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TND6318/D

On Board Charger (OBC) LLC Converter

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REFERENCE DESIGN

OBC LLC Board Setup Picture

Background

Nowadays, so called plug in hybrid as well as fully electric vehicles are catching more and more attraction triggered by the reduction of pollution as it is normally happening with pure combustion engine. Nevertheless, there is at least one feature that is common to all of them electric energy is accumulated in dedicated battery pack and it is used in electric motors afterwards. Although this technology still undergoes heavy development nowadays, so do also relevant technical standards, it is clear that charging energy is provided utilizing existing mains infrastructure.

Hand in hand, it implies certain requirements put on chargers, those installed On Board as well as on those installed Off Board.

LLC Converter in OBC Applications

As can be seen also in Figure 1, a typical battery charger application consists of two different stages, AC−DC converter and DC−DC converter. PFC goal is to rectify the input voltage normally provided by a mains, keeping power factor as close as possible to unity. DC−DC converter provides galvanic isolation and the output voltage / current levels as requested by the battery management system. Therefore DC−DC converter is a key block of any OBC system. Number of topologies can be used, however LLC converter is favorite one, among others well known for good efficiency figures and mild EMI fingerprint.

On the other hand, wide output voltage range generally seen in OBC applications may present serious design complications. Board presented in this document has been designed for evaluation of not only, but most of all, new ON Semiconductor Silicon Carbide MOSFET NVHL080N120SC1 (N−Channel, 1200 V, 80 mΩ, TO247−3L, suggested to be used with dedicated ON Semiconductor SiC MOSFET driver NCP51705), in OBC like application.

Key Features

- Input Voltage 700 ±35 V
- Output Voltage 200 / 450 V
- Output Current 0 / 40 A
- Maximum Output Power 10 kW
- Maximum Switching Frequency 400 kHz
- Microcontroller Control with USB and CAN Bus Interface
- Liquid Cooling
- Board Size without Resonant Tank Board 360 × 187× 92 mm

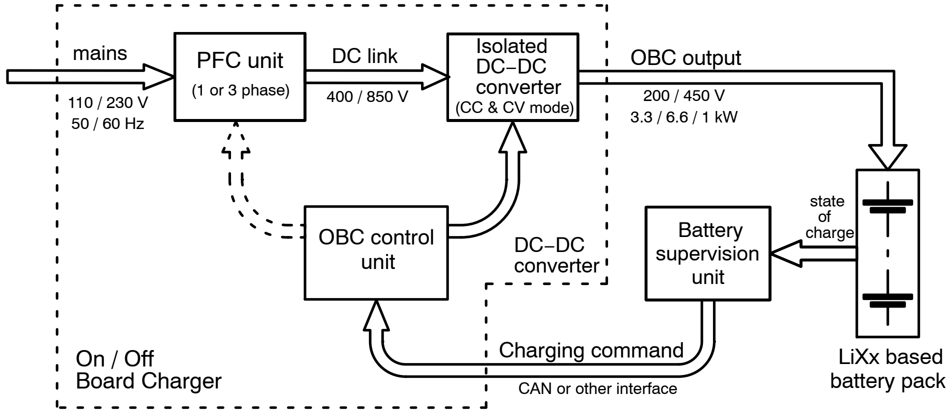


Figure 1. Typical Structure of OBC System

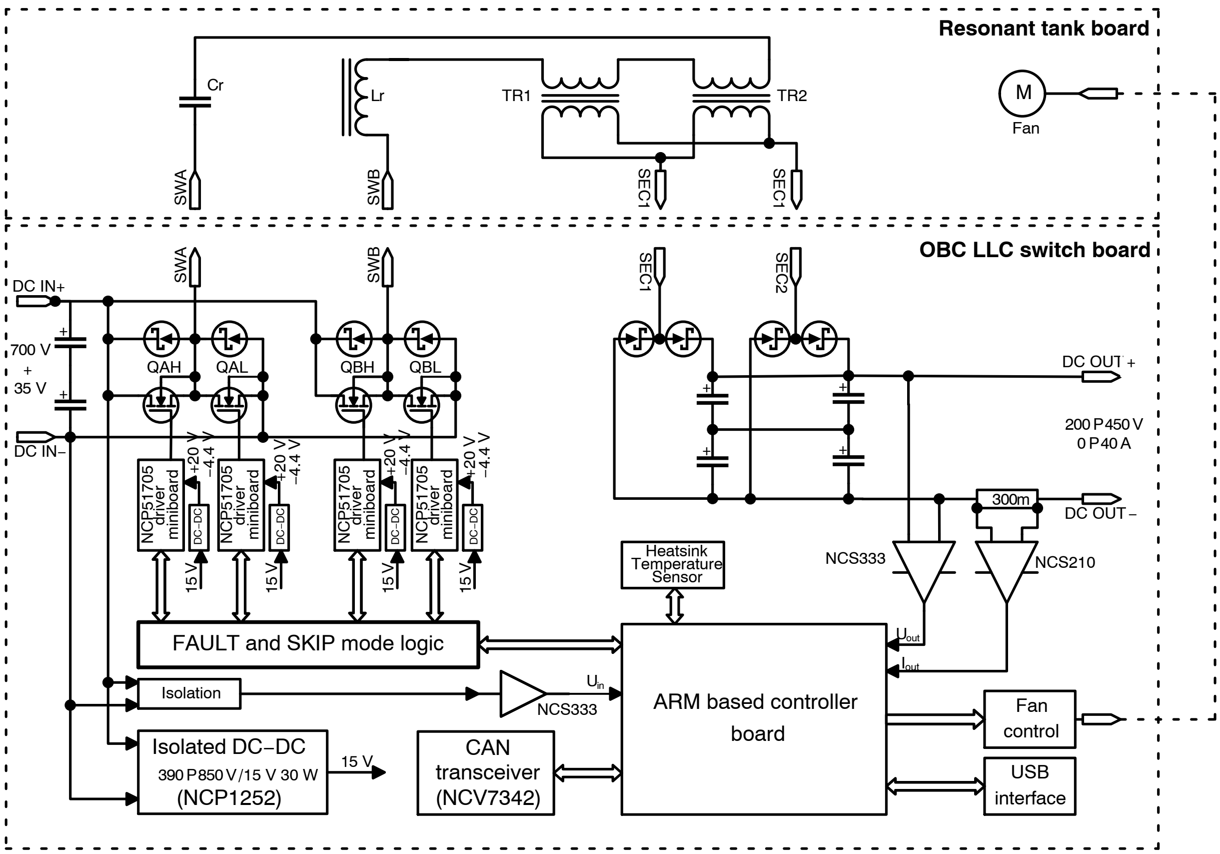


Figure 2. OBC LLC Block Diagram

Concept Overview

Overall concept is shown in block diagram above (Figure 2). Since higher priorities have been put on testability, flexibility, modularity and reusability than to overall test setup dimensions, presented concept is definitely not aiming for highest power densities and compactness.

One can even notice that whole OBC LLC converter evaluation set up has been split into two separate boards. One board, called OBC LLC switch board, containing all active components and next board, called resonant tank board, containing LLC converter resonant members – resonant inductor, resonant capacitor, transformer(s). Although it could be found as a suboptimal solution from various perspectives at first glance, there is one major advantage of this approach – virtually any resonant tank solution can be tested and compared to another one, without a need to change anything on switch board. This can be very helpful, especially for OBC like applications, where wide range of output voltages makes resonant tank design more complex. Furthermore, with certain small modifications also other converter topologies, full bridge phase shifted converter for example, could be tested as well.

Power Stage

Target output power level at around 10 kW and LLC topology indicates that full bridge power stage is the preferred option for power stage. As already mentioned before, original intention was to support SiC MOSFETs application evaluation. Naturally, it implies certain requirements for MOSFETs driving circuitry, in this board addressed by NCP51705 driver.

From concept point of view, modularity approach has been followed again – every transistor has its driver installed on own small so called driver mini−board. Consequently, also different driver solutions can be eventually tested. Although NCP51705 driver contains also charge pump circuitry to generate negative supply voltage for SiC gate driver part, it is turned off on this board in its default state.

Driver power supply (+20 V and −4.4 V) is provided by external small, low coupling capacitance DC−DC converter, which may be advantageous in case also different power stage configurations are about to be tested. It means that application compare among regular, super junction MOSFET and even IGBT devices is feasible, while still using the same setup.

It is important to mention that insulation barrier between primary and secondary side at MOSFET drivers level is provided by a digital insulator, located on driver mini board.

Although targeted input voltage is 700 ±35 V, in principle, also different voltage levels can be tested. Maximum applicable input voltage is basically limited by two 450 V rated electrolytic capacitors connected in series at the power stage input, by 900 V Ceralinks capacitors installed across both half bridges and of course transistors installed in power stage and housekeeping converter. Minimum input voltage level housekeeping converter still operates is around 390 V.

Secondary Side Rectification

Full bridge has been selected for output voltage rectification, even if synchronous rectification is one of the main measures for efficiency improvements. Relatively high output voltage makes synchronous rectification more complicated and costly. Real OBC applications typically obey rule of simplicity therefore appropriate, sometimes also SiC diodes are utilized. Presented board uses four FFSH3065A diodes, but selected mechanical concept provides very convenient access to them, as well as to all power transistors, so they can be changed quite easily and quickly to any other type.

Thermal Management

Selected liquid cooling not only simplifies power components thermal management, but also provides an option to have power components temperature under tighter control. Consequent results compare of different configurations is sometimes more objective and more appropriate. On the other hand, classic air cooling, seen almost exclusively in all Off Board charging solutions may work under slightly different conditions in reality. Cold plate actual temperature can be measured via I2C temperature sensor mounted on it, however no special measurement accuracy has been considered. Intended usage covers debugging purposes and eventual additional safety measures implemented in controller firmware, if needed.

As can be observed in block diagram, there is also fan control interface, providing thus a possibility to use standard transformer and inductor solutions on resonant tank board. These components very often require forced airflow to operate safely.

Input & Output Voltage, Output Current Sensing

Naturally, information about actual output voltage and output current is crucial for regulation purposes. Keeping simplicity in mind, output voltage sensing is provided by simple resistive divider which output is buffered by NCS333 amplifier and input to control board. Similarly, output current is sensed at negative DC output line as a voltage drop over 300 μΩ shunt, amplified by special current sensing amplifier NCS210.

Since controller board sits on secondary side, primary side input voltage information has to be insulated in reasonable way. Simple voltage to current converter at primary side is driving optocoupler, which output current is converted back to voltage, which can be measured directly by controller board. Of course, price paid for this simple approach is certain non−linearity and limited input voltage measurable range, but it has been considered as a sufficient solution. Note, that input voltage information is not necessarily needed for output voltage and current regulation, in case simple algorithms are being considered. Actual board firmware uses input voltage information for protection purposes only.

Housekeeping DC−DC Converter

Implemented two switch fly−back converter controlled by NCP1252 controller provides insulated 15 V at its output, up to 30 W maximum. This voltage is used as a main power source for all low voltage circuitry at the secondary side – MOSFET drivers, controller board as well as eventual fan installed on resonant tank board. Housekeeping DC−DC converter can be easily disconnected from input voltage. In that case external 15 V power supply can be connected over dedicated connector to operate the board.

Brown out protection gets activated below 390 V (can be lowered if needed), maximum input voltage tested is about 830 V. For higher input voltages selected MOSFETs as well as capacitors at input LC filter have to be checked.

Communication Interfaces

Two interfaces are present on board – USB and CAN bus interface. CAN bus interface is typically preferred in OBC applications, but because of potential software complexity related to it and standard variations no control over CAN interface has been implemented in current firmware version, since this board is not targeted to verify CAN bus protocols related to OBC. A python based application is currently available to interact with the switch board/micro−controller board. It communicates over USB. Also firmware flashing takes place over the same interface.

Resonant Tank Design

Generally speaking, selection of resonant tank members is the key factor to achieve the specified operating conditions for the LLC converter. To determine passive components values, so called First Harmonic Approximation (FHA) method has been applied. In fact, real experience shows that it is very valuable while still quite simple and straightforward method to evaluate regular LLC designs. Accuracy of estimations based on this method is more than fair for typical *fixed output voltage* LLC converters with relatively narrow input voltage ranges. Important point is that resonant tank is designed to operate ideally at its main resonance frequency (or very close to it) while exhibiting all its advantages, like efficient operation and quite mild EMI fingerprint by nature.

Unfortunately, such operating conditions are rarely present in OBC applications, since battery pack voltage varies quite substantially over battery state of charge space. Common situation example is depicted in Figure 3. It can be seen that fully depleted battery pack voltage can be as low as 220 V. On the other side, fully charged battery pack voltage of 410 V or higher can be expected. Of course, voltage range 220 / 410 V may not be taken as something generally valid, while these numbers are changing among others with battery pack temperature slightly. They are also affected by selected battery technology.

Nevertheless, it is apparent, that *OBC output voltage can vary easily by factor 2 or more*, which is huge difference compared to 10 / 15 % variation typical LLC converter has to usually face to. Number of publications dedicated to this problem and its impact to proper LLC resonant tank design are available in literature, various approaches can be selected, unfortunately, every approach comes hand in hand with certain compromise and probably no universally applicable cook book can be given.

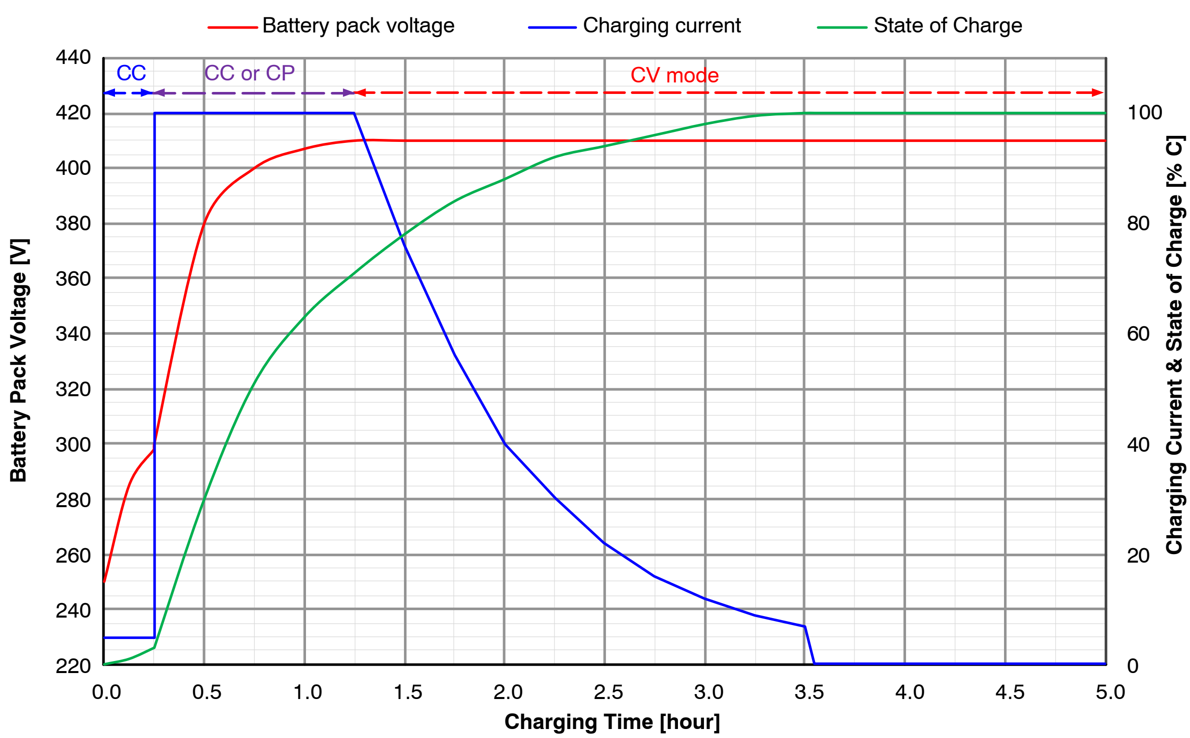


Figure 3. Charging Profile Example for 410 V Li−Ion Based Battery Pack

The problem with FHA analysis can be identified in its name already – first *harmonic* analysis. As already mentioned above, typical LLC converter with narrow input to output voltage ratio range operates in close vicinity of so called main resonance point, where current waveforms are not very distorted from their ideal sinusoidal shape. Even if frequency excursion range in OBC LLC converters could be reduced up to a certain degree with adequate resonant components, it is almost sure that converter's operating frequency will be shifted relatively far from main resonance point. This happens especially for maximum input voltage with minimum output voltage and minimum load current, or vice versa, for minimum input voltage with maximum output voltage and maximum load current. It results in by far non−sinusoidal current waveforms that FHA is not considering. Unfortunately, no other, comparably simple method exists, so one has to be aware of operating point calculation errors while applying this method for distant operating points.

A practical approach used for the LLC passive calculation is summarized in [1] and it has been used as a reference for this application:

- *Select Transformer Primary to Secondary Turns' Ratio*

Number of different approaches can be taken when considering optimal transformer turns ratio. Efficiency aspect may dictate to select turns ratio in a way that LLC converter operates at its optimum operating point (e.g. typically main resonant point) as long as possible. Especially in OBC applications, this is where the information about intended battery pack charging profile is very useful. Looking back in example profile above, it can be found, that maximum constant power or maximum constant current delivery can be expected in output voltage range from about 290 V up to 410 V. Selecting middle point of this range gives out 350 V. Considering nominal input voltage of 700 V implies a transformer turns ratio of 2.

$$N = \frac{U_{IN,nominal}}{U_{OUT,middle}}$$

- *Calculating Minimum Converter Gain*

The minimum converter gain is typically given by the ratio between the minimum output voltage and the maximum input voltage, however in an OBC application it would result in a very high switching frequency (several times the main resonant frequency). This is very often not practically possible if considering light load conditions. Therefore the usage of some kind of skip mode functionality is unavoidable. Thus, instead of minimum output voltage, a reasonable skip mode entry output voltage has to be selected for minimum converter gain calculation. Such selection can be driven by the minimum output voltage achieved under full load conditions are applied. This narrows output voltage range, however, entering skip mode operation below this output voltage is automatically connected with increased charging current ripple. It is usually acceptable, but it has to be checked in particular cases.

$$M_{min} = \frac{N \times U_{OUT,skip\ entry}}{U_{IN,max}}$$

Just for illustration, with minimum output voltage of 220 V, maximum input voltage of 735 V, transformer turns ratio 2 and skip mode entry voltage of 292.5 V required minimum converter gain is 0.796.

- *L_R to L_M Ratio Selection*

L_R to L_M ratio is one of the critical parameters of every LLC converter. Among others its selection has direct impact on converter frequency characteristics, e.g. also on frequency excursion needed to cover required converter gain range. In theory, reducing L_M can eventually lead to smaller transformer footprint, but hand in hand it increases circulating current in the resonant tank, implying higher stress to the windings and magnetic circuit of magnetic components. Typical L_R to L_M ratio seen in LLC converters is somewhere from 1:3 to 1:7. It is also not very different in OBC LLC converters, although lower ratios are more likely to be selected.

Here, such value is calculated considering the ratio between maximum switching frequency (minimum converter gain) and nominal resonant frequency (converter gain 1). Following equation can be used:

$$l = \frac{L_R}{L_M} = \left(\frac{1}{M_{min}} - 1\right) \times \frac{8 \times f_{n,max}^2}{8 \times f_{n,max}^2 - \pi^2}$$

where $f_{n,max}$ is the normalized maximum switching frequency – ratio of maximum switching frequency, applied just at skip mode entry output voltage and maximum input voltage, to nominal resonant frequency:

$$f_{n,max} = \frac{f_{max}}{f_r}$$

Both, f_r and f_{max} have to be selected as a design requirements. Typical LLC converters normally go with $f_{n,max}$ within the range 1.5 / 2.5. Because of Silicon Carbide MOSFET, maximum switching frequency of 400 kHz has been selected, even if the SiC MOSFET gate driver NCP51705 is capable of maximum switching frequency of 500 kHz. In order to mitigate switching losses resonant frequency of 108 kHz has been considered. With given frequency parameters and already calculated minimum converter gain (M_{min}), the resulting L_R to L_M ratio is 0.282 (1:3.549).

- *Calculate Critical Operating Point*

LLC converter should always operates at zero voltage switching (ZVS) mode. Such condition is guaranteed when the actual switching frequency is located in the inductive impedance nature of the resonant tank. The critical operating point is defined as a crossover point between the capacitive and the inductive impedance of the tank. The critical operating point can be analytically determined with the following two equations. The first represents the critical converter gain, M_{crit}, and the later represents the critical impedance, Z_{crit}:

$$M_{crit} = \sqrt{1 + \sqrt{\frac{l}{1 + l}}}$$

$$Z_{crit} = \frac{8}{\pi^2} \frac{U^2_{IN,min}}{P_{OUT,max}} \left(\sqrt{l \times (1 + l)} + 1\right)$$

According design parameters mentioned in previous paragraphs, it leads to a M_{crit} of 1.212 and a Z_{crit} of 31.6 Ω. Additionally, output voltage, output current and input current can be calculated for this critical condition:

$$U_{OUT,crit} = \frac{U_{IN,min} \times M_{crit}}{N}$$

$$I_{OUT,crit} = \frac{P_{OUT,max}}{U_{OUT,crit}}$$

$$I_{IN,crit} = \frac{P_{OUT,max}}{\eta \times U_{IN,min}}$$

where η is estimated converter efficiency at critical operating point. Even though exact efficiency value is not known at this point yet, rough estimated value is usually fair enough to use. Just for completeness for considered design example, calculated $U_{OUT,crit}$ is 403 V, $I_{OUT,crit}$ is 24.8 A and $I_{IN,crit}$ is 15.7 A, when considering 10 kW output power, 665 V minimum input voltage and 96 % efficiency.

- *Calculate Required Minimum L_M for ZVS Operation at Critical Operating Point*

Once all parameters for critical operating point are known, following equation can be used to calculate minimum magnetizing inductance L_M value needed so that converter still operates in ZVS mode at this critical point.

$$L_M = \frac{N^2}{f_r} \frac{U_{OUT/crit}}{4NI_{IN,crit} + (pi^2 \times l \times M_{crit} - 4)I_{OUT,crit}}$$

- *Calculate Maximum L_M for ZVS Operation at Maximum*

There is one additional condition which needs certain attention – as selected previously, switching frequency during very light load or no load condition is clamped at given maximum f_{max}. The problem is that at no load condition only circulating resonant tank current takes care about zero voltage switching. It is only current charging and discharging switch nodes parasitic capacitances. Once this current gets naturally reduced by high frequency operation compared to operation at resonant frequency (there is not enough time available for relevant current increase in magnetizing inductance) selected commutation time (e.g. dead time) may become too short and MOSFET switches are turned on before their body diode starts to conduct. Following equation can be used to calculated maximum magnetizing inductance L_M providing ZVS operation:

$$L_{M,max} = \frac{\text{dead time}}{8\pi f_r C_{oss}} \sqrt{\left(1 + \frac{1}{l}\right) M^2_{min} - \frac{1}{l(1 + l)}}$$

where C_{oss} is one MOSFET junction capacitance. Using 80 pF and 100 ns dead time for design example above maximum acceptable magnetizing inductance is 154.7 μH. In case value calculated in this point is lower than value calculated in previous point some of design inputs needs to be changed and whole calculation reiterated. Usually, manipulating $f_{n,max}$ (f_r or f_{max}) or increasing dead time does the trick. In case control circuitry allows it, dead time can also be manipulated across operating space, using reasonable short dead time during normal operation and increasing it once approaching light load or no load condition.

- *Calculate L_R and C_R, Verify Z_o*

Last, but not least step is to calculate own resonant inductor and resonant capacitor values. Since l value has been already calculated L_R is very easy to calculate as well

$$L_R = l \times L_M$$

Similarly, main resonant frequency f_r has been given as a design input parameter, calculation of C_R is straightforward

$$C_R = \frac{1}{L_R \times (2\pi f_r)^2}$$

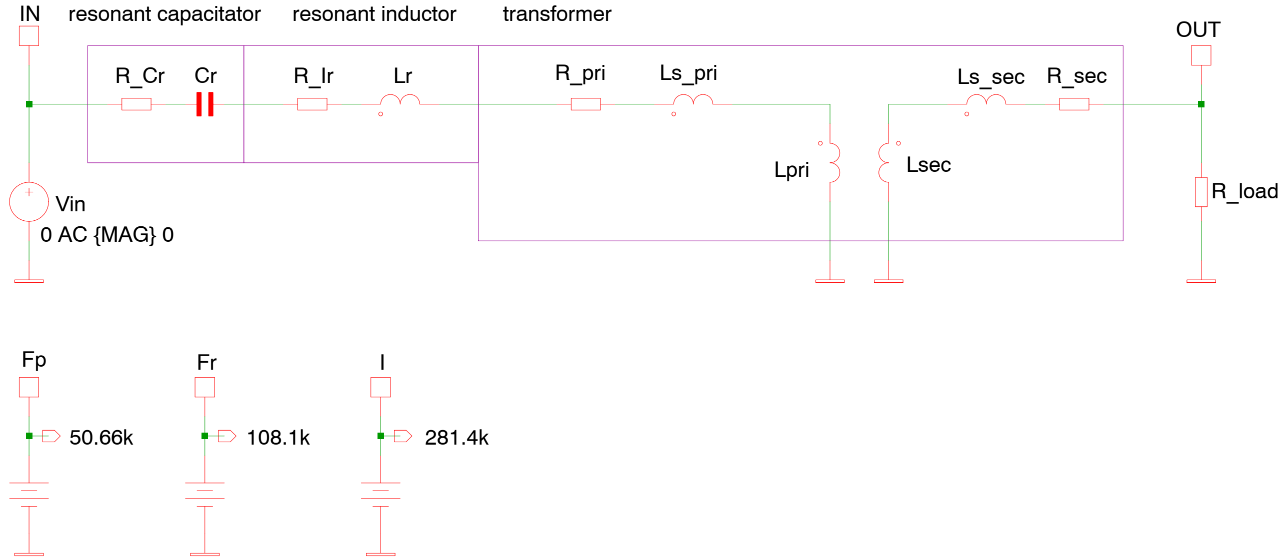
Finally, characteristic resonant tank impedance has to be calculated

$$Z_0 = \sqrt{\frac{L_R}{C_R}}$$

The resulting characteristic impedance values has to be lower than Z_{crit} value calculated previously. If not, reducing $f_{n,max}$ (increasing main resonant frequency or reducing maximum switching frequency) usually solves situation. Calculation for considered design example leads to L_r inductance 38.3 μH, C_R capacitance 56.6 nF and Z_0 impedance 26 Ω, which is less than Z_{crit} 31.6 Ω, therefore proposed resonant tank will operate safely in ZVS also during constant maximum power operation.

Although the previous paragraph introduces a numeric approach to calculate the tank parameters, a SPICE simulation analysis is added in Figure 4 for completeness.

Just for illustration, SIMetrix simple FHA model used for design example in this document and its outputs are presented briefly in next Figures (5 to 9).



****
* transformer parameters

* turn ratio – primary to secondary
.PARAM N 2

* primary magnetizing inductance
.PARAM Lm 136.1u

* prinary winding resistance
.PARAM R_pri 33m

* primary stray inductance
.PARAM Ls_pri 1p

* secondary inductance
.PARAM Lsec {Lm/(N^2)}

* coupling to primary = 1 → ideal transformer, stray inductance are modeled as a separate elements

K1 Lpri Lsec 1

* secondary winding resistance
.PARAM R_sec 13m

* secondary stray inductance
.PARAM Ls_sec 1p

****
* resonance inductor

.PARAM Lr 38.3u

.PARAM R_Lr 11m

****
* resonance capacitor

.PARAM Cr 56.6n
.PARAM R_Cr 2m

Figure 4. Simple SPICE Simulation Model Example for AC Analysis

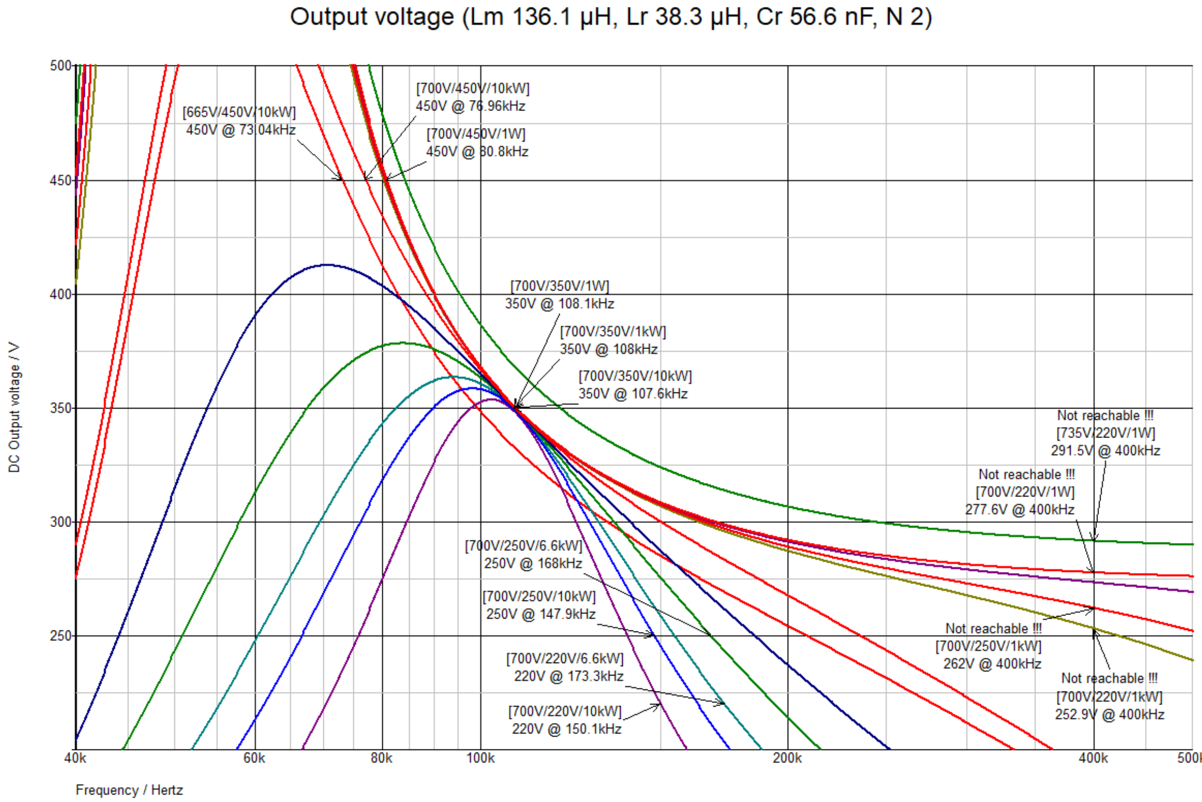


Figure 5. FHA Results − Output Voltage

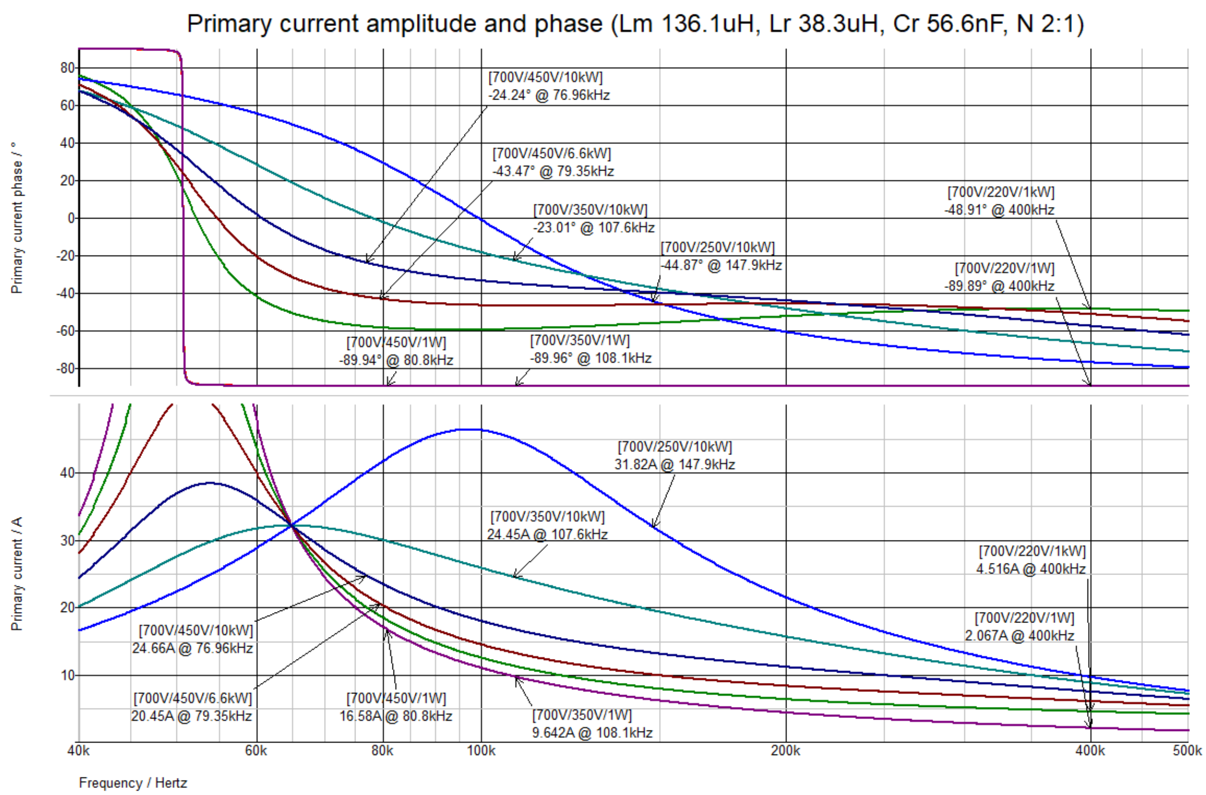


Figure 6. FHA Results − Primary Current

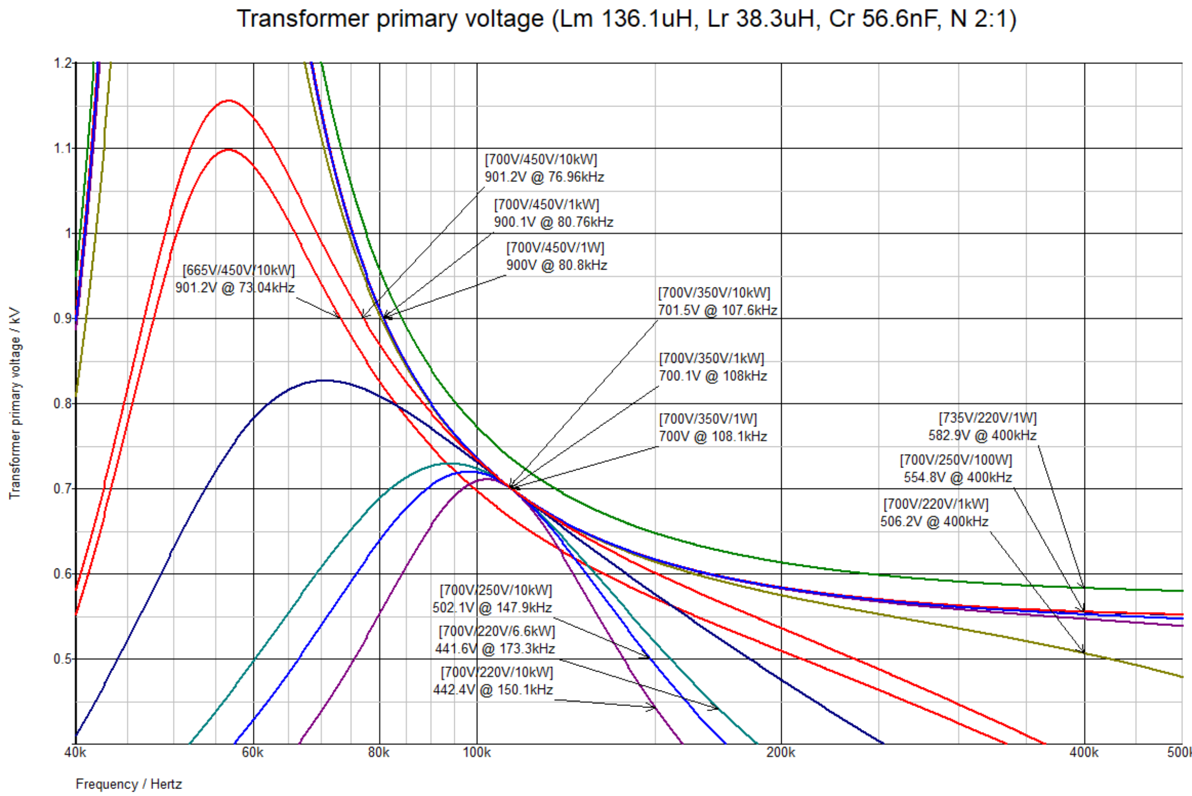


Figure 7. FHA Results – Transformer Primary Voltage

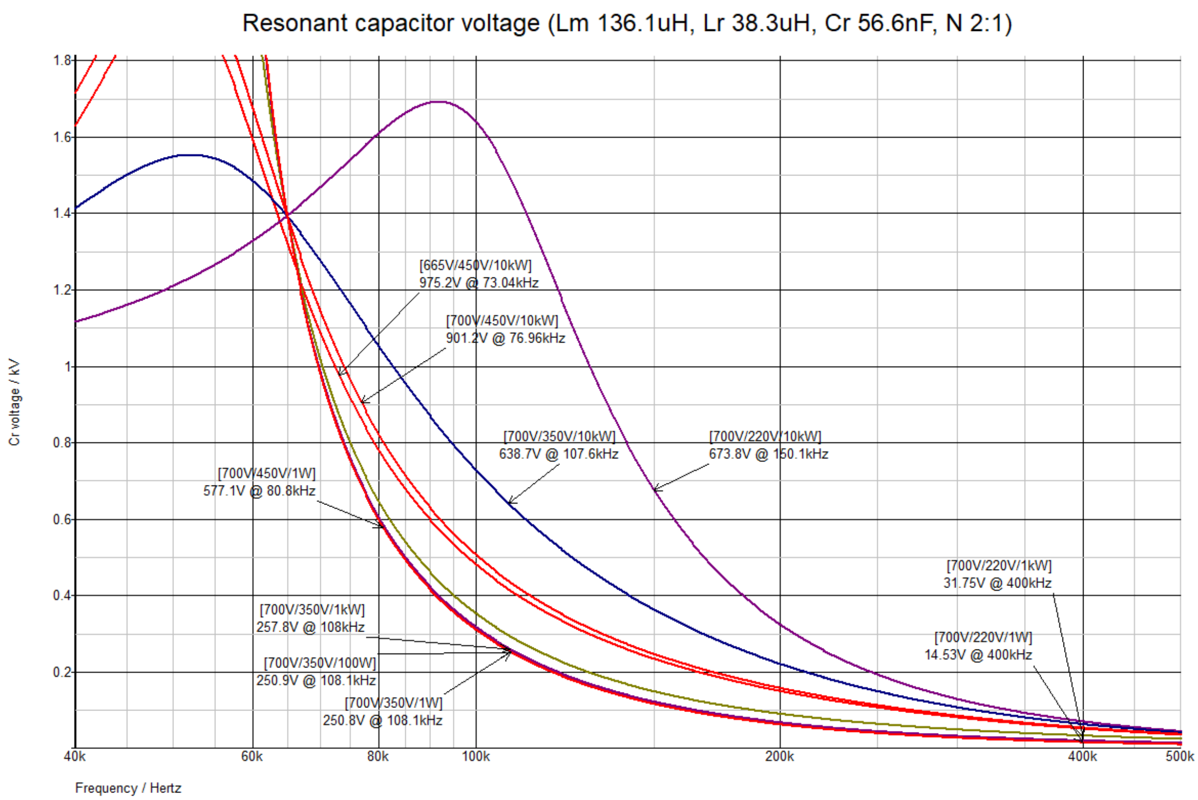
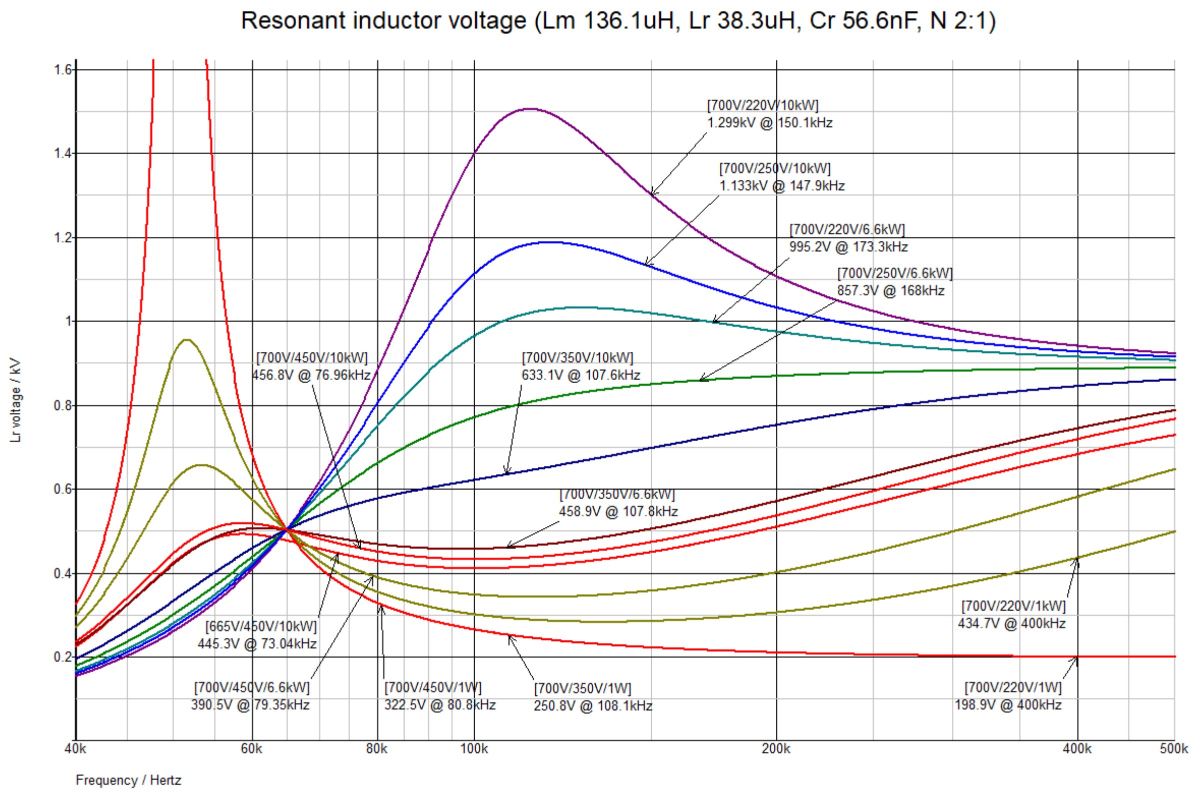


Figure 8. FHA Results – Resonant Capacitor Voltage



LLC working area search
****
Processing sweep for 665 V/450 V/10 kW => 548 V peak found at 56.62 kHz
Nominal switching frequency: 73.04 kHz, current phase: −20.06°
****
Processing sweep for 700 V/220 V/1 W => 139.1 kV peak found at 50.7 kHz
ERROR: Target voltage not reachable − max Fsw 400 kHz reached !!!
Lowest reachable voltage is 277.6 V
****
Processing sweep for 700 V/220 V/1 kW => 1.28 kV peak found at 51.64 kHz
ERROR: Target voltage not reachable − max Fsw 400 kHz reached !!!
Lowest reachable voltage is 252.9 V
****
Processing sweep for 700 V/220 V/6.6 kW => 363.3 V peak found at 93.97 kHz
Nominal switching frequency: 173.3 kHz, current phase: −50.53°
****
Processing sweep for 700 V/220 V/10 kW=>353.4 V peak found at 102.3 kHz
Nominal switching frequency: 150.1 kHz
Maximum current phase: −50.15 deg
****
Processing sweep for 700 V/250 V/1 W => 141 kV peak found at 50.7 kHz
ERROR: Target voltage not reachable − max Fsw 400 kHz reached !!!
Lowest reachable voltage is 277.6 V
****
Processing sweep for 700 V/250 V/1 kW=>1.643 kV peak found at 51.17 kHz
ERROR: Target voltage not reachable − max Fsw 400 kHz reached !!!
Lowest reachable voltage is 262 V
****

Processing sweep for 700 V/250 V/10 kW => 358.3 V peak found at 98.17 kHz
Nominal switching frequency: 147.9 kHz, current phase: −43.85°
****
Processing sweep for 700 V/350 V/1 W => 144 kV peak found at 50.7 kHz
Nominal switching frequency: 108.1 kHz, current phase: −89.96°
****
Processing sweep for 700 V/350 V/10 kW => 412.3 V peak found at 70.63 kHz
Nominal switching frequency: 107.6 kHz, current phase: −21.62°
****
Processing sweep for 700 V/450 V/1 W => 145.2 kV peak found at 50.7 kHz
Nominal switching frequency: 80.8 kHz, current phase: −89.94°
****
Processing sweep for 700 V/450 V/1 kW => 5.225 kV peak found at 50.7 kHz
Nominal switching frequency: 80.76 kHz, current phase: −82.2°
****
Processing sweep for 700 V/450 V/6.6 kW => 831.2 V peak found at 53.09 kHz
Nominal switching frequency: 79.35 kHz, current phase: −43.23°
****
Processing sweep for 700 V/450 V/10 kW => 576.8 V peak found at 56.62 kHz
Nominal switching frequency: 76.96 kHz, current phase: −23.66°
****
Processing sweep for 735 V/220 V/1 W => 146.1 kV peak found at 50.7 kHz
ERROR: Target voltage not reachable − max Fsw 400 kHz reached !!!
Lowest reachable voltage is 291.5 V
****
5 errors found ...
****

Figure 9. FHA Results − Resonant Inductor Voltage

With the FHA results, it is possible to define basic electrical parameters of resonant tank components. As further comment to the primary current chart shown earlier, a peak value greater than 22 A is expected when working with an input voltage of 700 V. However this peak current does not necessary represent the switching current, which is going to be different and useful to determine the switching losses of the switching devices. In case of lower input voltage operation, a higher peak current is expected as depicted in the next table.

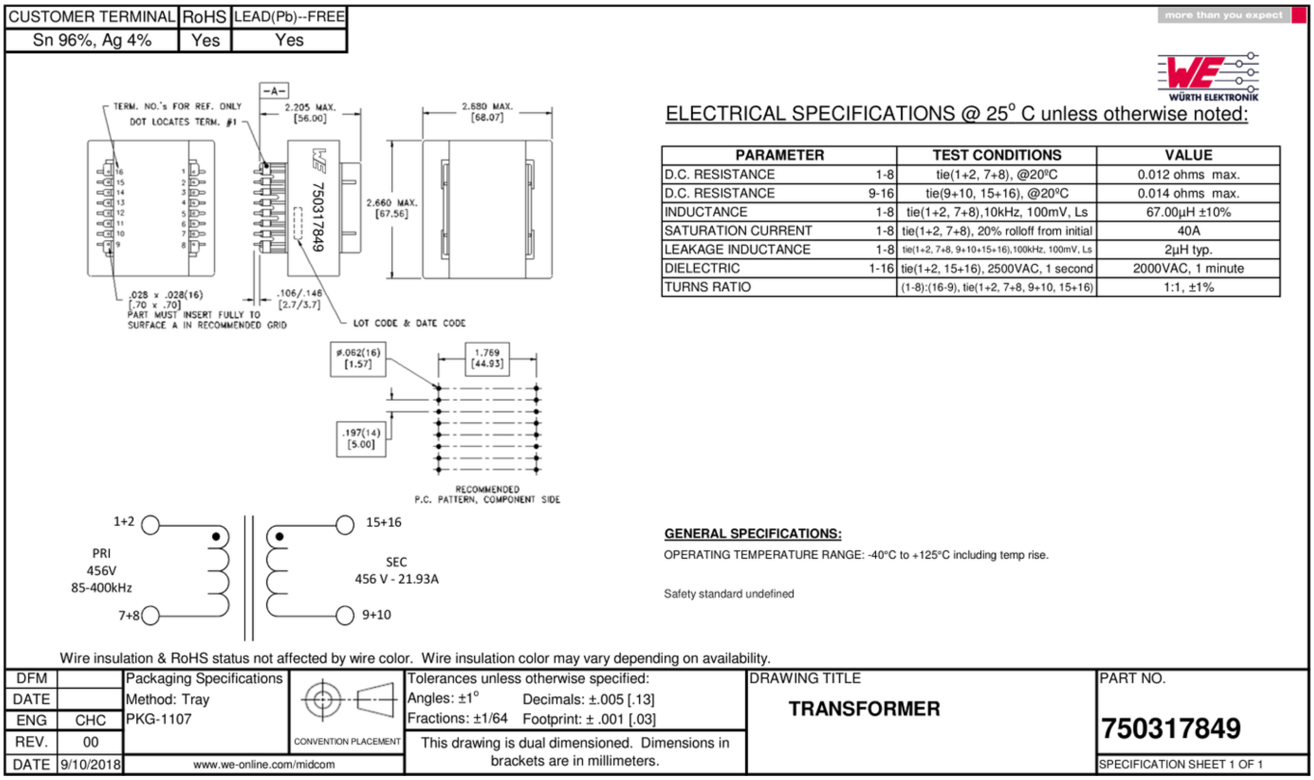
Note, that transformer has been split into two smaller components: their primary windings are connected in series and secondary windings in parallel.

On top of it, usage of transformer leakage inductance as resonant inductor, often used in few hundreds watts solutions, is usually not feasible in ~ 10 kW converters. Most of all, from efficiency point of view, but also from EMI perspective, it is good to minimize stray fluxes around transformer. Furthermore, regular magnetic component manufacturer specifies only maximum value of leakage inductance, because from production line point of view precise control of leakage inductance may be quite tremendous task requiring extra effort. It naturally results in usage of an external inductor, as a separate component acting as the resonant inductor. Sometimes also this one can be split into two components, providing certain benefits.

Nevertheless, it is definitely worthwhile to build also simulation model for transient simulations, ideally with real simulation models of transistors, rectifier diodes and all resonant tank members. It allows designer to investigate real operating conditions and verify design margins, especially when operating points distant from main resonant point are subject of interest. As an example, expected operating points have been summarized in below Figure 10 for discussed example design.

	OBC LLC 10kW simulations, load 10 kW, tank proposal: Lm 136.1 μH, Lr 38.3 μH, Cr 56.6 nF, N 2														
	Input voltage [V] 665					Input voltage [V] 700					Input voltage [V] 735				
	Output voltage [V]					Output voltage [V]					Output voltage [V]				
	250	300	350	400	450	250	300	350	400	450	250	300	350	400	450
Switching frequency [kHz]	134.832	120.517	98.476	85.453	78.067	140.000	127.080	105.528	90.032	81.159	144.828	133.333	113.976	95.022	84.507
Primary current [A_{PEAK}]	31.5	26.3	26.7	27.7	28.1	31.9	26.5	25.6	26.3	25.1	32.3	26.6	23.9	25.6	25.4
Primary current [A_{RMS}]	22.9	19.1	18.4	18.4	18.9	22.8	19.3	18.1	17.9	17.7	23.0	19.4	17.2	17.7	17.6
Transformer primary voltage [V_{PEAK}]	513.1	611.2	712.0	813.0	912.9	512.4	611.1	711.3	811.6	911.1	512.7	611.3	710.9	812.1	912.0
Transformer primary current [A_{PEAK}]	31.5	26.3	26.7	27.7	28.1	31.9	26.5	25.6	26.3	25.1	32.3	26.6	23.9	25.6	25.4
Transformer magnetizing current [A_{PEAK}]	9.9	9.2	11.9	13.7	16.3	6.7	8.7	12.2	14.0	16.2	6.4	8.3	11.4	14.2	16.2
Transformer primary winding resistance [m Ω[	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Transformer primary winding power loss [W]	17.3	12.1	11.2	11.2	11.8	17.2	12.3	10.8	10.5	10.4	17.4	12.4	9.8	10.3	10.2
Transformer secondary voltage [V_{PEAK}]	255.5	304.7	355.1	405.5	455.6	255.1	304.7	354.8	404.9	454.7	255.2	304.8	354.7	405.2	455.2
Transformer secondary current [A_{PEAK}]	66.0	48.6	49.8	49.8	49.9	59.4	48.3	46.7	47.7	45.2	60.0	48.2	43.3	45.5	45.1
Transformer secondary current [A_{RMS}]	44.1	35.8	33.4	31.3	29.6	43.9	36.0	32.2	30.5	27.2	44.2	36.2	31.2	29.8	27.9
Transformer secondary winding resistance [m Ω[	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Transformer secondary winding power loss [W]	19.4	12.8	11.2	9.8	8.8	19.3	13.0	10.4	9.3	7.4	19.5	13.1	9.7	8.9	7.8
Resonant capacitor voltage [V_{PEAK}]	669.1	631.9	744.4	868.5	994.6	646.9	602.3	684.2	798.6	884.3	624.5	573.3	600.6	748.4	852.1
Resonant capacitor ESR [m Ω[	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Resonant capacitor power loss [W]	5.3	3.7	3.4	3.4	3.6	5.2	3.7	3.3	3.2	3.1	5.3	3.7	3.0	3.1	3.1
Resonant inductor voltage [V_{PEAK}]	1812.7	1862.2	1723.1	1853.1	998.7	1823.4	1844.5	842.0	1845.0	1555.5	1838.8	1877.5	1986.8	964.6	1573.3
Resonant inductor ESR]mΩ[	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Resonant inductor power loss [W]	5.3	3.7	3.4	3.4	3.6	5.2	3.7	3.3	3.2	3.1	5.3	3.7	3.0	3.1	3.1
Single transistor average power loss [W]	25.5	15.8	14.0	14.1	14.9	26.6	16.9	13.5	13.4	12.7	27.9	17.7	12.4	13.1	13.0
All transistors losses [W]	102.2	63.4	56.2	56.2	59.5	106.6	67.7	54.2	53.4	50.8	111.4	70.9	49.5	52.4	51.9
Output current [A]	40.0	33.3	28.6	25.0	22.2	40.0	33.3	28.6	25.0	22.2	40.0	33.3	28.6	25.0	22.2
Single rectifier diode average power loss [W]	34.5	26.1	23.1	19.8	17.7	34.5	26.4	22.3	19.4	15.8	34.7	26.5	21.6	19.4	16.9
Rectifier overall power loss [W]	138.0	104.3	92.2	79.4	70.6	138.1	105.8	89.1	77.7	63.3	138.6	106.0	86.3	77.7	67.8
Input capacitor ripple current [A_{RMS}]	7.1	3.3	2.1	2.5	3.3	7.9	4.3	2.8	2.8	3.5	8.7	5.1	2.5	3.4	3.6
Input capacitor ESR]mΩ[	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0	93.0
Input capacitor power loss [W]	4.7	1.0	0.4	0.6	1.0	5.8	1.7	0.7	0.8	1.1	7.1	2.4	0.6	1.0	1.2
Output capacitor ripple current [A_{RMS}]	17.4	13.6	17.1	18.8	19.1	17.7	13.6	14.9	17.4	16.9	18.1	13.8	12.4	16.1	16.8
Output capacitor ESR]mΩ[	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Output capacitor power loss [W]	24.3	14.8	23.3	28.2	29.2	25.2	14.8	17.9	24.1	22.8	26.3	15.2	12.3	20.6	22.5
Input power - simulated [W]	10317.2	10238.3	10193.7	10192.4	10186.9	10324.3	10223.9	10187.7	10163.4	10153.5	10331.3	10240.4	10185.3	10186.1	10168.9
Output power - simulated [W]	9998.5	10016.2	9993.8	9990.5	9995.3	9998.2	9998.5	9997.0	9980.1	9974.6	9998.4	10009.5	10009.6	10007.3	9995.5
Power losses - simulated [W]	318.7	222.1	199.9	201.9	191.6	326.1	225.4	190.7	183.3	178.9	332.9	230.9	175.7	178.8	173.4
Power losses - summed by components above [W]	316.3	214.6	200.8	191.6	187.1	316.8	220.9	188.8	181.5	161.0	323.9	225.0	173.5	176.1	166.4
Transformer primary winding power loss ratio [%]	5.5	5.6	5.6	5.8	6.3	5.4	5.6	5.7	5.8	6.5	5.4	5.5	5.6	5.9	6.1
Transformer secondary winding power loss ratio [%]	6.1	6.0	5.6	5.1	4.7	6.1	5.9	5.5	5.1	4.6	6.0	5.8	5.6	5.0	4.7
Transformer overall power loss ratio [%]	11.6	11.6	11.1	11.0	11.0	11.5	11.4	11.2	10.9	11.1	11.4	11.3	11.2	10.9	10.8
Resonant capacitor power loss ratio [%]	1.7	1.7	1.7	1.8	1.9	1.6	1.7	1.7	1.8	2.0	1.6	1.7	1.7	1.8	1.9
Resonant inductor power loss ratio [%]	1.7	1.7	1.7	1.8	1.9	1.6	1.7	1.7	1.8	2.0	1.6	1.7	1.7	1.8	1.9
Transistors power loss ratio [%]	32.3	29.5	28.0	29.4	31.8	33.6	30.6	28.7	29.4	31.5	34.4	31.5	28.5	29.7	31.2
Rectifier power loss ratio [%]	43.6	48.6	45.9	41.4	37.7	43.6	47.9	47.2	42.8	39.3	42.8	47.1	49.8	44.1	40.7
Output capacitor power loss ratio [%]	7.7	6.9	11.6	14.7	15.6	7.9	6.7	9.5	13.3	14.1	8.1	6.7	7.1	11.7	13.5
Efficiency - simulated [%]	**96.91**	**97.83**	**98.04**	**98.02**	**98.12**	**96.84**	**97.80**	**98.13**	**98.20**	**98.24**	**96.78**	**97.74**	**98.28**	**98.25**	**98.29**

Figure 10. Summary Example of Transient Simulations with Real Device Models



CUSTOMER TERMINAL	RoHS	LEAD(Pb)--FREE
Sn 96%, Ag 4%	Yes	Yes

ELECTRICAL SPECIFICATIONS @ 25° C unless otherwise noted:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	1-8	tie(1+2, 7+8), @20ºC	0.012 ohms max.
D.C. RESISTANCE	9-16	tie(9+10, 15+16), @20ºC	0.014 ohms max.
INDUCTANCE	1-8	tie(1+2, 7+8),10kHz, 100mV, Ls	67.00µH ±10%
SATURATION CURRENT	1-8	tie(1+2, 7+8), 20% rolloff from initial	40A
LEAKAGE INDUCTANCE	1-8	tie(1+2, 7+8, 9+10+15+16),100kHz, 100mV, Ls	2µH typ.
DIELECTRIC	1-16	tie(1+2, 15+16), 2500VAC, 1 second	2000VAC, 1 minute
TURNS RATIO		(1-8):(16-9), tie(1+2, 7+8, 9+10, 15+16)	1:1, ±1%

GENERAL SPECIFICATIONS:

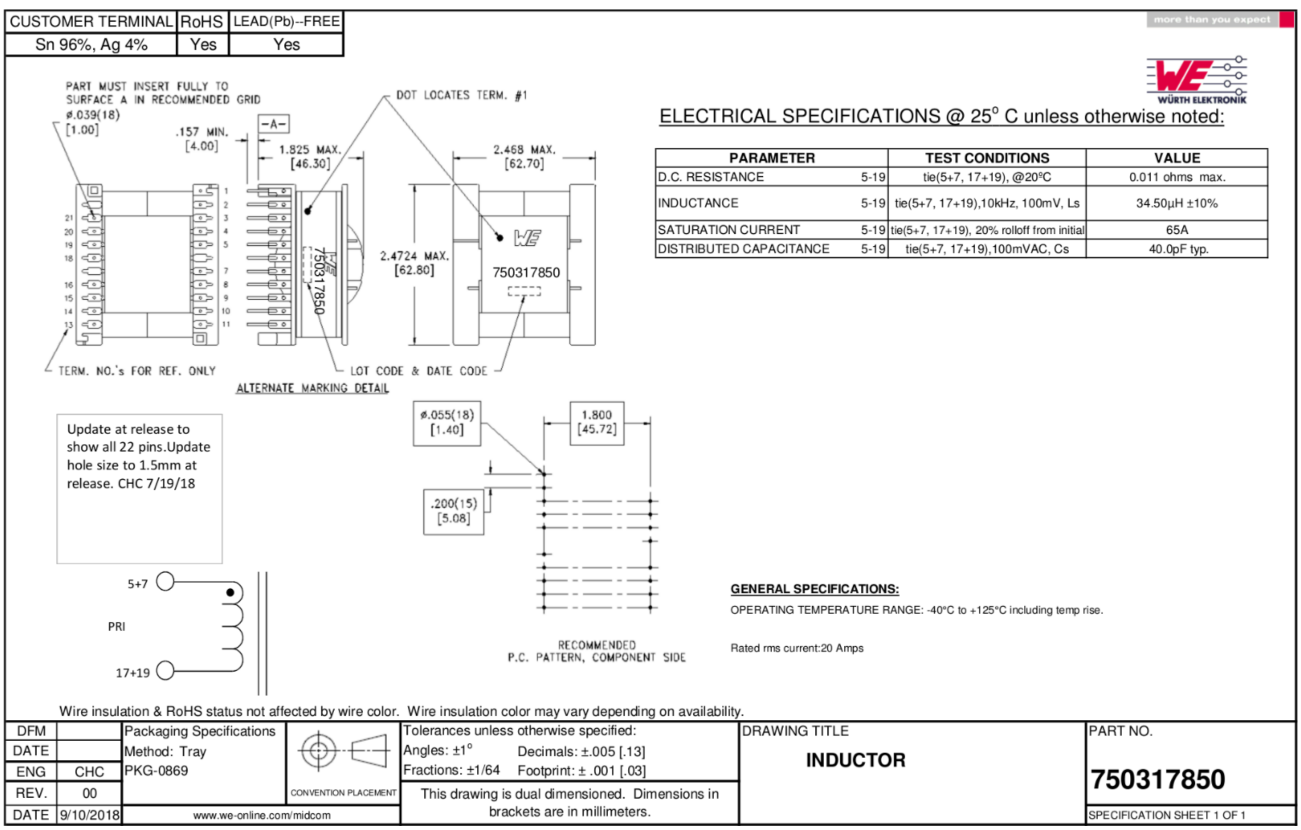
OPERATING TEMPERATURE RANGE: -40ºC to +125ºC including temp rise.

Safety standard undefined

Wire insulation & RoHS status not affected by wire color. Wire insulation color may vary depending on availability.

DFM		Packaging Specifications		Tolerances unless otherwise specified:	DRAWING TITLE	PART NO.
DATE		Method: Tray		Angles: ±1° Decimals: ±.005 [.13]	TRANSFORMER	
ENG	CHC	PKG-1107		Fractions: ±1/64 Footprint: ± .001 [.03]		750317849
REV.	00		CONVENTION PLACEMENT	This drawing is dual dimensioned. Dimensions in brackets are in millimeters.		
DATE	9/10/2018	www.we-online.com/midcom				SPECIFICATION SHEET 1 OF 1

Figure 11. Transformer Selected for Resonant Tank in Design Example



CUSTOMER TERMINAL	RoHS	LEAD(Pb)--FREE
Sn 96%, Ag 4%	Yes	Yes

ELECTRICAL SPECIFICATIONS @ 25° C unless otherwise noted:

PARAMETER		TEST CONDITIONS	VALUE
D.C. RESISTANCE	5-19	tie(5+7, 17+19), @20ºC	0.011 ohms max.
INDUCTANCE	5-19	tie(5+7, 17+19),10kHz, 100mV, Ls	34.50µH ±10%
SATURATION CURRENT	5-19	tie(5+7, 17+19), 20% rolloff from initial	65A
DISTRIBUTED CAPACITANCE	5-19	tie(5+7, 17+19),100mVAC, Cs	40.0pF typ.

GENERAL SPECIFICATIONS:

OPERATING TEMPERATURE RANGE: -40ºC to +125ºC including temp rise.

Rated rms current:20 Amps

Wire insulation & RoHS status not affected by wire color. Wire insulation color may vary depending on availability.

DFM		Packaging Specifications		Tolerances unless otherwise specified:	DRAWING TITLE	PART NO.
DATE		Method: Tray		Angles: ±1° Decimals: ±.005 [.13]	INDUCTOR	
ENG	CHC	PKG-0869		Fractions: ±1/64 Footprint: ± .001 [.03]		750317850
REV.	00		CONVENTION PLACEMENT	This drawing is dual dimensioned. Dimensions in brackets are in millimeters.		
DATE	9/10/2018	www.we-online.com/midcom				SPECIFICATION SHEET 1 OF 1

Figure 12. Resonant Inductor Selected in Design Example

Design Simulations

As already mentioned in previous chapters, *reasonable* simulation became very valuable and valid step within design of almost any power converter recently. Its relevance probably does not need any special dispute anymore. Despite of its general acceptance, level of simulation model abstraction is always in question. The more detailed, closer to the reality the model is, the lower error between simulation results and reality will be, however, too detailed model can result in heavy simulations, which could result in impractical usage. Moreover, usage of digital control (DSP, microcontroller. FPGA) in converters is becoming more and more standard approach, thus it is suggested to include the digital behavior in the model in order to guarantee simulation results closer to the reality. However the introduction of digital behavior brings a further computational complication to the modeling because of the timing discretization, here two different approaches have been considered, a simplified (lighter) one and a full (heavier) one.

Simplified SIMPLIS model

SIMPLIS modelling offers very convenient way to reduce simulation time needed for full SPICE models. The main idea is to build simplified model, which is still replicating reality at high level, but which is simplifying certain very complex events substantially as it happens in MOSFET switching transitions.

Full SIMetrix model

Once particular operating point has been found using simplified SIMPLIS model, detailed simulation with real components models can be run around the identified operating point with the “known” initial conditions.

As can be seen in Figure 13 below, also digital control can be modelled very close to intended design approach.

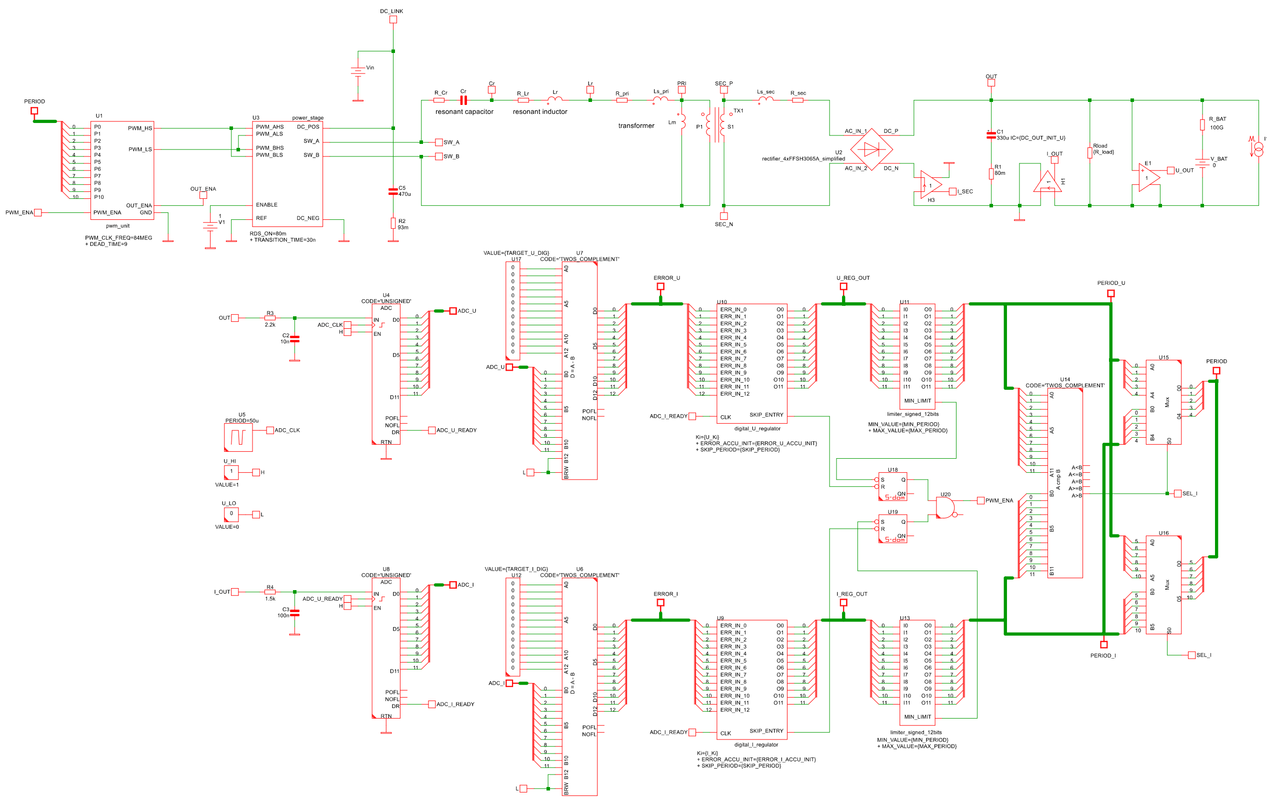


Figure 13. SIMPLIS Simplified Mode Example for Fast Operating Conditions Search

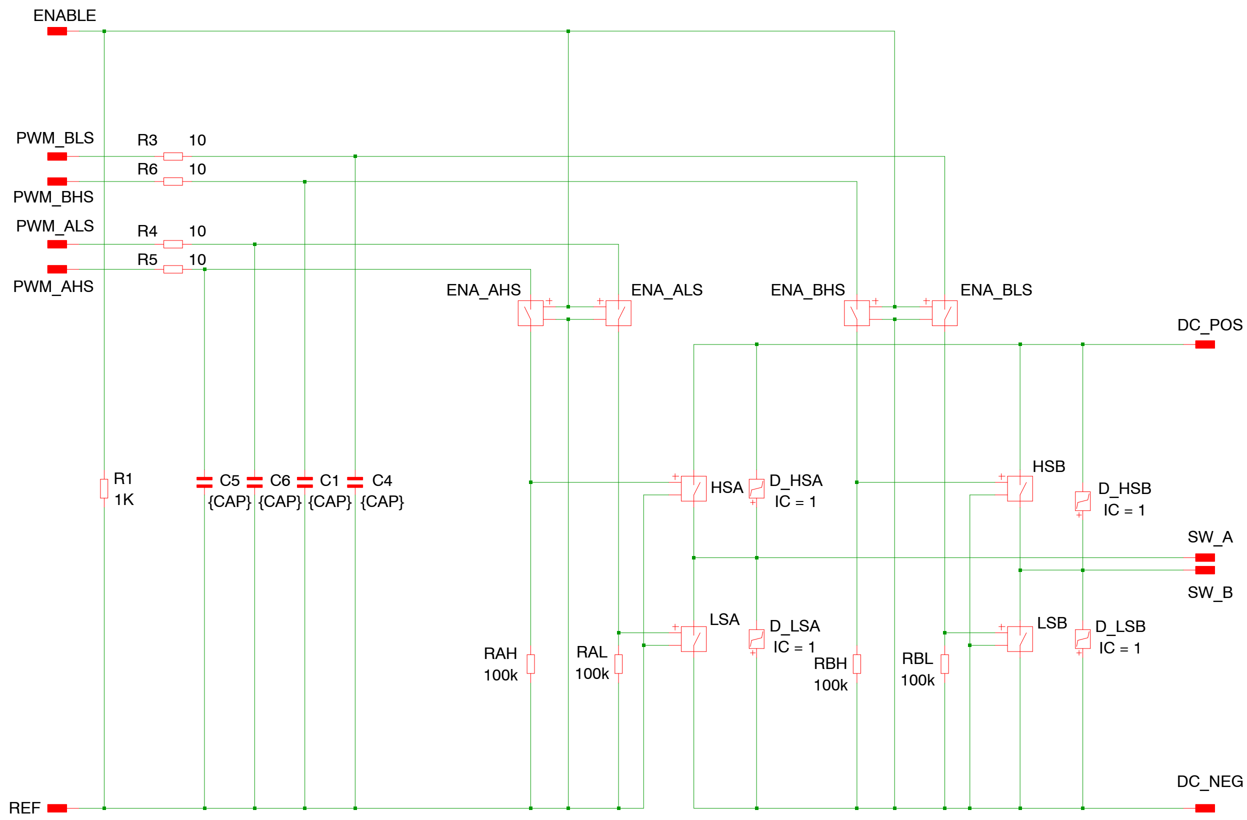


Figure 14. Simplified Full Bridge Power Stage Model for SIMPLIS Simulations

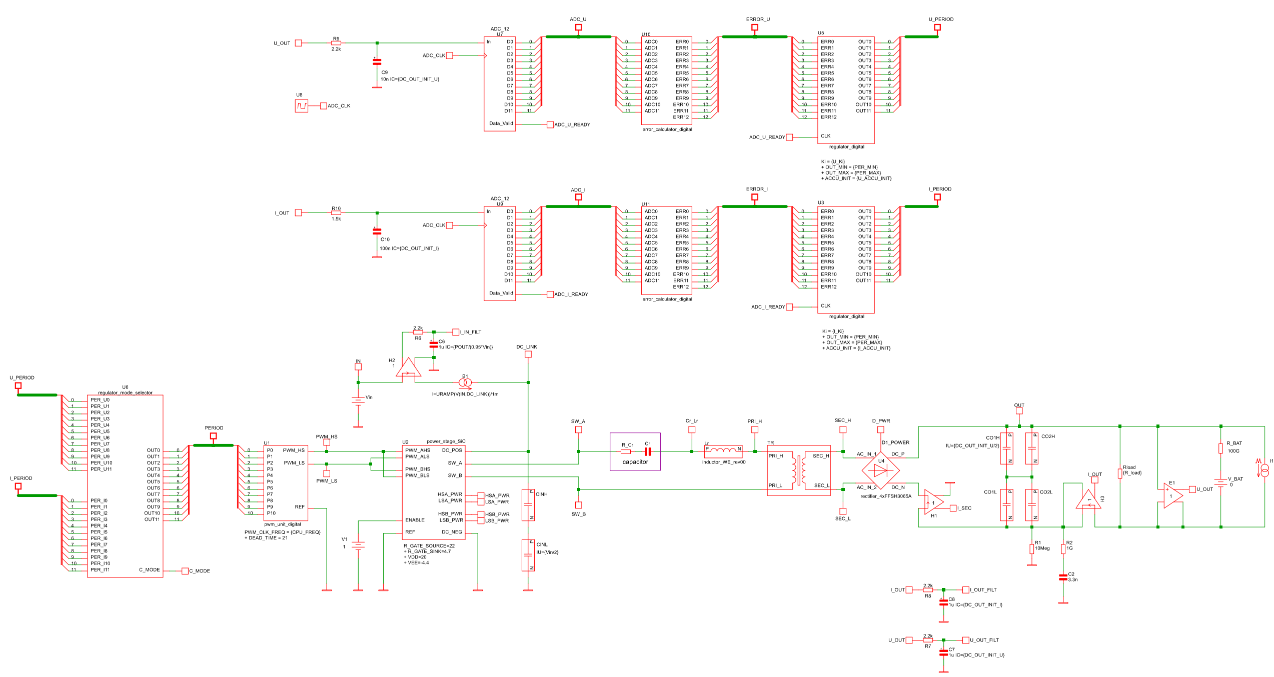


Figure 15. Mixed (SPICE & Digital) Simulation Model Example for SIMetrix – Top Level

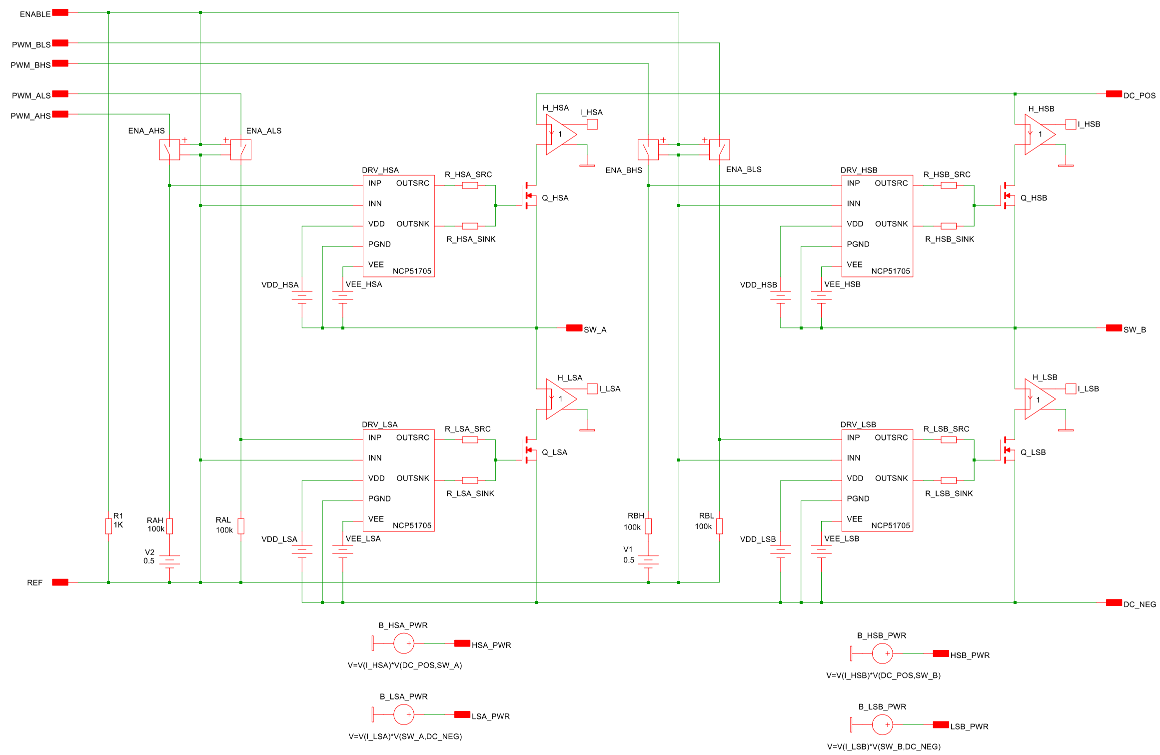
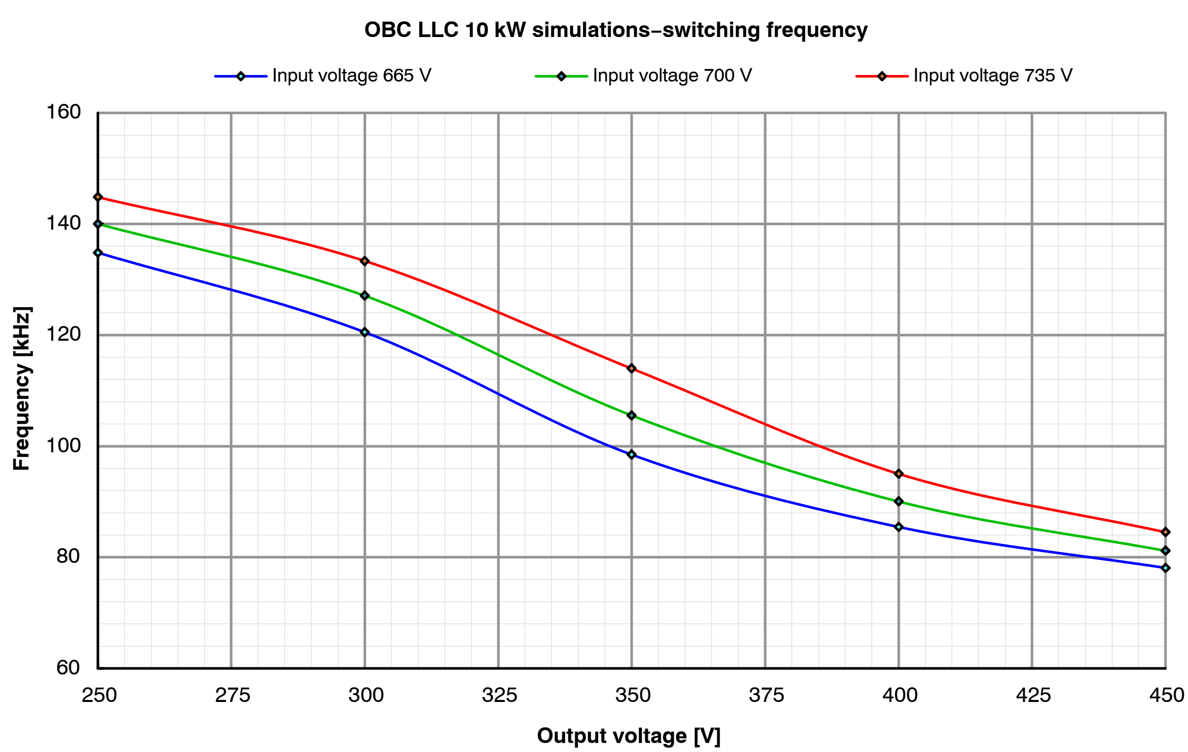


Figure 16. Power Stage SIMetrix Model using Real SiC MOSFET Model



Proposal: L_M 136.1 μH, L_R 38.3 μH, C_R 56.6 nF, N 2

Figure 17. Transient Simulation Results Summary − Switching Frequency

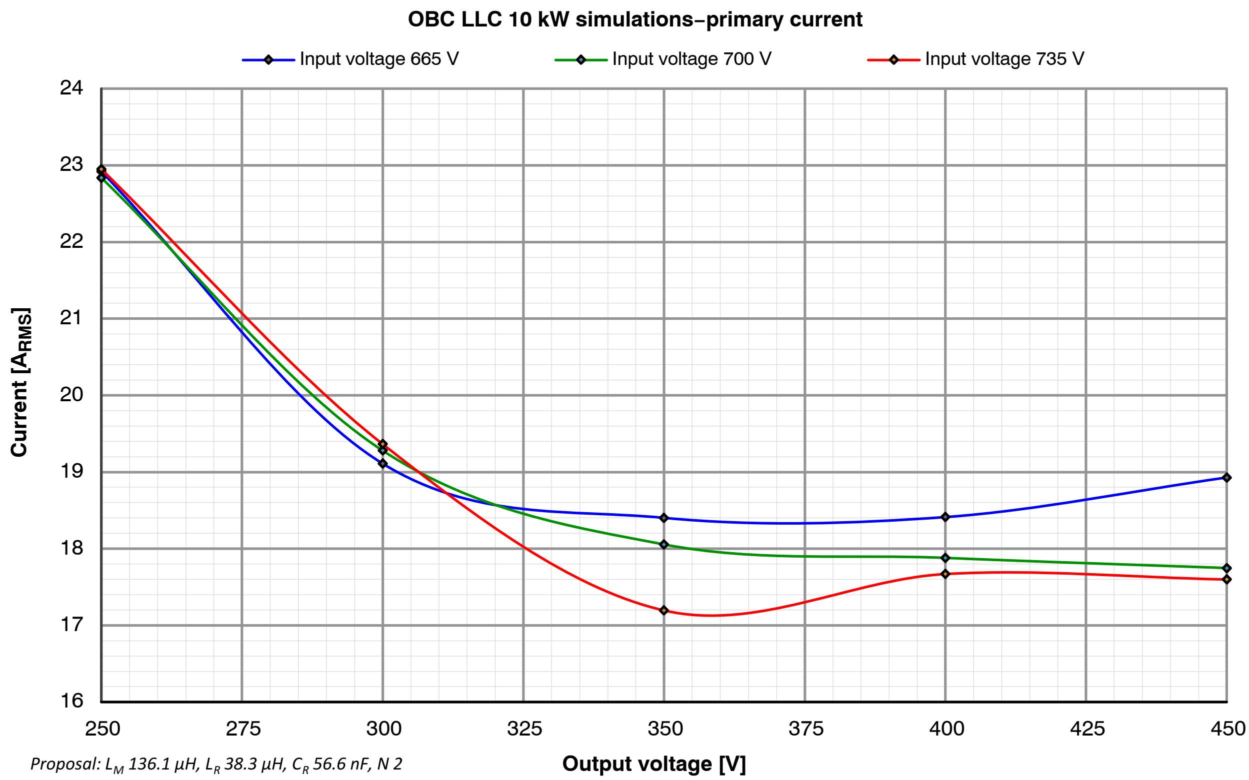


Figure 18. Transient Simulation Results Summary − Primary Side Current

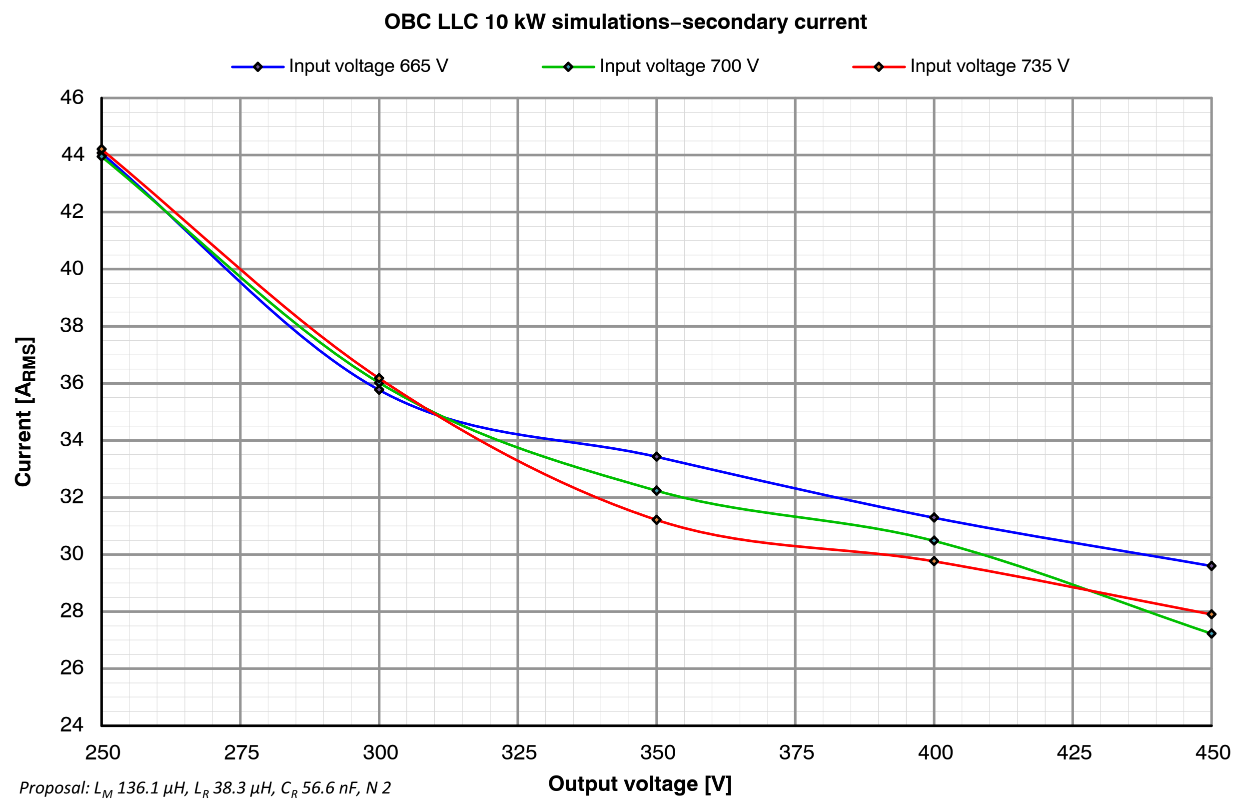


Figure 19. Transient Simulation Results Summary – Secondary Side Current

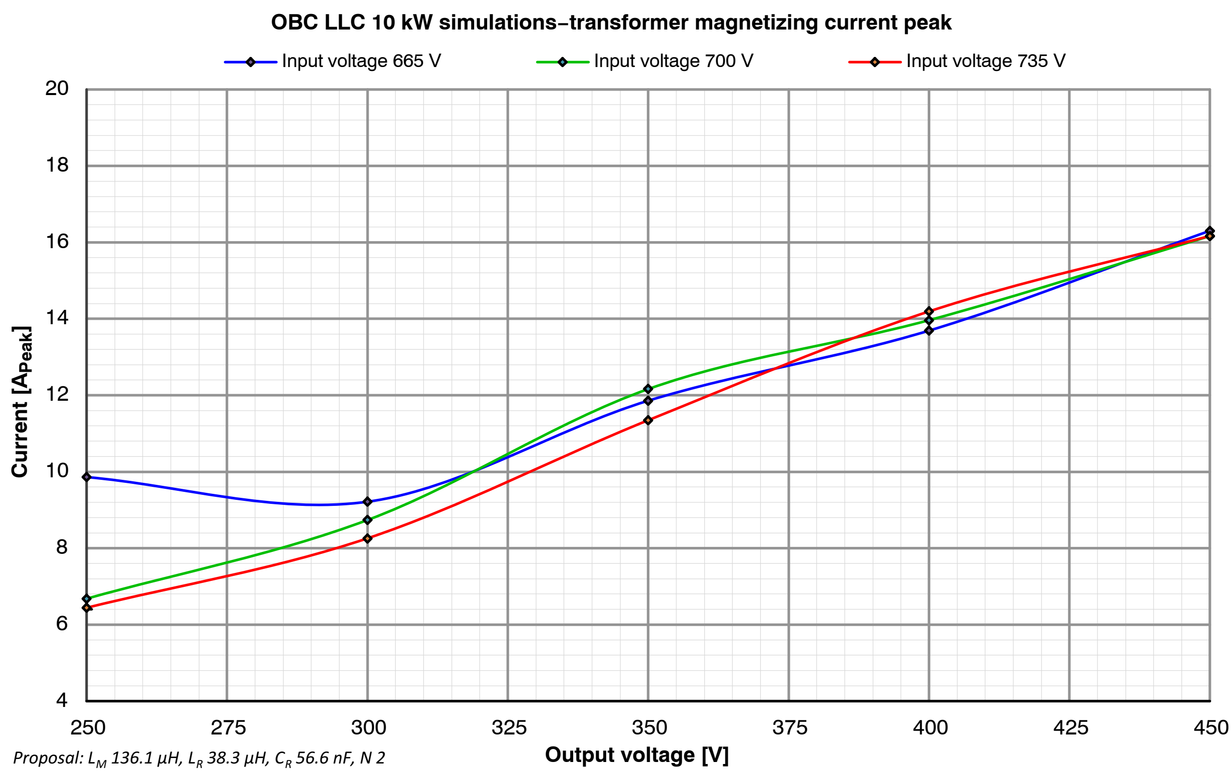


Figure 20. Transient Simulation Results Summary − Transformer Magnetizing Peak Current

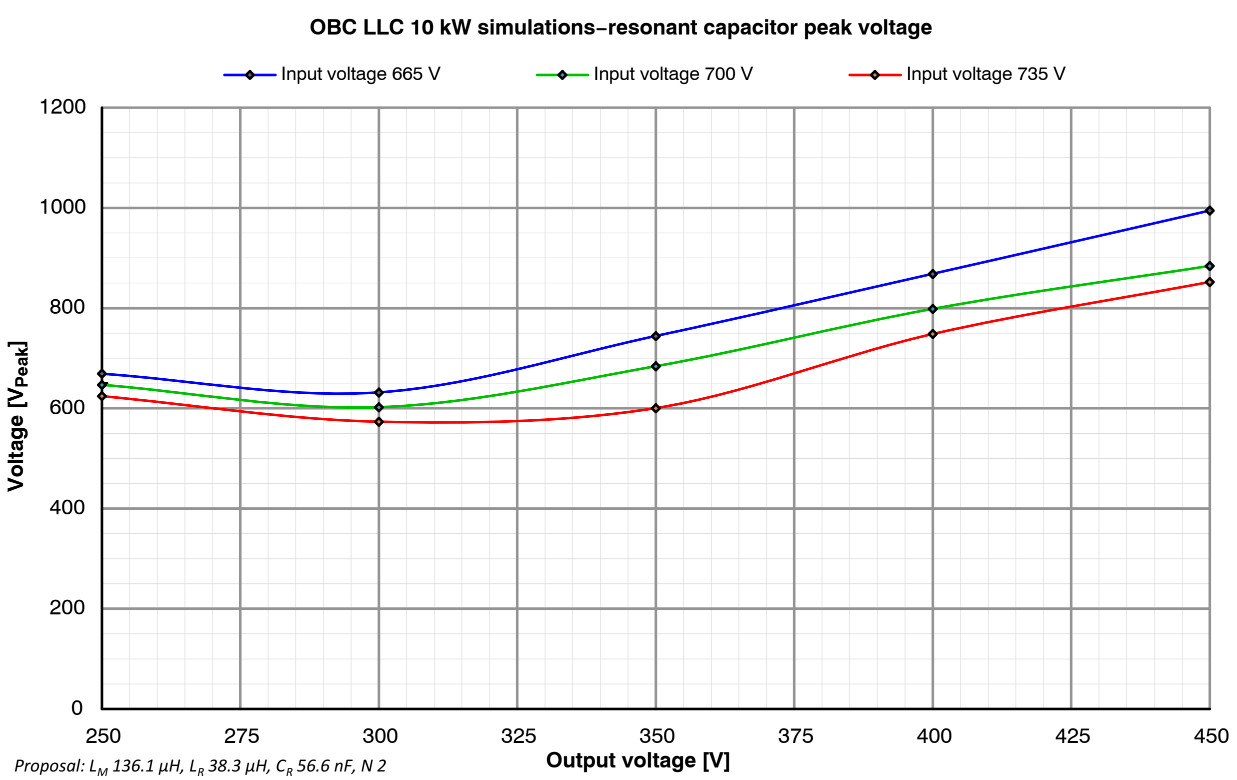


Figure 21. Transient Simulation Results Summary – Resonant Capacitor Peak Voltage

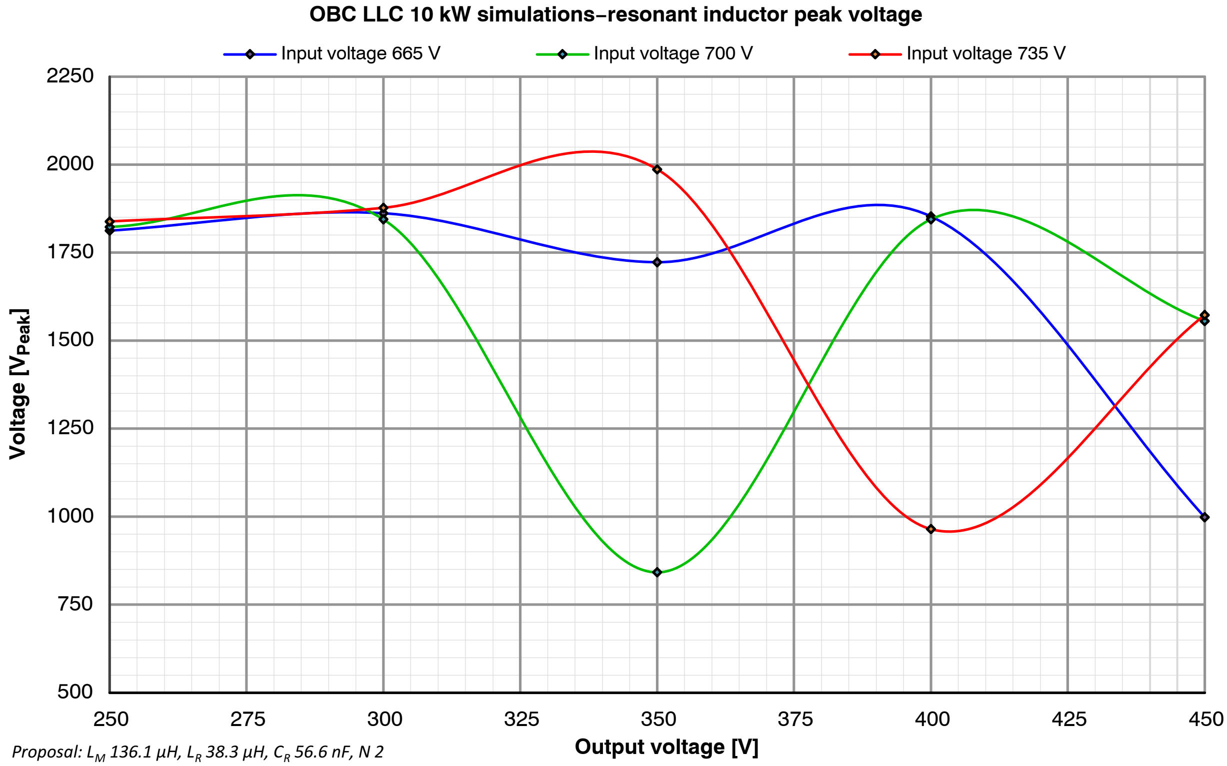


Figure 22. Transient Simulation Results Summary – Resonant Inductor Peak Voltage

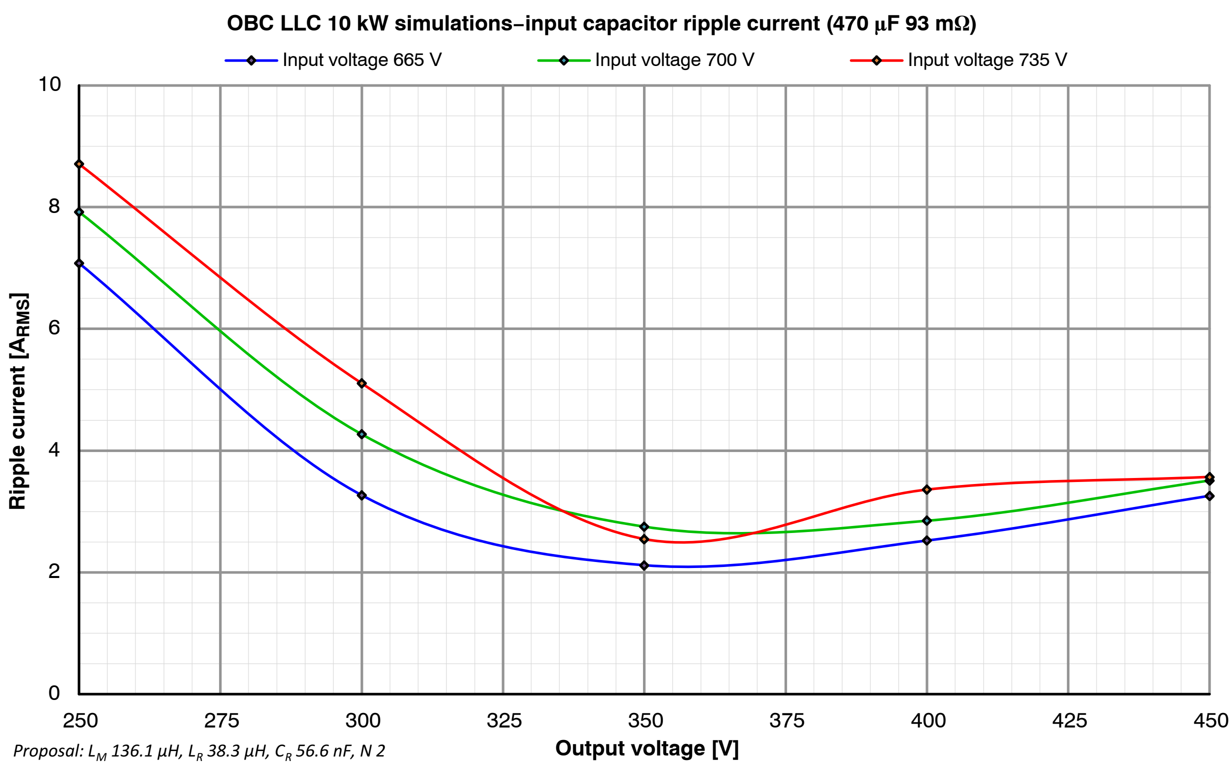


Figure 23. Transient Simulation Results Summary – Input Capacitor Ripple Current

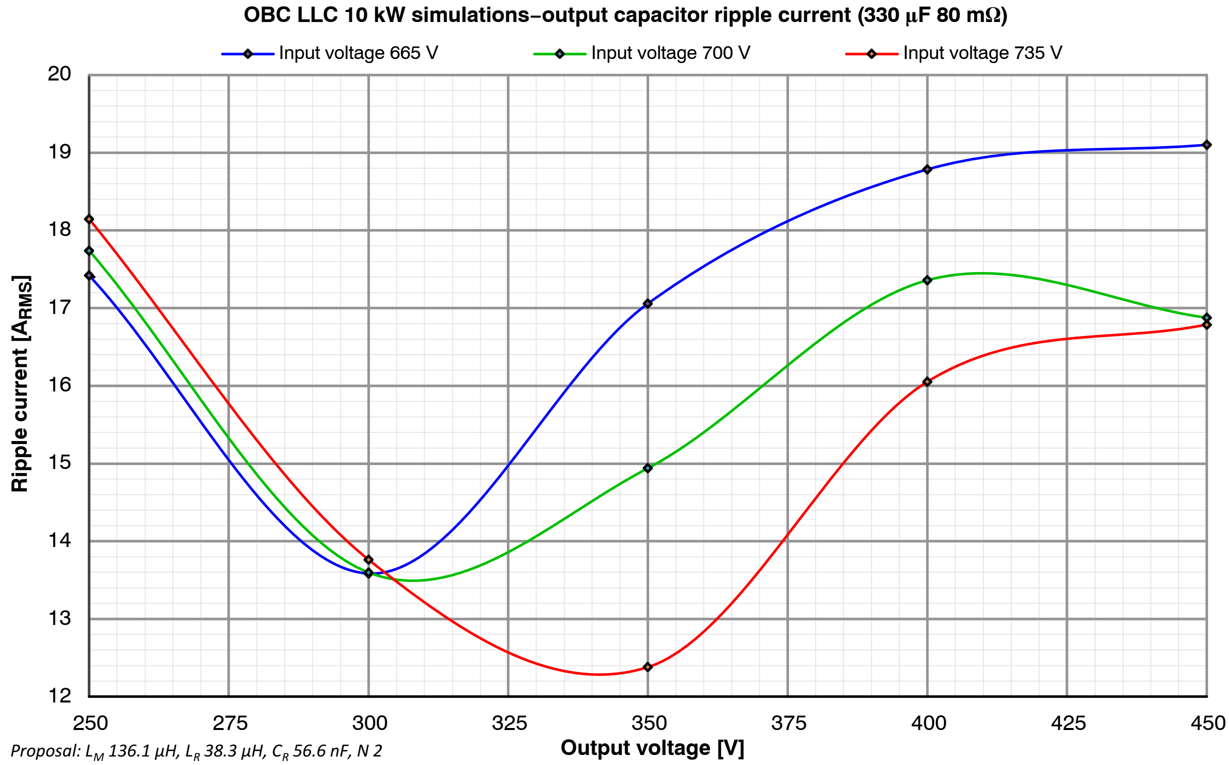


Figure 24. Transient Simulation Results Summary – Output Capacitor Ripple Current

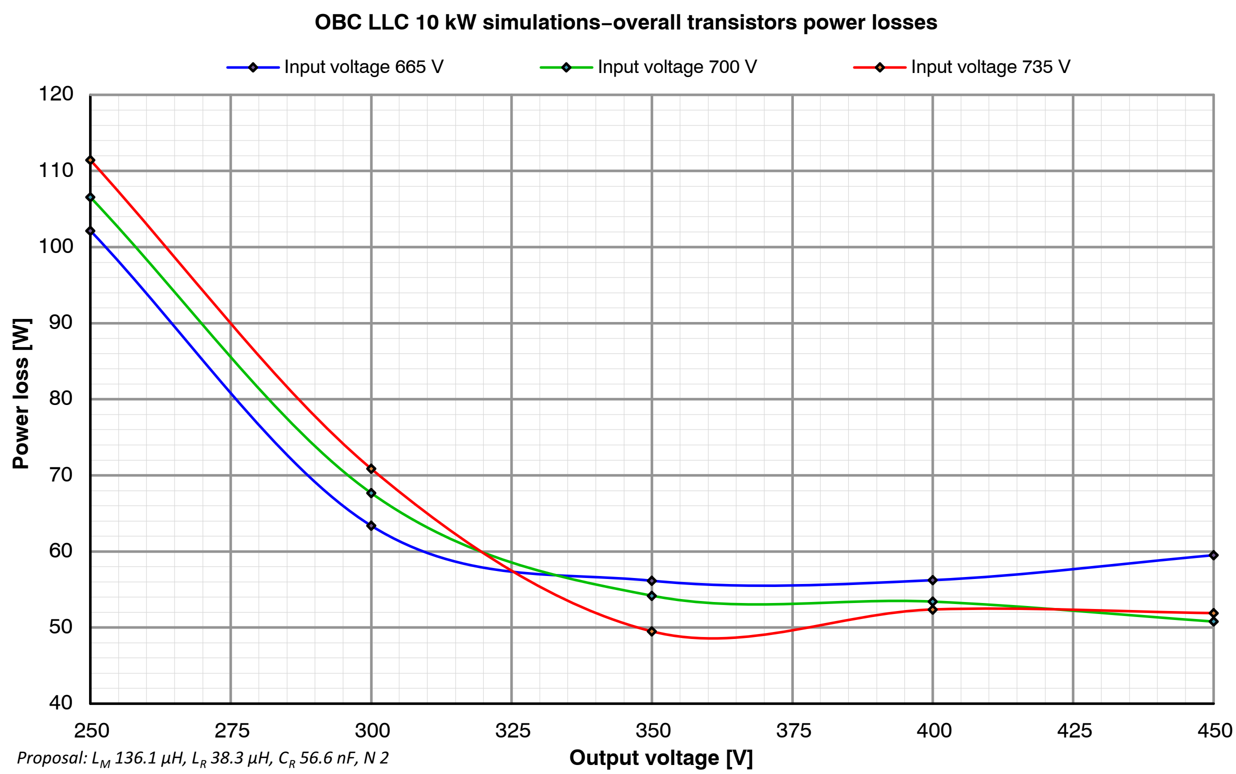


Figure 25. Transient Simulation Results Summary – Overall Transistor Power Losses

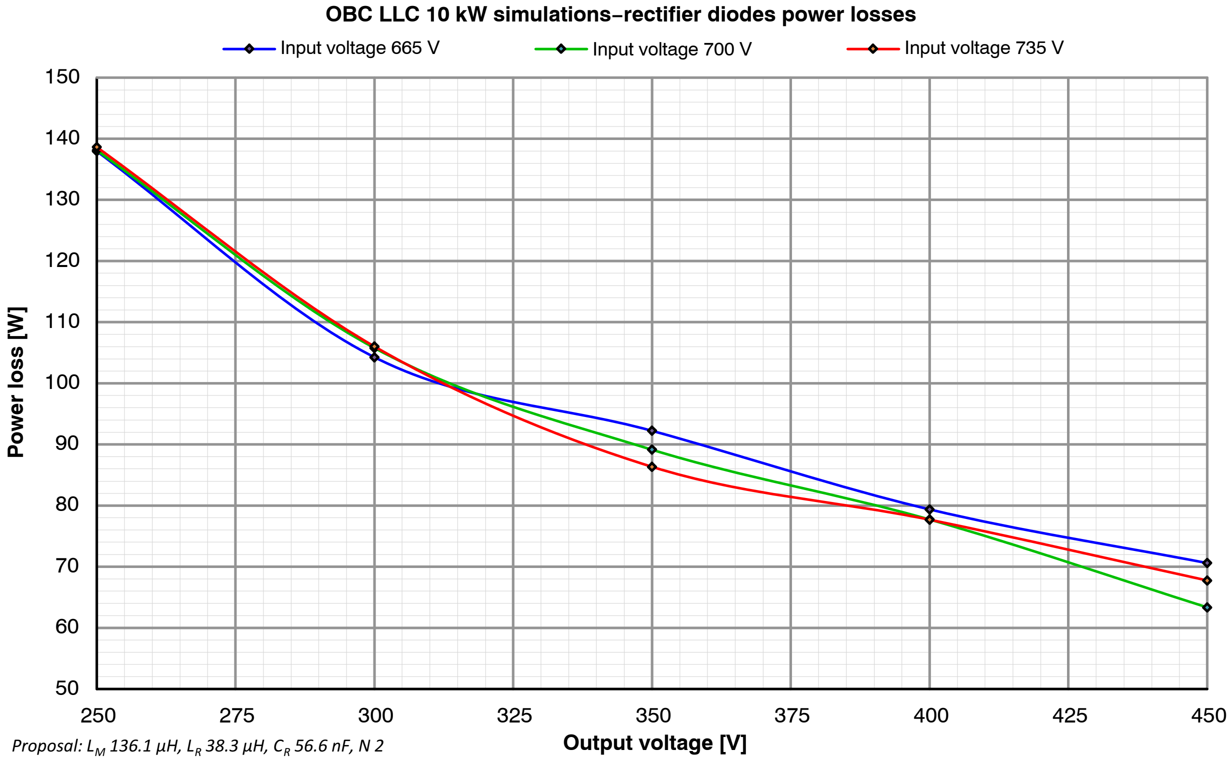


Figure 26. Transient Simulation Results Summary – Overall Power Losses in Rectifier

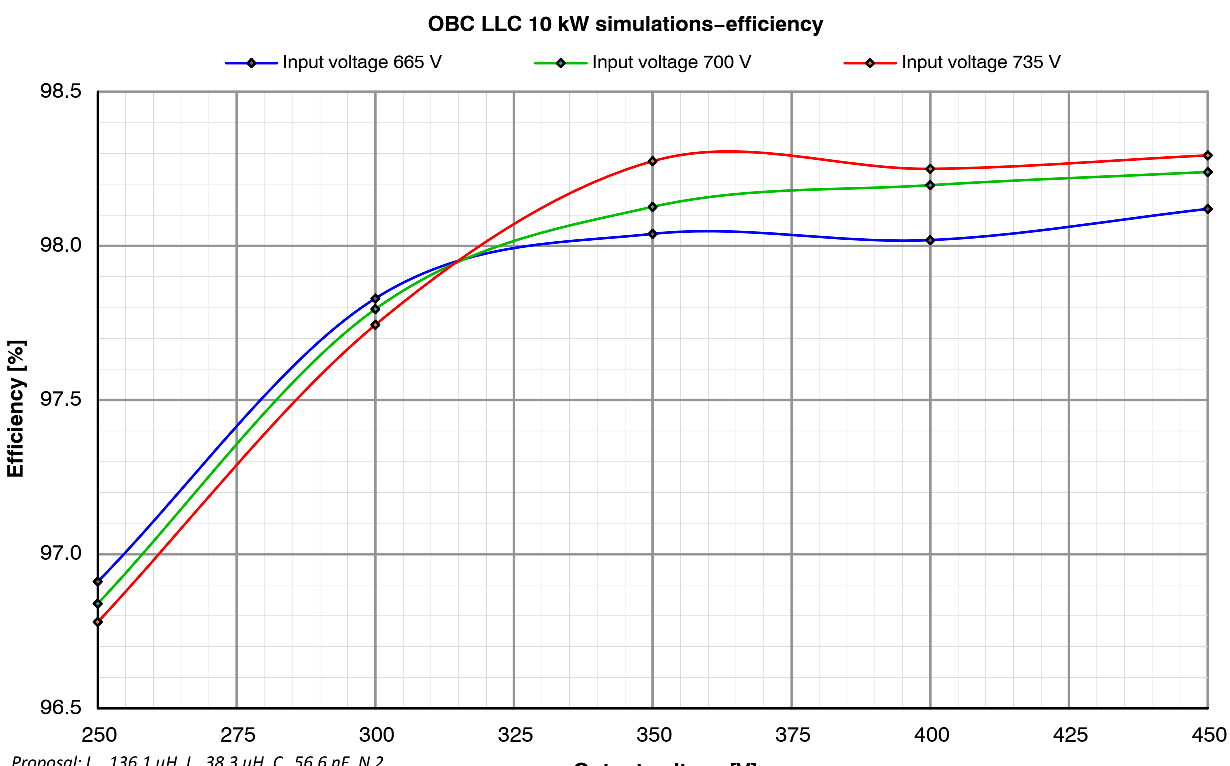


Figure 27. Transient Simulation Results Summary – Estimated Efficiency (Core Losses not Considered)

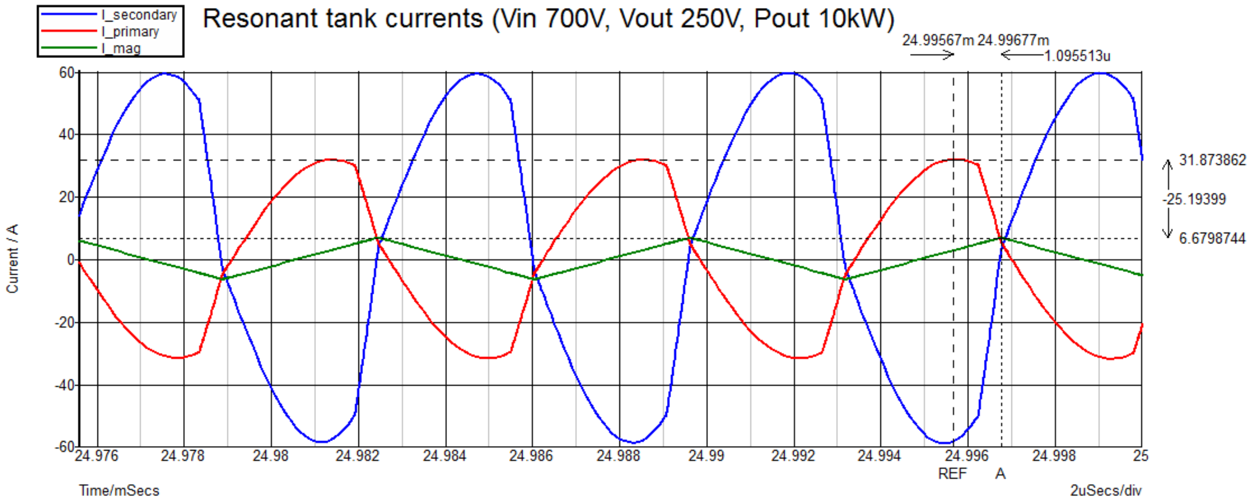


Figure 28. Transient Simulation Waveforms

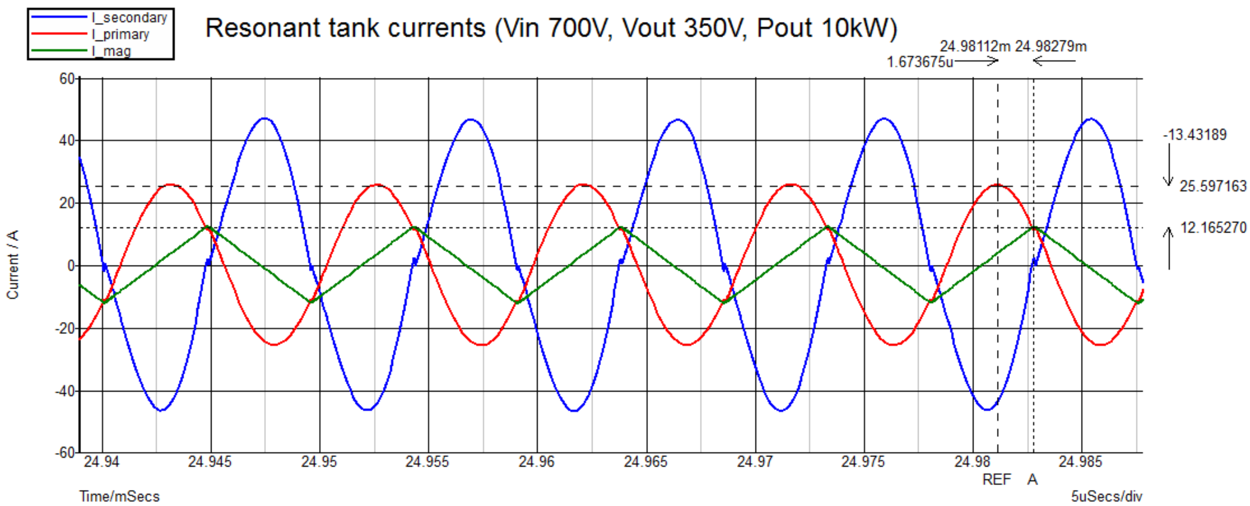


Figure 29. Transient Simulation Waveforms

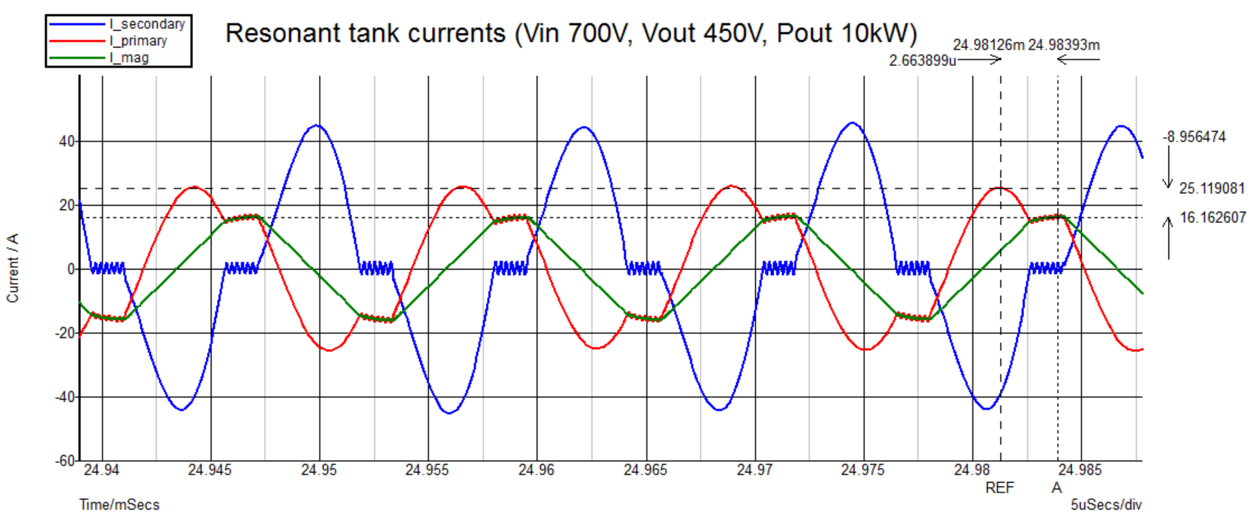


Figure 30. Transient Simulation Waveforms

SPICE Model for PCB Parasitic Evaluation

Even though number of design rules exist for good PCB layout, sometimes it is not possible to obey all of them. In the end, one of the important questions after PCB layout has been closed, usually is whether parasitic impedances introduced by PCB will or will not have substantial impact on voltage / current stress of components in circuitry. Analysis can also uncover some critical parts from EMI perspective. Various specialized software tools exist for these tasks, however even SPICE simulator can be used to get a behavioral feeling. The key point is to take a look at PCB layout and try to model all basic relations on it, building thus approximate representation of the circuit, segment by segment. Many equations and even online tools exist for flat wire inductance calculations. As an example, relatively simple one:

$$L_{\text{flat wire}} = 0.0002 \times l \times \left[0.5 + \ln\left(\frac{2l}{w + t}\right) + 0.2235\left(\frac{w + t}{l}\right)\right][\mu H]$$

Where is wire length, is wire width and is wire thickness, all in mm.

Example of power stage PBC part modeled can be seen also in Figure 31. Various operating conditions can be tested quite easily, example waveforms can be found below as well. Although this kind of analysis is not a must, it can be used very well for design validation. Among others, it can be also used for evaluation of snubber components effectiveness. For example so called Ceralinks very low E_{SL} and E_{SR} capacitors are gaining more and more attraction. Their impact on switching waveforms can be seen very clearly in waveforms below.

Similar analysis has been done also for described evaluation board. As already mentioned previously, this board has been designed so that also external diodes can be connected in parallel to transistors. Since higher priority has been assigned to accessibility of these components than lowest PCB parasitic impedances, definite impact of these parasitic elements exist. On the other hand, although not perfect solution, it can be closer to real applications where perfect power stage layout cannot be always achieved.

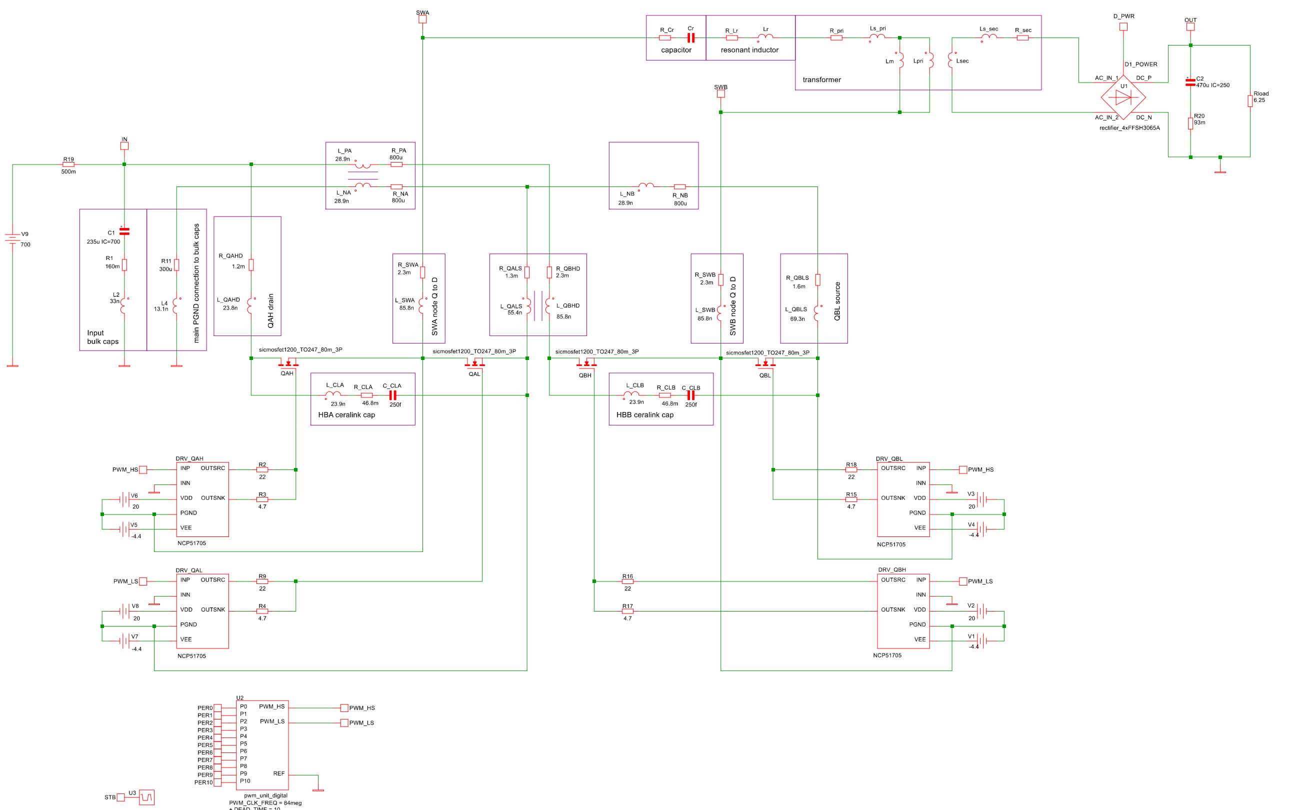


Figure 31. SPICE Model for Power Stage PCB Parasitic Evaluation

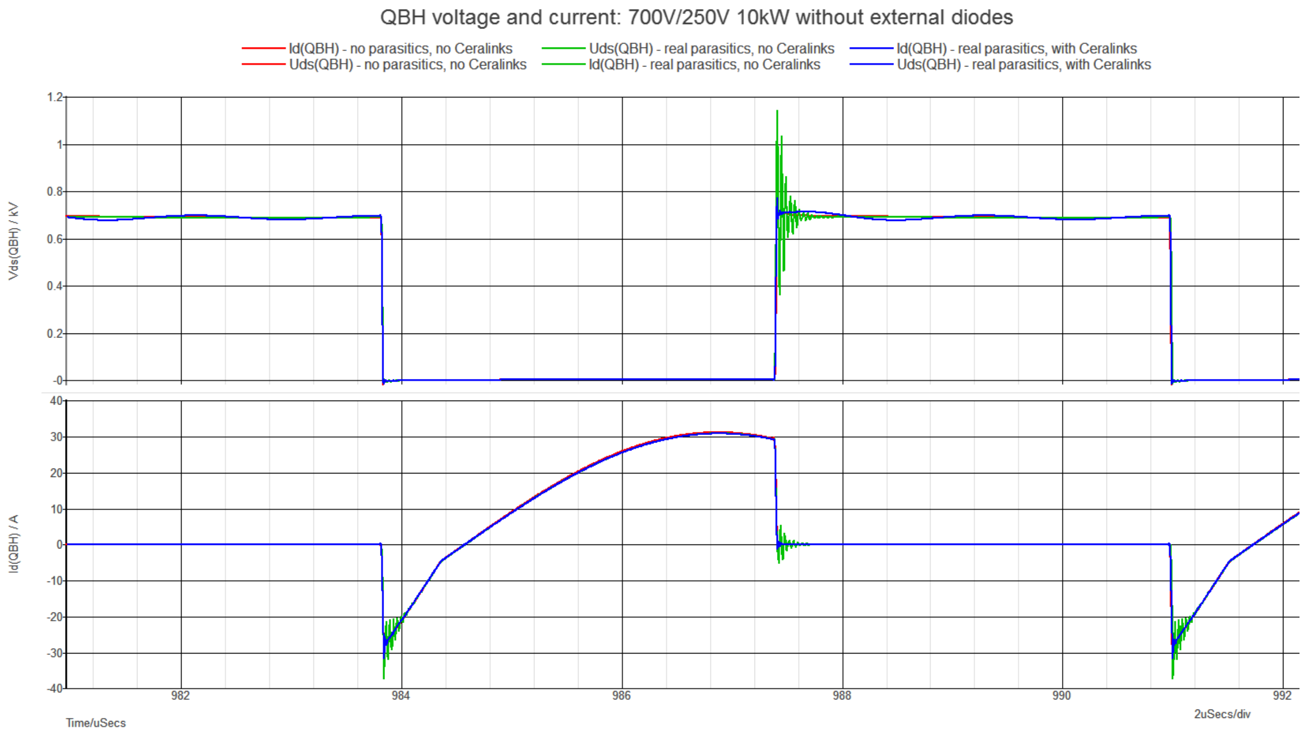


Figure 32. QBH Transistor V_{DS} and I_D without External Diodes – Overview

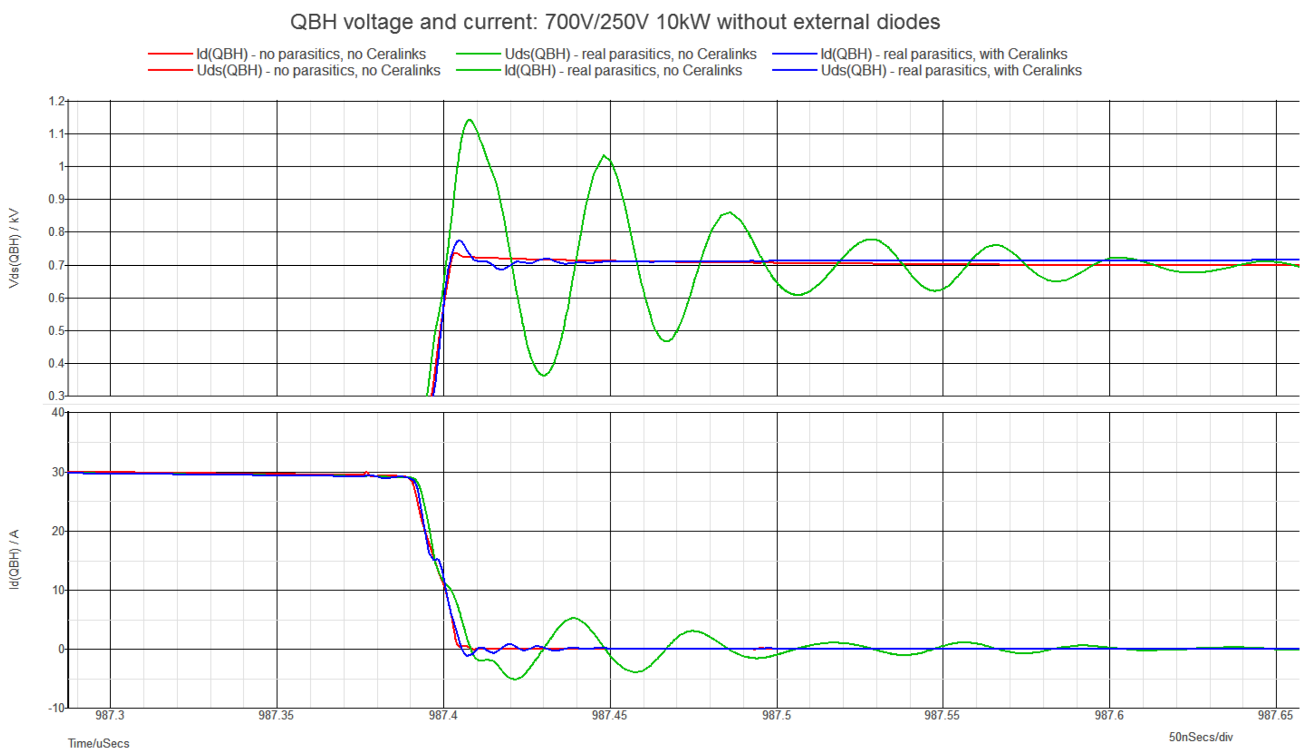


Figure 33. QBH Transistor V_{DS} and I_D without External Diodes – Turn Off Detail

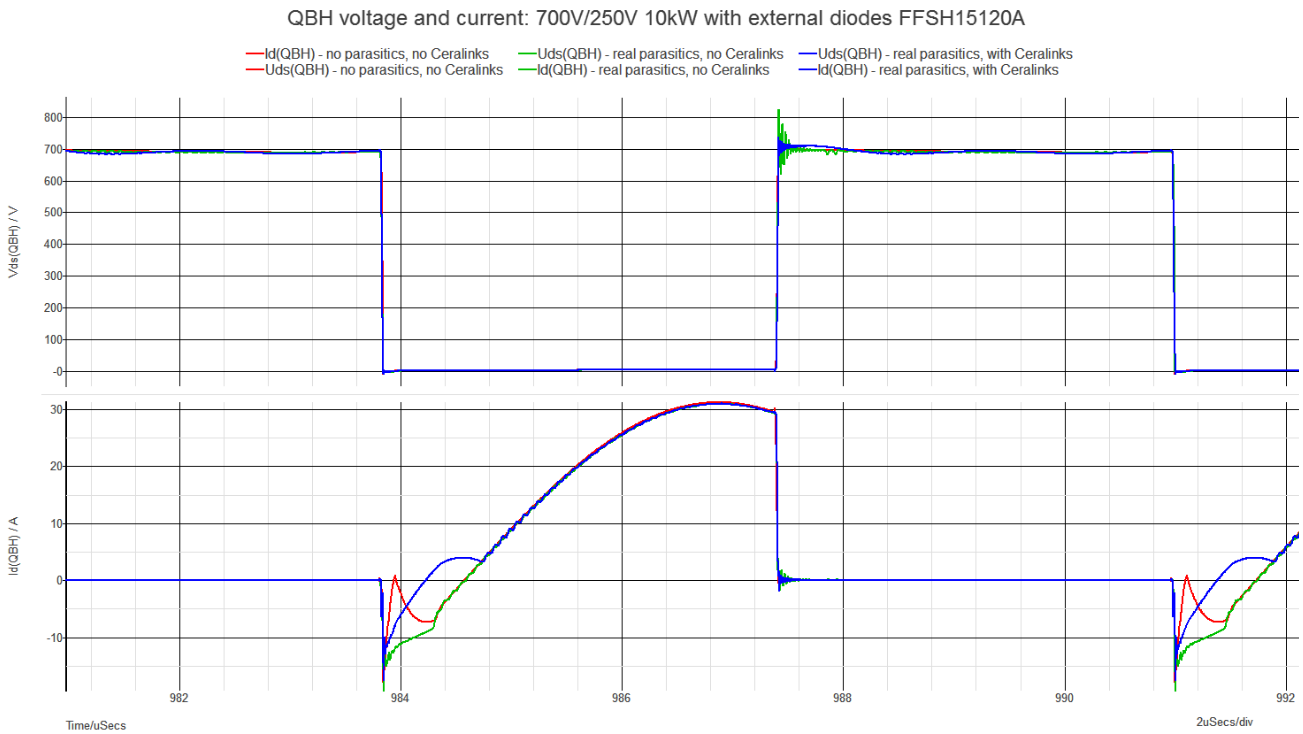


Figure 34. QBH Transistor V_{DS} and I_D with External Diodes Installed – Overview

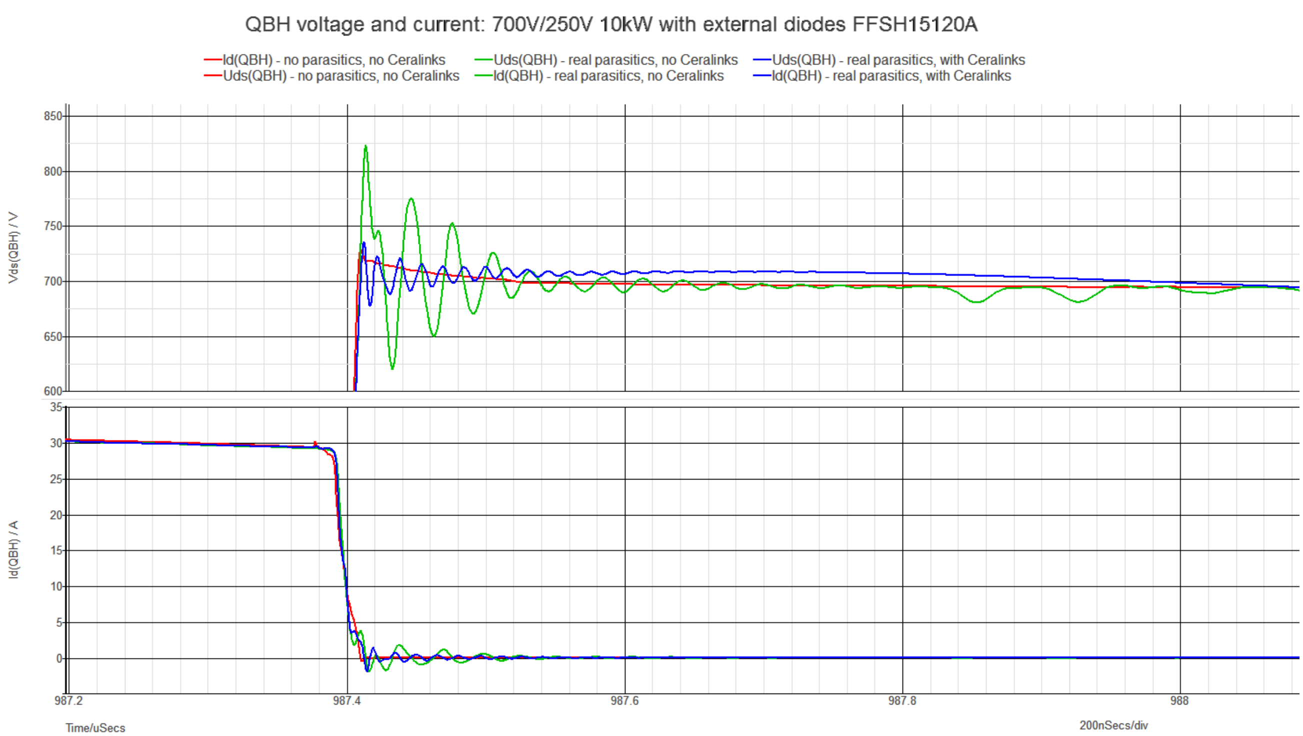


Figure 35. QBH Transistor V_{DS} and I_D with External Diodes Installed – Turn Off Detail

Simulink System Level Model

Nowadays, digital control is getting involved almost in every application. Also presented evaluation board is not an exception. Generally, the more complex the system is, the more complicated the algorithm and its implementation could be. Luckily, various methods and tools exist today to simplify these tasks. One of the options, meanwhile quite well established, is to utilize Simulink suite. It offers very good toolset for building virtually any mathematical model without any particular attention to the devices used at hardware level. It simplifies the way to build an electric model and to give higher priority to the algorithm development and testing.

Although basic control task in LLC converter is not so complicated, compared for example to 3 phase motor control or PFC applications, in principle – "only" switching frequency has to be swept within pre−specified range, there is usually always at least one PI(D) regulator needed within the system. Different methods exist to calculate particular regulator constants, but Simulink modeling can make selection of these much more convenient.

Related control loops, constant voltage and constant current for example are very typical, can be tailored for required responses. Additionally, also their practical limits can be demonstrated, if needed. Even if optimal regulator constants have to be verified on real prototypes, simulation model can provide very good start points, shifting first prototyping tests more to the safe side.

Figure 36 depicts Simulink simulation model used during software development for presented evaluation board. As can be seen, main converter blocks visible in real hardware are replicated in model as well.

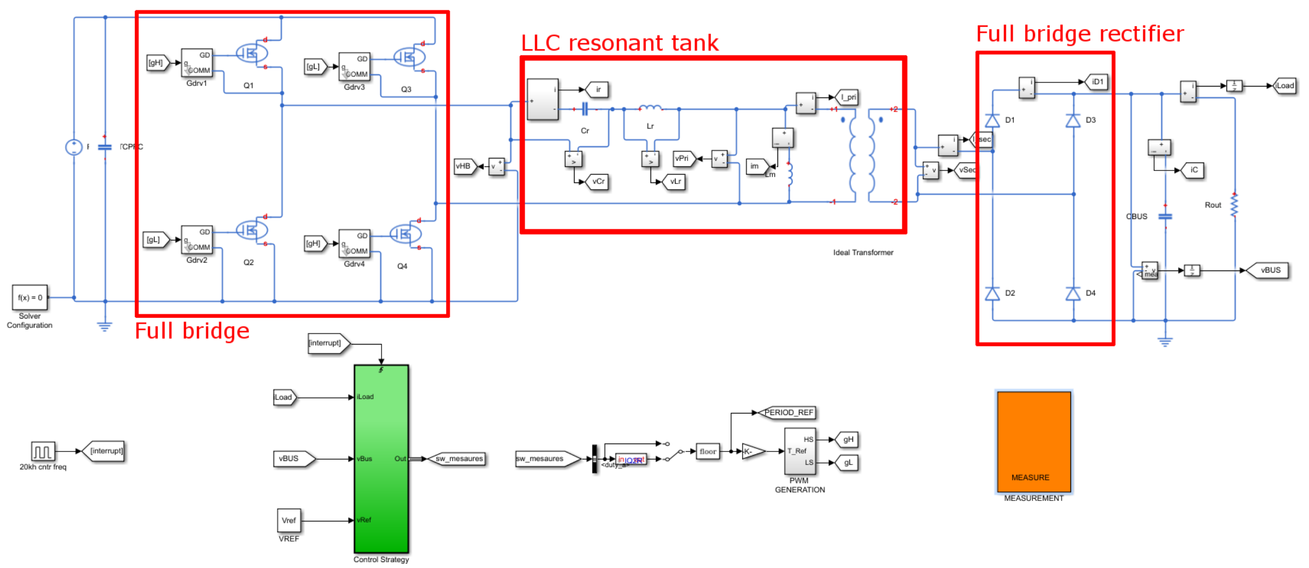


Figure 36. System Model in Simulink

HW Schematic and Board Realization

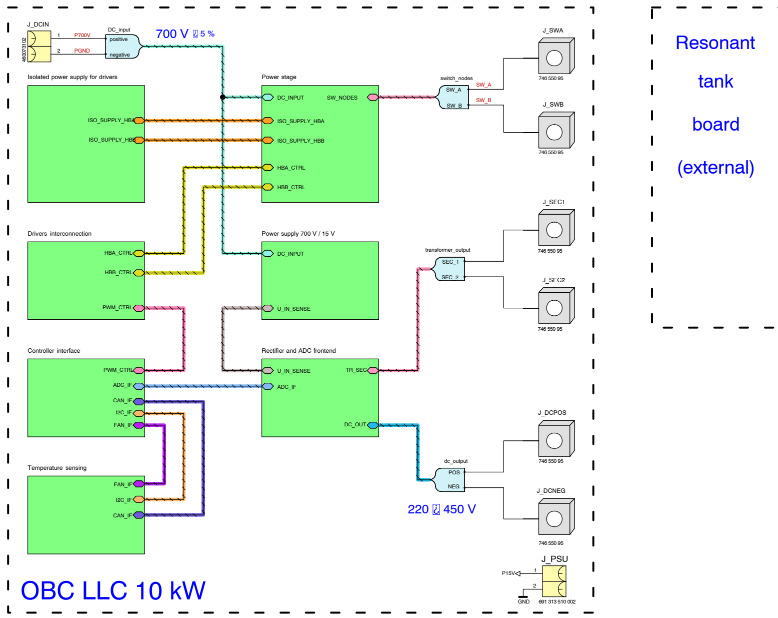


Figure 37. OBC LLC Switch Board, Top Level Diagram

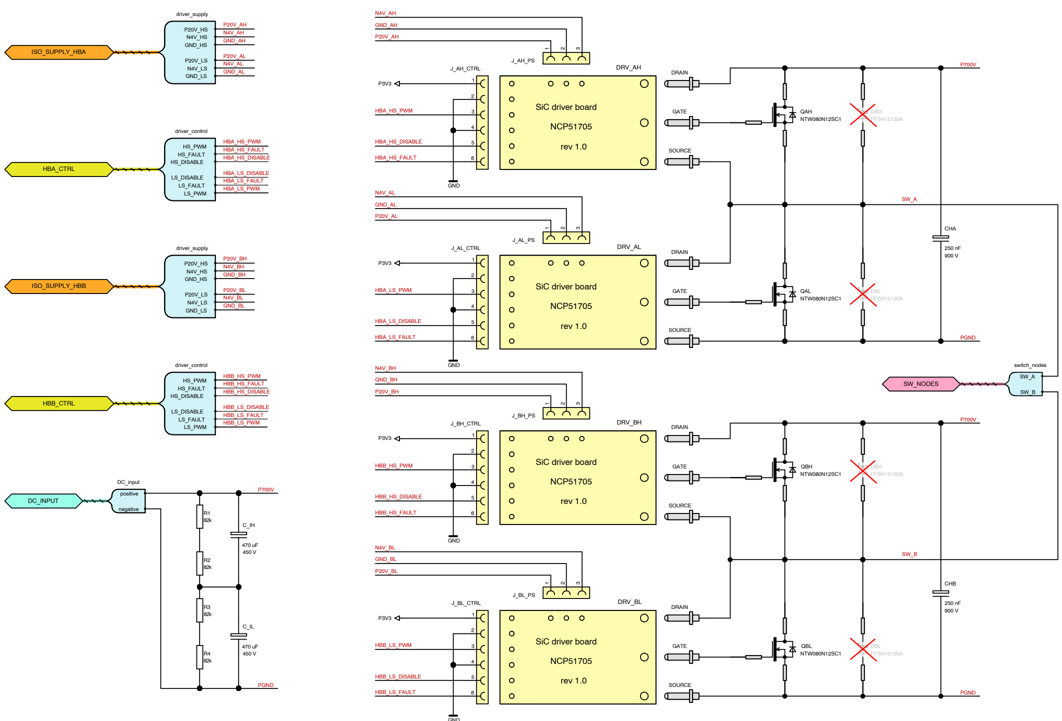


Figure 38. OBC LLC Switch Board, Power Stage

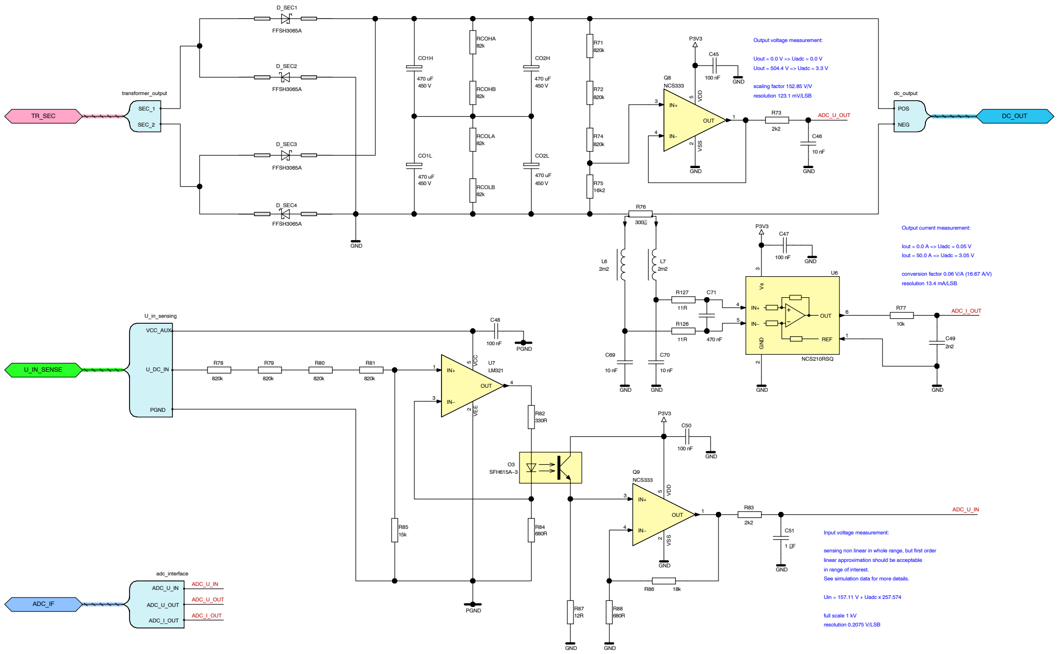


Figure 39. OBC LLC Switch Board, Rectifier

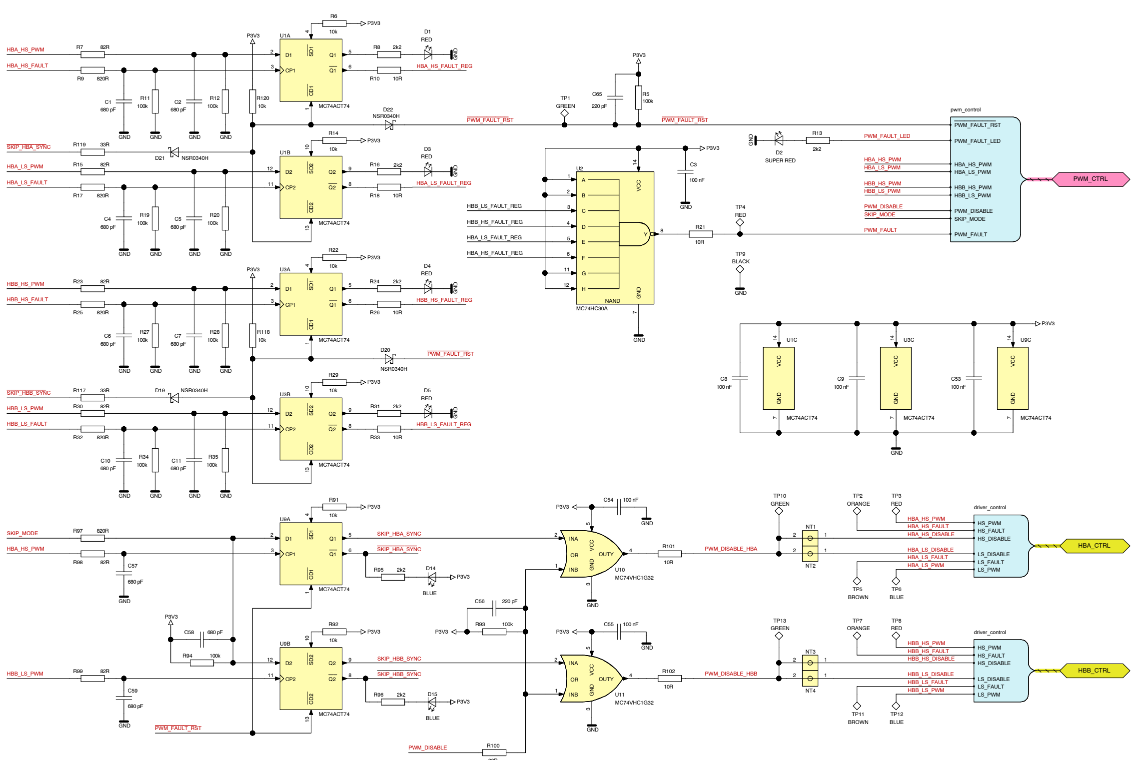


Figure 40. OBC LLC Switch Board, Drivers Interconnection, Fault Protection Logic

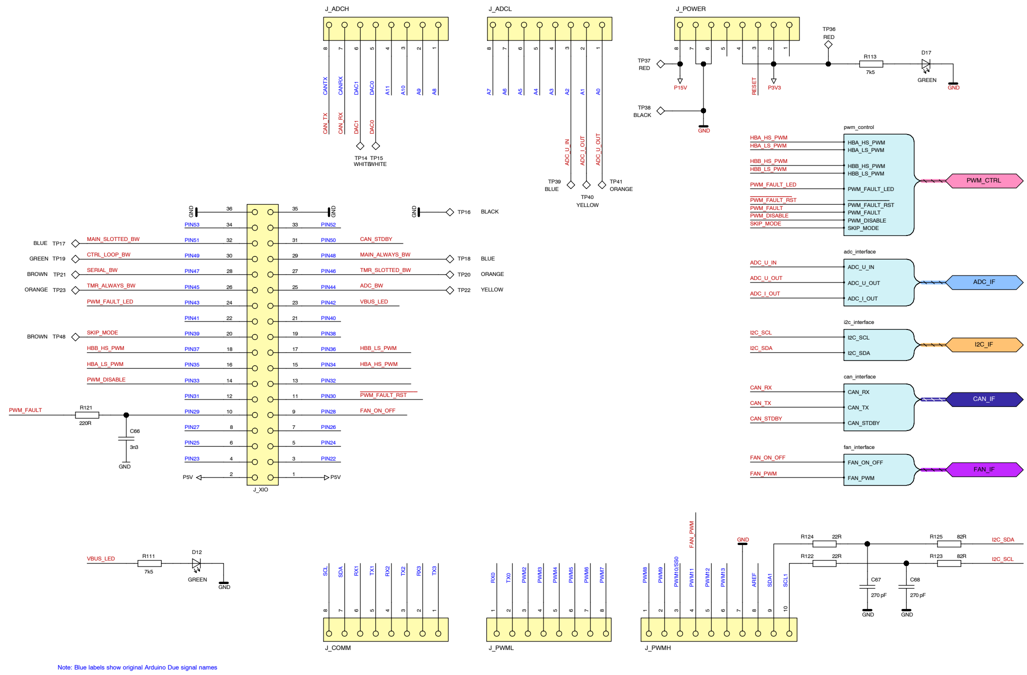


Figure 41. OBC LLC Switch Board, Controller Interface

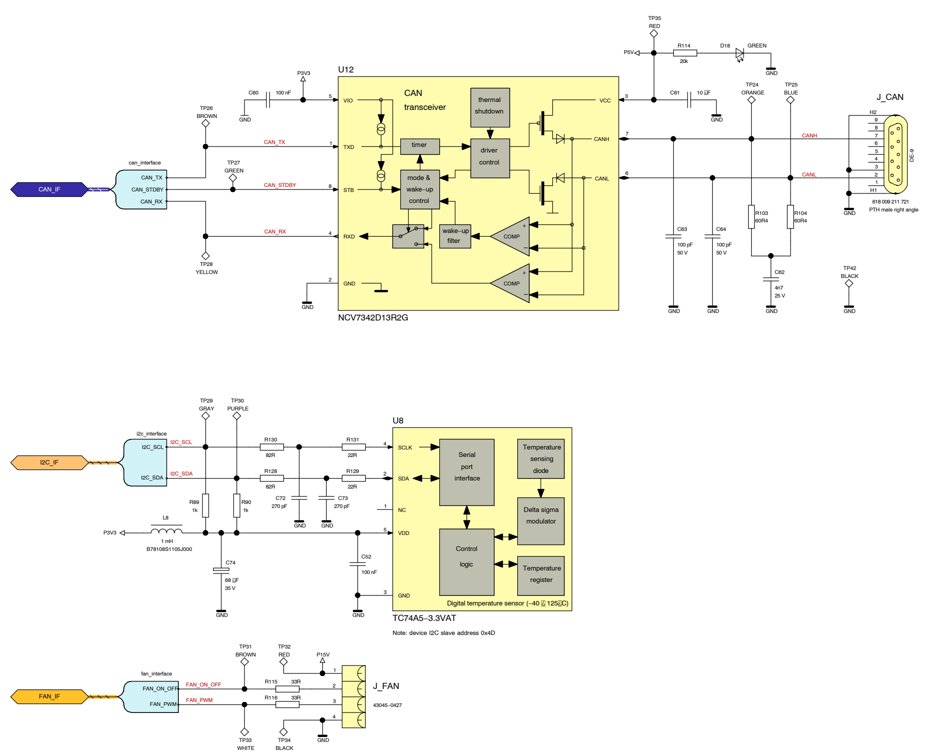


Figure 42. OBC LLC Switch Board, Temperature Sensing and CAN Bus Interface

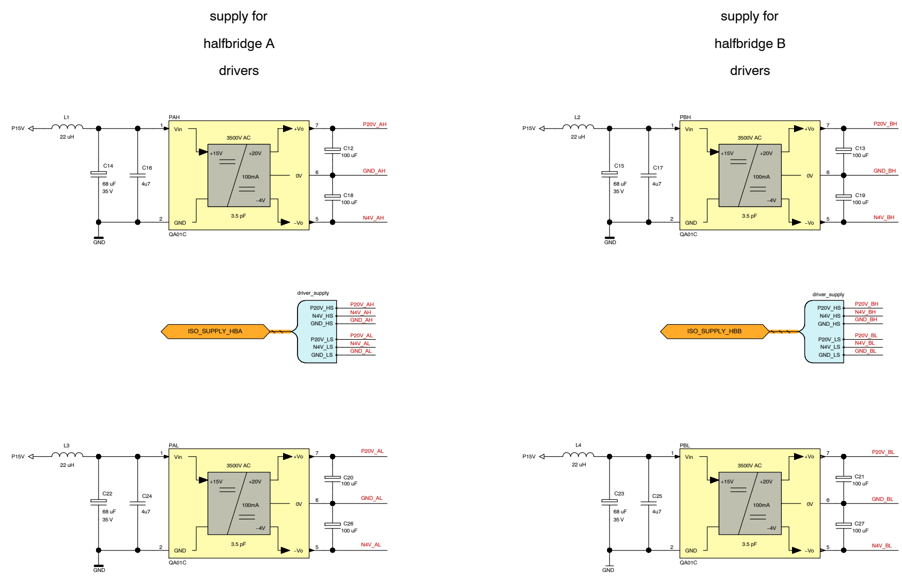


Figure 43. OBC LLC Switch Board, Insulated DC−DC Converters for MOSFET Drivers

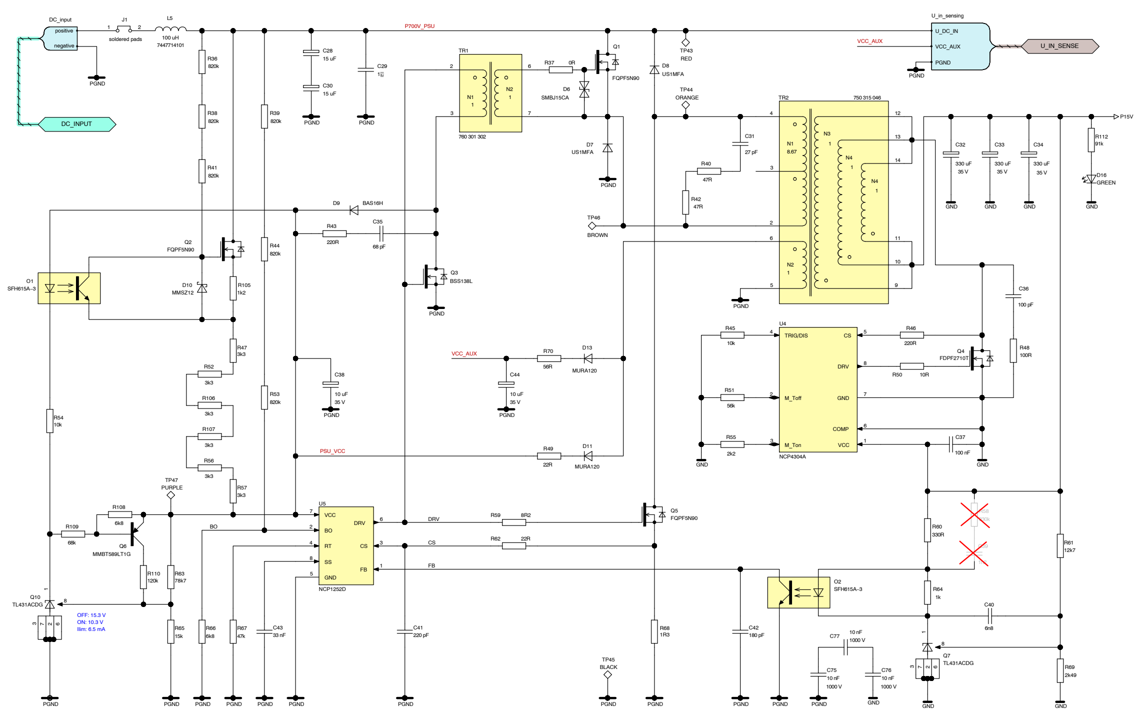


Figure 44. OBC LLC Switch Board, DC−DC converter 700 V − 15 V 30 W

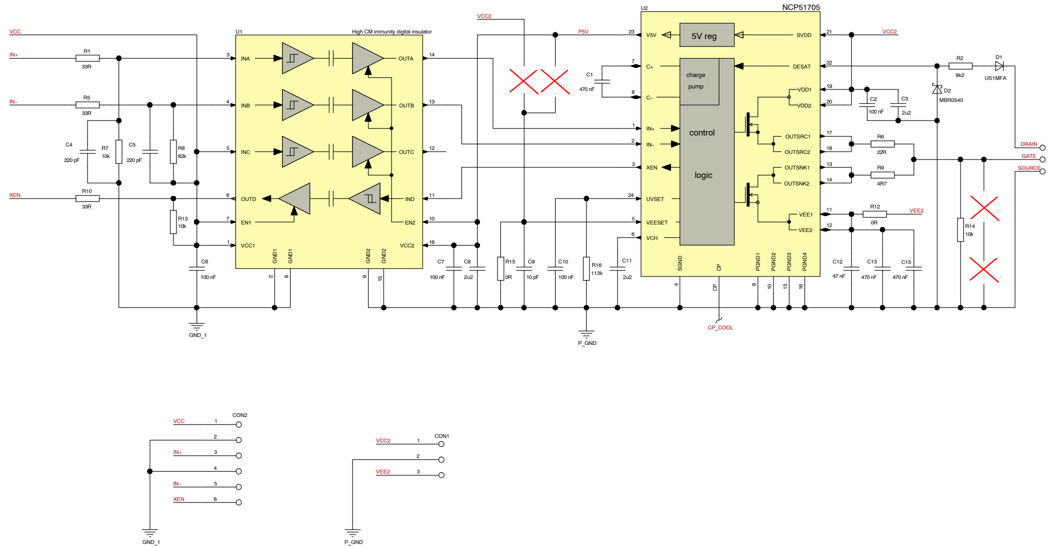


Figure 45. SiC Driver Board Circuit Diagram

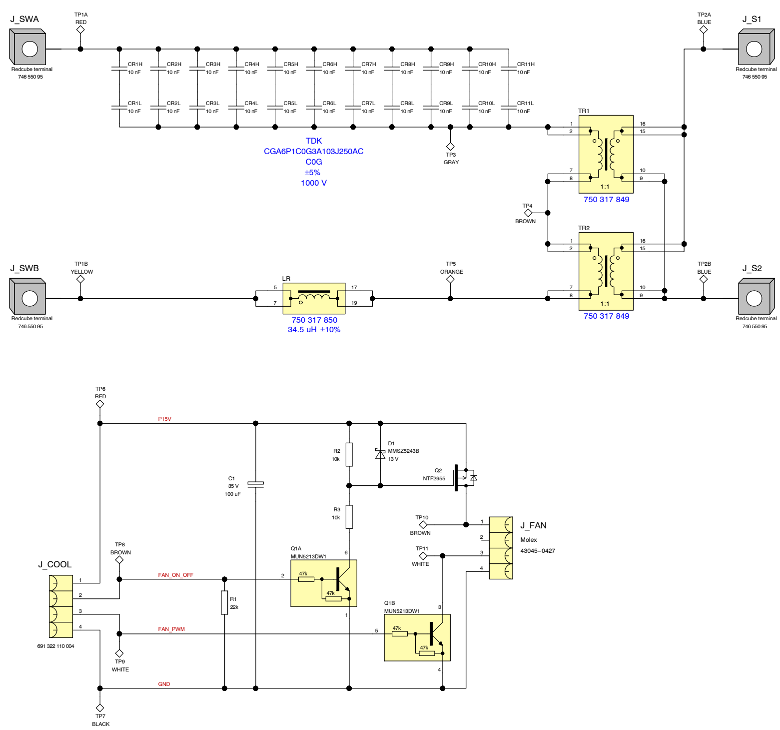


Figure 46. OBC LLC Resonant Tank WE Board, Resonant Tank Board

OBC LLC SWITCH BOARD – BILL OF MATERIALS

Project: OBC_LLC_switch_board.PrjPcb
Source Data From: OBC_LLC_switch_board.PrjPcb
Project: OBC_LLC_switch_board.PrjPcb
Variant: standard_board

#	Designator	Comment	Description	Manufacturer	Manufacturer Part Number	Quantity
1.	C1, C2, C4, C5, C6, C7, C10, C11	680 pF	MLC capacitor 680 pF 50 V X7R 10% Murata	Murata	GRM188R71H681KA01D	8
2.	C3, C8, C9, C53, C54, C55	100 nF	MLC capacitor 100 nF 25 V X7R 10% Murata	Murata	GRM219R71E104KA01D	6
3.	C12, C13, C18, C19, C20, C21, C26, C27	100 μF	Polymer ALU elco 100 μF 35 V 30 mΩ 20% Würth Elektronik	Würth Electronik	875115652007	8
4.	C14, C15, C22, C23, C74	68 μF	ALU electrolyte low impedance 68 μF 35 V 400 mΩ 20% Würth Elektronik	Würth Electronik	865080545011	5
5.	C16, C17, C24, C25	4 μ7	MLC capacitor 4 μ7 100 V X7S 10% soft termination Murata	Murata	GRJ32DC72A475KE11L	4
6.	C28, C30	15 μF	ALU electrolyte long life 15 μF 450 V 20% Würth Elektronik	Würth Electronik	865061463005	2
7.	C29	1 μ	MKP film X1 capacitor 1 μ 530Vac TDK	TDK	B32914A5105M	1
8.	C31	27 pF	MLC capacitor 27 pF 1000 V C0G 5% Murata	Murata	GRM31A5C3A270JW01	1
9.	C32, C33, C34	330 μF	Polymer ALU elco 330 μF 35 V 20 mΩ 20% Würth Elektronik	Würth Electronik	875075661010	3
10.	C35	68 pF	MLC capacitor 68 pF 250 V C0G 5% Murata	Murata	GRM21A5C2E680JW01D	1
11.	C36	100 pF	MLC capacitor 100 pF 200 V C0G 5% Murata	Murata	GRM21A5C2D101JW01D	1
12.	C37	100 nF	MLC capacitor 100 nF 50 V X7R 10% Murata	Murata	GRM21BR71H104KA01L	1
13.	C38, C44	10 μF	ALU electrolyte low impedance 10 μF 35V 2.6 Ω 20% Würth Elektronik	Würth Electronik	865080540004	2
14.	C40	6n8	MLC capacitor 6n8 50 V C0G 5% Murata	Murata	GRM2195C1H682JA01D	1
15.	C41	220 pF	MLC capacitor 220 pF 50 V C0G 5% Murata	Murata	GRM2165C1H221JA01D	1
16.	C42	180 pF	MLC capacitor 180 pF 50 V C0G 5% Murata	Murata	GRM1885C1H181JA01D	1
17.	C43	33 nF	MLC capacitor 33 nF 25 V X7R 10% Murata	Murata	GRM188R71E333KA01D	1
18.	C45, C47, C48, C50	100 nF	MLC capacitor 100 nF 16 V X7R 20% Murata	Murata	GRM188R71C104MA01D	4
19.	C46	10 nF	MLC capacitor 10 nF 25 V X7R 20% Murata	Murata	GRM216R71E103MA01D	1
20.	C49	2n2	MLC capacitor 2n2 25 V X7R 10% Murata	Murata	GRM216R71E222KA01D	1
21.	C51	1 μF	MLC capacitor 1 μF 16 V X7R 10% Murata	Murata	GRM21BR71C105KA01L	1
22.	C52, C60	100 nF	MLC capacitor 100 nF 16 V X7R 20% Murata	Murata	GRM21BR71C104MA01L	2
23.	C56, C65	220 pF	MLC capacitor 220 pF 50 V C0G 5% Murata	Murata	GRM1885C1H221JA01D	2
24.	C57, C58, C59	680 pF	MLC capacitor 680 pF 50 V C0G 5% Murata	Murata	GRM1885C1H681JA01D	3
25.	C61	10 μF	MLC capacitor 10 μF 25V X5R 20% Murata	Murata	GRM21BR61E106MA73L	1
26.	C62	4n7	MLC capacitor 4n7 25V X7R 20% Murata	Murata	GRM216R71E472MA01D	1
27.	C66	3n3	MLC capacitor 3n3 50 V X7R 10% Murata	Murata	GRM188R71H332KA01D	1
28.	C67, C68, C72, C73	270 pF	MLC capacitor 270 pF 50 V X7R 10% Murata	Murata	GRM188R71H271KA01D	4
29.	C69, C70	10 nF	MLC capacitor 10 nF 25 V C0G 5% Murata	Murata	GRM1885C1E103JA01D	2
30.	C71	470 nF	MLC capacitor 470 nF 25 V X7R 10% Murata	Murata	GRM188R71E474KA12D	1
31.	C75, C76, C77	10 nF	MLCC capacitor 10 nF 1000 V C0G ±5% TDK	TDK	CGA6P1C0G3A103J250AC	3
32.	C_IH, C_IL, CO1H, CO1L, CO2H, CO2L	470 μF	ALU electrolyte high current ripple 470 μF 450 V 20% United Chemicon	United Chemicon	E92X451VSN471MA50T	6
33.	CHA, CHB	250 nF	Ceralink SMD capacitor 250 nF 900 V TDK	TDK	B58031I9254M062	2
34.	CP_DCINa, CP_DCINb	171825–0100	Crimp female terminal for wires AWG 12–10 Molex	Molex	171825–0100	2
35.	D1, D3, D4, D5	RED	SMD LED diode 30 mA RED 0603 Würth Elektronik	Würth Elektronik	150060RS75000	4
36.	D2	SUPER RED	SMD LED diode 30 mA SUPER RED 0603 Würth Elektronik	Würth Elektronik	150060SS75000	1
37.	D6	SMBJ15CA	TVS 15V 600W SMB bidirectional ON Semiconductor	ON Semiconductor	SMBJ15CA	1
38.	D7, D8	US1MFA	Super Fast diode 1000 V 1 A 75 ns SOD123FA ON Semiconductor	ON Semiconductor	US1MFA	2

OBC LLC SWITCH BOARD – BILL OF MATERIALS (continued)

#	Designator	Comment	Description	Manufacturer	Manufacturer Part Number	Quantity
39.	D9	BAS16H	Switching diode 100 V 200 mA SOD323 ON Semiconductor	ON Semiconductor	BAS16HT1G	1
40.	D10	MMSZ12	Zener diode 12 V 500 mW SOD123 ON Semiconductor	ON Semiconductor	MMSZ12T1G	1
41.	D11, D13	MURA120	Ultra Fast diode 200 V 1 A SMA ON Semiconductor	ON Semiconductor	MURA120T3G	2
42.	D12, D16, D17, D18	GREEN	SMD LED diode 30 mA GREEN 0603 Würth Elektronik	Würth Elektronik	150060GS75000	4
43.	D14, D15	BLUE	SMD LED diode 30 mA BLUE 0603 Würth Elektronik	Würth Elektronik	150060BS75000	2
44.	D19, D20, D21, D22	NSR0340H	Schottky diode 40 V 250 mA low Vf SOD323 ON Semiconductor	ON Semiconductor	NSR0340HT1G	4
45.	D_SEC1, D_SEC2, D_SEC3, D_SEC4	FFSH3065A	SiC Schottky diode 650 V 30 A ON Semiconductor	ON Semiconductor	FFSH3065A	4
46.	DRV_AH, DRV_AL, DRV_BH, DRV_BL	SiC MOSFET driver board with NCP51705	SiC MOSFET driver board with NCP51075 ON Semiconductor			4
47.	L1, L2, L3, L4	22 μH	WE TPC power inductor SMD 22 μH 0.925A Würth Elektronik	Würth Elektronik	744043220	4
48.	L5	100 μH	WE PD power inductor SMD 100 μH 1.5 A Würth Elektronik	Würth Elektronik	7447714101	1
49.	L6, L7	2m2	Bobbin core RF choke 2.2 mH 80 mA TDK	TDK	B78108S1225J000	2
50.	L8	1 mH	Bobbin core RF choke 1 mH 130 mA TDK	TDK	B78108S1105J000	1
51.	NQ1, NQ4	hex nut M3 DIN934	Hex nut M3 DIN934 ISO4032			2
52.	O1, O2, O3	SFH615A−3	Optocoupler, high realibility, 5300 Vrms Vishay	Vishay	SFH615A−3X007T	3
53.	PAH, PAL, PBH, PBL	QA01C	Insulated DC−DC converter for IGBT drivers 15 V−> +20 V/−4 V low capacity Mornsun			4
54.	Q1, Q2, Q5	FQPF5N90	NMOS 900 V 3 A 2.3R ON Semiconductor	ON Semiconductor	FQPF5N90	3
55.	Q3	BSS138L	NMOS 50 V 0.2 A 200 mA 3.5 Ω ON Semiconductor	ON Semiconductor	BSS138LT1G	1
56.	Q4	FDPF2710T	NMOS 250 V 25 A 42.5 mΩ ON Semiconductor	ON Semiconductor	FDPF2710T	1
57.	Q6	MMBT589LT1G	High Current surface mount PNP silicon switching transistor	ON Semiconductor	MMBT589LT1G	1
58.	Q7, Q10	TL431ACDG	Voltage reference 2.5 V 1 mA ON Semiconductor	ON Semiconductor	TL431ACDG	2
59.	Q8, Q9	NCS333	Single low noise zero drift OPAMP ON Semiconductor	ON Semiconductor	NCS333SN2T1G	2
60.	QAH, QAL, QBH, QBL	NTW080N12SC1	SiC NMOS 1200 V 36 A 80 mΩ ON Semiconductor	ON Semiconductor	NTW080N12SC1	4
61.	R1, R2, R3, R4, RCOHA, RCOHB, RCOLA, RCOLB	82k	SMD thick film resistor 82k 1206 1% 660 mW Panasonic	Panasonic	ERJP08F8202V	8
62.	R5, R11, R12, R19, R20, R27, R28, R34, R35, R93, R94	100k	SMD thick film resistor 100k 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF1003V	11
63.	R6, R14, R22, R29, R91, R92, R118, R120	10k	SMD thick film resistor 10k 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF1002V	8
64.	R7, R15, R23, R30, R98, R99, R123, R125, R128, R130	82R	SMD thick film resistor 82R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF82R0V	10
65.	R8, R16, R24, R31, R73, R95, R96	2k2	SMD thick film resistor 2k2 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF2201V	7
66.	R9, R17, R25, R32, R97	820R	SMD thick film resistor 820R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF8200V	5
67.	R10, R18, R21, R26, R33, R101, R102	10R	SMD thick film resistor 10R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF10R0V	7
68.	R13, R55, R83	2k2	SMD thick film resistor 2k2 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF2201V	3

OBC LLC SWITCH BOARD – BILL OF MATERIALS (continued)

#	Designator	Comment	Description	Manufacturer	Manufacturer Part Number	Quantity
69.	R36, R38, R39, R41, R44, R53, R71, R72, R74, R78, R79, R80, R81	820k	SMD thick film resistor 820k 1206 1% 660 mW Panasonic	Panasonic	ERJP08F8203V	13
70.	R37	0R	SMD thick film resistor 0R 0805 2A Panasonic	Panasonic	ERJ6GEY0R00V	1
71.	R40, R42	47R	SMD thick film resistor 47R 1206 1% 660 mW Panasonic	Panasonic	ERJP08F47R0V	2
72.	R43, R46	220R	SMD thick film resistor 220R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF2200V	2
73.	R45, R54, R77	10k	SMD thick film resistor 10k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1002V	3
74.	R47, R52, R56, R57, R106, R107	3k3	SMD thick film resistor 3k3 1206 1% 660 mW Panasonic	Panasonic	ERJP08F3301V	6
75.	R48	100R	SMD thick film resistor 100R 1206 1% 660 mW Panasonic	Panasonic	ERJP08F1000V	1
76.	R49, R62	22R	SMD thick film resistor 22R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF22R0V	2
77.	R50	10R	SMD thick film resistor 10R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF10R0V	1
78.	R51	56k	SMD thick film resistor 56k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF5602V	1
79.	R59	8R2	SMD thick film resistor 8R2 0805 5% 125 mW 150 V Vishay	Vishay Draloric	CRCW08058R20JNEAIF	1
80.	R60, R82	330R	SMD thick film resistor 330R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF3300V	2
81.	R61	12k7	SMD thick film resistor 12k7 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1272V	1
82.	R63	78k7	SMD thick film resistor 78k7 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF7872V	1
83.	R64, R89, R90	1k	SMD thick film resistor 1k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1001V	3
84.	R65, R85	15k	SMD thick film resistor 15k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1502V	2
85.	R66, R108	6k8	SMD thick film resistor 6k8 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF6801V	2
86.	R67	47k	SMD thick film resistor 47k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF4702V	1
87.	R68	1R3	SMD current sense resistor 1R3 1206 1% 330 mW Panasonic	Panasonic	ERJ8BQF1R3V	1
88.	R69	2k49	SMD thick film resistor 2k49 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF2491V	1
89.	R70	56R	SMD thick film resistor 56R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF56R0V	1
90.	R75	16k2	SMD thick film resistor 16k2 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1622V	1
91.	R76	300μ	SMD Current Sense Resistor with Kelvin connection, 300 μΩ, 7 W, ±1%, Power Metal Strip, Vishay	Vishay	WSL4026L3000FEB	1
92.	R84, R88	680R	SMD thick film resistor 680R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF6800V	2
93.	R86	18k	SMD thick film resistor 18k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1802V	1
94.	R87	12R	SMD thick film resistor 12R 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF12R0V	1
95.	R100, R115, R116, R117, R119	33R	SMD thick film resistor 33R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF33R0V	5
96.	R103, R104	60R4	SMD thick film resistor 60R4 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF60R4V	2
97.	R105	1k2	SMD thick film resistor 1k2 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1201V	1
98.	R109	68k	SMD thick film resistor 68k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF6802V	1
99.	R110	120k	SMD thick film resistor 120k 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF1203V	1
100.	R111, R113	7k5	SMD thick film resistor 7k5 0805 1% 125 mW Panasonic	Panasonic	ERJ6ENF7501V	2
101.	R112	91k	SMD thick film resistor 91k 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF9102V	1
102.	R114	20k	SMD thick film resistor 20k 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF2002V	1
103.	R121	220R	SMD thick film resistor 220R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF2200V	1
104.	R122, R124, R129, R131	22R	SMD thick film resistor 22R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF22R0V	4
105.	R126, R127	11R	SMD thick film resistor 11R 0603 1% 100 mW Panasonic	Panasonic	ERJ3EKF11R0V	2
106.	TR1	760 301 302	Transformer for gate drive one output	Würth Elektronik	760301302	1
107.	TR2	750 315 046	Transformer for DC−DC converter 750 315 046 Würth Elektronik	Würth Elektronik	750315046	1
108.	U1, U3, U9	MC74ACT74	Dual D−Type Positive Edge−Triggered Flip−Flop with asynchronous set/reset ON Semiconductor	ON Semiconductor	MC74ACT74DR2G	3
109.	U2	MC74HC30A	8−input NAND gate, high speed ON Semiconductor	ON Semiconductor	MC74HC30ADG	1
110.	U4	NCP4304A	Secondary side synchronous rectification driver	ON Semiconductor	NCP4304ADR2G	1

OBC LLC SWITCH BOARD – BILL OF MATERIALS (continued)

#	Designator	Comment	Description	Manufacturer	Manufacturer Part Number	Quantity
111.	U5	NCP1252D	Flyback/ Forward controller ON Semiconductor	ON Semiconductor	NCP1252DDR2G	1
112.	U6	NCS210RSQ	Current Sense Amplifier, 26 V, Low−/High−Side Voltage Out, Bidirectional Current Shunt Monitor, fixed gain 200	ON Semiconductor	NCS210RSQT2G	1
113.	U7	LM321	Single channel operational amplifier, 3−32 V, bipolar, ON Semiconductor	ON Semiconductor	LM321SN3T1G	1
114.	U8	TC74A5−3.3VAT	Digital temperature sensor with serial interface −40 − 125°C, I2C addres 0xA5, optimized for 3.3 V, Microchip	Microchip	TC74A5−3.3VAT	1
115.	U10, U11	MC74VHC1G32	2−Input OR Gate/CMOS Logic Level Shifter ON Semiconductor	ON Semiconductor	MC74VHC1G32DTT1G	2
116.	U12	NCV7342D13R2G	High speed low power CAN transceiver with dual supply ON Semiconductor	ON Semiconductor	NCV7342D13R2G	1

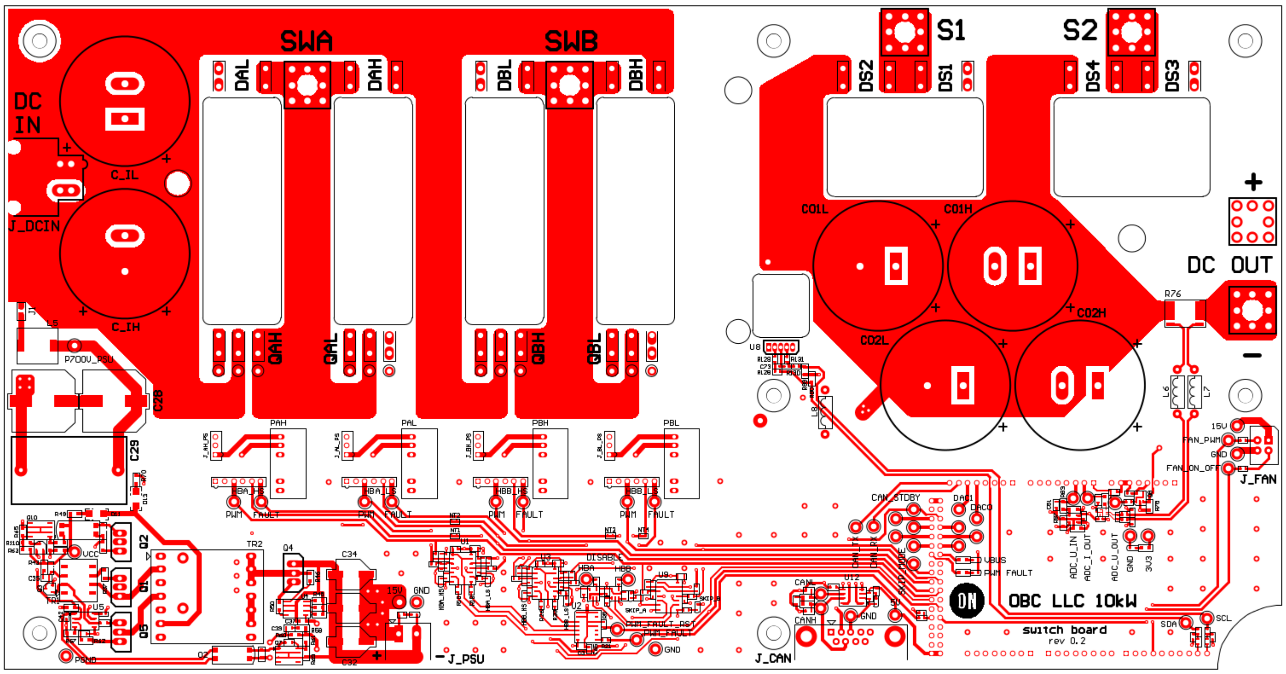


Figure 47. OBC LLC Switch Board PCB – Top Layer

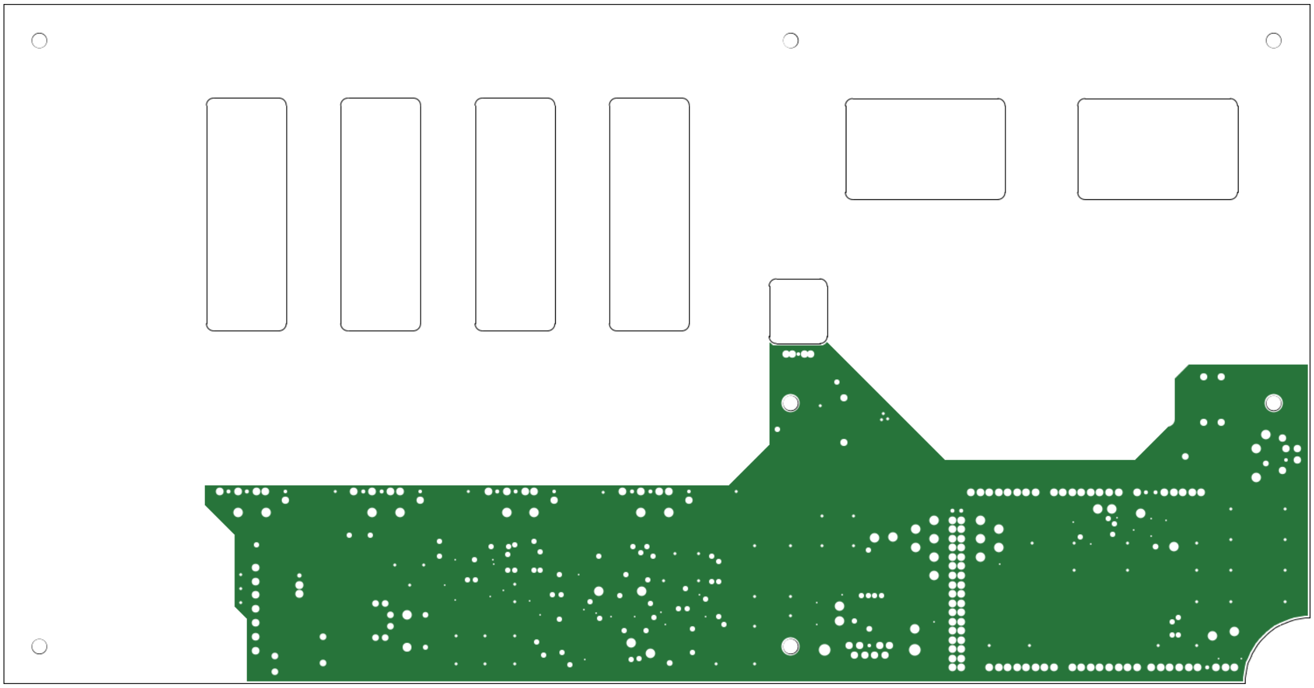


Figure 48. OBC LLC Switch Board PCB – Internal Groung Plane Layer

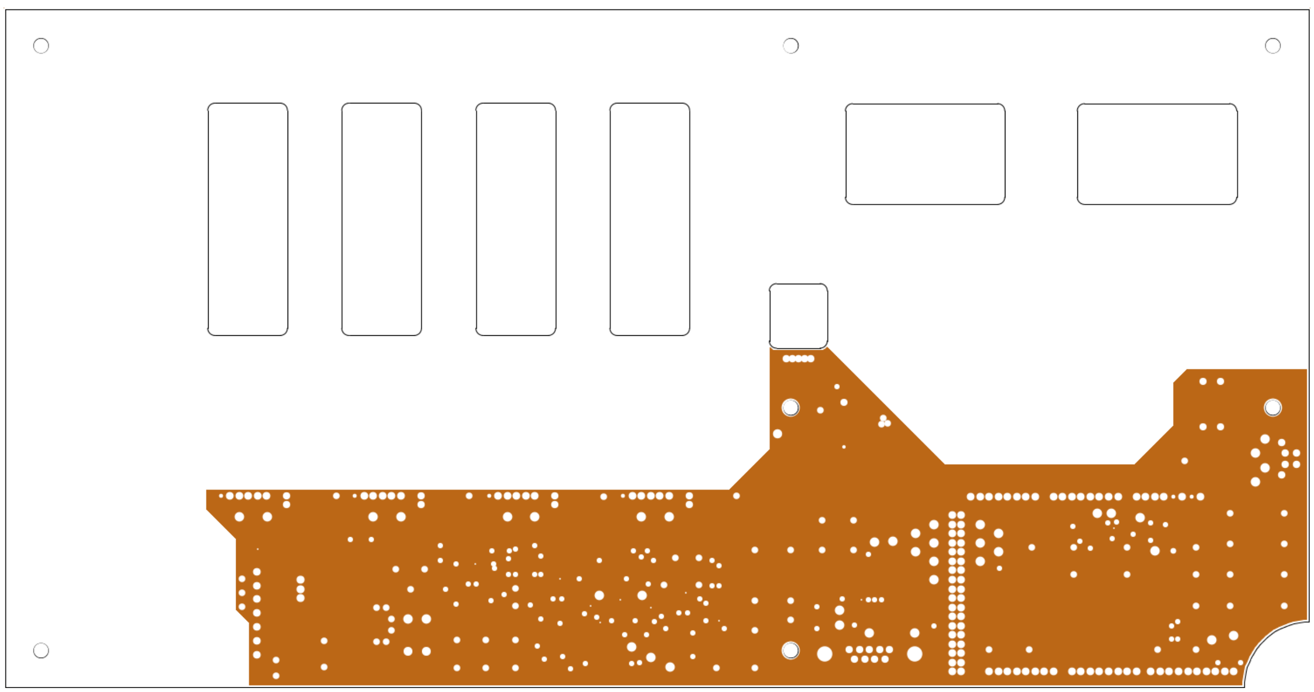


Figure 49. OBC LLC Switch Board PCB – Internal Power Plane Layer

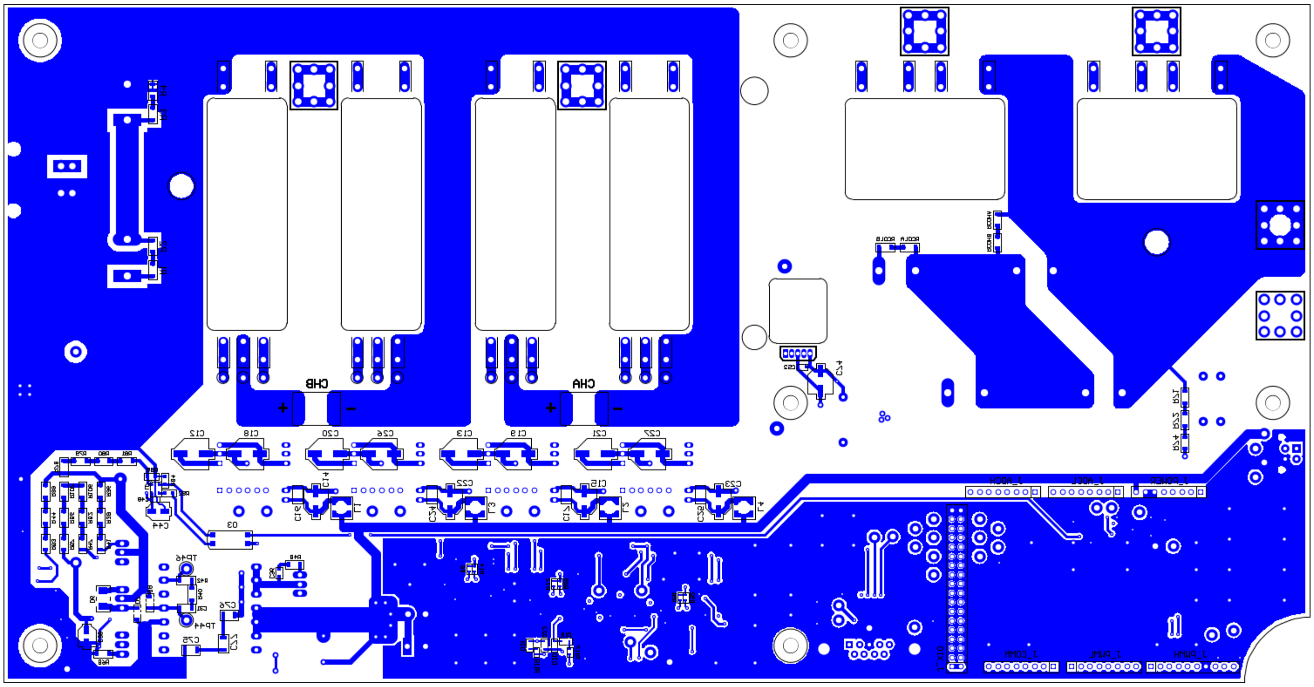


Figure 50. OBC LLC Switch Board PCB – Bottom Layer

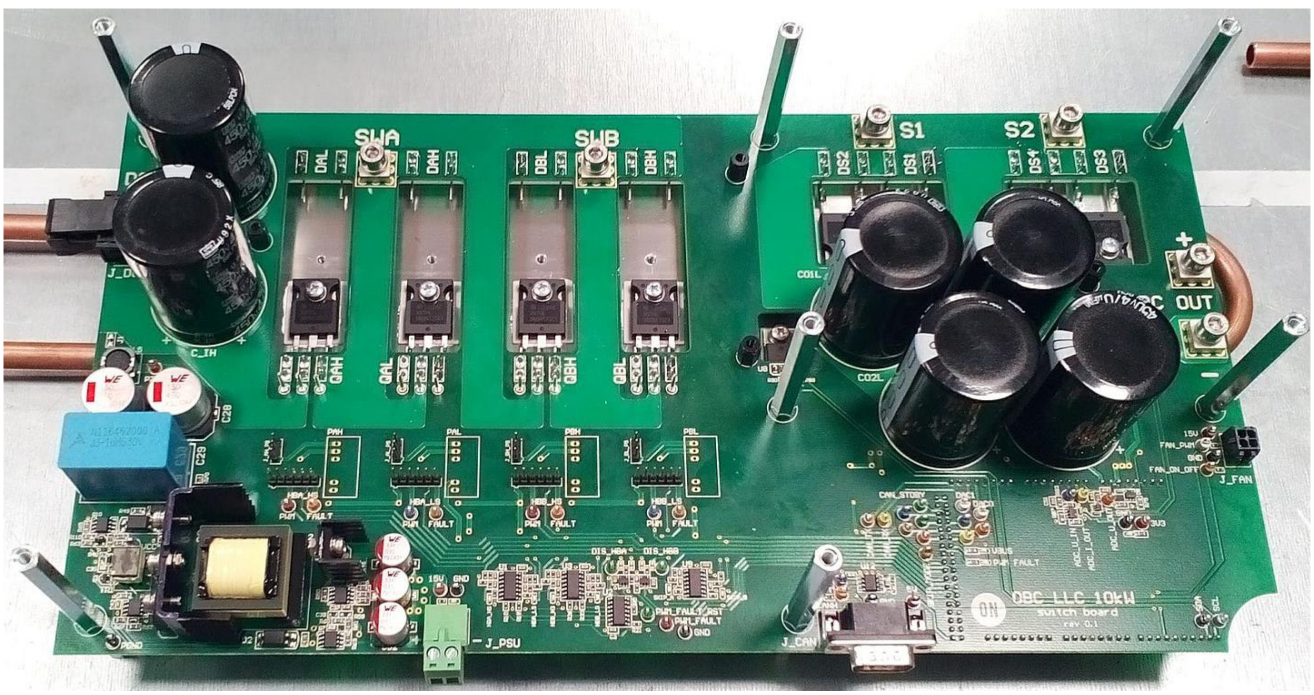


Figure 51. OBC LLC Switch Board – Top View

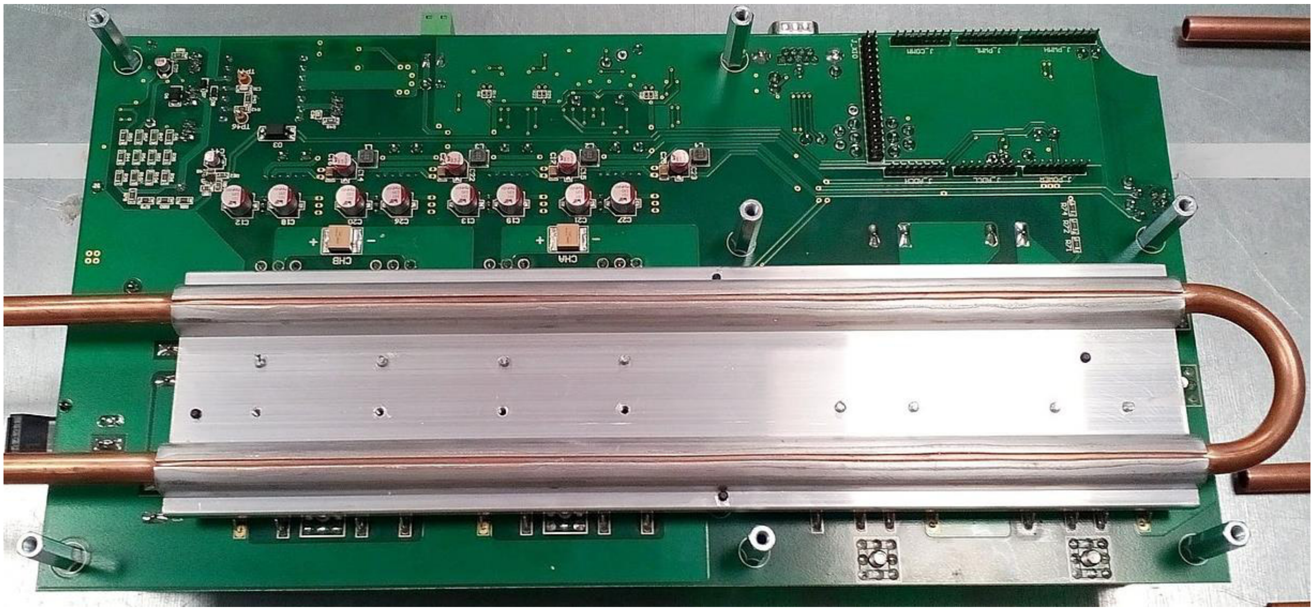


Figure 52. OBC LLC Switch Board – Bottom View

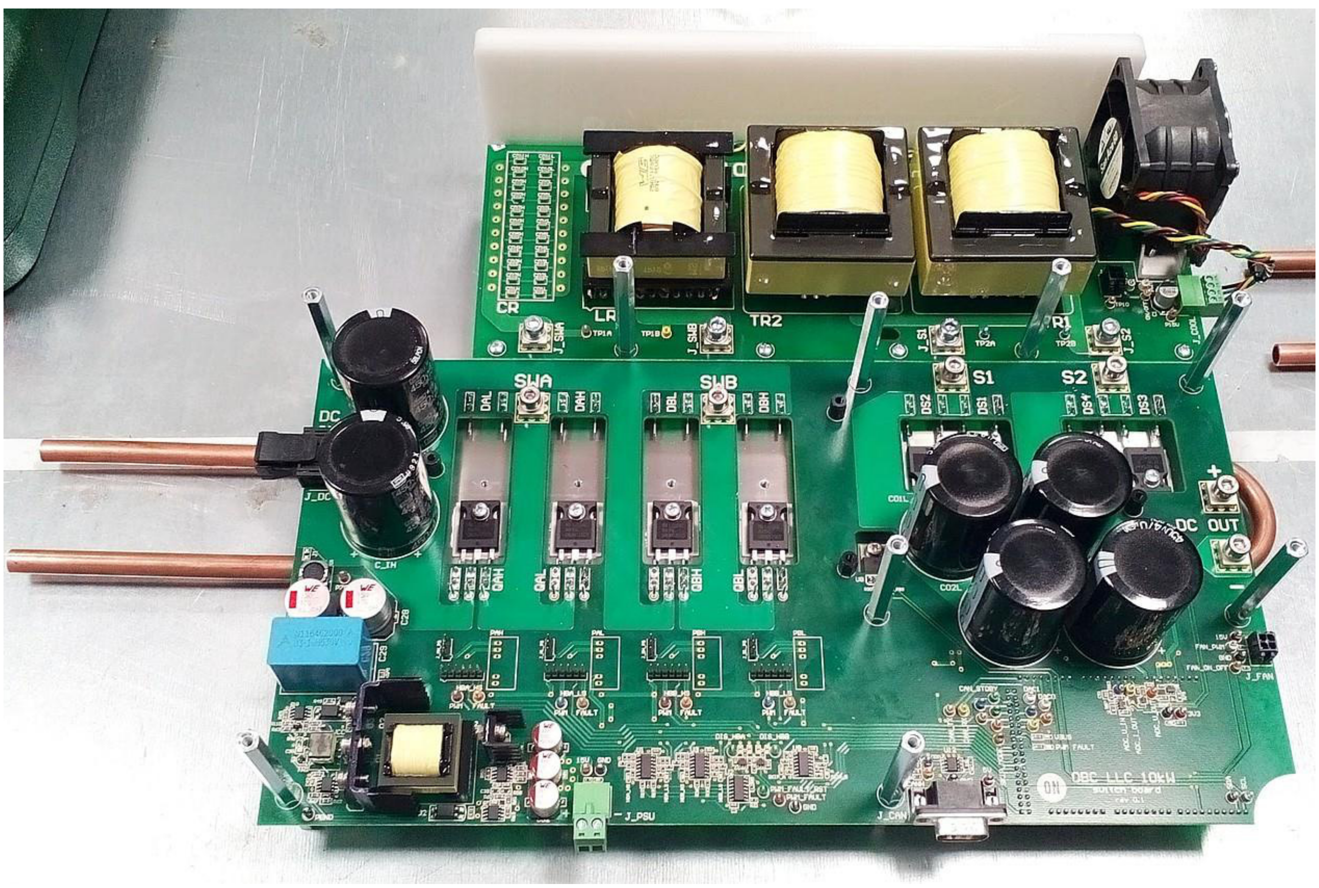


Figure 53. OBC LLC Switch Board with External Resonant Tank Board

Test Setup Usage

Following prerequisites are needed to operate presented OBC LLC evaluation setup:

- *OBC LLC switch board*
- *Resonant tank board*

OBC LLC evaluation setup has been designed so that passive components of resonant tank are located on another board connected to OBC LLC switch board. This provides high degree of flexibility, various tank solutions can be tested without complete redesign of the converter board.

- *Interconnection between OBC LLC Switch Board and External Resonant Tank Board*

4 short interconnection links are needed to connect external resonant tank to OBC LLC switch board. Good idea is to keep them short if possible. User has also to consider appropriate cross section of interconnection wires to handle flowing currents without substantial overheating. Maximum current foreseen in design phase is 40 ARMS at DC output. Switch board is equipped with so called red cube terminals for M5 screws.

OBC LLC switch board provides also an option to connect and control an external fan, which can be installed on external resonant tank board. Molex 43025−0400 connector and four 46235−0001 female crimp terminals are recommended.

- *High Voltage DC Power Supply*

Nominal input voltage of the board is 700 V, there are two 450 V capacitors in series at the board input side, so maximum input voltage is about 850 V. Note, that power supply has to provide enough power for intended test purposes, including also power losses within tested application.

Molex 44441−2002 connector with two female crimp terminals 1718125−0100 are needed for DC input connection.

- *High Voltage DC Load*

Maximal output voltage considered during design phase is 450 V, however, similarly to converter input, two branches of two 450 V capacitors in series are installed at the converter DC output, so even higher voltage could be tested, if required. Note that 650 V diodes are used in secondary side rectifier, so they need to be eventually changed for higher output voltages.

Electronic, so called recuperation loads are used very often to reduce electric energy amount used for tests. Unfortunately, sometimes their regulators are not so perfect under certain operating conditions, which may be exhibited as a various instabilities present at tested converter output. Consequently, false implications can be derived judging converter guilty even if it is not necessary true.
Similarly to resonant tank board connection, M5 red cube terminals are used for DC output connection.

- *External 15 V Power Supply*

Housekeeping 15 V output DC−DC converter on OBC LLC switch board starts to operate at about 390 V at board DC input. For test purposes, 15 V power line can be supplied also by external DC power supply. One 691351500002 connector from Würth Elektronik is needed to make this connection. Keep in mind that external DC power supply with appropriate insulation level has to be used eventually, once high voltage is present at OBC LLC switch board input and converter is running.

- *Recirculating Liquid Cooler*

All power semiconductor components on OBC LLC switch board are mounted on liquid cold plate, so appropriate external liquid cooler, like Julabo F500 for example, has to be used. Liquid connection to cold plate consists of two bare 3/8” (outer diameter) copper tubes. Cold plate rated recommended maximum flowrate is 1 gallon per minute. Effective thermal resistance is not reduced meaningfully above this flowrate.

- *PC with Installed GUI Application*

OBC LLC switch board does not start automatically once powered or reset. Firmware in controller requires active communication over USB interface with special GUI application on PC. As can be seen also in snapshot below, GUI provides basic diagnostic and control functions.

Basic GUI Usage

1. Connection to OBC LLC switch board is initialized by clicking *“CONNECT”* button located in right bottom corner of application window
2. As a next step, virtual oscilloscope can be activated using *“RUN”* button on right side
3. Voltage and / or current reference (e.g. output regulation target value) has to be entered
4. Control type (voltage or current control) has to be selected using combo box in left bottom corner of application window. Bear in mind that *only one control loop is active at the same time – constant voltage OR constant current*
5. Now, converter can be started by clicking *“SEND REF VALUE”* button. This button has to be used also if new target voltage or current value is needed while converter is already running
6. Finally, *“STOP LLC SWITCHING”* button can be used to stop converter operation

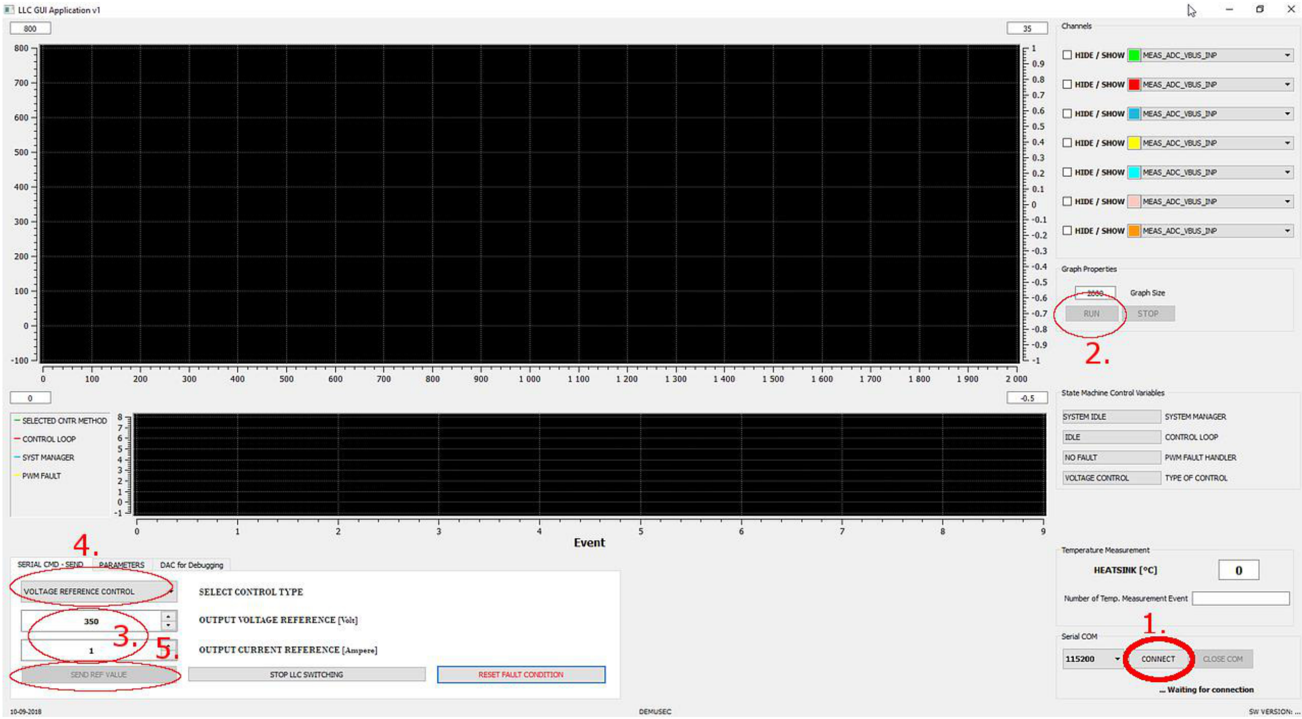


Figure 54. OBC LLC Switch Board PC GUI Application

Test results

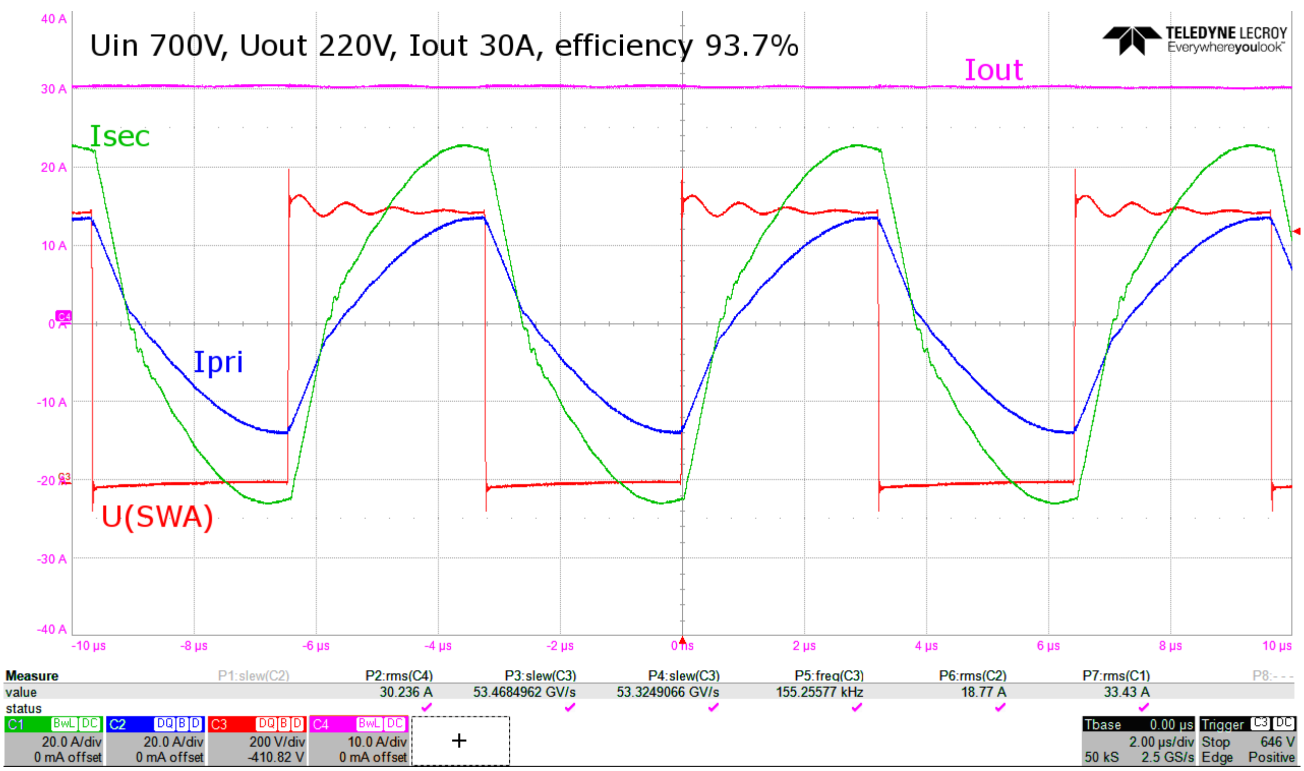


Figure 55. Converter Operating Waveforms – 700 V to 220 V, Load Current 30 A (6.6 kW)

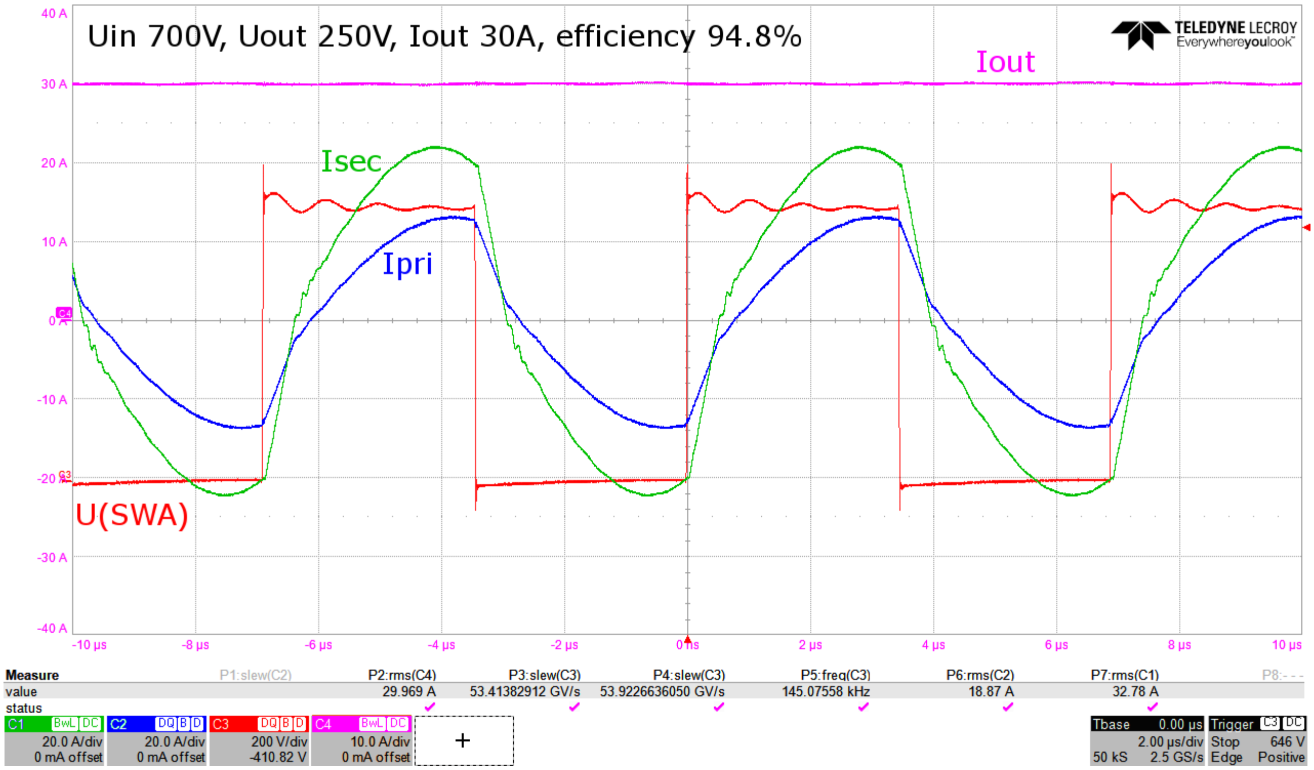


Figure 56. Converter Operating Waveforms – 700 V to 250 V, Load Current 30 A (7.5 kW)

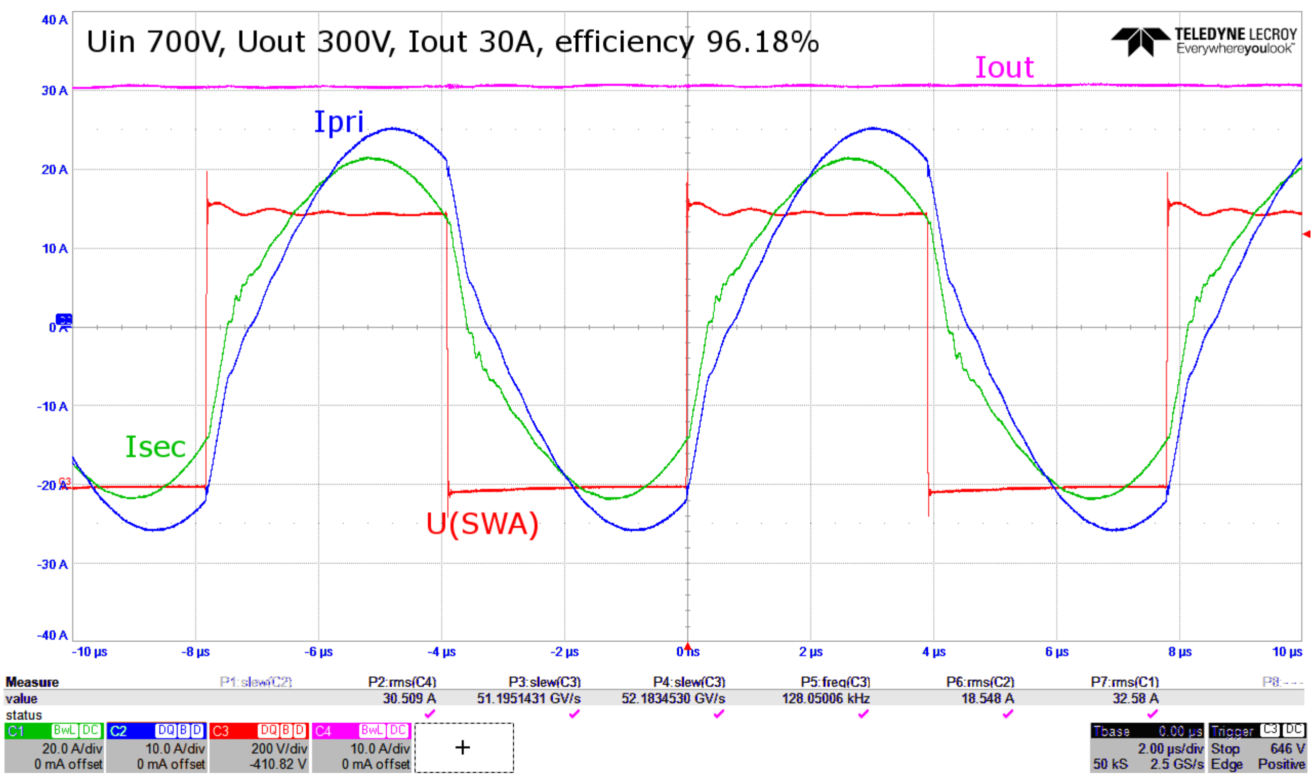


Figure 57. Converter Operating Waveforms – 700 V to 300 V, Load Current 30 A (9 kW)

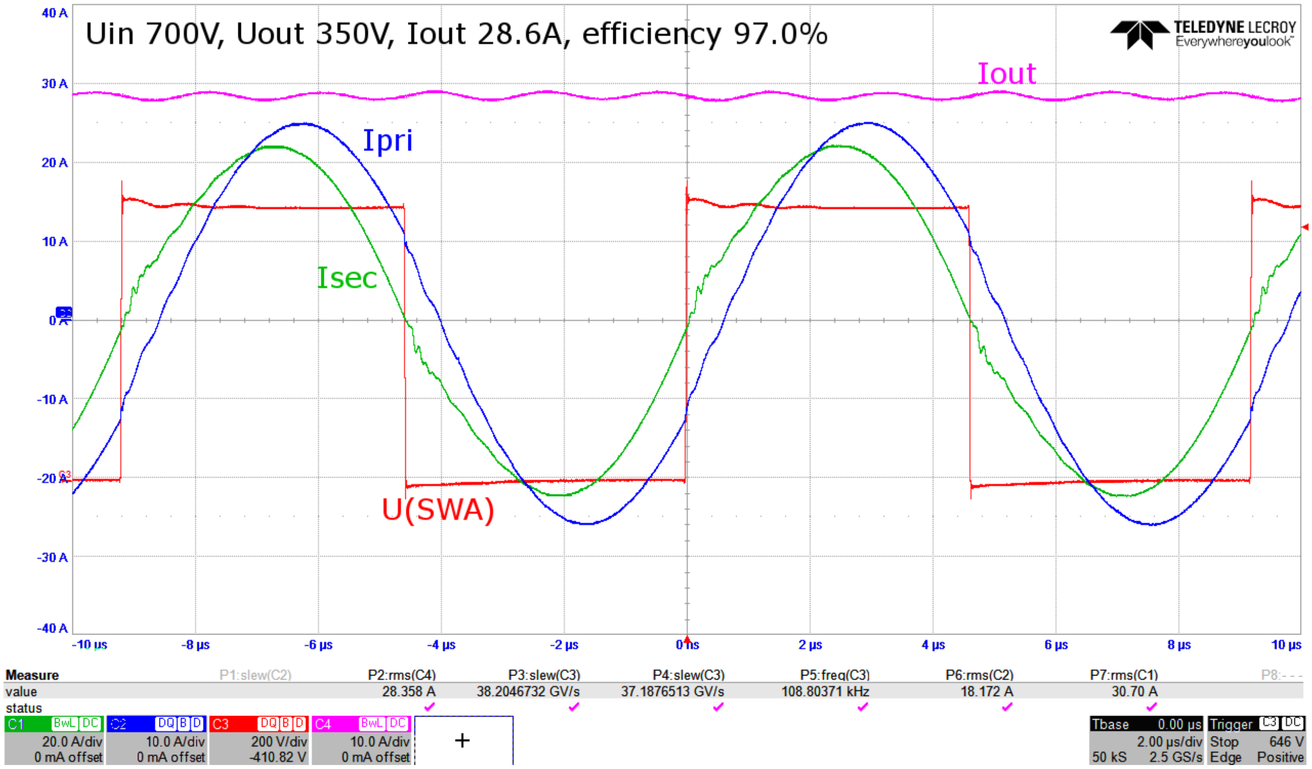


Figure 58. Converter Operating Waveforms – 700 V to 350 V, Load Current 28.6 A (10 kW)

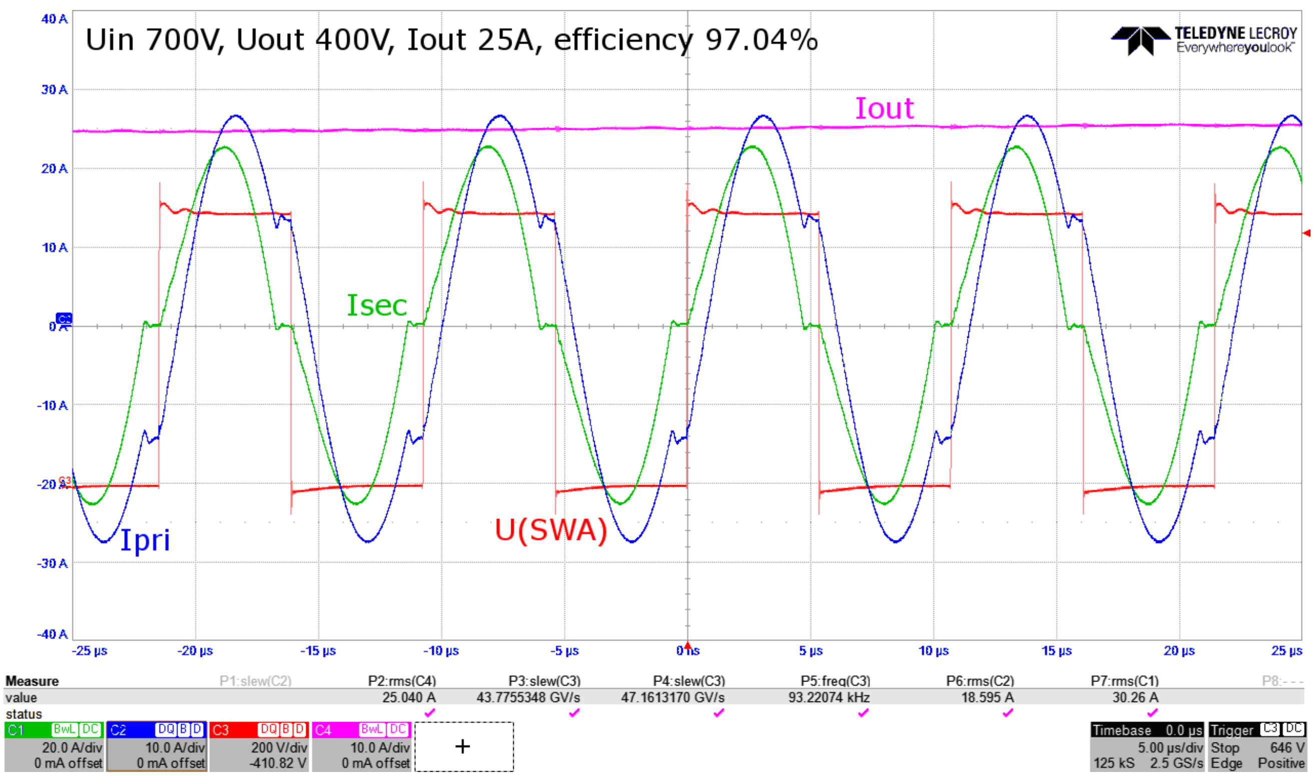


Figure 59. Converter Operating Waveforms – 700 V to 400 V, Load Current 25 A (10 kW)

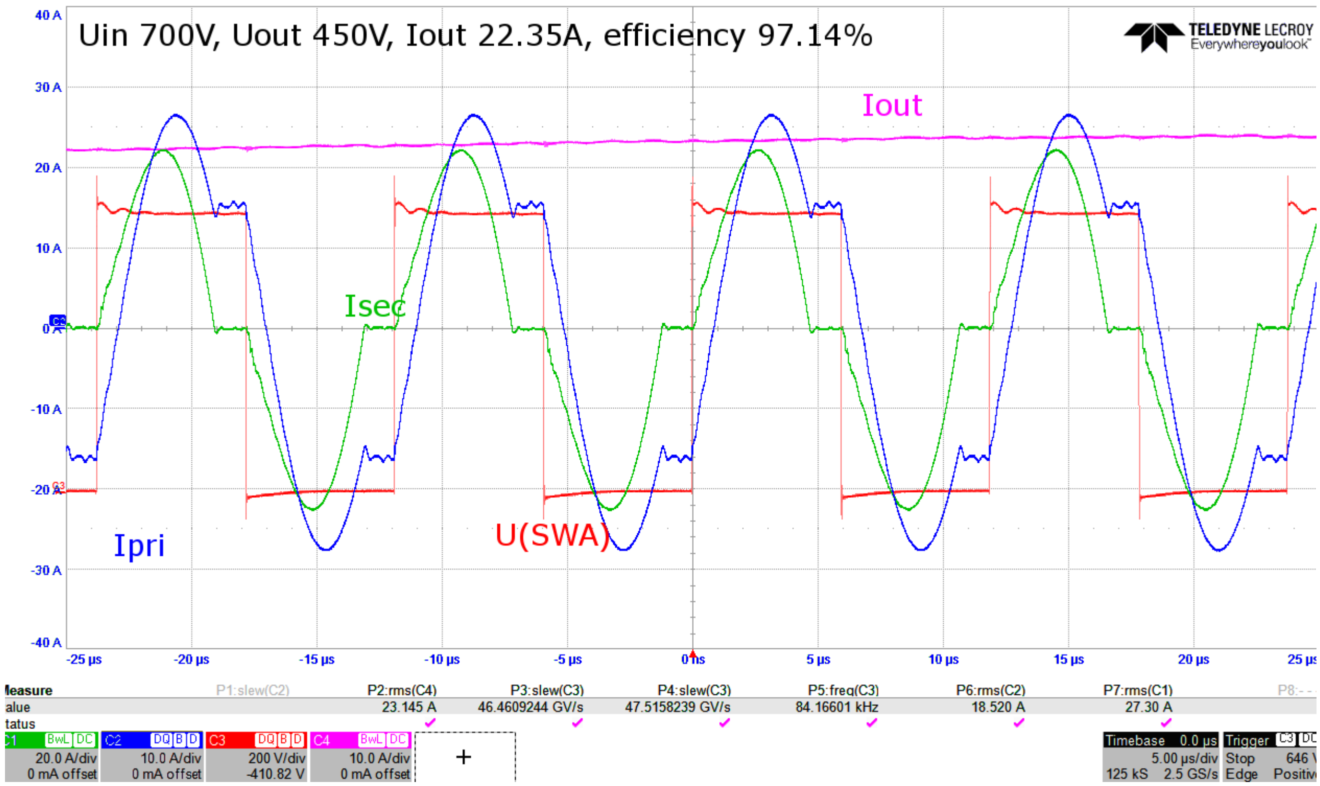


Figure 60. Converter Operating Waveforms – 700 V to 450 V, Load Current 22.35 A (10 kW)

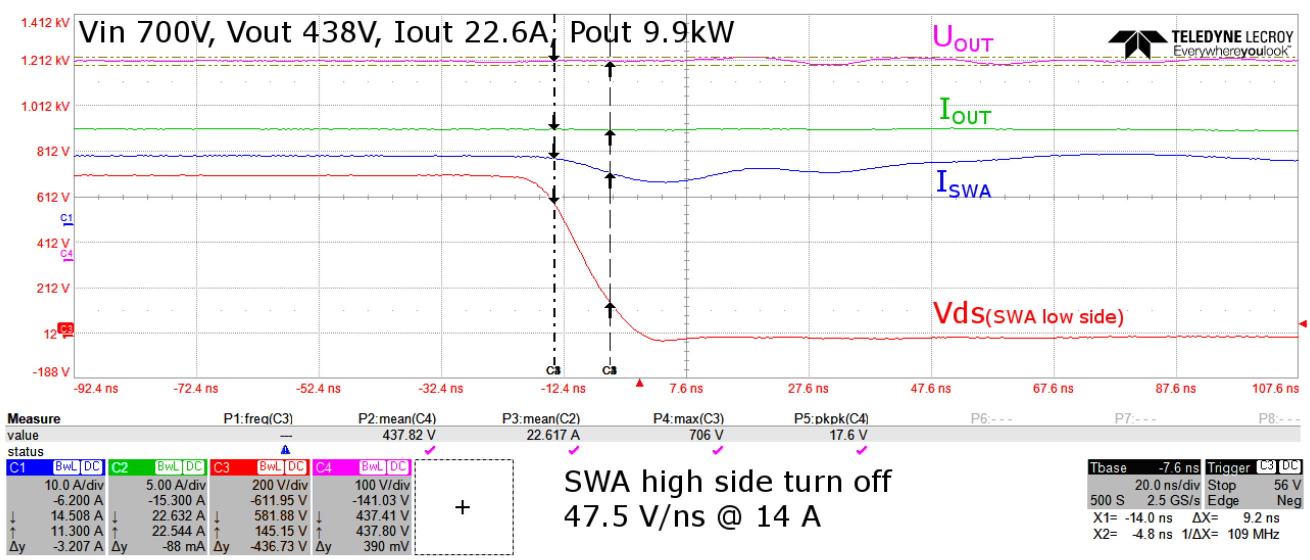


Figure 61. SWAHalf Bridge High Side Turn Off

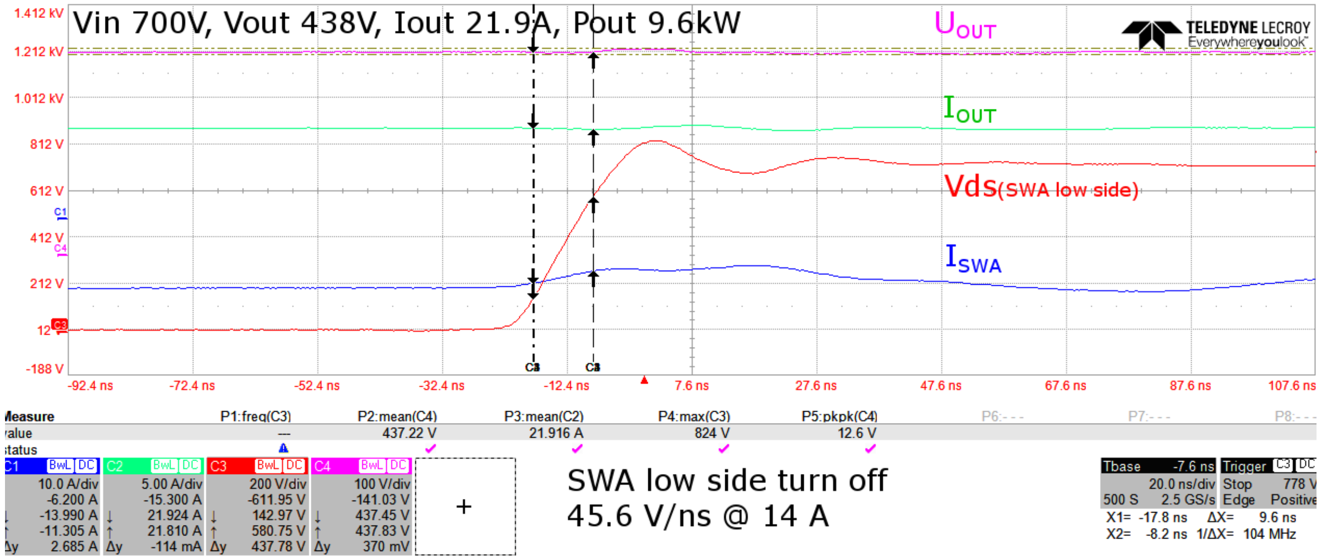


Figure 62. SWA Half Bridge Low Side Turn Off

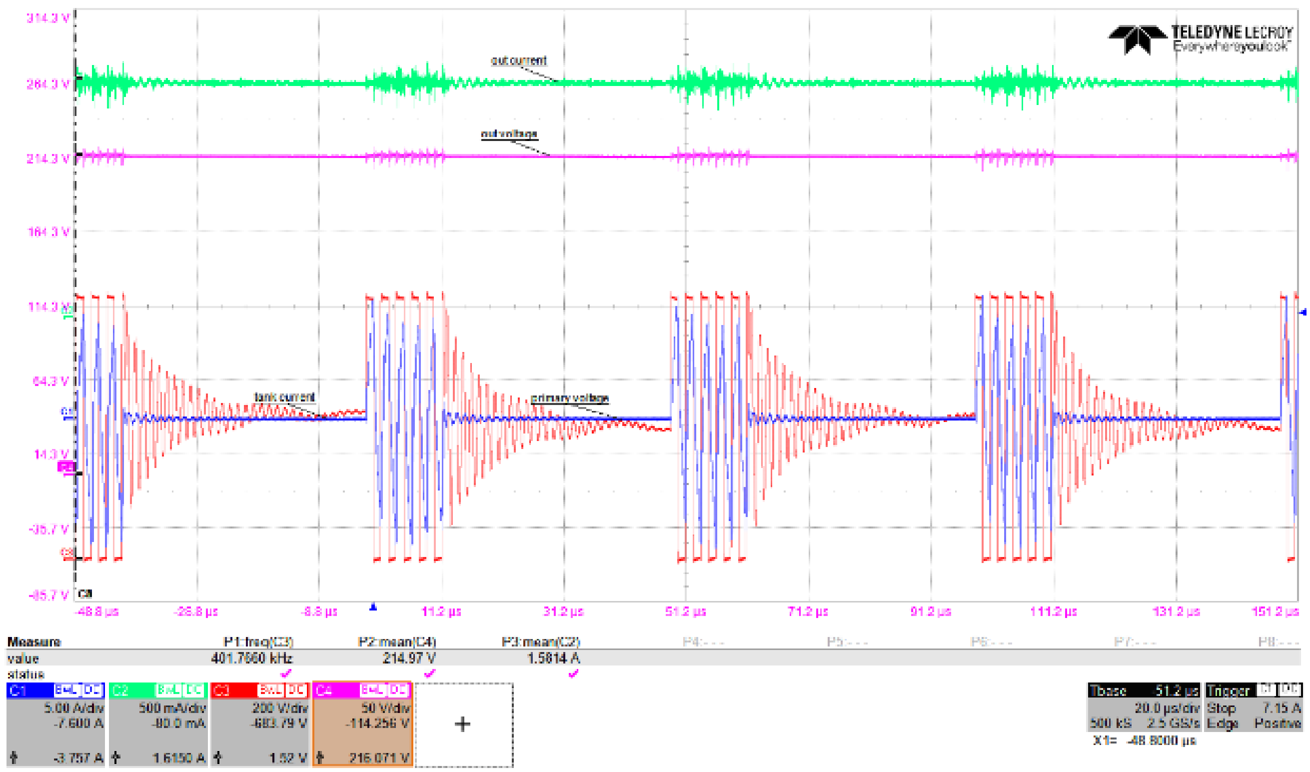


Figure 63. Skip Mode Operation − Input Voltage 700 V, Output Voltage 210 V, Load 136 Ω

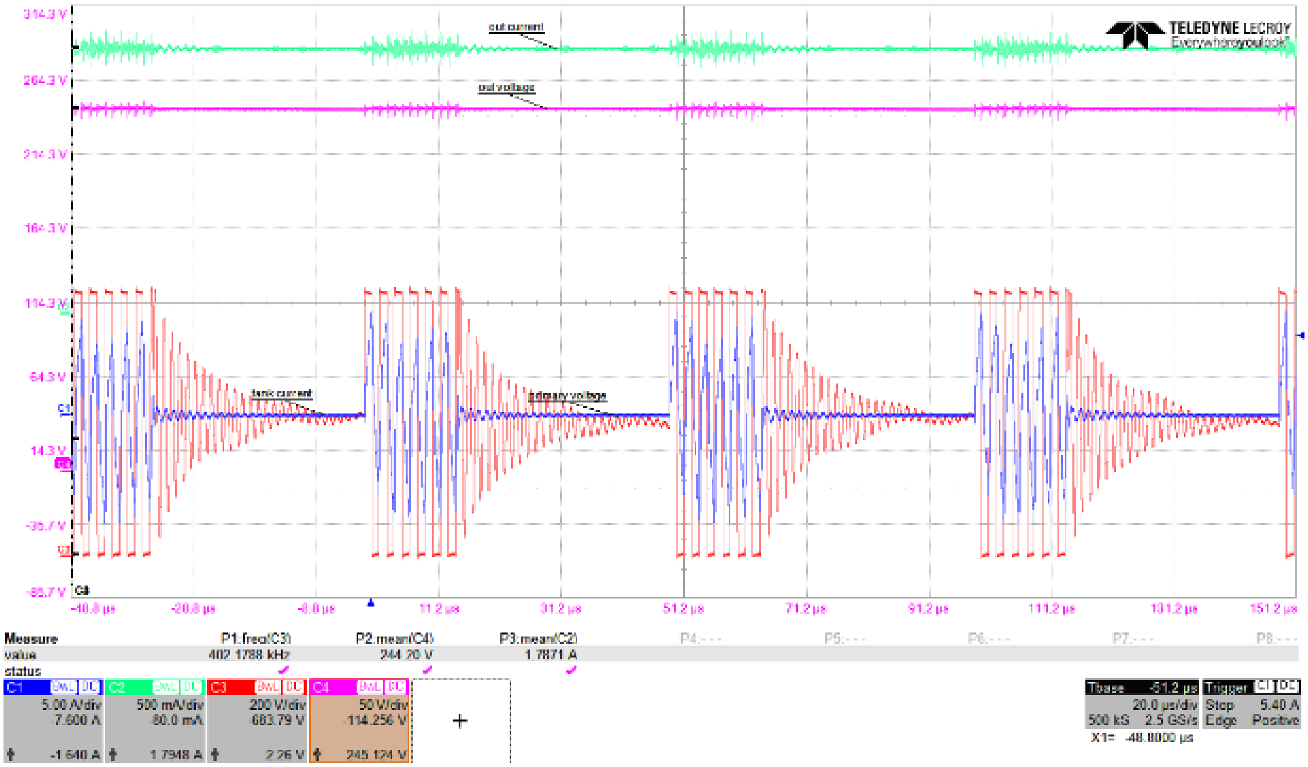


Figure 64. Skip Mode Operation − Input Voltage 700 V, Output Voltage 250 V, Load 136 Ω

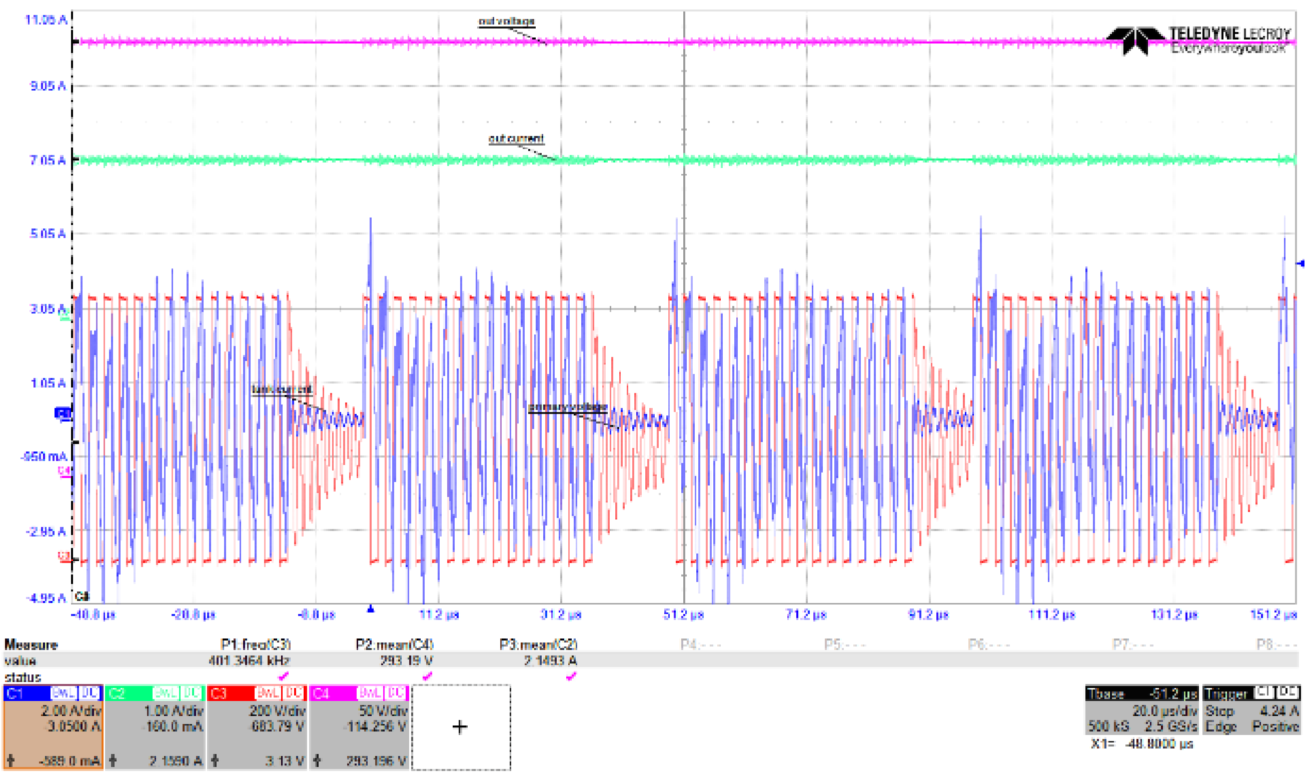


Figure 65. Skip Mode Operation − Input Voltage 700 V, Output Voltage 300 V, Load 136 Ω

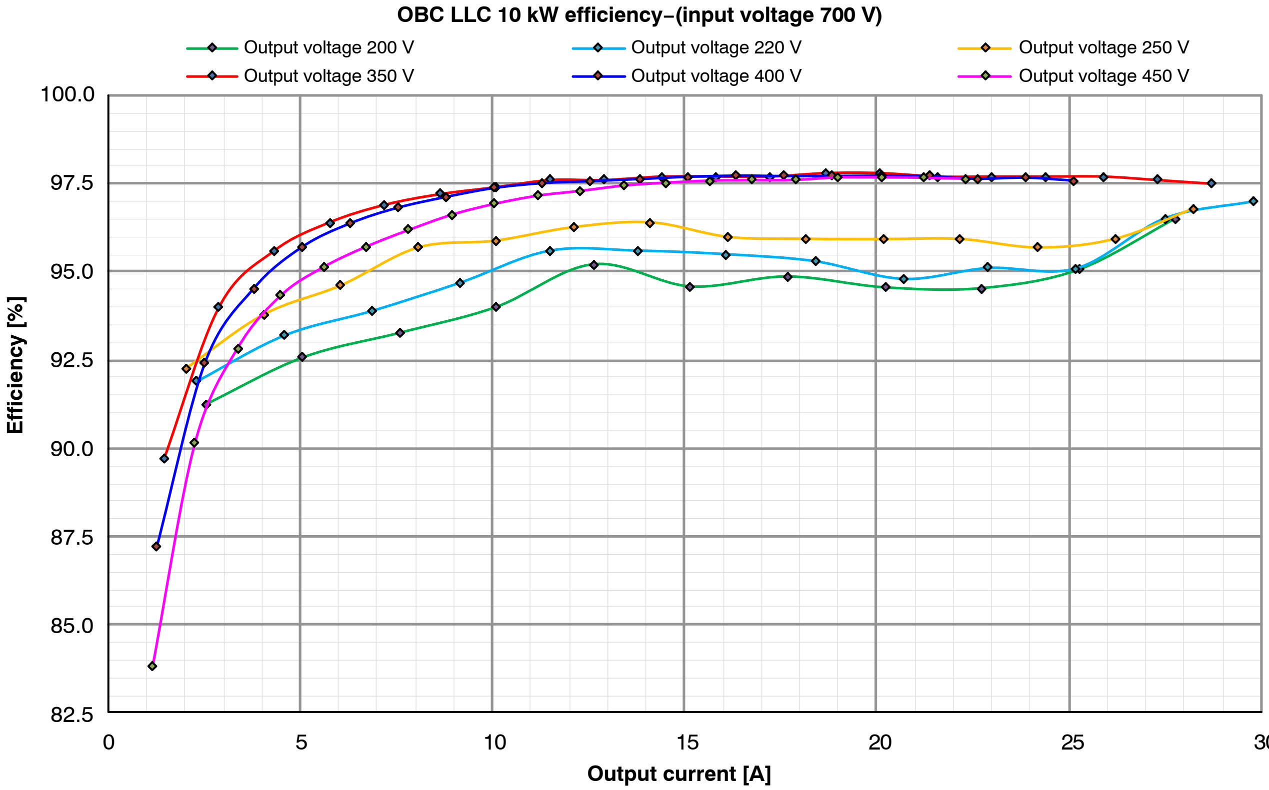


Figure 66. Measured Efficiency vs. Load Current – Overview

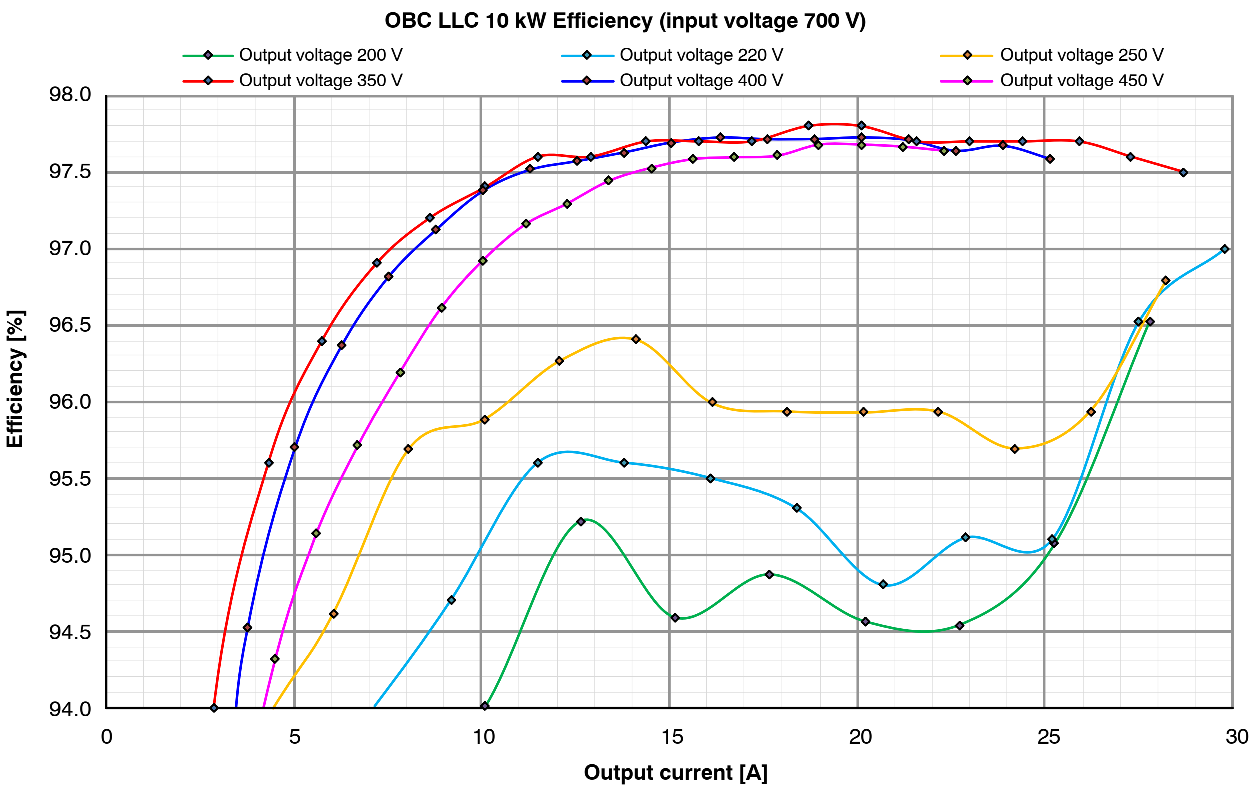


Figure 67. Measured Efficiency vs. Load Current – Detail

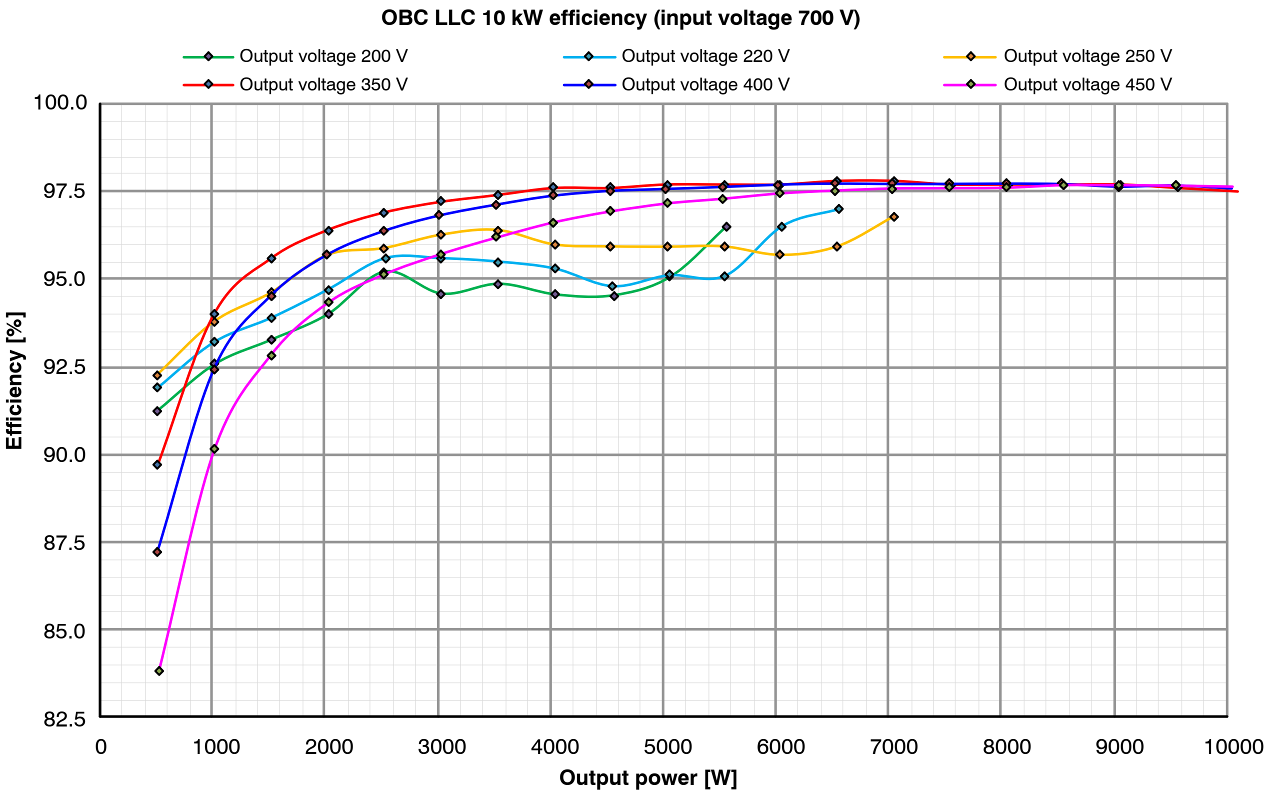


Figure 68. Measured Efficiency vs. Output Power – Overview

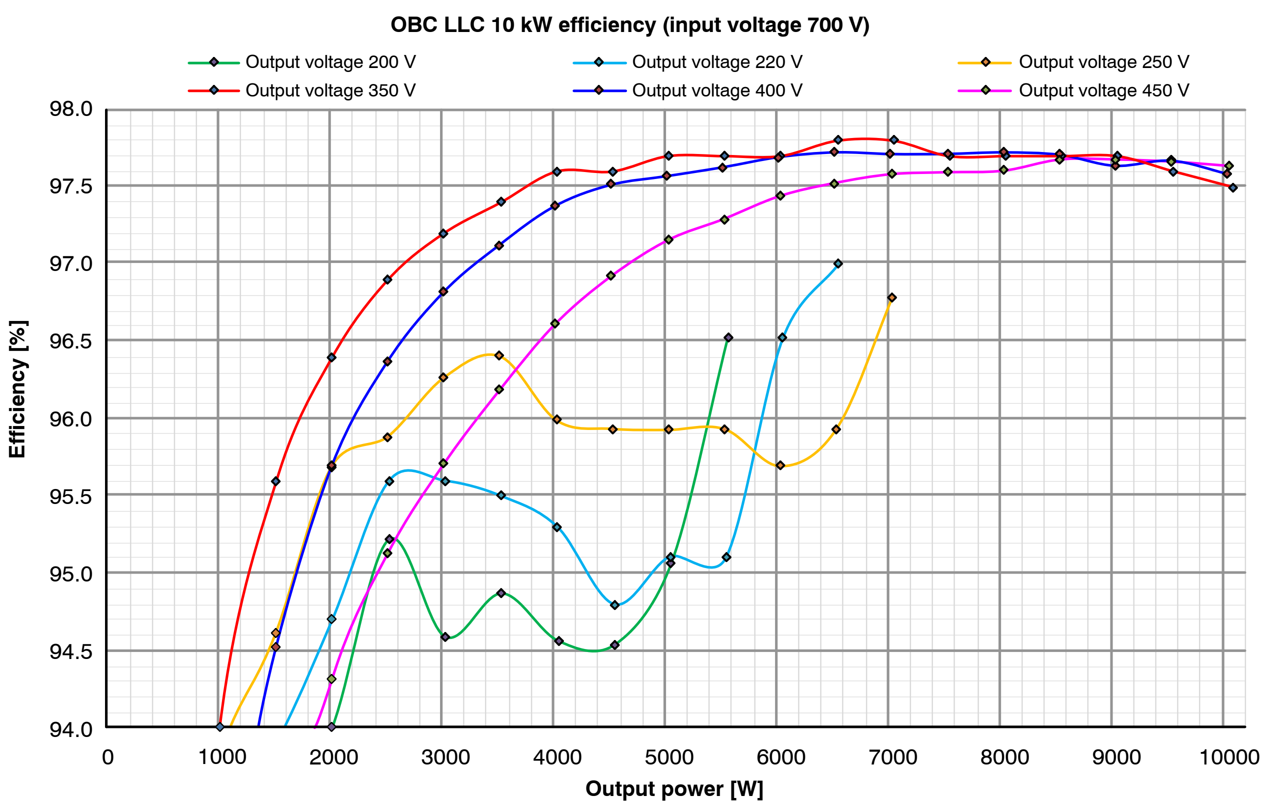


Figure 69. Measured Efficiency vs. Output Power – Detail

References

[1]. Junjun Deng, Siqi Li, Sideng Hu, Chunting Chris Mi, Ruiqing Ma *"Design Methodology of LLC Resonant Converters for Electric Vehicle Battery Chargers"* published in IEEE Transactions on Vehicular Technology, Volume 63, Issue 4, May 2014.

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