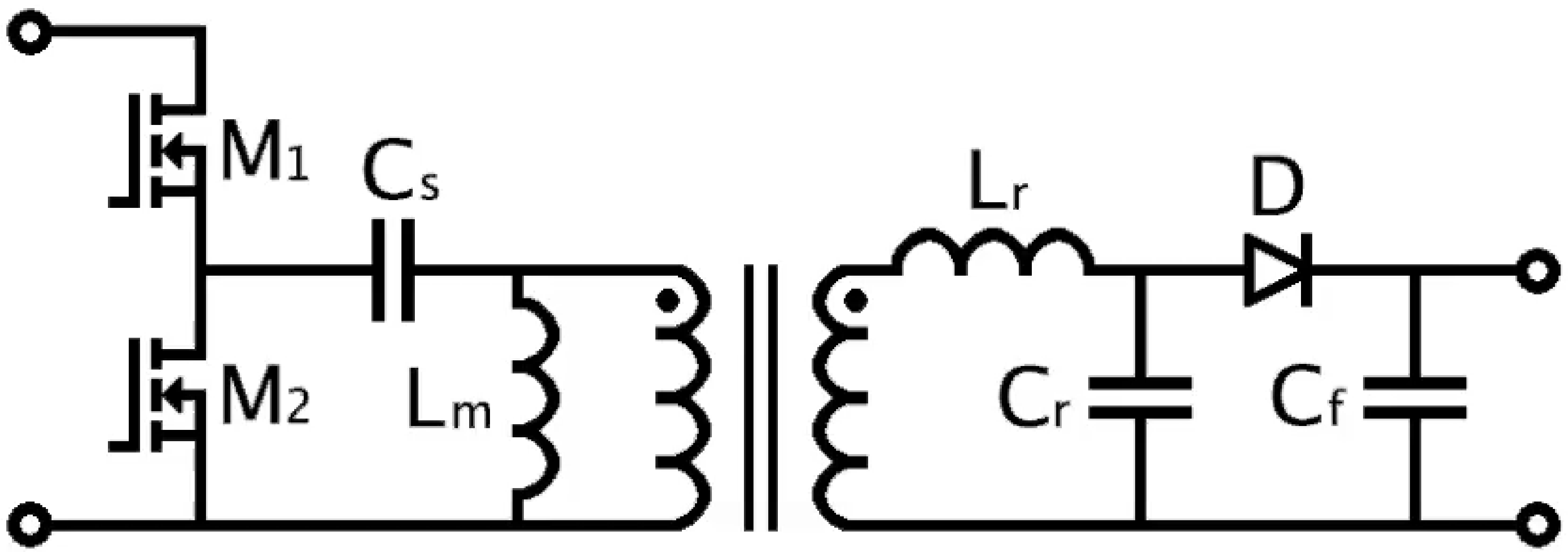
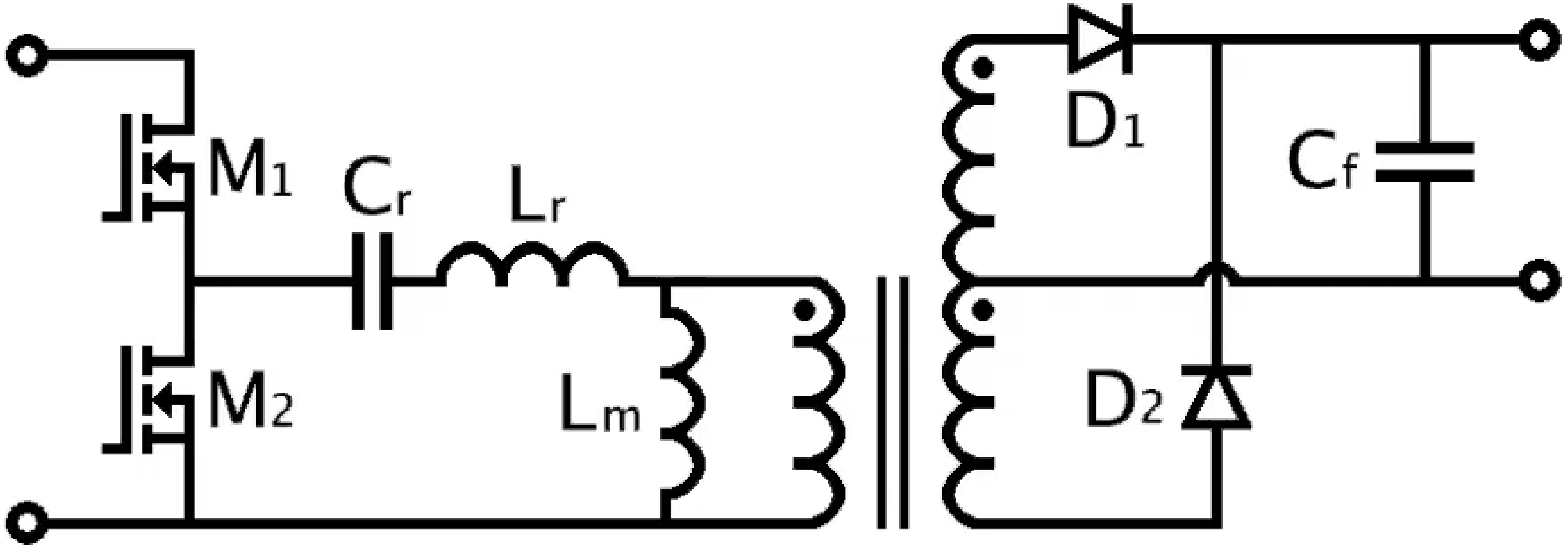
The Pe17 Circuit



vs.

The LLC Circuit



Comparison of the Pe17 circuit and the LLC resonant circuit for power supply DC-DC convertion.

Created by: Tal Abramovici

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-> 1. DC-DC Converter Stage

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2. Comparison

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Synchronous Rectification

3. Further Advantages

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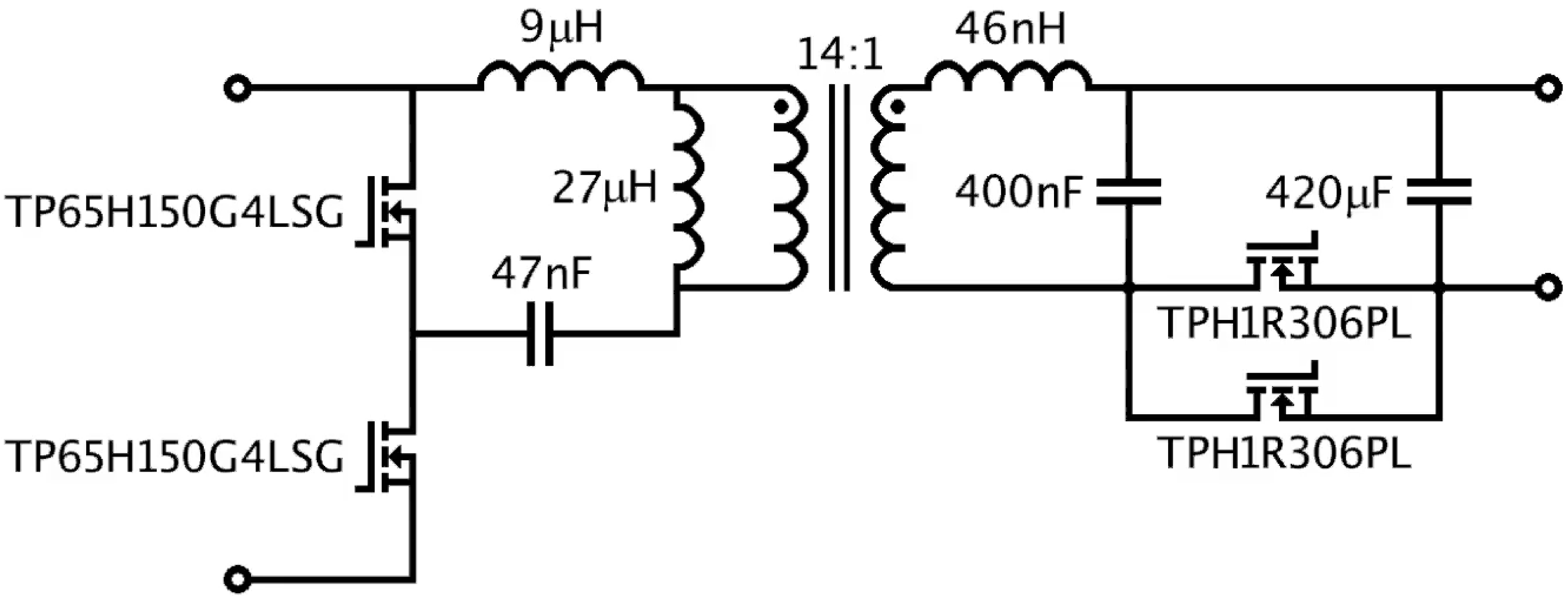
Specifications

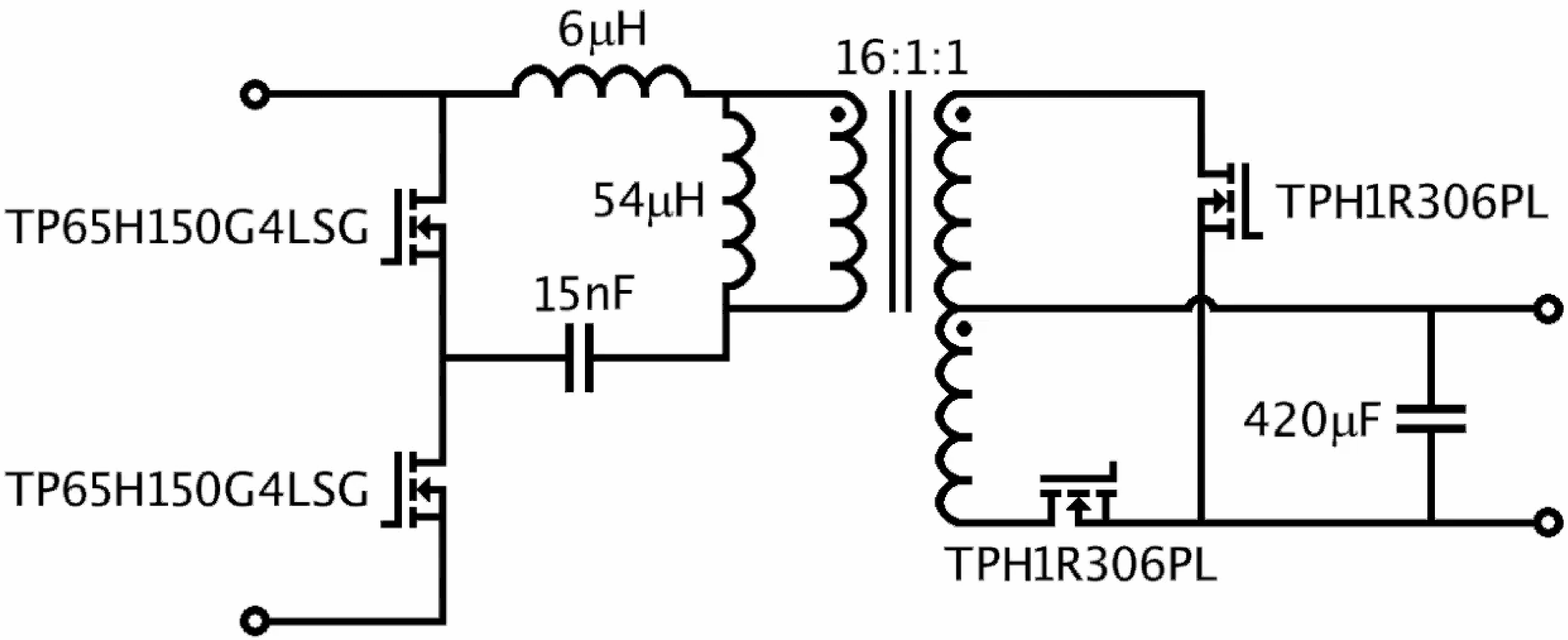
The input voltage is 380 V, as typically provided from a PFC stage.
The DC-DC converter outputs 500 W of power at a voltage of 12 V.
For a high power density design, the switching frequency is set at 500 kHz.

Circuit Implementation



The schematic above represents the implementation of the DC-DC converter with the Pe17 circuit. 650V GaNFETs are used for the half bridge inverter, while two 60V MOSFETs are connected in parallel as synchronous rectifiers. The resonant inductors are integrated with the transformer. All of the capacitors are assumed to be loseless.

Circuit Implementation



The schematic above is the implementation of the DC-DC converter with the LLC resonant circuit. The same GaNFETs and MOSFETs are used for the half bridge inverter and the synchronous rectifiers. In order to reduce the overshoot of the reverse voltage across the synchronous rectifiers, the resonant inductor is external and the transformer avoids leakage inductance.

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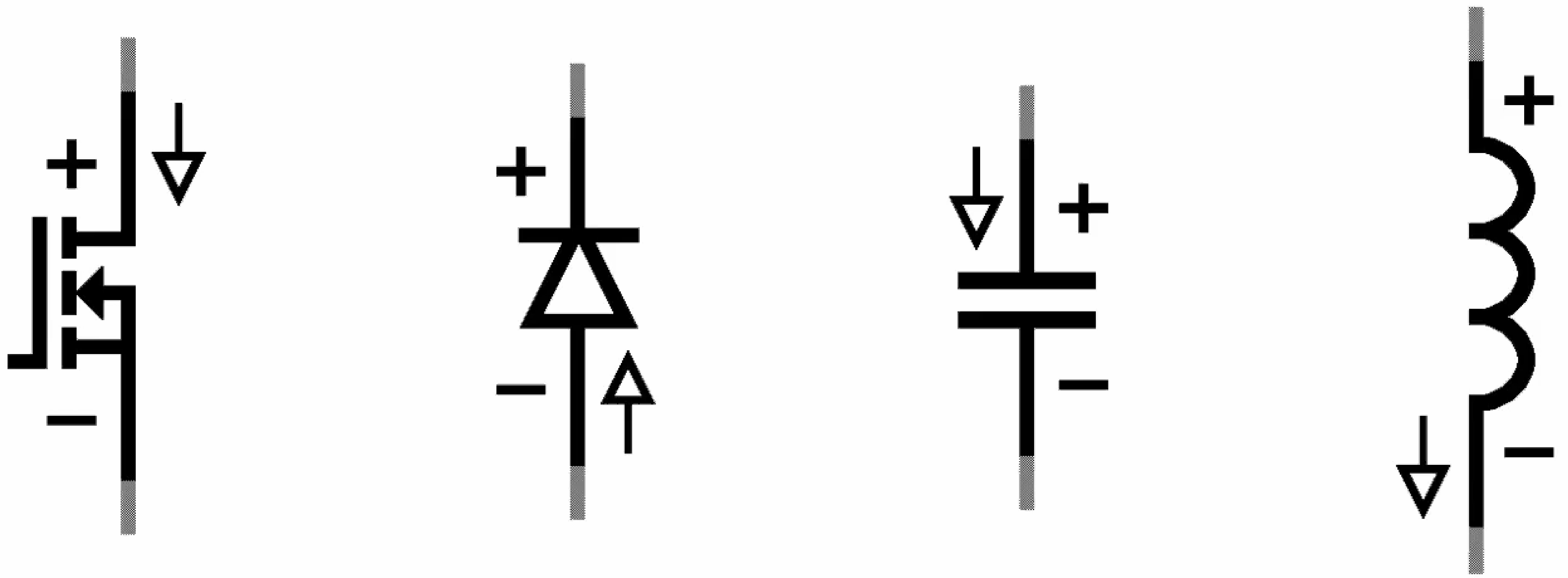
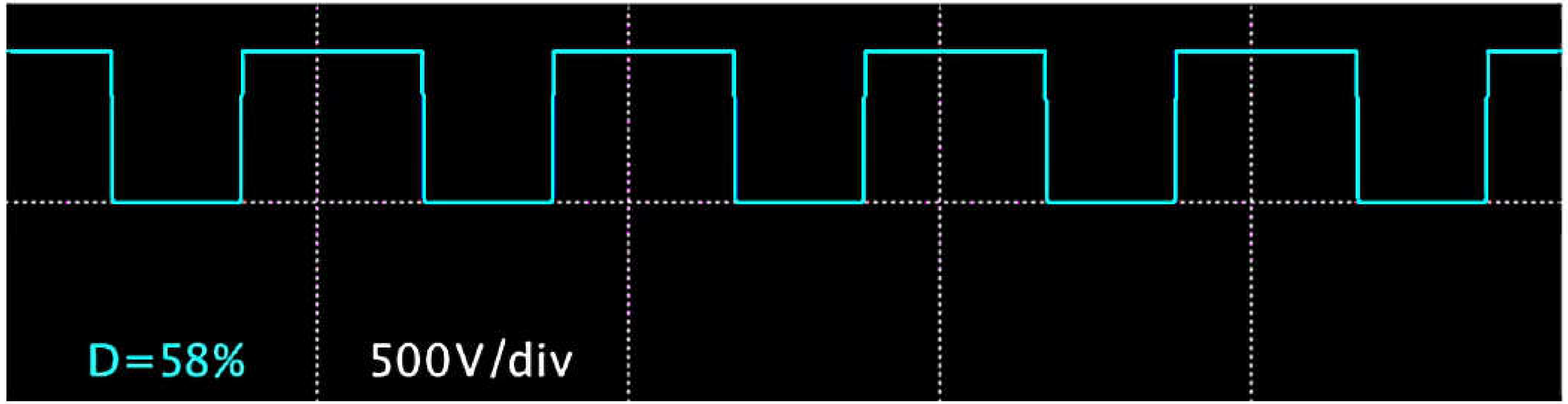
Component Stresses



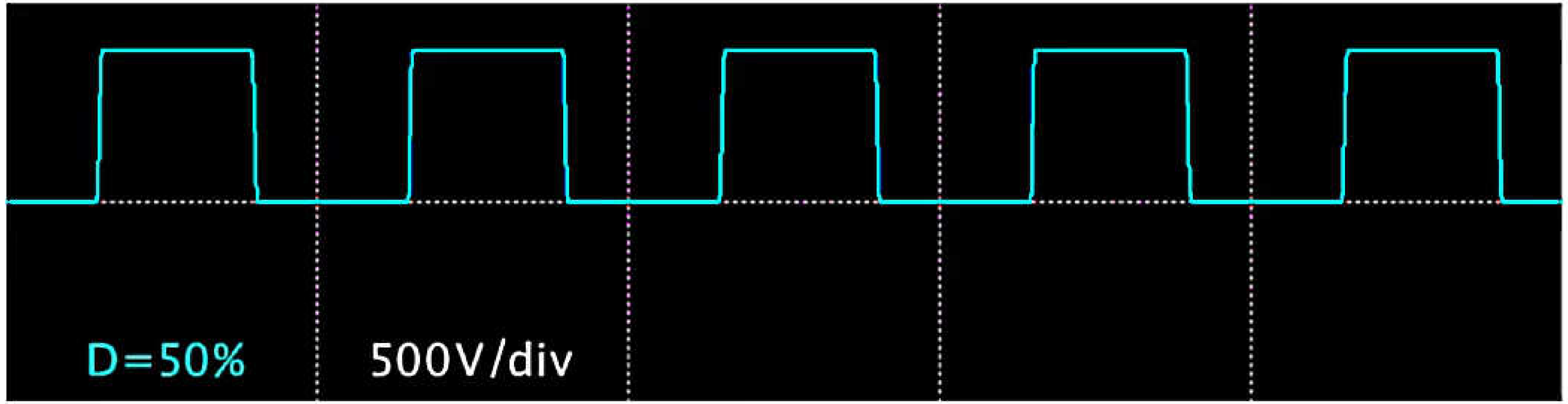
The voltages and currents depicted in the following graphs are based on simulations made with the Spice program.

Component Stresses

Pe17 Circuit



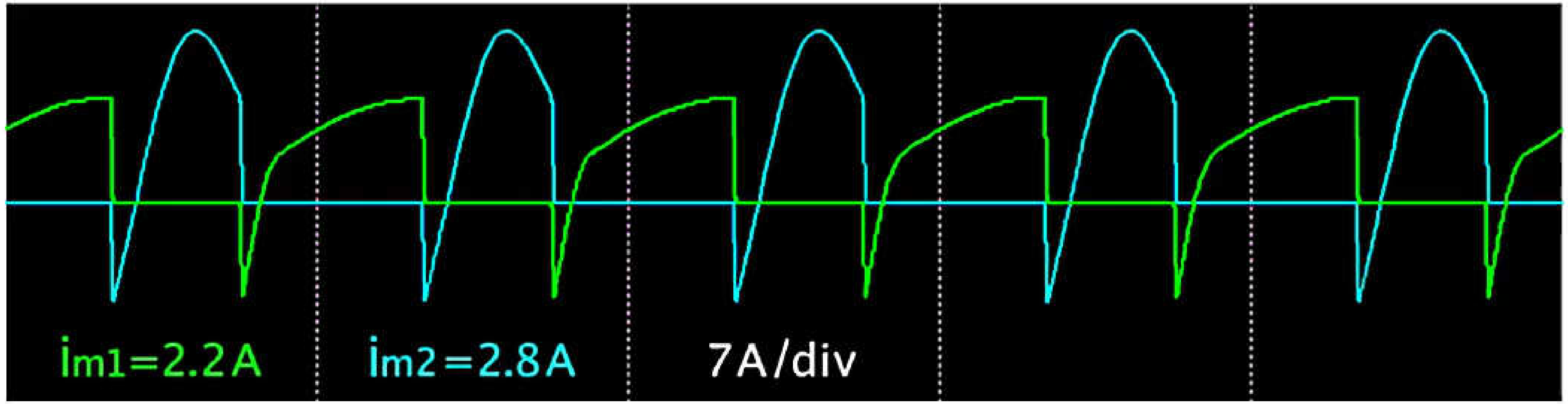
LLC Circuit



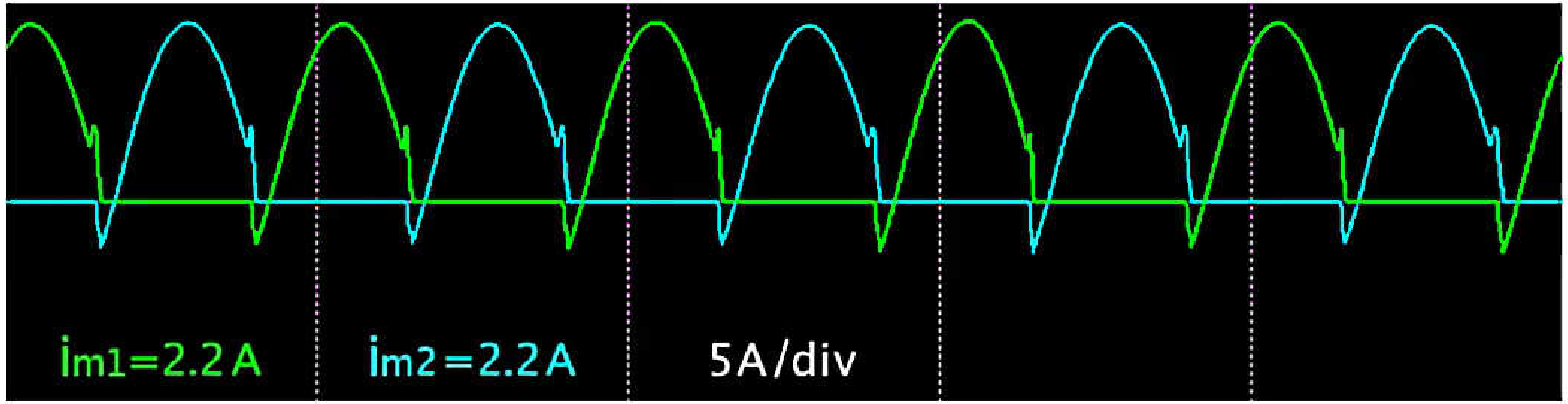
In the Pe17 circuit, the half bridge inverter outputs a pulse wave voltage with a duty cycle of 58%.
In the LLC resonant circuit, the half bridge inverter outputs a pulse wave voltage with a duty cycle of 50%.

Component Stresses

Pe17 Circuit



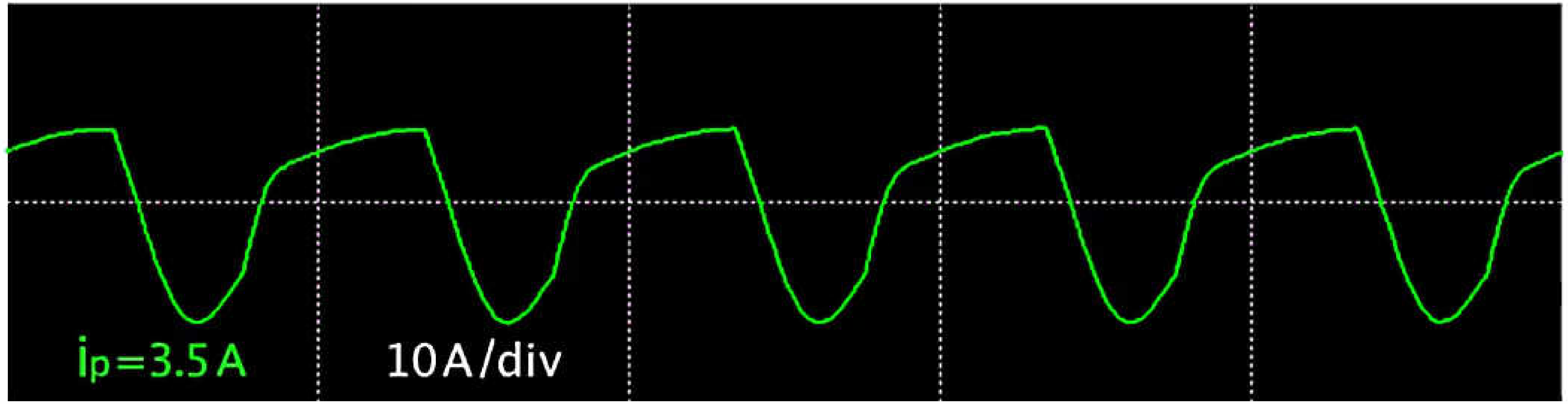
LLC Circuit



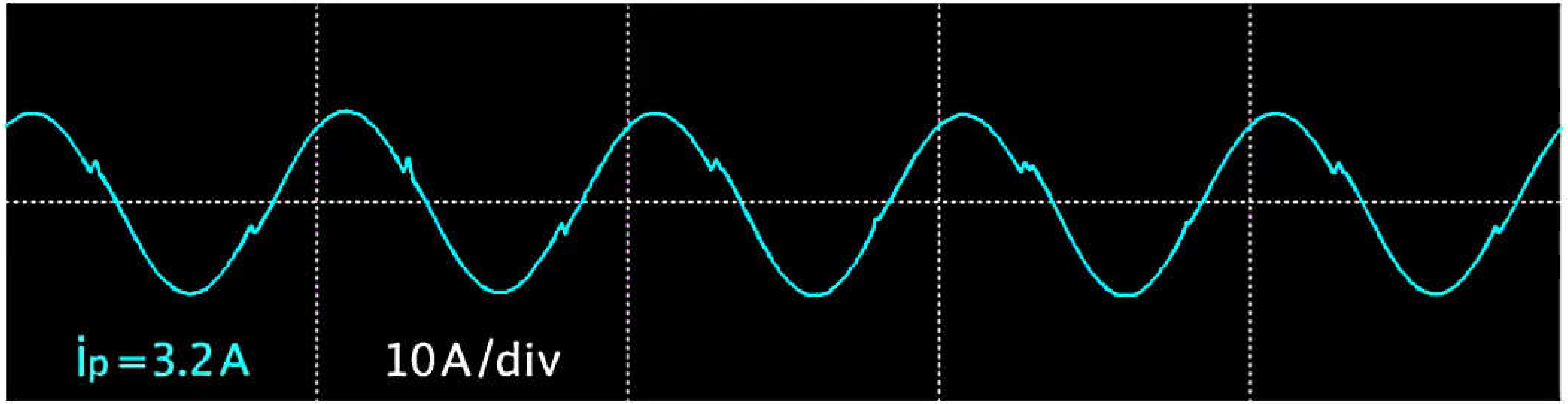
In the Pe17 circuit, the current through the top half bridge GaNFET is 2.2 Arms and its loss is 0.7 W, while the current through the bottom GaNFET is 2.8 Arms and its loss amounts to 1.2 W.
In the LLC circuit, the current through each GaNFET is 2.2 Arms, and thus both wastes 0.7 W each.

Component Stresses

Pe17 Circuit



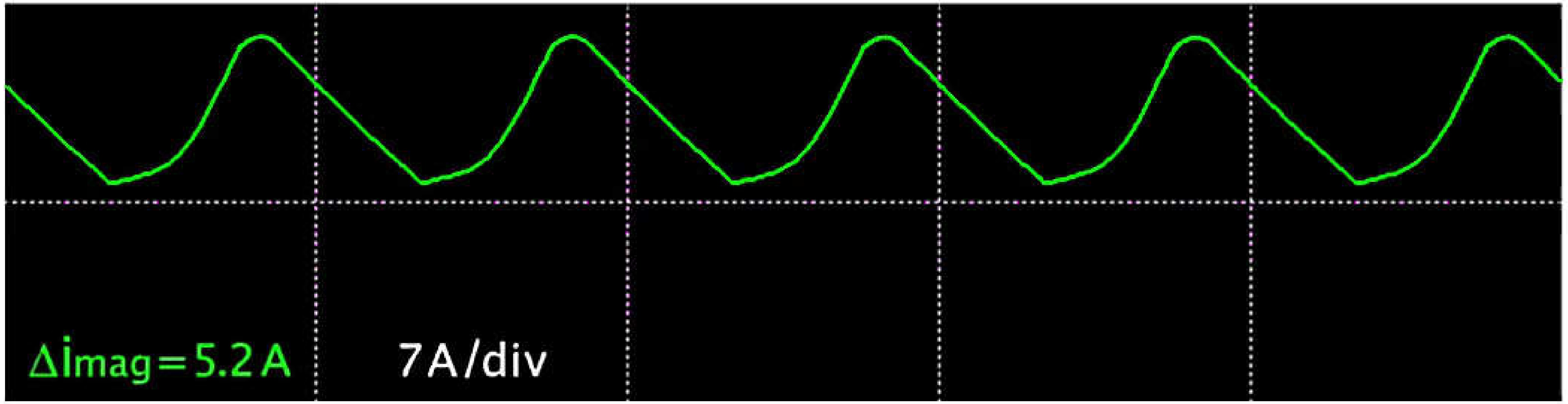
LLC Circuit



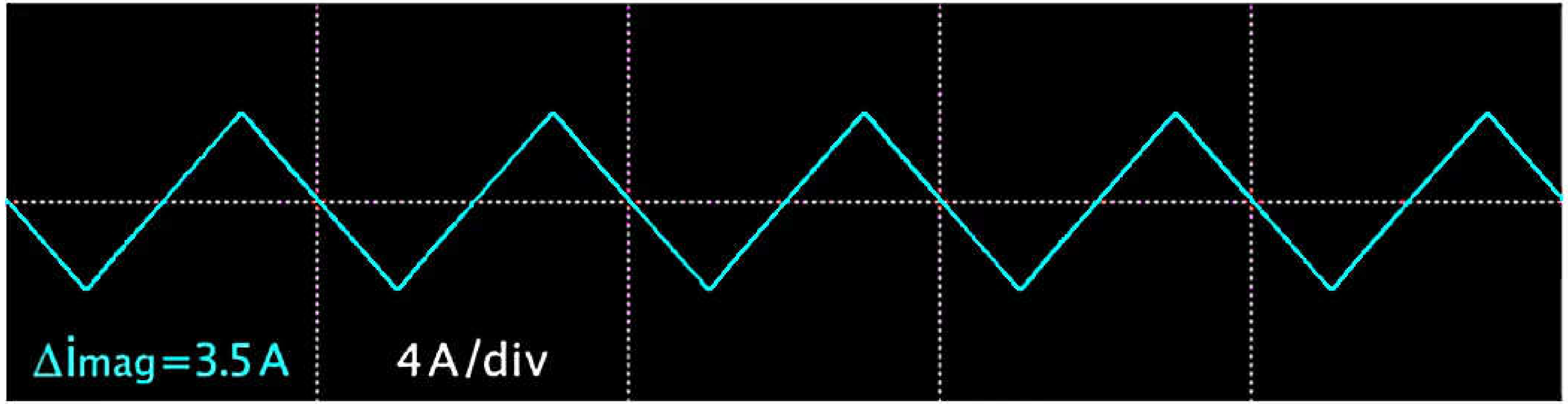
In the Pe17 circuit, the primary current through the DC blocking capacitor is 3.5 Arms.
In the LLC resonant circuit, the primary current through the resonant capacitor is 3.2 Arms.

Component Stresses

Pe17 Circuit



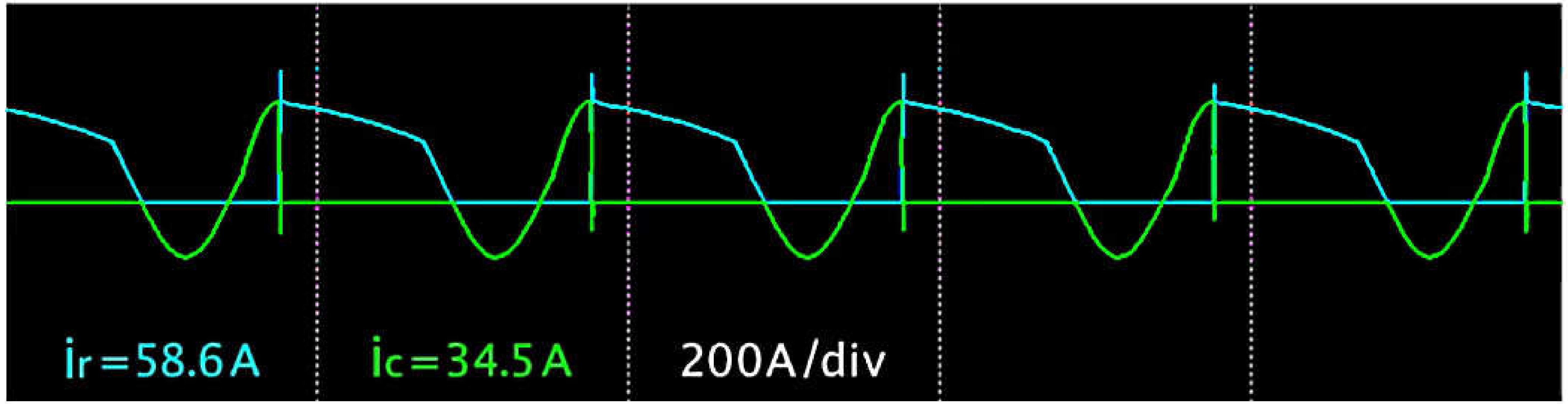
LLC Circuit



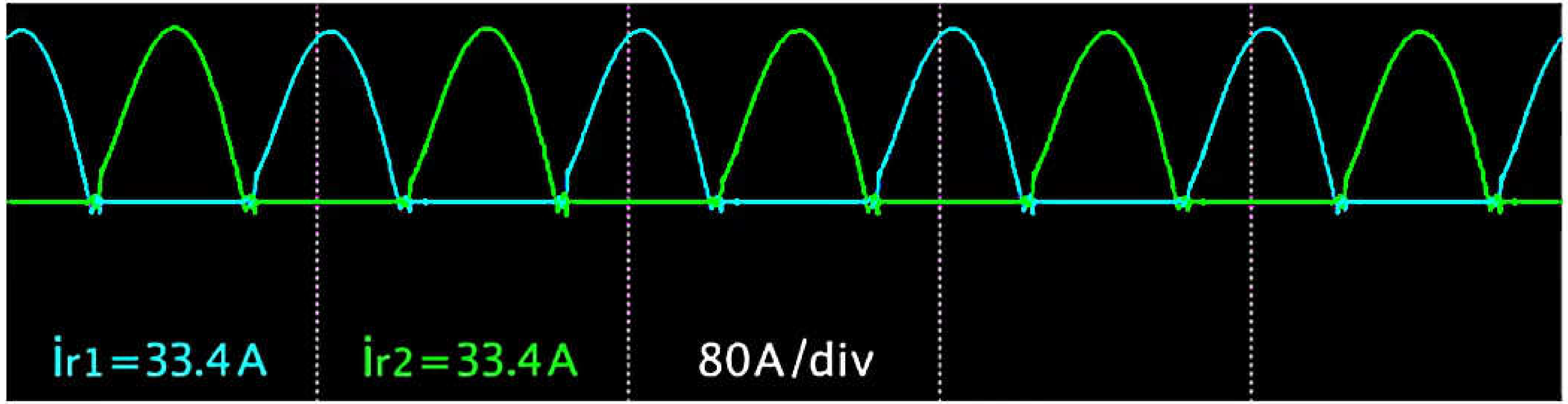
In the Pe17 circuit, the peak to peak current through the magnetizing inductance is 5.2 A. Thus, the magnetic flux through 14 turns of the primary winding is 10 μWb. In the LLC circuit, the peak to peak current through the magnetizing inductance is 3.5 A and the magnetic flux through 16 turns of the primary winding is 12 μWb.

Component Stresses

Pe17 Circuit

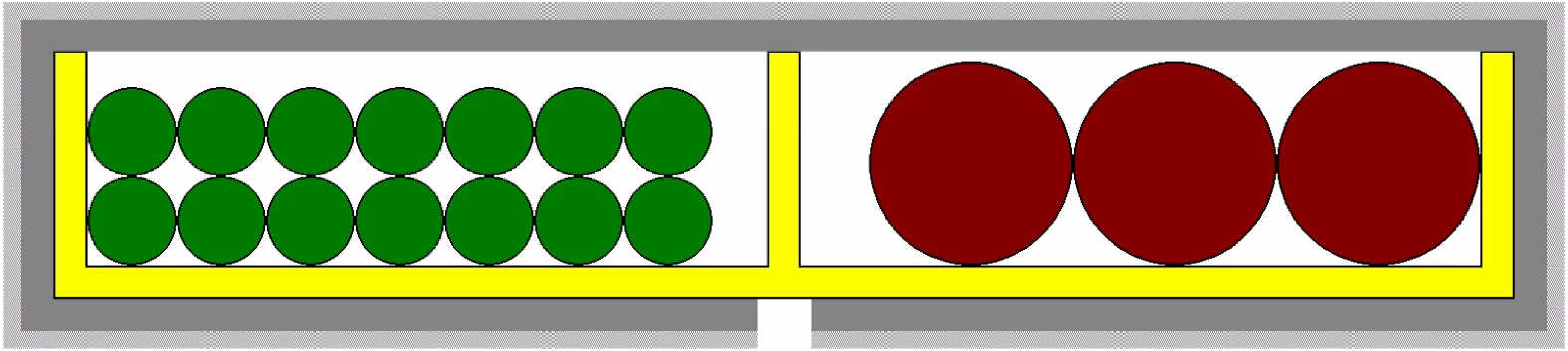


LLC Circuit



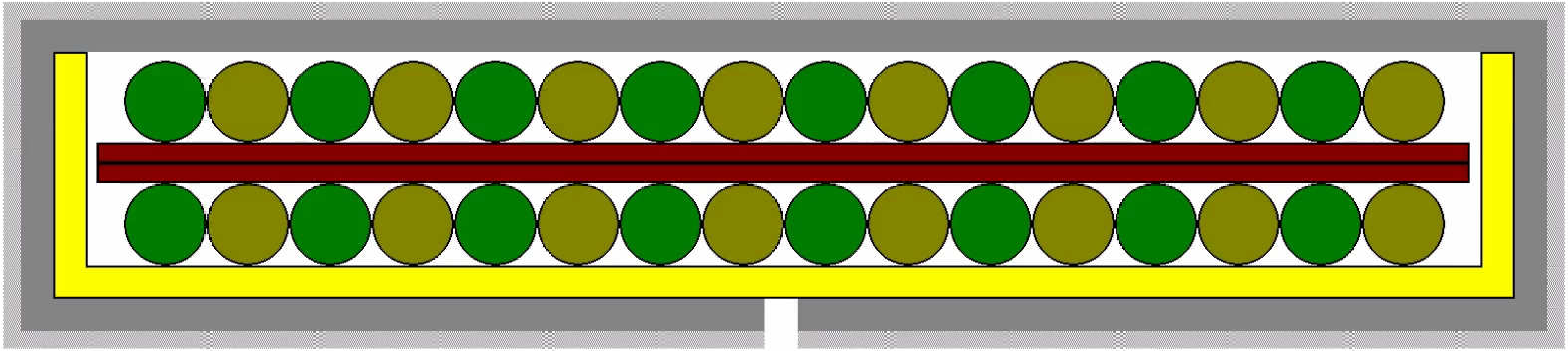
In the Pe17 circuit, the two synchronous rectifiers share a current of 58.6 Arms. The current through the resonant capacitor is 34.5 Arms. Thus, the total current through the secondary winding is 68.1 Arms.
In the LLC circuit, the current through each secondary winding and each synchronous rectifier is 33.4 Arms.

Magnetic Components



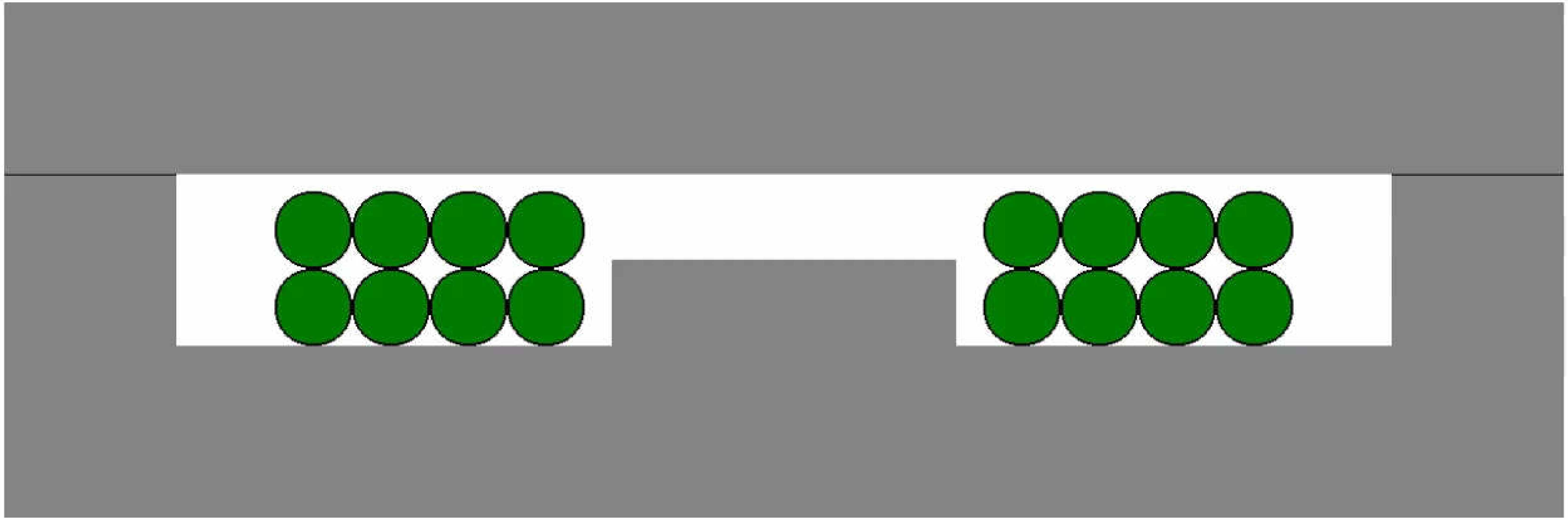
The following figure shows the structure of the transformer in the Pe17 circuit. The geometry and size of the core is that of EFD30/15/9, having a center leg area of 69 µm^2. The magnetic core is assumed to be made from the TP5 ferrite material or equivalent. The air-gap in the center leg is 0.8 mm. The primary and the secondary windings are wound side by side and isolated from each other by a split-section bobbin. The primary winding consists of 14 turns of litz wire having a diameter of 1.3 mm. The secondary winding consists of three parallel litz wires, each having a single turn and a diameter of 3 mm. The expected leakage inductance is approximately 20 µH, and can be fine-tuned by adjusting the gap between the windings. With a flux density swing of 145 mT, the core loss is estimated at 1.3 W. The resistance of the primary winding is 22 mOhm, and its loss is 300 mW. The resistance of the secondary winding is 130 µOhm, and its loss is 600 mW.

Magnetic Components



The following figure shows the structure of the transformer in the LLC resonant circuit. The magnetic core and its size are the same as that of the transformer in the Pe17 circuit. The air-gap in the center leg is 0.5 mm. The primary winding is interleaved on the bottom and the top, while the two secondery windings are sandwiched in-between. The primary winding consists of two parallel litz wires, each having 16 turns and a diameter of 1.2 mm. The secondary windings consist of a copper foil, each having a single turn with a width of 20 mm and a thickness of 250 μm. The terminations of the secondary windings are 5 mm in width and 5 mm in length. With a flux density swing of 174 mT, the core loss is estimated at 2.2 W. The resistance of the primary winding is 22 mOhm, and its loss is 200 mW. The DC resistance of each secondary winding is 250 μOhm, but their AC resistance is estimated at 800 μOhm. Thus, the loss of the secondary windings amounts to 1.3 W.

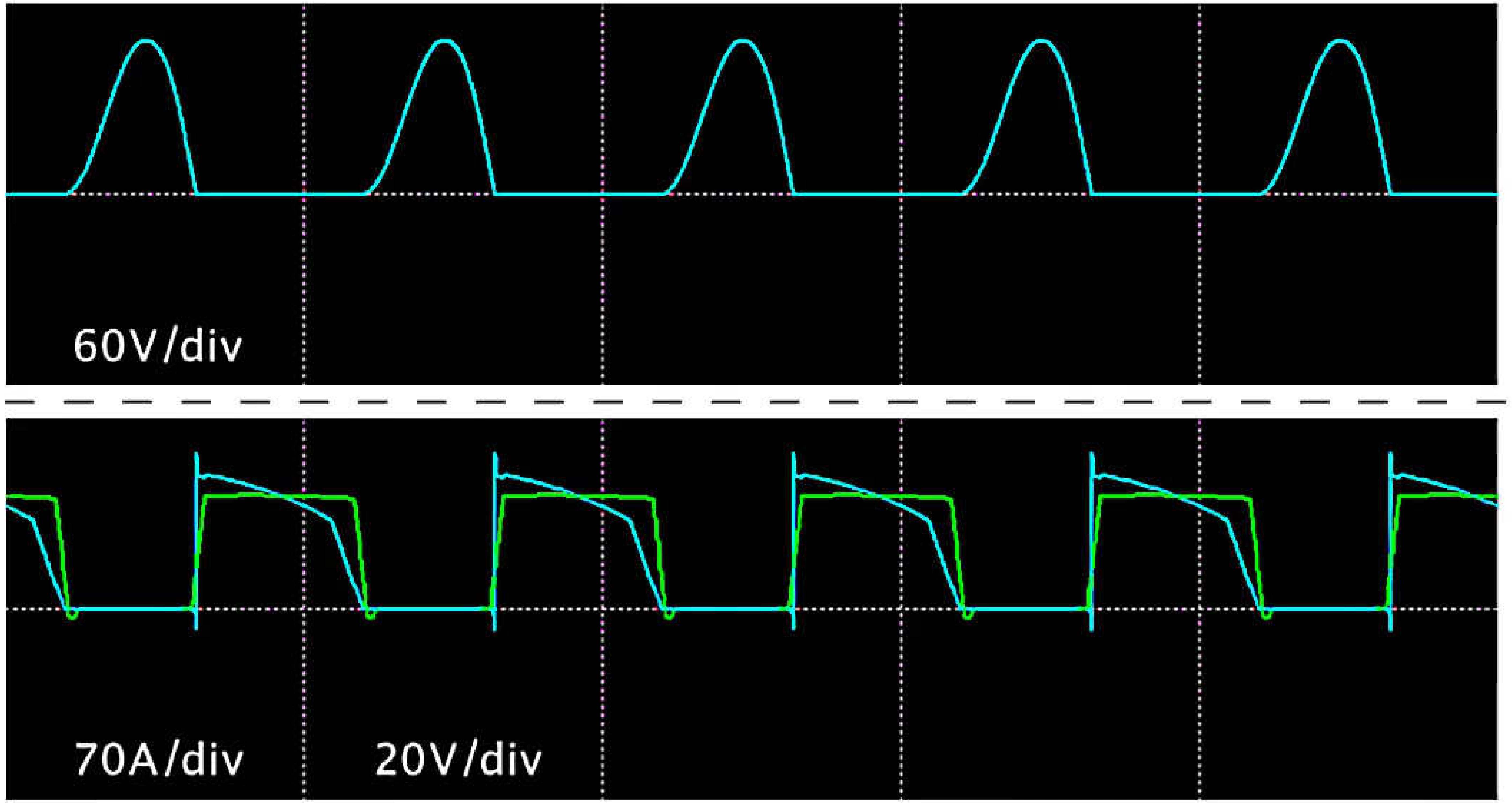
Magnetic Components



The following figure shows the structure of the inductor in the resonant LLC circuit. The geometry of the magnetic core is that of a planar ER18/3/10, with a center leg area of 39 μm^2. The air-gap in the center leg is 1 mm. The winding consists of 8 turns of litz wire having a diameter of 0.9 mm. With a flux density swing of 170 mT, the core loss is 400 mW. The winding's resistance is 24 mOhm, and its loss is 200 mW.

Synchronous Rectification

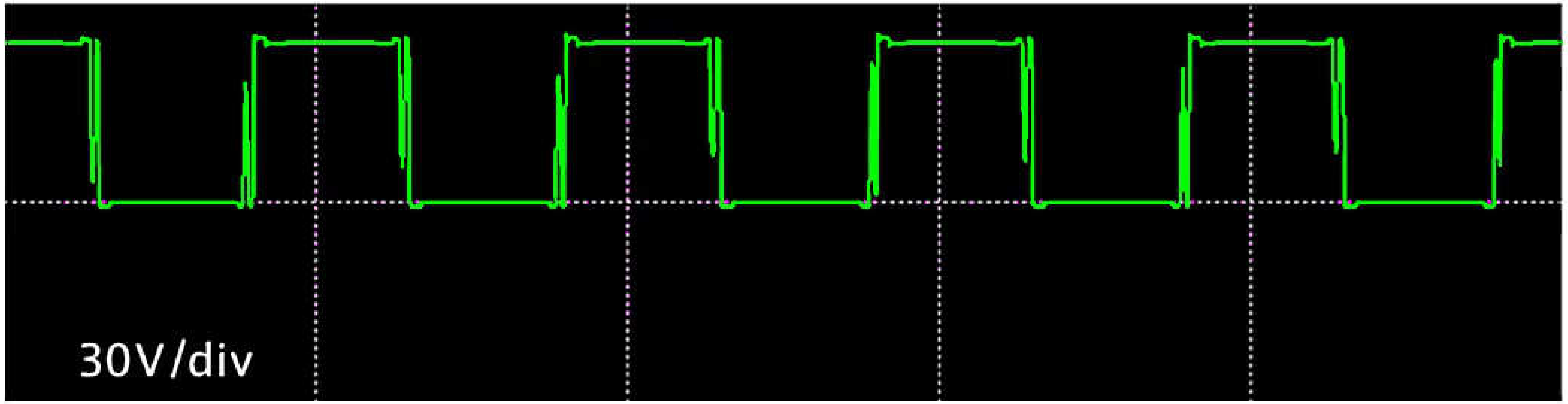
Pe17 Circuit

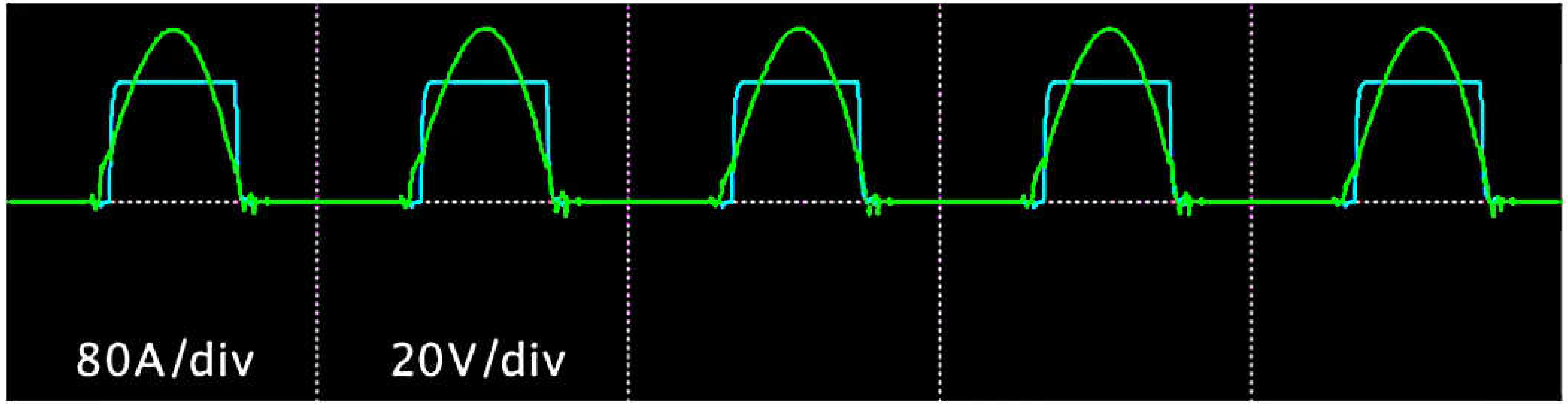


In the Pe17 circuit, one gate driver is required for activating the synchronous MOSFETs. The peak reverse voltage is 48 V at full load, and gets lower as the load decreases. The synchronous MOSFETs are turned on just before zero-crossing of the reverse voltage. The turn-off transition occurs at the zero-crossing of the current. Each MOSFET wastes 1 W due to their on-resistance. Thus, the power loss in the synchronous rectification amounts to 2 W.

Synchronous Rectification

LLC Circuit

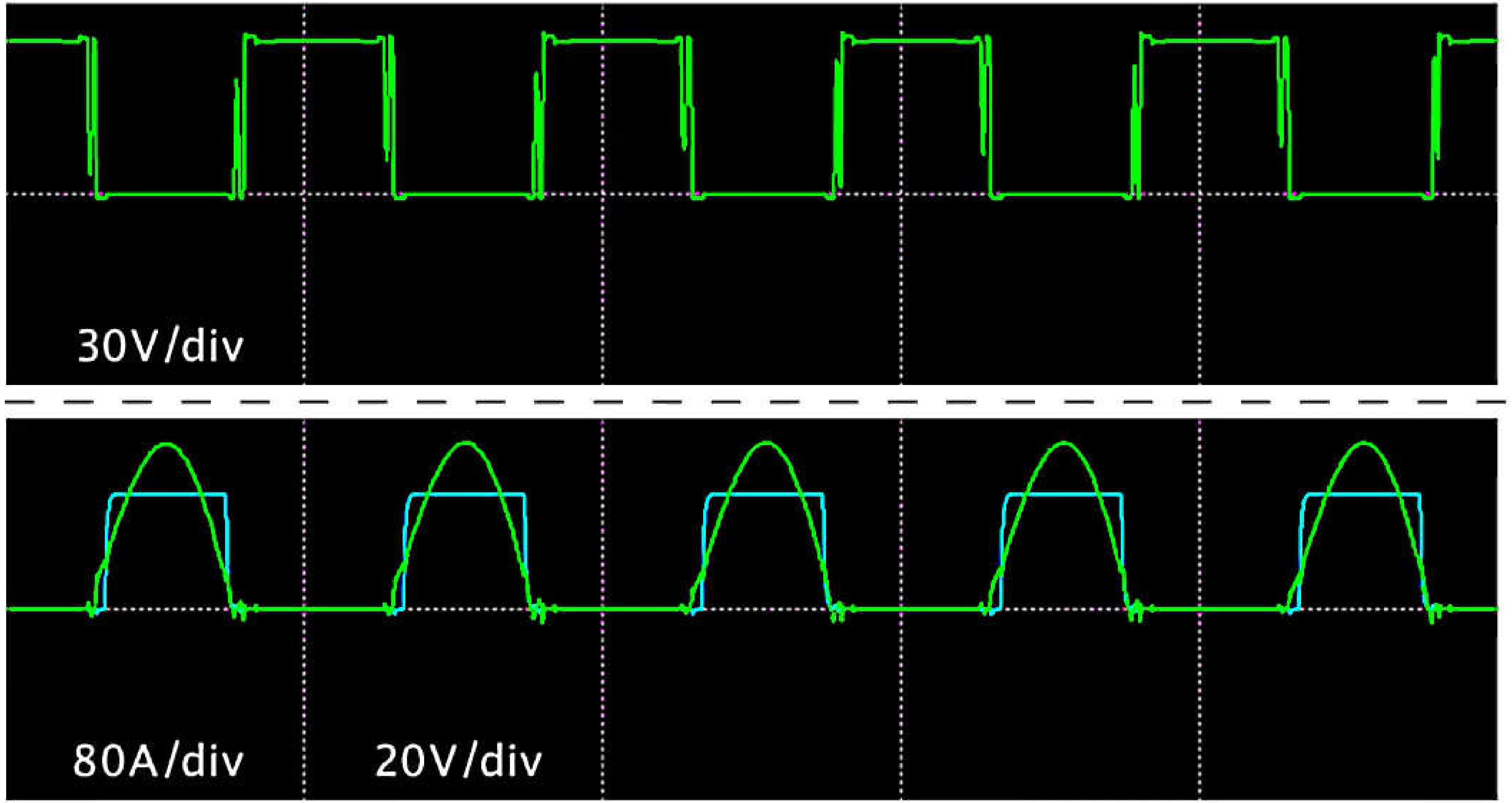




In the LLC resonant circuit, two gate drivers are required for activating the synchronous MOSFETs. When the LLC circuit is operating at input voltage of 380 V, the reverse voltages across the synchronous MOSFETs peak at about twice the output voltage. However, when the input voltage increases by 5 V, the synchronous MOSFETs lose ZCS condition and the reverse voltages become elevated due to ringing and overshoot, caused by parasitic inductances and reverse recovery currents.

Synchronous Rectification

LLC Circuit



In order to prevent a short circuit situation, each synchronous MOSFET is turned on after conduction begins, and turned off before its current reaches 0 A. Due to propagation delays from the controller and the gate driver, the turn-on transition occurs after about 70 ns. These delays create dead-time intervals during which the inherent body diodes of the synchronous MOSFETs conduct. Thus, each MOSFET wastes 1.7 W, and the total power loss in the synchronous rectification amounts to 3.4 W.

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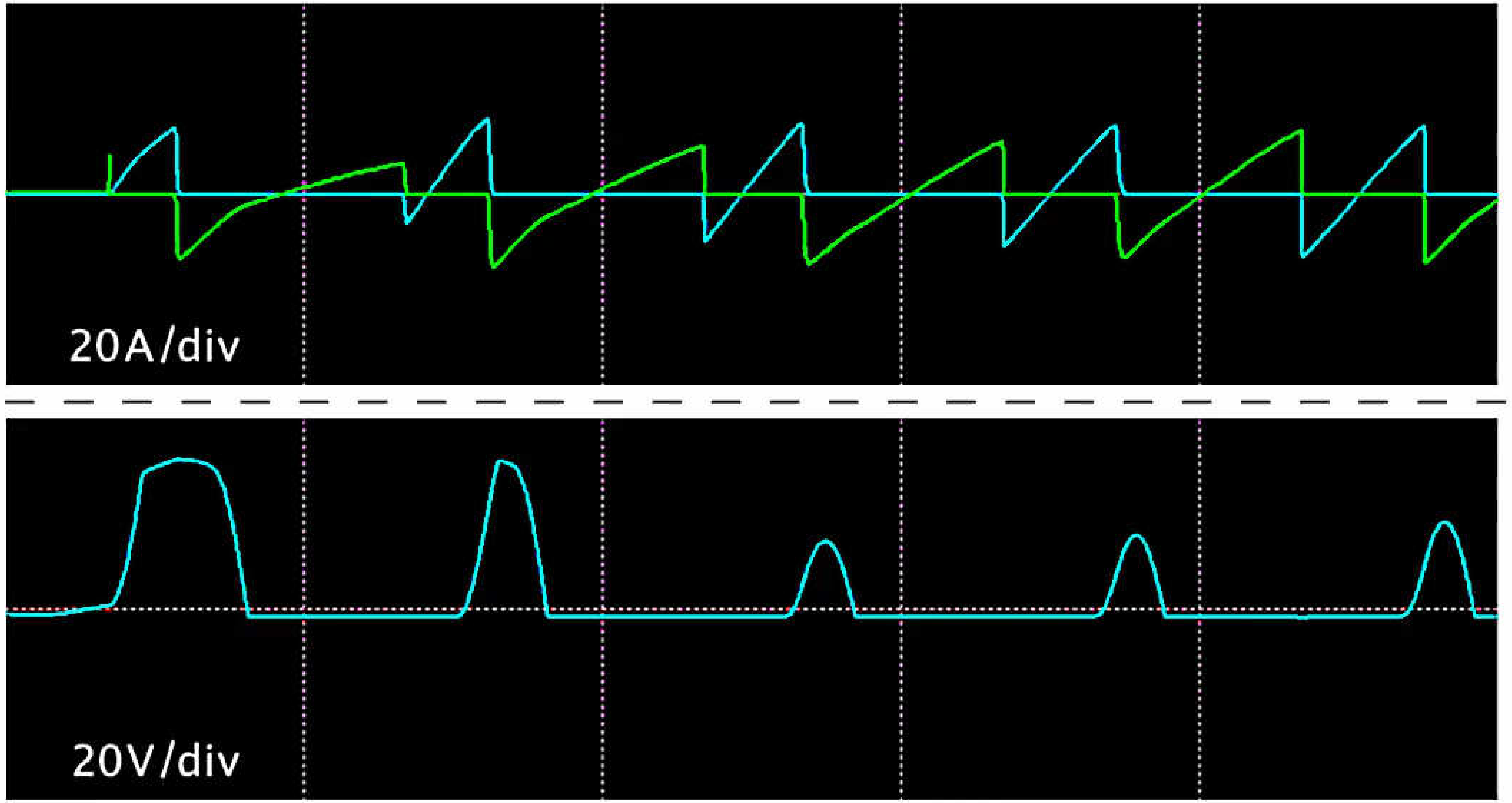
Operation at Start

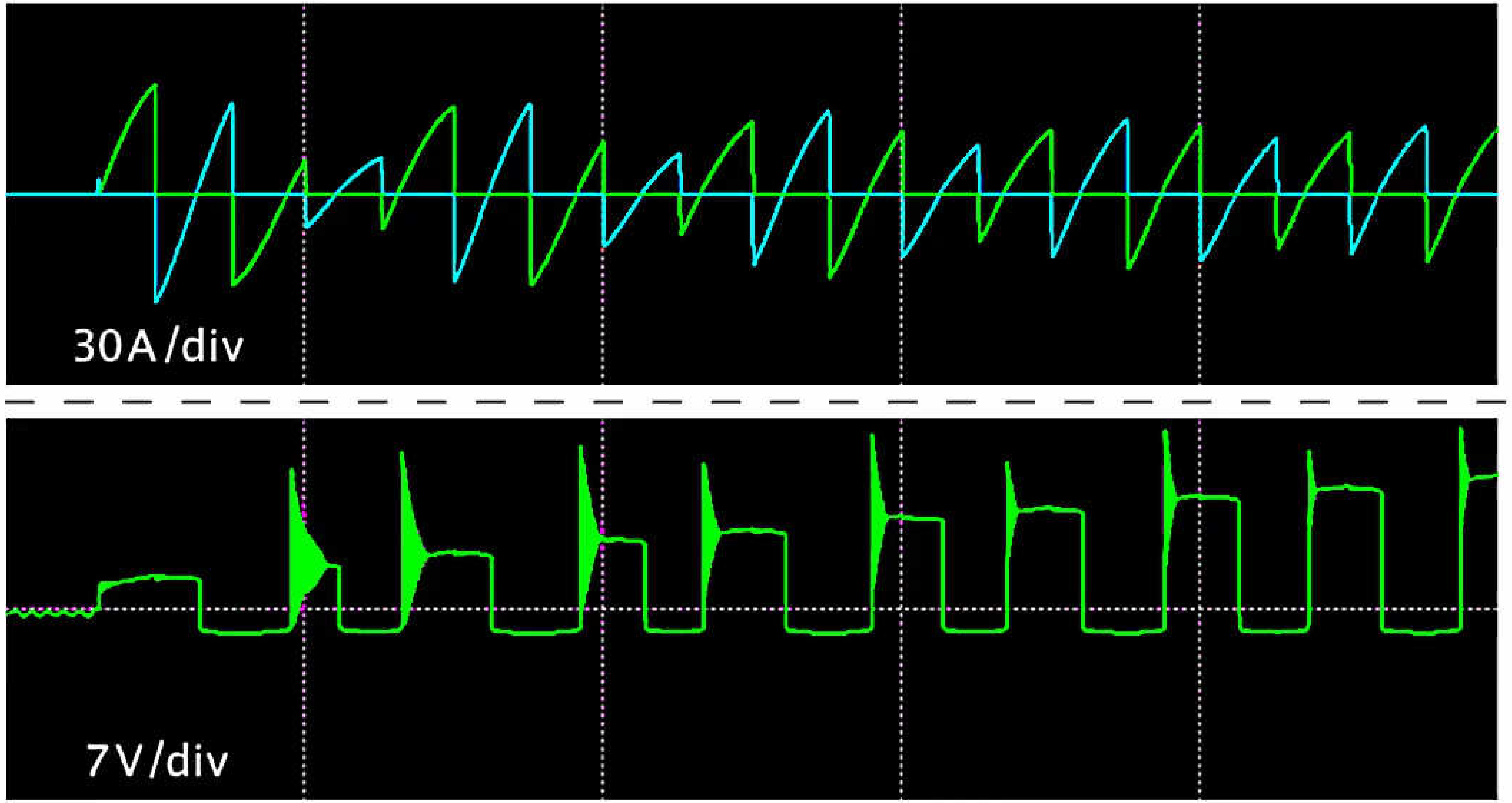
Pe17 Circuit



In the Pe17 circuit, the switching operation at the start maintains ZVS condition at any duty cycle. The reverse voltage across the synchronous MOSFETs can be used to power the controller on the secondary side.

Operation at Start

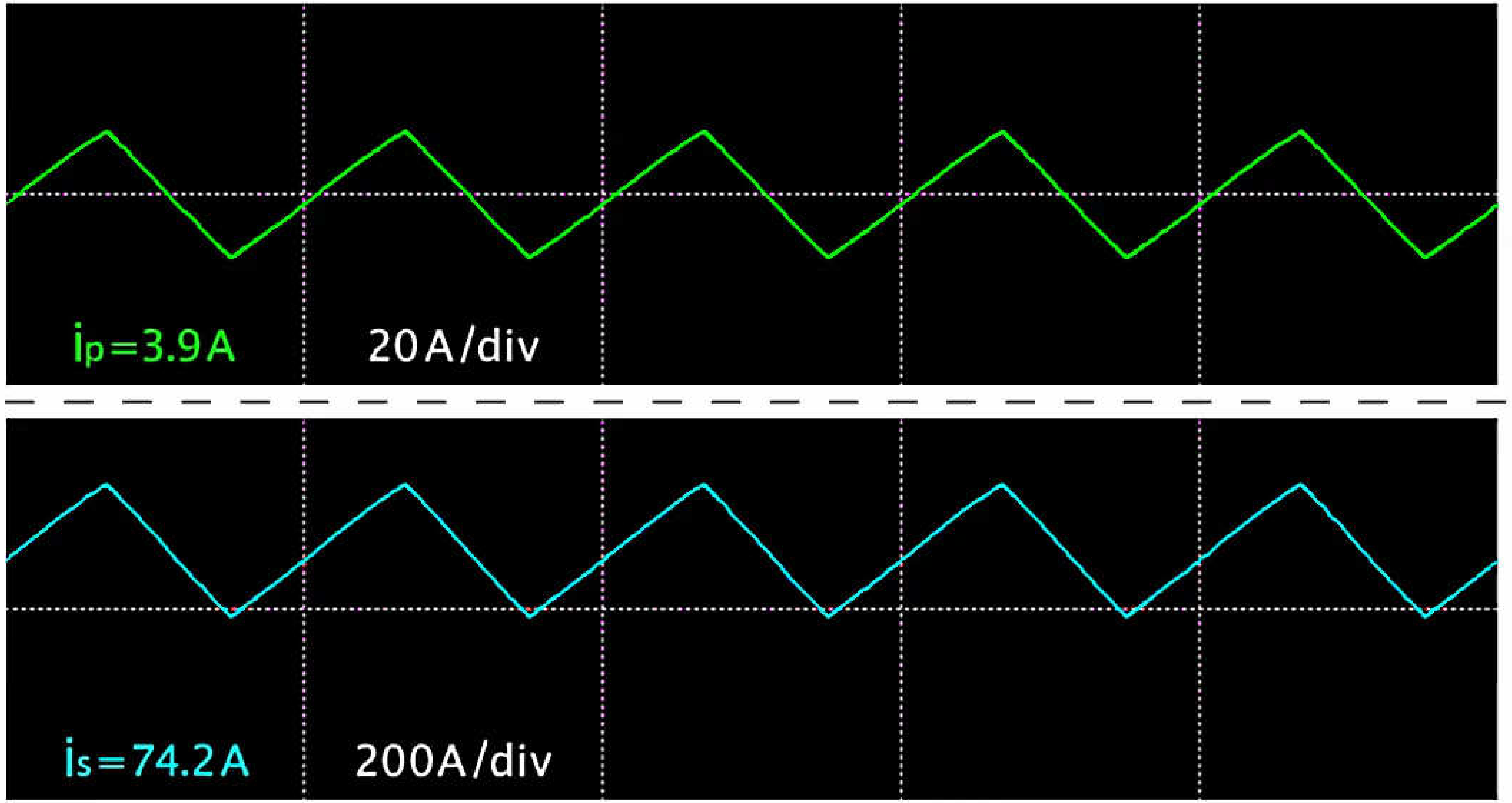
LLC Circuit



In the LLC resonant circuit, the switching frequency at the start is approximately twice the resonant frequency, in order to maintain acceptable inrush current. The reverse voltage across the synchronous MOSFETs is too low to provide power to the secondary side.

Short Circuit Operation

Pe17 Circuit



In the Pe17 circuit, a short circuit at the output results in a primary current of 3.9 Arms and a secondary current of at 74.2 A.

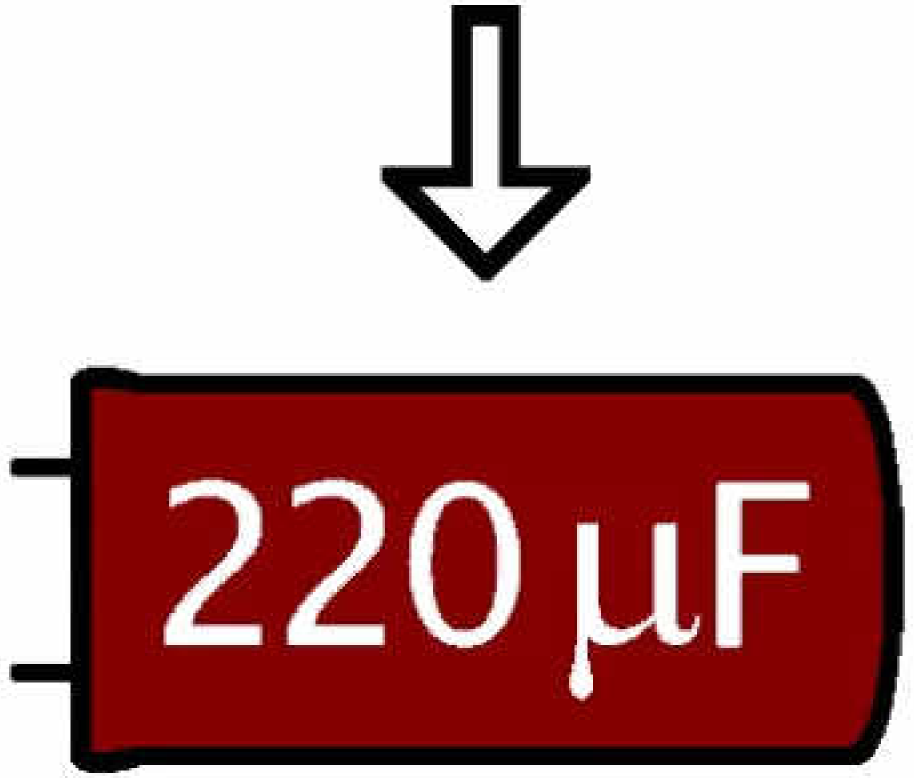
Short Circuit Operation

LLC Circuit	$I_p > 50\ A_{rms}$
	$I_s > 600\ A_{rms}$

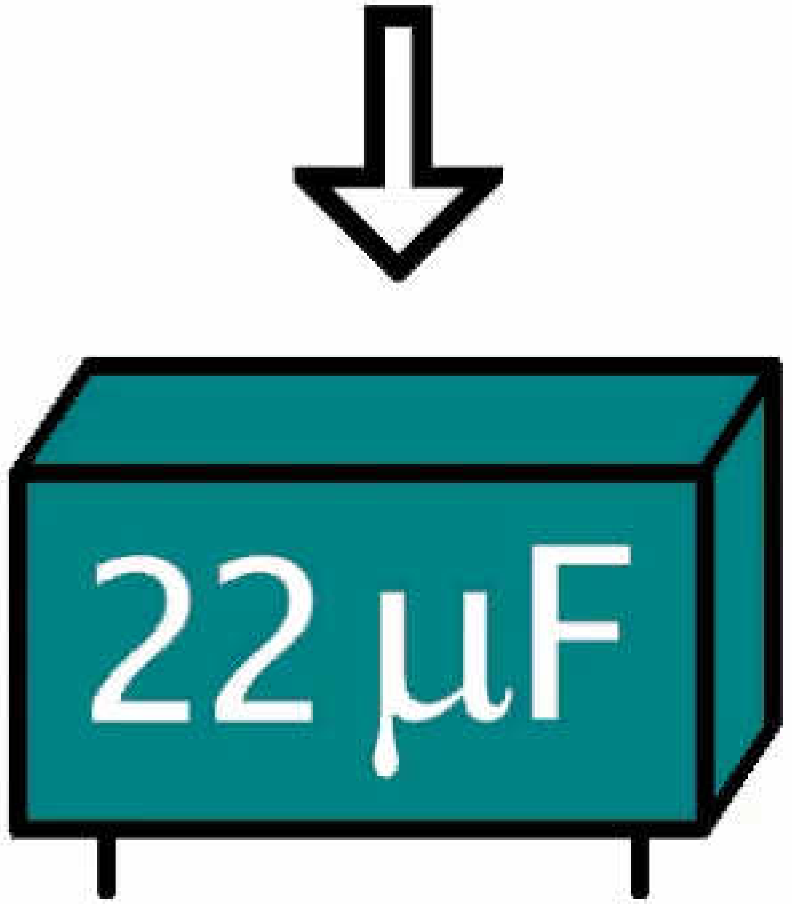
In the LLC resonant circuit, a short circuit at the output results in unacceptably high primary and secondary currents.

Wide Input Voltage Range Operation

$V_{in} = 390 \pm 10\,V$



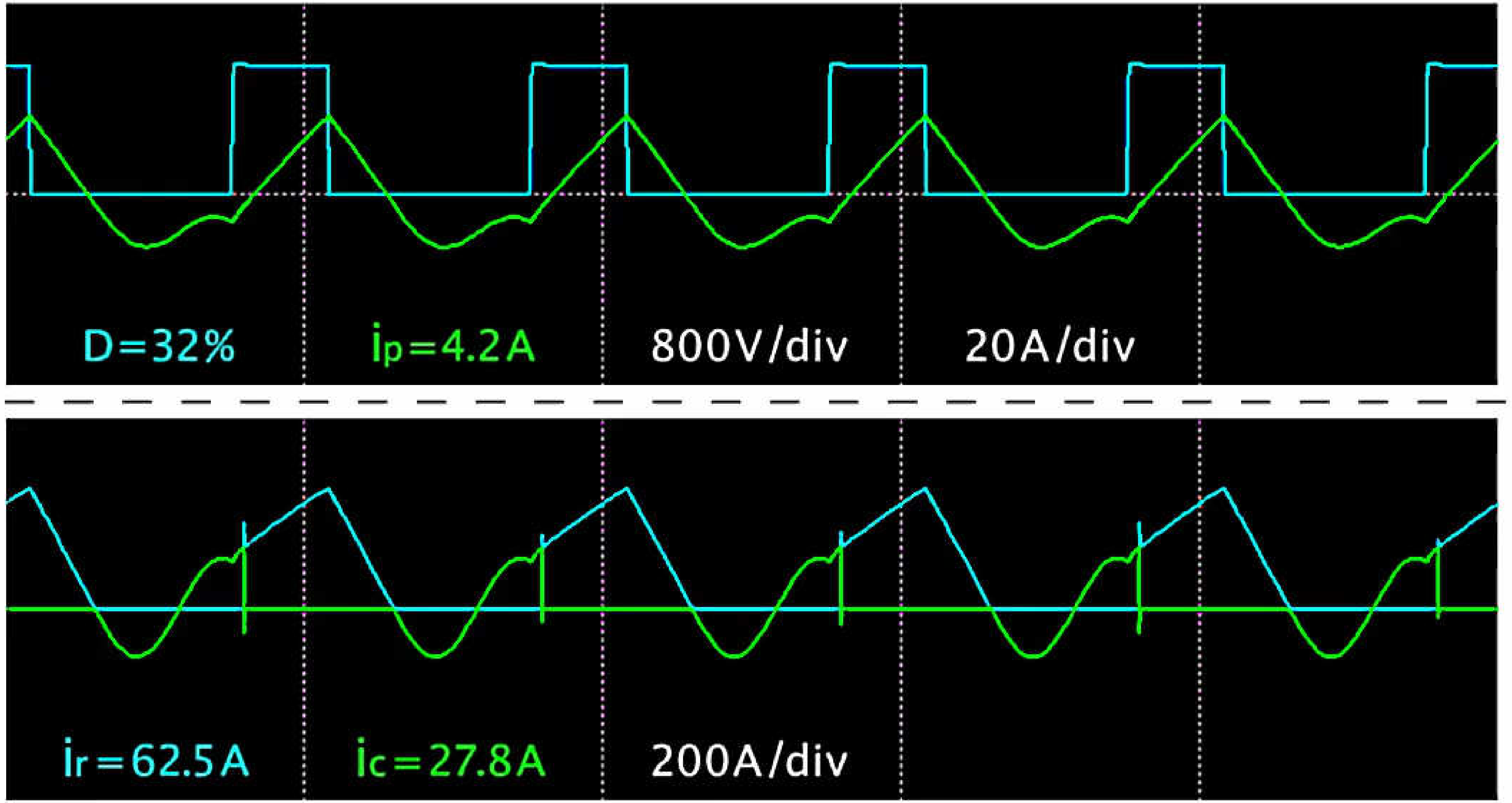
$V_{in} = 460 \pm 80\,V$



The capability of the DC–DC converter to operate under variable input voltage allows the PFC capacitance to be smaller. Thus, a cheaper and more reliable film capacitor can be used instead of an electrolytic capacitor.

Wide Input Voltage Range Operation

Pe17 Circuit



In the Pe17 circuit, at input voltage of 540 V, the duty cycle decreases to 32%. The primary current through the DC blocking capacitor is 4.2 Arms. The two synchronous rectifiers share a current of 62.5 Arms, and the current through the resonant capacitor is 27.8 Arms. Thus, the total current through the secondary winding is 68.5 Arms.

Wide Input Voltage Range Operation

LLC Circuit	$F_{SW} > 1\ MHz$

In the LLC circuit, at input voltage of 540 V, the switching frequency needs to increase beyond 1 MHz in order to regulate the output voltage. Therefore, operation under variable input voltage is impractical for the LLC circuit.

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Loss Breakdown and Efficiency Results

Power Loss (W)	Pe17 Circuit	LLC Circuit
Half Bridge Inverter	1.9	1.4
Primary Winding	0.3	0.2
Secondary Winding	0.6	1.3
Magnetic Core	1.3	2.2
Resonant Inductor	0	0.6
Synchronous Rectifiers	2	3.4
Efficiency	**98.8 %**	**98.2 %**

THANK YOU