Ratio between resonant and borderline frequencies f_r/f_o
Input impedance Z_{in}

DESIGN

Let's start, and derive key equations that connect properties (parameters) with performance (specifications).

The LLC converter gain $G_{(\omega)}$ has three components:

Gain = (switching bridge gain)*(transformer turns ratio (n = N_s/N_p)*(impedance ratio gain)

The switching bridge gain depends on the topology employed. The full-bridge (FB) topology has gain equal to one, while the HB topology has a gain of half. Let's represent topology gain as "p".

$$p = 1 \ldots \mathit{for\ full\ bridge\ topology} \quad (1)$$

$$p = ½ \ldots\ for\ half\ bridge\ topology\ (2)$$

The resonant tank gain is based on the load and resonant tank impedance ratio. Note that it behaves like a frequency-driven voltage divider $G_{(\omega)}$ composed of resonant tank impedance and load impedance. See **Figure 2** and equation (3) below.

2.1 LLC as a frequency-controlled voltage divider

$$G(\omega) = \frac{V_o}{V_{in}} = \frac{Z_{lp}(\omega)}{Z_{lp}(\omega) + Z_r(\omega)}\ (3)$$

Where:

- resonant tank impedance: $Z_r(\omega_o) = j * \omega_o * L_r + \frac{1}{j*\omega_o*C_r}$ (4)
- parallel load impedance: $Z_{lp}(\omega o) = \frac{R_{ac}*(j*\omega_o*L_m)}{R_{ac}+j*\omega_o*L_m}$ (5)
- series load impedance $Z_{ls}(\omega o) = R_{ac} + j * \omega_o * L_m$ (6)

Also, we would use another form of this equation (3), called the inverse gain equation (7):

$$\frac{1}{G(\omega)} = 1 + \frac{Z_r(\omega)}{Z_{lp}(\omega)}\ (7)$$

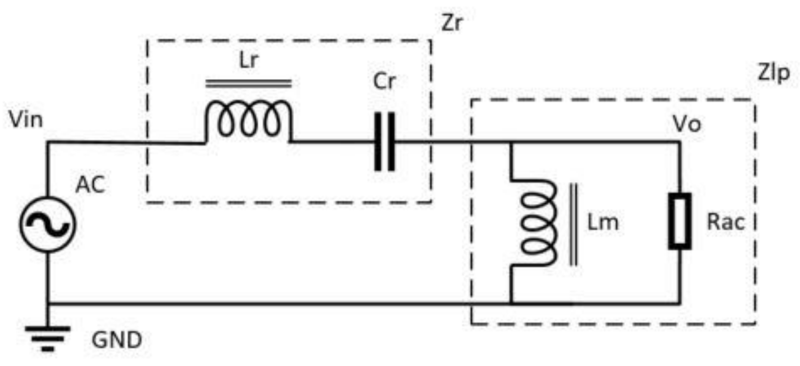

Figure 2 LLC converter as a voltage divider, with resonant tank and load impedances

When the frequency changes, both impedances (Z_r and Z_{lp}) will change and the divider will change the effective ratio, providing a different gain. It is important to monitor the input impedance of the divider. The input impedance is equal to the sum of resonant impedance Z_r and load impedance Z_{lp}:

$$Z_{in}(\omega) = Z_{lp}(\omega) + Z_r(\omega) \qquad (8)$$

The load impedance Z_{lp} always has an inductive character. Let's have a look at the resonant impedance Z_r (**Figure 2**). When the operating frequency is equal to the resonant frequency f_r, the reactive portion of the Z_r impedance is equal to zero, and the total impedance of Z_r is equal just to the parasitic resistance of L_r and has its minimal value. When the frequency is changing around the resonant frequency f_r, the resonant impedance Z_r is changing both its amplitude and character, from capacitive to inductive. When the operating frequency drops below the resonant frequency, the capacitive impedance becomes larger and larger, and at a certain point it prevails over the load impedance Z_{lp}, so the total impedance becomes capacitive.

In a nutshell, when:

1. **Operating frequency $\boldsymbol{\omega_{sw}}$ (switching frequency) $\geq \boldsymbol{\omega_r}$ (resonant tank frequency),**
   $\boldsymbol{Z_r}$ is inductive, $\boldsymbol{Z_{lp}+Z_r > Z_l}$ gain is less than one (buck) and input impedance is inductive.
2. **Operating frequency $\boldsymbol{\omega_{sw}}$ (switching frequency) $= \boldsymbol{\omega_r}$ (resonant tank frequency),**
   $\boldsymbol{Z_r} = 0$, $\boldsymbol{Z_{lp}+Z_r = Z_l}$ gain is one and input impedance is inductive.
3. **Operating frequency $\boldsymbol{\omega_{sw}}$ (switching frequency) $< \boldsymbol{\omega_r}$ (resonant tank frequency),**
   $\boldsymbol{Z_r}$ is capacitive, $\boldsymbol{Z_{lp}+Z_r < Z_l}$ and input impedance is still inductive, the gain is larger than one (boost).

Borderline case:

Input impedance $\boldsymbol{Z_i(\omega o)}$ angle is equal zero.

$\boldsymbol{\omega_{sw}}$ (switching frequency) $= \boldsymbol{\omega_o}$ (zero angle frequency).

If the operating frequency is less than ω_o, the input impedance has a capacitive character and the converter will operate in so-called capacitive mode. The primary-side MOSFET body diodes are hard commutated during MOSFET turn-on, and switching losses are becoming very high. We don't want the converter to operate in that mode. Note that the input impedance angle is a very important parameter to monitor.

2.2 Input impedance angle

Let's analyze the input impedance in detail:

$$Z_{in} = Z_{lp}(\omega) + Z_r(\omega) = Z_{lp}(\omega) * \frac{Z_{lp}(\omega)+Z_r(\omega)}{Z_{lp}(\omega)} \quad (9)$$

$$Z_{in}(\omega) = \frac{Z_{lp}(\omega)}{G(\omega)} \quad (10)$$

The borderline case is when the input impedance angle is equal to zero. If the frequency goes up, the angle becomes positive (or inductive); if the frequency goes down, the angle becomes negative (or capacitive). Let's say that the impedance angle is equal to zero, at minimum operating frequency $\boldsymbol{\omega_o}$:

$$Angle(Z_{in}(\boldsymbol{\omega_o})) = 0 \quad (11)$$

This leads to the most important conclusion:

$$Angle\left(\frac{\mathbf{1}}{G(\boldsymbol{\omega_o})}\right) = -Angle\left(Z_{lp}(\boldsymbol{\omega_o})\right) = Angle\big(Z_{ls}(\boldsymbol{\omega_o})\big) - \frac{\pi}{2} \quad (12)$$

It means that vectors $\left(\frac{1}{G(\omega_o)}\right)$ and $Z_{ls}(\omega_o)$ are orthogonal at minimum operating frequency ω_o. Where Z_{lp} is a parallel combination of R_{ac} and $(j * \omega_o * L_m)$, while Z_{ls} is a serial combination of R_{ac} and $(j * \omega_o * L_m)$.

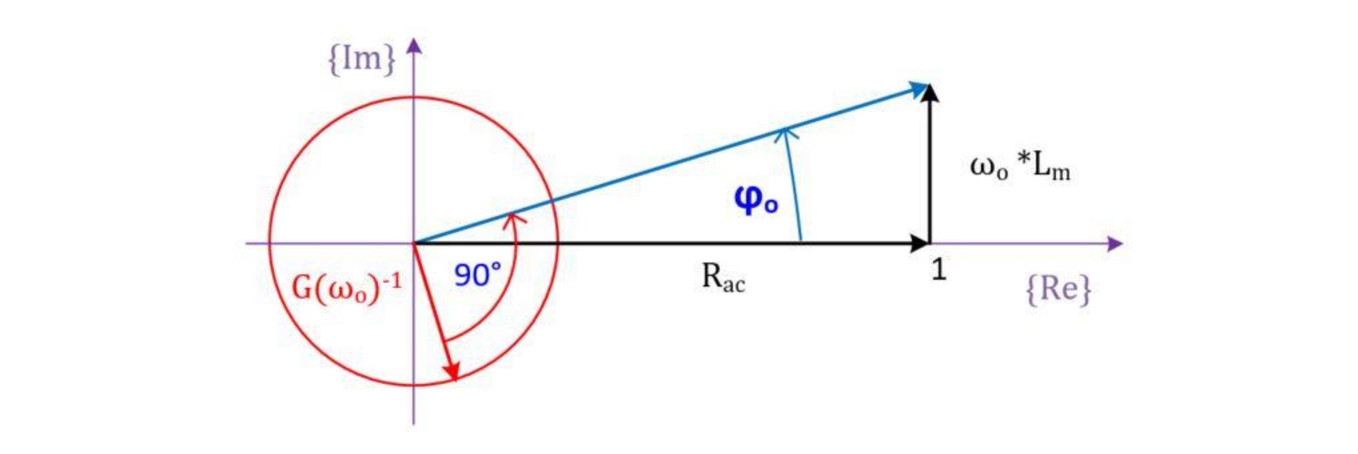

Figure 3 **Vectors $\frac{1}{G(\omega_o)}$ and $Z_{ls}(\omega_o)$ are orthogonal at ω_o**

Input impedance angle is a key element of the solution. It will help us to find a simple solution for the LLC maximum useful gain point that is borderline between the inductive and capacitive mode of operation. When operating frequency is lowering, LLC gain is increasing. The gain is useful until LLC stays in the inductive mode of operation. When the impedance character changes from inductive to capacitive the LLC gain can still go up, but that increment is not useful for us because current will advance the voltage, LLC MOSFET body diodes will operate in hard commutation and switching losses will greatly increase. The relation (12) is visualized in the vector diagram in **Figure 3**.

2.3 LLC gain

Let's use the LLC inverse gain equation (7) for further analysis. The vector diagram of inverse gain $\left(\frac{1}{G(\omega_o)}\right)$ and the serial equivalent impedance $Z_{ls}(\omega_o)$ are given in **Figure 4**. The LLC gain equation is given in the inverse gain form (13):

$$\frac{1}{G(\omega_o)} = 1 + \frac{Z_r(\omega_o)}{Z_{lp}(\omega_o)} \quad (13)$$

This equation could be written in a different form (14), and it is used to draw a vector diagram in Figure 4:

$$\frac{1}{G(\omega_o)} = 1 + p * (Z_r) * (Z_{ls}) \text{ where p } = \frac{1}{\omega_o * R_{ac} * L_m} (14)$$

Key equation (15) is derived using the vector diagram (**Figure 4**). It connects LLC gain, magnetizing inductance L_m of the transformer and equivalent AC load R_{ac}, operating at a border frequency between inductive and capacitive modes.

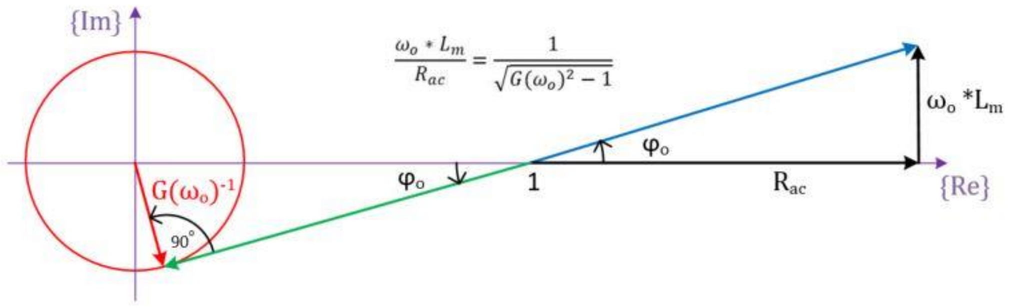

Figure 4 LLC converter inverse gain vector diagram

This shows a simple relation between LLC gain $G(\omega_o)$ and LLC parameters at the maximum useful gain operating point defined by minimum operating frequency $\boldsymbol{\omega_o}$.

$$\frac{\boldsymbol{\omega_o * L_m}}{\boldsymbol{R_{ac}}} = \frac{\boldsymbol{1}}{\sqrt{\boldsymbol{G(\omega_o)^2 - 1}}} \quad (15)$$

2.4 Component calculation

Using the vector diagram in **Figure 4** and equation (12), all components of the LLC converter can be calculated as a function of the maximum gain at border frequency $\boldsymbol{G(\omega_o)}$, equivalent AC load R_{ac}, border frequency ω_o and resonant tank frequency ω_r. Please see reference **[1]** for details.

$$L_m = \frac{1}{\sqrt{G(\omega_0)^2 - 1}} * \frac{R_{ac}}{\omega_o} \qquad (16)$$

$$L_r = L_m * \frac{1 - \frac{1}{G(\omega_0)^2}}{(\frac{\omega_r}{\omega_o})^2 - 1} \qquad (17)$$

$$C_r = \frac{1}{\omega_r{}^2 * L_r} \qquad (18)$$

Equations (16) to (18) connect performance and properties of the LLC to allow easy analysis and design and movement in either direction (analysis <=> design).

3 Design steps

The key performance parameter of the LLC converter is LLC gain at a given equivalent AC load. This could be directly generated from the specification. The frequency parameters used in the design are minimum operating frequency and resonant tank frequency. How selection of the minimum operating frequency and resonant tank frequency impacts the size of the passive components of the LLC converter is explained in detail in references [1], [4]. Briefly, when minimum operating frequency ω_o is equal to the half of the resonant tank frequency, the resonant tank component has the smallest size. That value will be used in the design below.

3.1 Input design data

Table 1 gives an overview of the design input variables and parameters.

Table 1 Design input variables and parameters

Description	Minimum	Nominal	Maximum
Input voltage	350 V DC	400 V DC	415 V DC
Output voltage	43.5 V DC	51.5 V DC	59.5 V DC
Output power			3300 W
Efficiency at 50 percent P_{max}	98 percent *		
Switching frequency	45 kHz	70 kHz	250 kHz
Dynamic output voltage regulation (5 A <=> 35 A; 35 A <=> 65 A; 1 A/µS			Max. overshoot = 1 V Max. undershoot = 1 V
V_{out_ripple}			200 $mV_{pk\text{-}pk}$

3.2 Design parameters

Here are the variables listed in **Table 1**:

Nominal input voltage $V_{in.nom}$ = 400 V

Minimum input voltage $V_{in.min}$ = 350 V

Nominal output voltage $V_{out.nom}$ = 51.5 V

Nominal output power P_{out} = 3300 W

Minimum operating frequency (borderline) f_o = 45 kHz

Resonant tank frequency f_r = 72 kHz

Maximum operating frequency f_{max} = 250 kHz

LLC efficiency $\eta = 98\,percent$

Note that circular frequency $\omega = 2 * \pi * f$ might be used along with frequency f in the formulas below.

We will use design inputs to calculate design parameters, such as:

i. Transformer transfer ratio **n**
ii. Equivalent AC load $\boldsymbol{R_{ac}}$
iii. Required LLC maximum gain $\boldsymbol{G(\omega_o)}$

Transformer transfer ratio is given as (19):

$$\boldsymbol{n} = \frac{\boldsymbol{N_p}}{\boldsymbol{N_s}} = p * round\left(\frac{V_{in.nom}}{V_{o.nom}}\right) = 3.88\ (19), \qquad where\ p = \frac{1}{2}\ \ for\ Half\ Bridge\ \ LLC$$

The designer of the 3300 W LLC demonstrator has decided to choose 15 turns. This determines the swing of the magnetic flux density at a given operating frequency and input voltage, and transformer ferrite core losses, accordingly. Let's analyze how that choice impacts the transfer function and operating modes of the LLC converter. Assuming the number of primary winding turns is in the range of 14 to 16, the secondary number of turns using equation (19) is then 3.6, 3.86 or 4.12. This indicates that the number of secondary turns should be rounded to 4. The optimum operating point is when the LLC has a gain equal to 1. The given secondary winding number of turns is equal to 4. The different number of primary turns will provide different operating conditions at nominal input voltage of 400 V:

$$LLC_{gain}(N_p, V_{in.nom}) = \ 2 * \frac{N_p}{N_s} * \frac{V_{o.nom}}{V_{in.nom}} \qquad (20)$$

$$LLC_{gain}(14, 400V) = 0.901 \quad \text{buck mode}$$

$$LLC_{gain}(15, 400V) = 0.965 \quad \text{buck mode}$$

$$LLC_{gain}(16, 400V) = 1.030 \quad \text{boost mode}$$

With 14 turns, the LLC will operate more deeply in buck mode, which will increase switching losses on the secondary-side synchronous rectifier and lower the efficiency. Meanwhile with 16 turns, the LLC will operate in boost mode, with higher RMS current and conduction losses. With the primary number of turns as 15, the LLC will operate closer to the optimum boost mode, having ZVS on the primary side and ZCS on the secondary side. These operating conditions will provide the maximum efficiency. The transformer transfer ratio of 15/4 is the optimum one. In addition, a real LLC converter would require slightly higher gain to cover losses in the power transmission path, so the option with 15 turns will operate very close to the optimum $LLC_{gain} = 1$.

Maximum LLC gain is required at the minimum input voltage of 350 V, and border operating frequency (minimum frequency) is given by (20):

$$\boldsymbol{G(\omega_o)} = \left(\frac{2 * n * V_{o.nom}}{V_{in.min}}\right) = 1.1\ (21)$$

Equivalent AC load based on the first harmonic model (21):

$$\boldsymbol{R_{ac}} = \frac{8}{\pi^2}\frac{n^2 * V_{o.nom}{}^2}{P_o} = 9.2\ \Omega\ \ (22)$$

3.3 Calculation of LLC parameters

The minimum real operating frequency of the LLC converter is higher than the minimum operating frequency calculated by the FHA model. A good starting point for calculating parameters is to use the minimum operating frequency that gives minimum size of the resonant tank in the FHA model [1].

$$fo = 0.485 * fr \qquad (23)$$

Using formulas (16) to (18), it is easy to calculate LLC converter parameters as:

Transformer magnetizing inductance:

$$L_m = \frac{1}{\sqrt{G(\omega_0)^2 - 1}} * \frac{R_{ac}}{2 * \pi * 0.485 * f_r} = 92uH \ (24)$$

Let's round it to:

$$L_{mn} = 90uH$$

Resonant tank inductance using [1] is given by:

$$L_{rn} = L_{mn} * \frac{1 - \frac{1}{G(\omega_0)^2}}{\left(\frac{\omega_r}{\omega_o}\right)^2 - 1} = 4.9\ uH \qquad (25)$$

Resonant tank capacitance:

$$C_{rn} = \frac{1}{{\omega_r}^2 * L_r} = 998nF \qquad (26)$$

Let's explore this LLC setup:

Transformer transfer ratio	$\boldsymbol{n} = 3.75$
Transformer magnetizing inductance	$L_{mn} = 90\ \mu H$
Resonant tank inductance	$L_{rn} = 4.9\ \mu H$
Resonant tank capacitance	$C_{rn} = 998\ nF$

3.4 LLC transfer function

The useful operating range of the LLC is in the frequency range where input impedance has inductive character, as in **Figure 5**. The input impedance angle is positive. Current is lagging behind the voltage, allowing usage of the input current to charge/discharge MOSFET parasitic capacitances during turn-off.

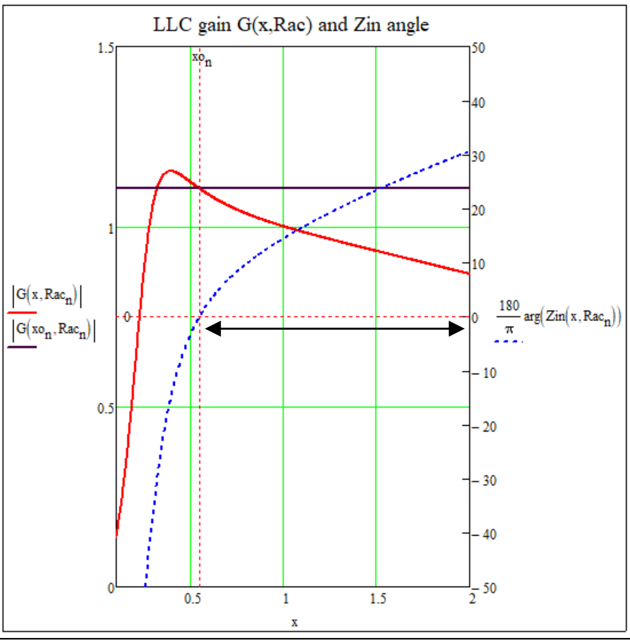

Figure 5 LLC useful operating range marked with black arrow

Input voltage and input current are in phase at boundary frequency (**Figure 6**). The question naturally arises: how can ZVS exist in a real LLC converter at boundary frequency, because the current is zero? This question could not be answered in the FHA domain. Simulation of the LLC converter, including more details that were disregarded during FHA approximation, will provide the answer.

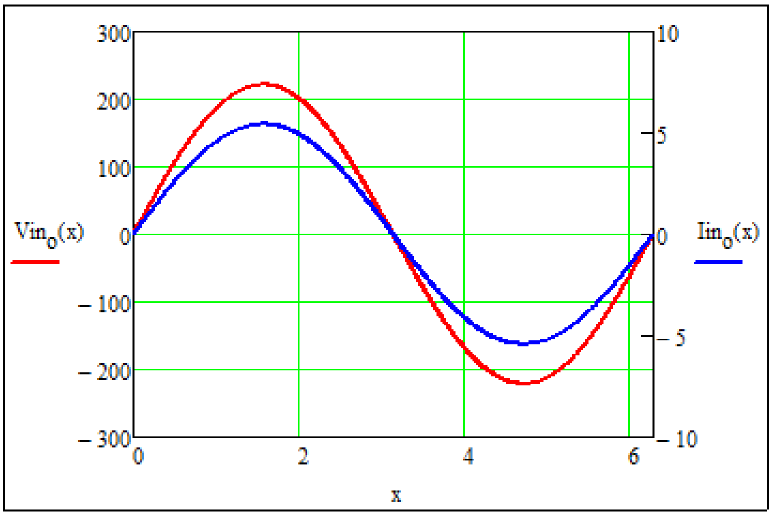

Figure 6 FHA: input voltage and input current at boundary frequency

3.5 Designer's choice

We may notice that the designer has made different choices compared to FHA optimum design and typical LLC topology. The objective was to improve efficiency at 50 percent load and light load. Let's list these changes and see how they impact LLC behavior and performance.

3.5.1 Magnetizing inductance

Magnetizing inductance is responsible for the LLC gain. Lower inductance provides more gain. Lower inductance means a high primary-side magnetizing current, which causes high primary-side RMS current and higher conduction losses. This is especially visible at light load, so when the designer needs better efficiency at light load, they may sacrifice some LLC gain. In this example the designer has changed the primary objective for the minimum input voltage from 350 V to 375 V. And accordingly, they have changed the magnetizing inductance from $\boldsymbol{L_{mn} = 90\ \mu H}$ to $\boldsymbol{L_m = 100\ \mu H}$.

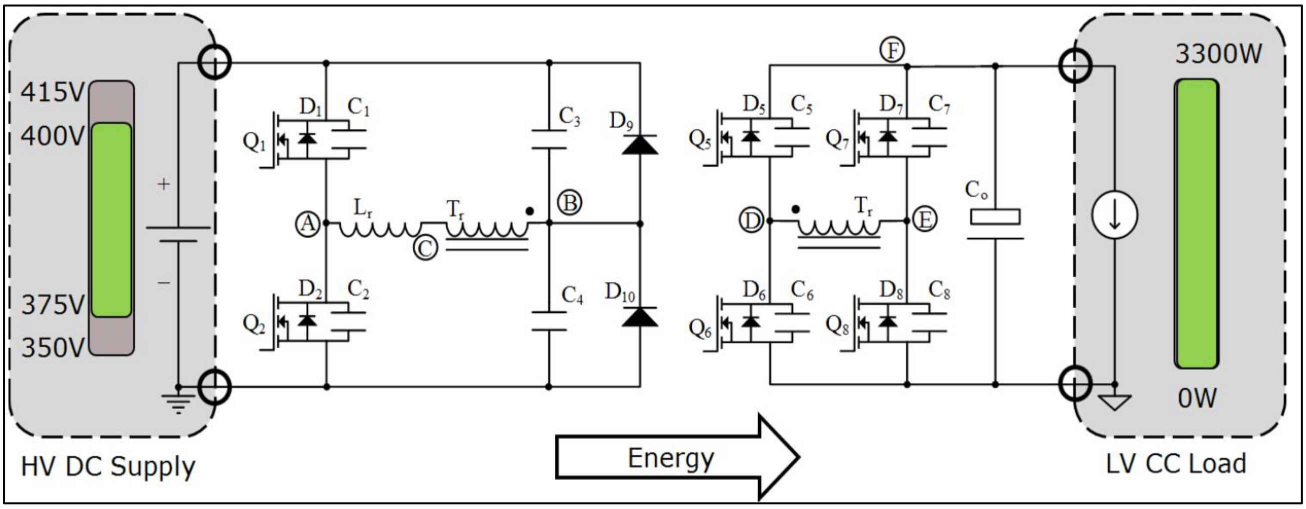

Figure 7 FHA: input voltage and input current at boundary frequency

3.5.2 Antiparallel diodes

Antiparallel diodes (D9 and D10) can be added across resonant capacitors (C3 and C4). The diodes (D9 and D10) limit capacitor peak voltage to the bus voltage. This means that with a given frequency they limit the maximum power that can be transferred from the primary to the secondary. Also, they protect the LLC from the capacitive mode of operation in the case of overload and/or step load changes.

3.5.3 Resonant tank impedance

Resonant tank parameter impedance is changed from 2.2 Ω to 4.75 Ω.

The resonant tank parameters are changed as:

Resonant tank inductance from $\boldsymbol{L_{rn}} = \mathbf{4.9}\ \mu\boldsymbol{H}$ to $\boldsymbol{L_n} = \mathbf{10.5}\ \mu\boldsymbol{H}$

Resonant tank capacitance from $\boldsymbol{L_{rn}} = \mathbf{998}\ \boldsymbol{nF}$ to $\boldsymbol{L_n} = \mathbf{465}\ \boldsymbol{nF}$

This change moves minimum operating frequency from $\boldsymbol{fo} = \mathbf{0.485} * \boldsymbol{fr}$ to $\boldsymbol{fo} = \mathbf{0.79} * \boldsymbol{fr}$. The main impact is that the operating range becomes narrower and improves (makes smaller) RMS currents on the primary and the secondary side. This impact is not visible in the FHA model, because of the sinewave nature. Simulation will clearly show this improvement.

4 Design verification using LTspice® simplified model

4.1 LTspice® simulation setup

A simplified HB LLC converter is shown in **Figure 8**. The primary side of the LLC is modeled as a variable-frequency unipolar pulse with amplitude equal to the input voltage. The transformer has unit transfer ratio to enable better simulation and minimize the losses caused by the output diodes (D3, D4, D5, D6). The load is represented with the voltage source equal to the output voltage multiplied by the transformer ratio. The control loop is closed around the output power.

Input current information at the beginning of the switching cycle is very important, because it determines transition time from one switch to another, charging and discharging MOSFET output capacitances. It is monitored using a sample-and-hold circuit, and measured at each positive edge of the input voltage. The output of the A1 sample-and-hold circuit is initial current (I_{OUT} current).

Output power is also monitored using the sample-and-hold circuit. The intention is to minimize the size of the output filter and measure the power at the same point and eliminate the impact of the ripple.

Operating frequency range is set by resistors RVCO1 and RSET1. The equations are given in **Figure 9**. Output voltage of the error amplifier V_{con} is in the range from 0 V to 1 V. It is used to vary switching frequency from minimum to maximum according to demand from the control loop. The output of the source B4 represents the operating frequency.

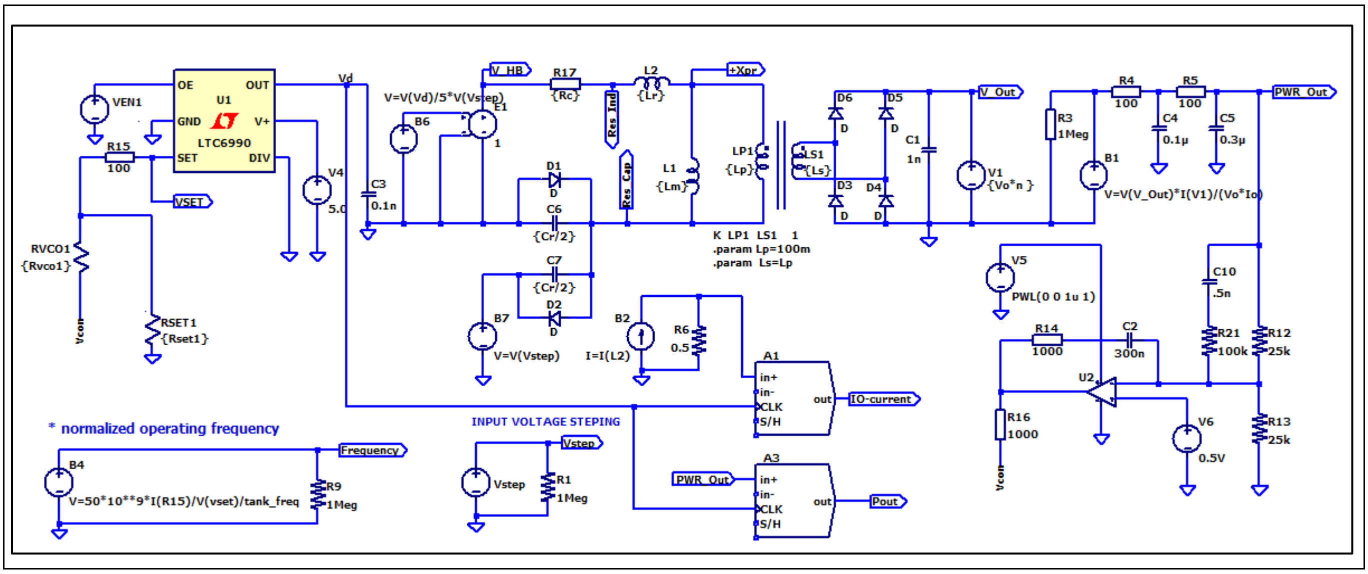

Figure 8 HB LLC simplified schematic

Voltage and current nominal values are taken from the specification, while LLC parameters are given by design output using design formulas (24), (25) and (26); see **Figure 9**. Notice that parameter R_c (resistor R17) represents the total serial resistance of the primary side, which may include $R_{DS(on)}$ of the MOSFET, resistance of the resonant tank and transformer resistance. This could be selected in the design process and used to estimate conduction losses.

The simulation/verification plan is to simulate the LLC circuit for two sets of parameters. One was from the FHA optimum design and another was selected by the designer. With regard to load, the simulation range includes full-load, half-load and one-quarter of the load. With regard to the voltages, the input voltage is varied from 375 V to 415 V, and will be divided into seven steps. One simulation set will be executed using nominal output voltage (V_{out} = 51.5 V) and another simulation set will use maximum output voltage (V_{out} = 59 V). The intention is to compare performance of the two sets of LLC parameters: FHA optimum choice (C_r = 998 nF, L_r = 4.9 µH, L_m = 90 µH) vs. the designer's choice (C_r = 465 nF, L_r = 10.5 µH, L_m = 100 µH) across the full operating range.

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* USER SUPPLIED TEST PARAMETERS
* UPDATE HERE FOR YOUR VERIFICATION TEST
*******************************************
***LLC converter operating range***
* Minimum Input voltage:
.param  Vin =400

* Nominal output voltage:
.param  Vo =51.5
.param   Io =65

***Parameters from LLC Calculator***
.param  Cr =998n
.param  Lr = 4.9u
.param  Lm=90u

* Transfromer parameters:
.param n = 15/4;
```

```
*** DO NOT MODIFY INDIRECTLY CALCULATED PARAMETERS  ***
* Range of operating frequency
.param  tank_freq=1/(2*3.14*SQRT(Lr*Cr))

.param fmin=0.4*tank_freq
.param fmax =3*tank_freq

* Resistor setup for the given frequency operating range:
.param Rset1 = 50k*(1000k/fmin)
.param Rvco1= 1/(fmax/1000k/50k -fmin/1000k/50k)
```

Figure 9 LLC parameters and operating frequency setup

Input voltage steps are generated by the step voltage source represented by voltage generator step, and then multiplied with the output voltage of LTC6990. At each input voltage step, a control loop will adjust the operating frequency, and key voltage and current variables will be measured in stationary conditions. Time intervals and voltage steps for this voltage source are given in **Figure 10**.

```
*Transient simulation setup:
.PARAM Ts=28m;
.PARAM Te = 5m
.tran 0 {Te+Ts} 0.5m
.options plotwinsize=0 ;.options numdgt=7; .options maxstep 20n
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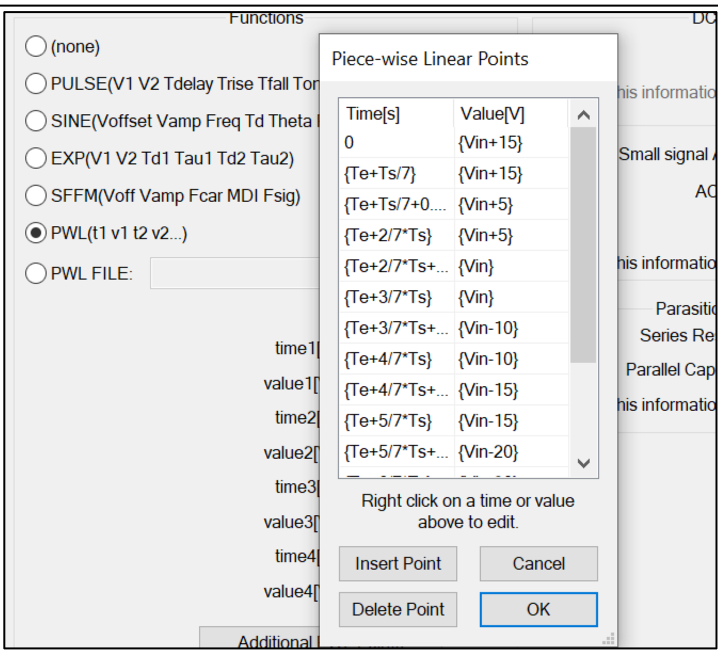

Figure 10 V_{step} voltage source setup

4.2 Nominal operating conditions V_{out} = 51.5 V and V_{in} = 375 V to 415 V

4.2.1 Buck/boost operating modes

The response of the LLC converter (based on the FHA optimum parameters selection) is given in **Figure 11**. The details of the voltages and currents for the nominal input voltage are given in **Figure 12** and **Figure 13**.

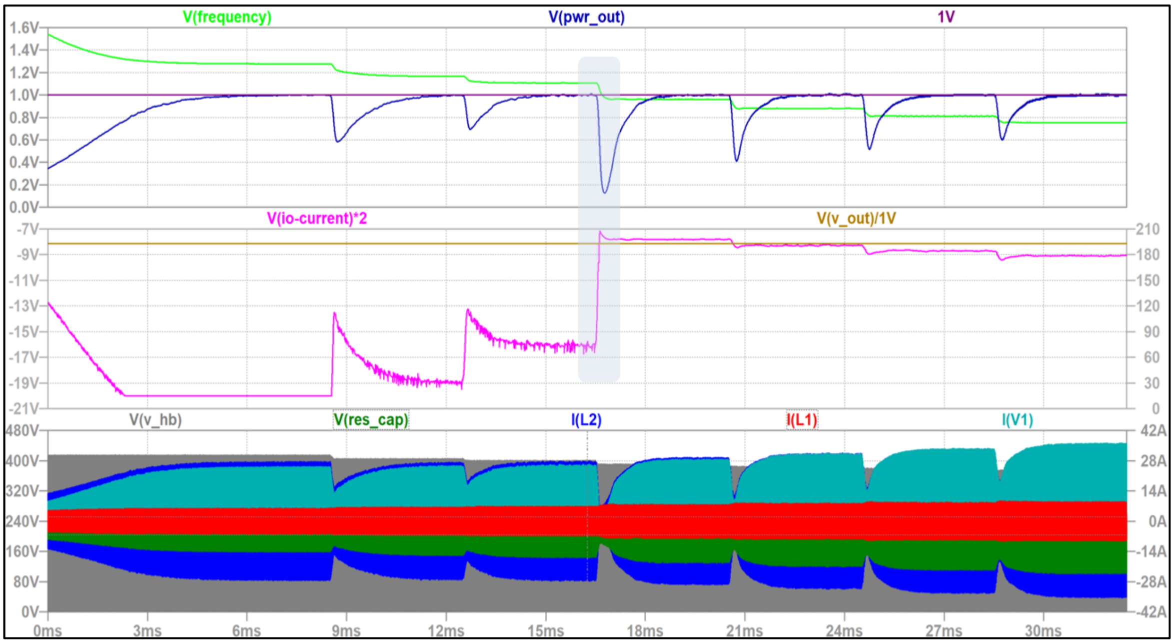

Figure 11 FHA optimum option LLC setup response to the series steps input voltage

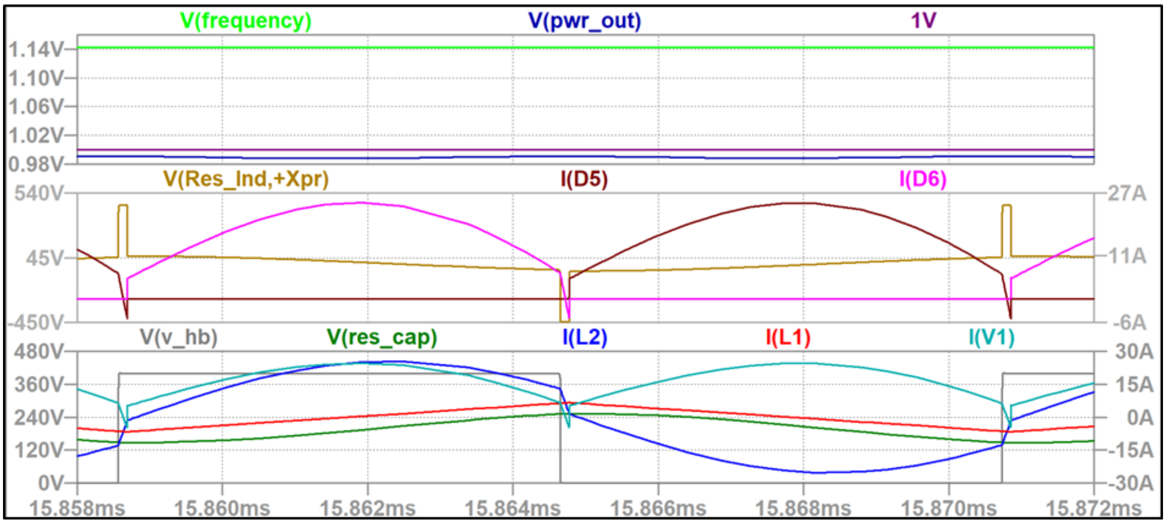

Figure 12 V_{in} = 400 V and LLC operating in buck mode

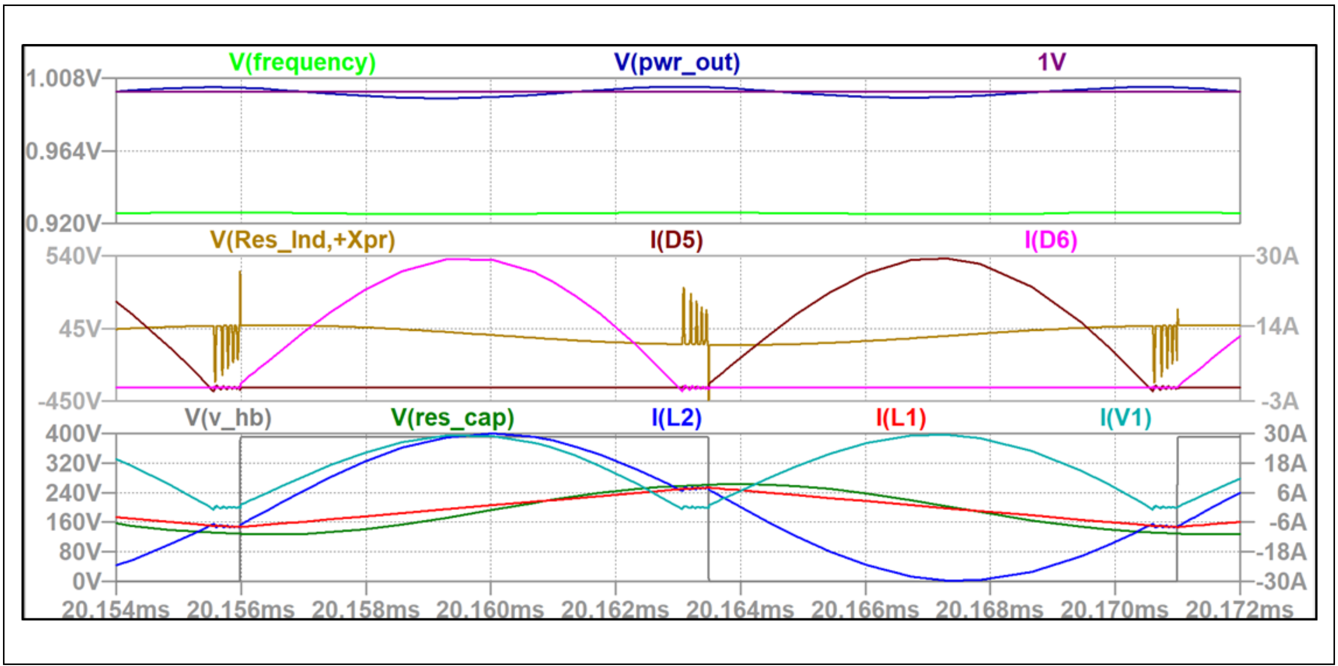

Figure 13 V_{in} = 390 V and LLC operating in boost mode

When the converter operates in buck mode, the switching frequency is higher than the resonant tank frequency. The green trace $V_{(frequency)}$ in **Figure 11** represents operating frequency. That curve crosses value 1, when input voltage changes from 400 V to 390 V. This means that the LLC converter is changing operating mode from buck to boost. It is interesting to notice that primary-side current at the beginning of the switching cycle, initial current (pink trace $V_{(io\text{-}current)}$, shows significant change when operation moves from buck to boost mode. It is very high in buck mode. At the higher input voltage, the switching event is closer to the peak input current, and $V_{(io\text{-}current)}$ has a higher value. When the input voltage drops in small steps, the frequency also drops in small steps and switching happens farther from the peak of the sinusoidal current, but there is a big change in the initial current. The behavior changes when the voltage drops below 390 V, and the converter starts to operate in boost mode. Then the initial current is determined by magnetizing current, and for the similar steps down of the input voltage initial current stays almost constant.

Figure 12 shows key voltages and currents for buck operating mode in more detail. The key characteristic of buck mode is that turn-off switching happens before the resonant tank completes the switching cycle. The turn-off slope of the output current is very high (di/dt = 95 A/µS), causing higher peak current recovery for the output rectifier diode I(D5) or I(D6). In the real LLC converter it will also cause ringing and more switching losses. The simulation schematic does not include parasitic parameters, and ringing is not visible.

Figure 13 shows key voltages and currents for boost operating mode. The key characteristic of boost mode is that turn-off switching happens after the resonant tank completes the switching cycle. The turn-off slope of the output current is slow (di/dt = 14 A/µS), and it is determined by the resonant circuit parameters. It will cause very low or almost no peak current recovery for the output rectifier diode I(D5) or I(D6). This means that in boost mode the LLC converter operates in the so-called ZCS mode and does not have turn-off switching losses, while having a better (less noisy) EMI signature.

4.2.2 LLC gain – mixed buck and boost modes

FHA describes the behavior of the LLC very well around resonant tank frequency. The gain of the LLC is close to 1. Due to the LLC operation requiring higher gain, larger than 1, operating frequency moves below resonant tank frequency. FHA becomes less accurate and the discrepancy between FHA and real LLC becomes more apparent. The same happens if the frequency moves above the resonance. On the other hand, the LTspice® simulation represents real LLC much better. The only discrepancies between the real converter and the simulation are the LLC switching and conduction losses because they are not accounted for in this model. **Figure 14** shows that real LLC gain is lower than predicted by the FHA model.

LLC based on the parameter set called "designer's choice" (C_r = 465 nF) shows a narrower frequency operating range across all load ranges. The biggest difference is at light load (25 percent). This means that switching losses will be lower for this LLC setup.

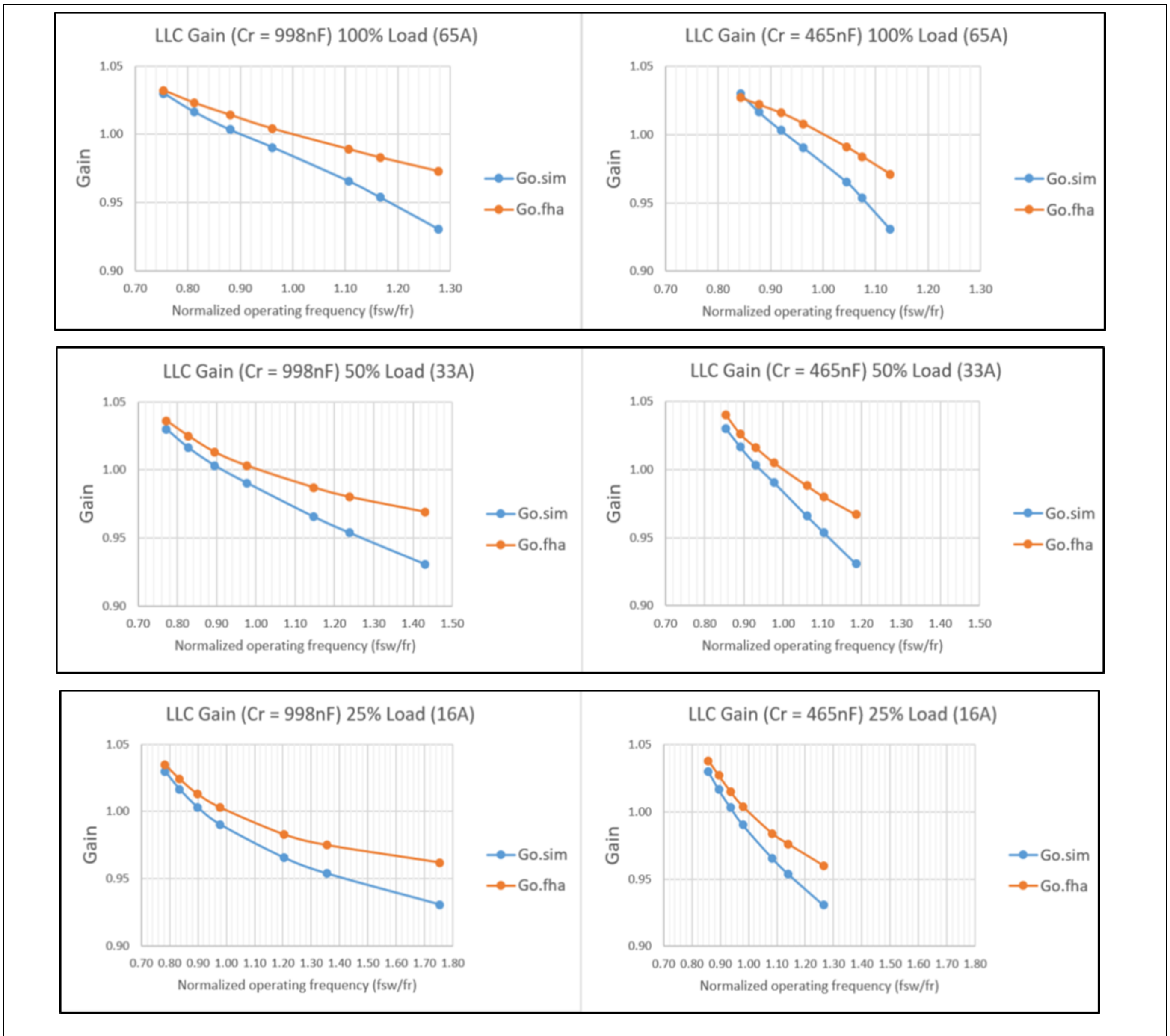

Figure 14 LLC gain for both options across input voltage ranges and different loads

4.2.3 Conduction losses

Conduction losses are proportional to the square of the RMS current. ($P_{con} = I_{RMS}^2 * R$). RMS current simulation data for the primary and secondary sides are collected for both LLC sets of parameters: FHA optimum and designer's choice. The ratio between RMS currents is shown in **Figure 15**. When the curve is above 1, it means that FHA optimum selection has higher RMS current = conduction losses. We may notice the following:

- Full-load condition – almost the same, difference is in the range of 2 percent
- Half-load condition – difference of around 5 percent and advantage of designer's choice
- Light-load condition – difference goes up to 20 percent in favor of designer's choice

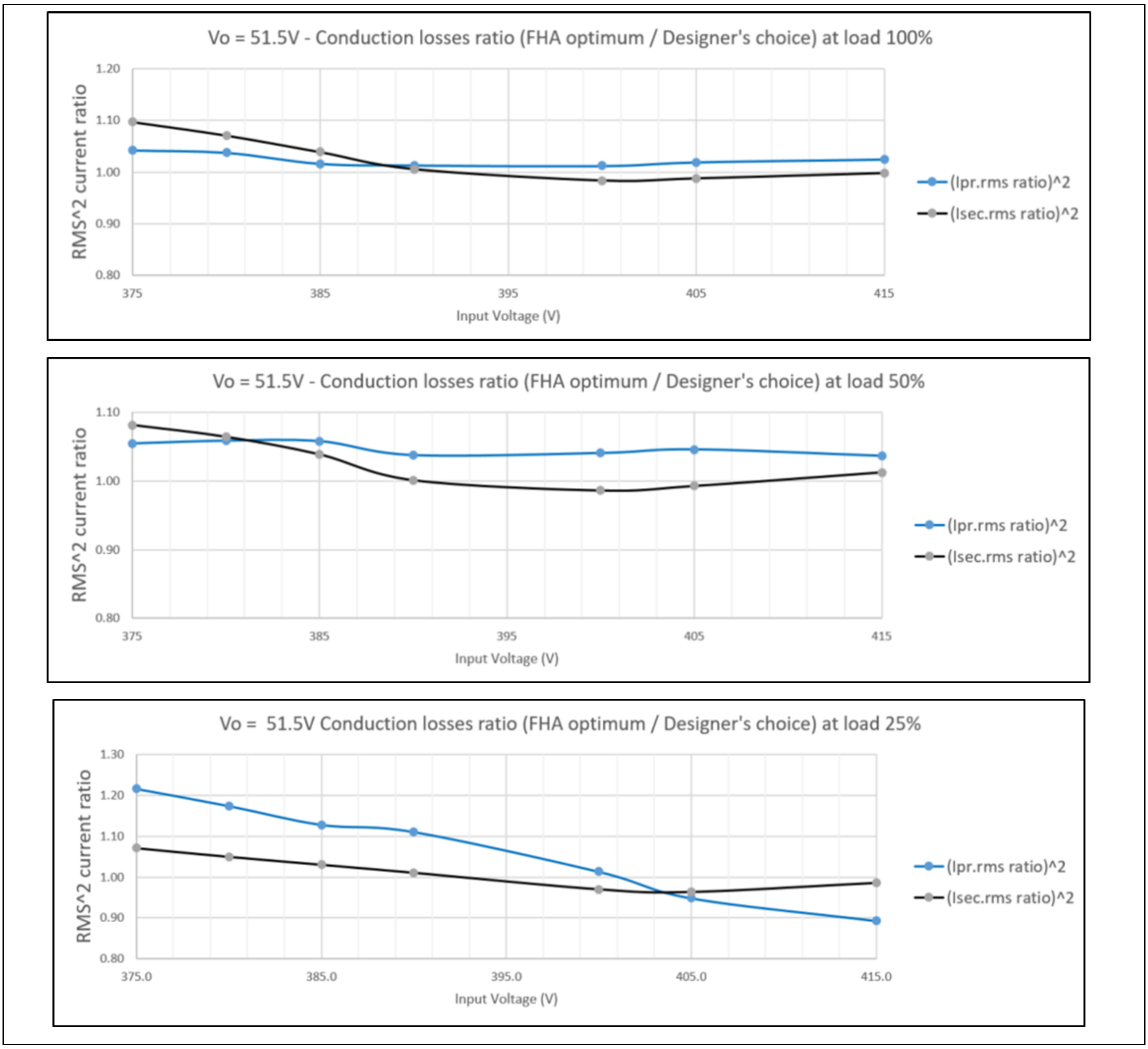

Figure 15 RMS current ratio between (FHA optimum)/ (designer's choice) at V_{out} = 51.5 V

4.3 Nominal operating conditions at V_{out} = 59 V and V_{in} = 375 V to 415 V

4.3.1 LLC gain – boost mode

When output voltage is equal to 59 V, the LLC converter operates in boost mode only. The LLC converter based on the FHA optimum parameters selection operates down to half of the resonant tank frequency. At full load condition LLC converter based on designer's choice (C_r = 465 nF) does not provide enough gain and cannot deliver full power to the output. This is shown in **Figure 16**. When the requirement for the output power drops to half (C_r = 465 nF) the setup can deliver that power to the output.

Frequency range (max./min. ratio) is similar for both setups, but FHA optimum setup (C_r = 998 nF) operates in the lower frequency range. This will cause higher RMS currents.

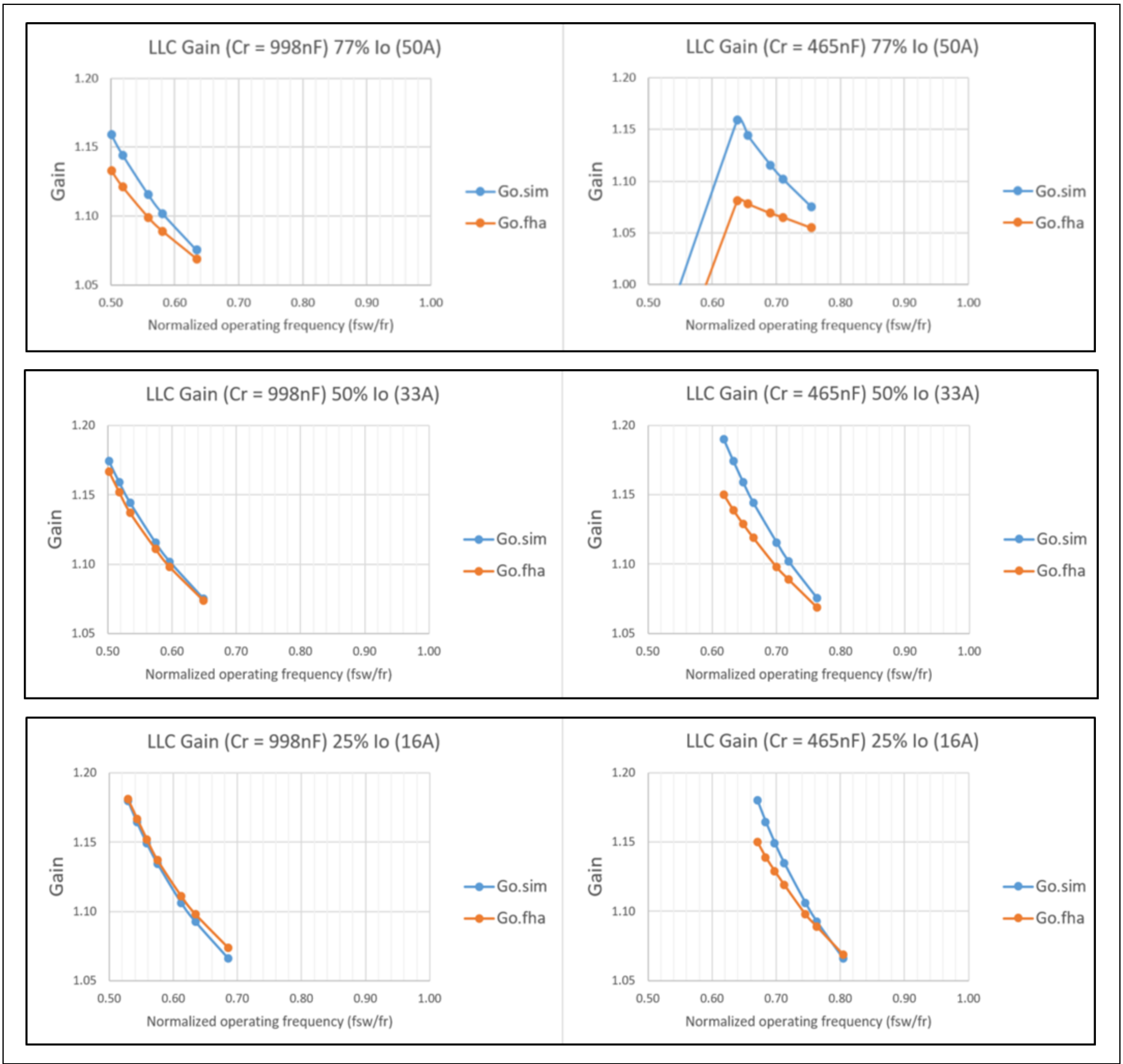

Figure 16 LLC gain for both options across input voltage ranges and different loads

4.3.2 Conduction losses

Conduction losses are proportional to the square of the RMS current. ($P_{eon} = I_{RMS}^2 * R$). RMS current for the primary and secondary sides is collected for both LLC sets of parameters: FHA optimum and designer's choice. The ratio between RMS currents is shown in **Figure 17**. When the curve is above 1, it means that FHA optimum selection has higher RMS^2 current = conduction losses. We may notice the following:

- Full-load condition – difference is in the range from 5 percent to 20 percent
- Half-load condition – difference is in the range from 10 percent to 20 percent
- Light-load condition – difference is in the range from 12 percent to 35 percent

The designer's choice set of parameters (C_r = 465 percent) demonstrates the advantage of lower conduction losses over the complete input voltage and load ranges.

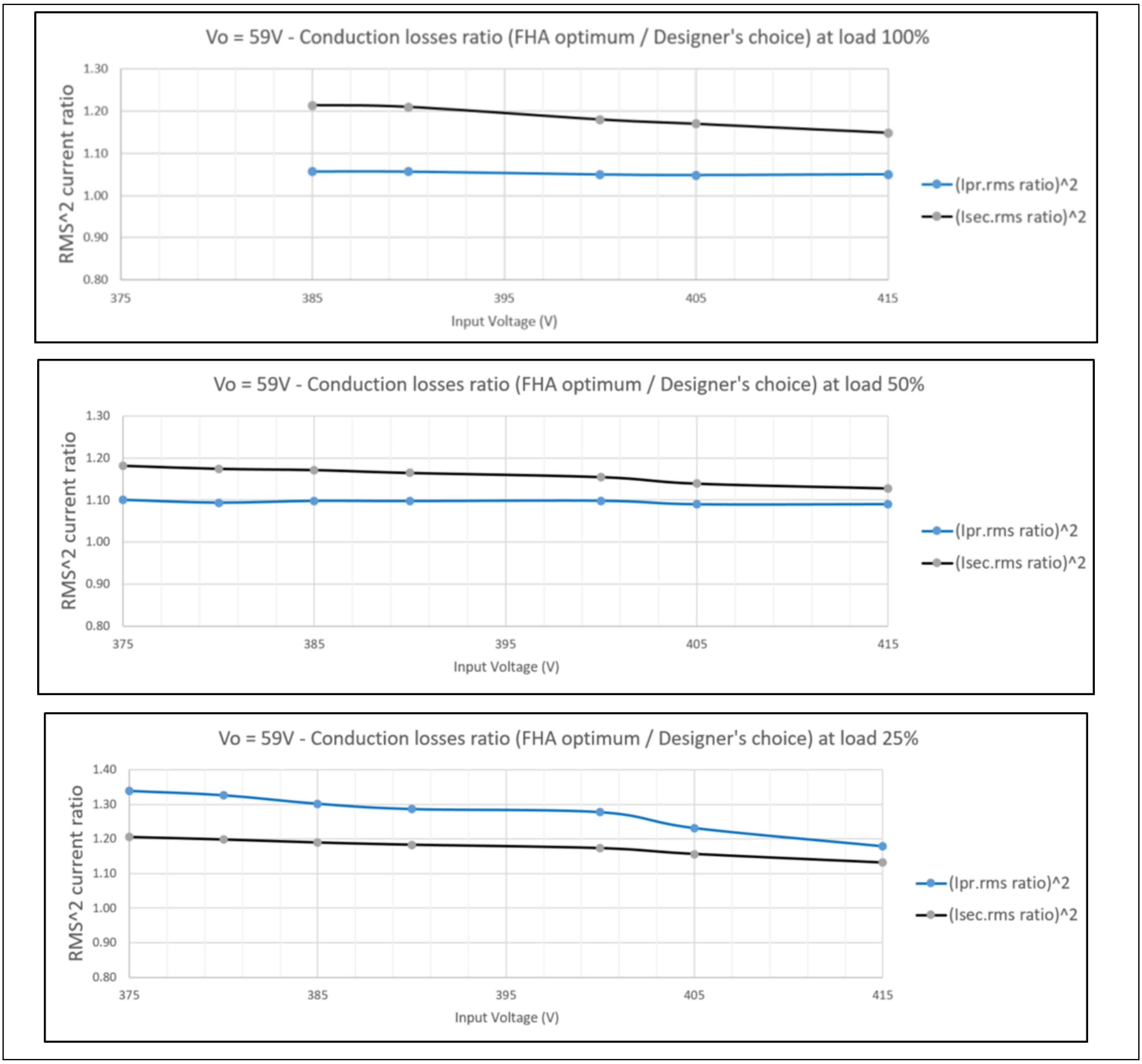

Figure 17 RMS current ratio between (FHA optimum)/ (designer's choice) at V_{out} = 59 V

5 Summary

This application note showed the use of simple algorithms for LLC design, based on the FHA model. The novel vector method provided simple formulas to calculate LLC parameters. The essence of the vector method is to use the input impedance angle between voltage and current on the primary side of the LLC converter as a key variable to distinguish operating modes of the LLC and determine the boundary condition between inductive and capacitive modes of operation. The major benefit of this method is simplicity and clarity.

The vector method is based on FHA and AC circuit analysis. The critical transfer point between inductive and capacitive modes is identified as a simple vector criterion, where the inverse transfer function vector and the vector of serial combinations of load components are orthogonal. Simple sets of equations followed this conclusion.

The calculation procedure becomes straightforward. Key formulas are derived by using simple trigonometry. The minimum operating frequency (ω_o) is such that it gives a minimum size for the resonant tank. A simple design procedure follows through calculations of LLC parameters.

The design algorithm has the following steps:

1. Provide a basic specification for the LLC converter:
    a. Input voltage range
    b. Output voltage
    c. Output power
    d. Efficiency
    e. Frequency operating range
2. Select LLC topology option:
    a. FB or HB
3. Calculate performance parameters of the LLC:
    a. Transformer transfer ratio $\boldsymbol{n}$ – equation (19)
    b. LLC gain $\boldsymbol{G(\omega_o)}$ – equation (21)
    c. Equivalent AC load $\boldsymbol{R_{ac}}$ – equation (22)
4. Calculate property parameters of the LLC:
    a. Magnetizing inductance $\boldsymbol{L_m}$ – equation (24)
    b. Resonant tank inductance $\boldsymbol{L_r}$ – equation (25)
    c. Resonant tank capacitance $\boldsymbol{C_r}$– equation (26)
5. Verify the design using LTspice® simulation.

The designer has decided to make the following changes:

- Add antiparallel diodes to the resonant capacitors. The benefit of this change is twofold. One is to eliminate the capacitive mode of operation and the second is to provide a maximum power limit by limiting resonant capacitor peak voltage.
- Change the resonant capacitor from C_r = 998 nF to C_r = 465 nF. This change moves the LLC minimum operating frequency closer to the resonant tank frequency, and the result is lower RMS currents, lower conduction losses and better efficiency. The only drawback is lower gain at maximum output voltage and full load.
- Magnetizing inductance is changed from 90 µH to 100 µH. This will lower XFMR magnetizing current, and primary-side RMS current will be lower too.

This is one of the ways to optimize efficiency. Start from the FHA optimum parameters setup and make changes toward smaller RMS current and better efficiency. Optimization may go in different directions, and there are a number of options as described in [5] and [6]. The designer's choices are justified with better overall efficiency.

References

[1] Infineon Technologies AG: *Evaluation board EVAL_3K3W_LLC_HB_CFD7*; **Available online**

[2] Ivankovic, M: *LLC design guide for 600W converter*; **Available online**

[3] Ivankovic, M./ Sawyer, F.: *System and Method for LLC converter design (US patent 9,906,136)*; **Available online**

[4] Infineon Technologies AG: *Part I: LLC calculator*; **Available online**

[5] Infineon Technologies AG: *Part II: Using the LLC calculator with rules of thumb (ROT) and fast verification with LTspice*; **Available online**

[6] Ivankovic, M./ Hancock, J.: *LLC converter design using novel vector method and free cost tools*; APEC; 2020

[7] Infineon Technologies AG: *Resonant LLC Converter – Operation and Design*; **Available online**

[8] Infineon Technologies AG: *LLC Converter Design Note*; **Available online**

[9] Infineon Technologies AG: *600 W half-bridge LLC evaluation board with 600 V CoolMOS™ C7 and digital control by XMC*; **Available online**

[10] R. D. Middlebrook, R.: *Low-Entropy Expressions: The Key to Design-Oriented Analysis*; **Available online**

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