Three-phase systems in LLC and CLLC switching power supply technology
By Heinz Schmidt-Walter

1. Introduction

The three-phase electrical system is one of the greatest inventions in electrical engineering. Although the three phases carry alternating current, meaning each phase has a power output pulsating at twice the grid frequency, the power input or output of a three-phase system with a symmetrical load is without power pulsation. As a result, for example, the turbines in a power plant are loaded with constant torque, and three-phase motors deliver a torque that is constant over time. Switched-mode power supply technology has not yet taken advantage of this behavior of a three-phase system. Instead, switched-mode power supplies operate with high-frequency controlled switches that deliver power in pulsating fashion at the output or absorb it at the input. The resulting pulsation is buffered by capacitors, ensuring a sufficiently continuous power output.

2.LLC and CLLC Converters (state of the art)

LLC and CLLC converters are resonant converters, with the switching transistors turning on at zero voltage (zero voltage switching, ZVS). This results in minimal losses in the transistors and consequently in minimal heating during operation. Efficiencies of >98% could be realized. Modern GaN transistors achieve switching frequencies of >500 kHz to 1 MHz at power levels of several kW and voltages in the 500 V range. The transformers are often designed as so-called matrix transformers, in which windings are distributed across multiple legs to minimize their size. In this technology, converters with a power output of several kW are reduced to the size of a cigarette pack.
The LLC converter conducts energy in only one direction. The CLLC converter can conduct energy in both directions, thus being capable of regenerating energy. Figure 1 shows an example of the LLC converter.

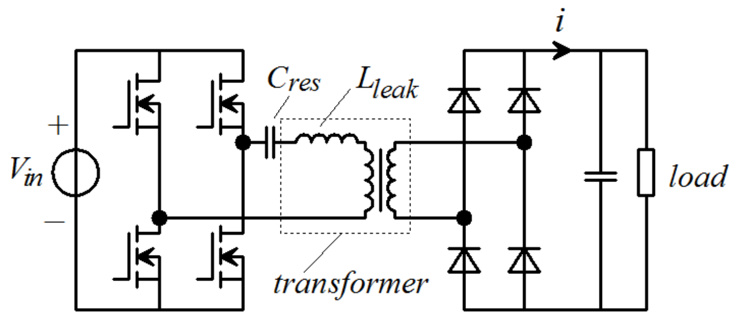


Fig. 1: LLC converter with pulsating power transmission

Both converters have the problem that the output capacitor is charged in a pulsating manner, thus subjecting it to high loads. Likewise, the input is loaded with a pulsating current (see Figure 2).
LLC and CLLC converters are state-of-the-art when it comes to high efficiency and compact size.

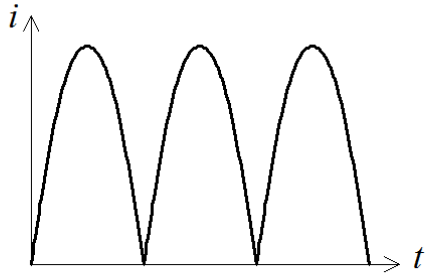


Fig.2: Example of the pulsating current i from Fig. 1

The resonance capacitor C_{res} and the leakage inductance of the transformer L_{leak} form a series resonance with the resonance frequency f_{res} equal to the switching frequency f_{sw} .
(Formel 1):

$$f_{res} = \frac{1}{2\pi\sqrt{L_{leak} \cdot C_{res}}} = f_{sw}$$

The transistors are switched with a duty cycle of 50%. At resonance, the current in the transformer is sinusoidal. The output capacitor is charged with pulsed half-sine waves.
The output voltage is controlled by frequency variation. At switching frequencies f_{sw} lower than f_{res}, the output voltage increases; at frequencies higher than f_{res}, the output voltage decreases. The control range of LLC and CLLC converters is quite narrow.
The transformer typically has an air gap. This is dimensioned so that L_p / L_{leak} = 3…5 (see relevant literature).

3. The LLC converter in three-phase design
The converter described below (Fig. 3) distributes the transmitted power using a three-phase transformer in such a way that the power flow is largely continuous, allowing the output capacitor to be reduced to a very small value (see Fig. 4). The supply source is also loaded with approximately a direct current. This is especially important when both the source and load are batteries.

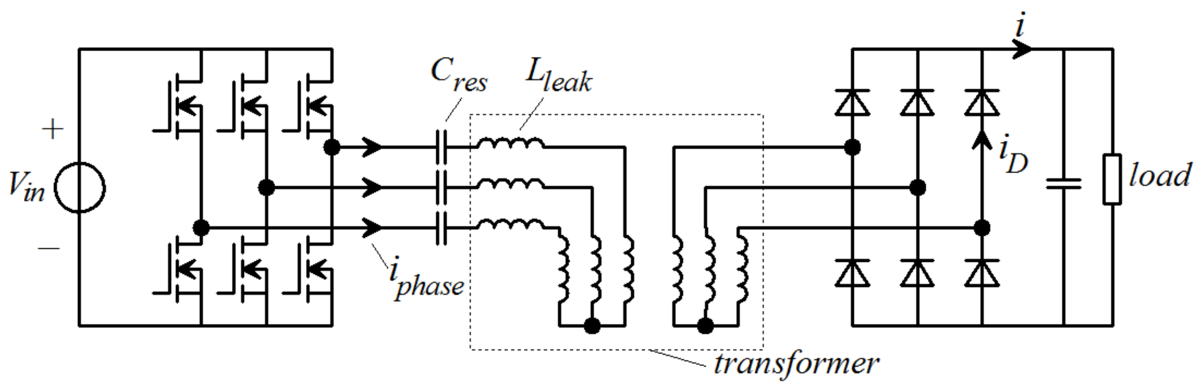
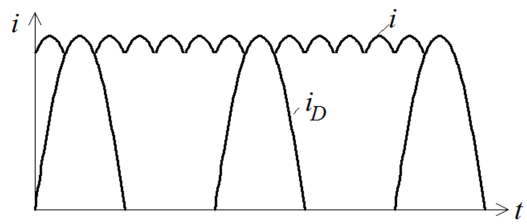


Fig.3: Basic circuit of the LLC three-phase converter



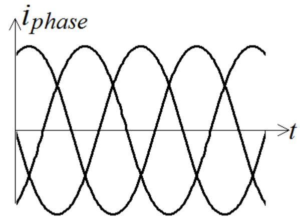


Fig. 4: Current *i* and current i_D in a rectifier diode, Fig. 5: Primary currents in the transformer

The bridge outputs are controlled with a 120° phase shift. This creates a three-phase voltage system that generates approximately sinusoidal currents in the three-phase transformer, offset by 120°, see Fig. 5. A three-phase rectifier is located on the output side. It does not have to consist of diodes; instead, active rectifiers using transistors are used today. In the CLLC converter, the primary and secondary active transistor bridges must be used due to the symmetrical power transmission.
The star point of both the primary and secondary sides must remain free.

The magnetic volume of the three-phase transformer is slightly smaller than that of an LLC converter of the same power. The total switching capacity of the transistors remains the same.

4. The three-phase transformer

The three-phase transformer has three legs, which, thanks to the ferrite core design, can be arranged symmetrically. This results in identical magnetic conditions for all three legs (Fig. 6).

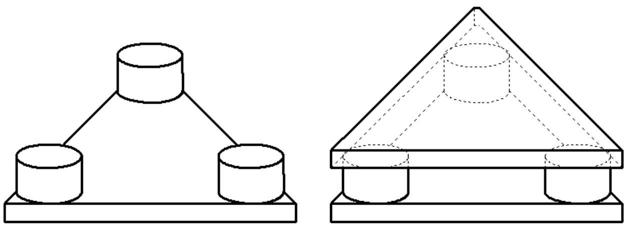


Fig. 6. left ferrite core with base and legs, right core with cover plate

However, the traditional geometry of a three-phase transformer is also possible, Fig. 7. In this case, however, the magnetic ratios of the three legs are not entirely identical, which can affect the leakage as well as the resonance capacitor.

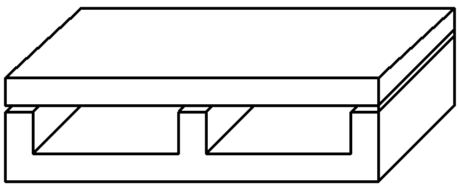


Fig.7: Three-leg planar core

The respective primary and secondary windings are applied in the same way to the three legs with the same winding direction, see Fig. 7a.

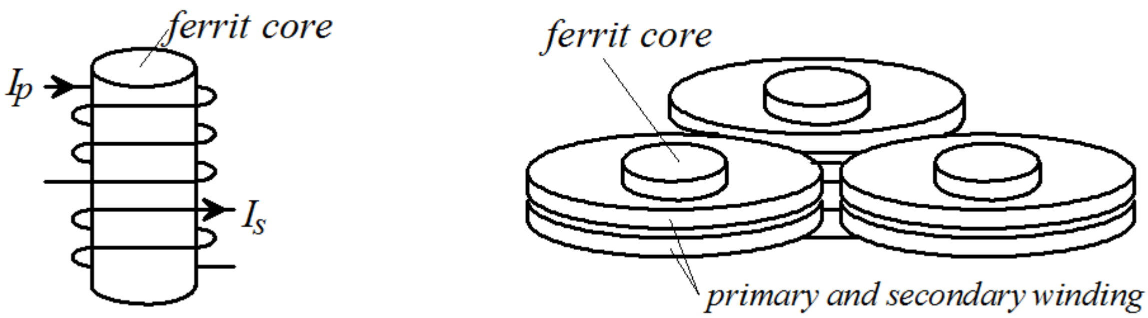


Fig. 7a: left winding direction, right physical view of the windings

5. Calculation example for the transformer
Several parameters are taken into account when calculating the transformer. Therefore, we speak of a transformer "design", which includes core parameters, winding parameters, switching frequency, and insulation distances. The designer has many options, but of course, physical laws must also be taken into account.

The following LLC three-phase converter serves as an example for calculating the transformer:
Input voltage V_{in}=400V,
Output voltage V_{out}=24V,
Power P=1.5kW,
Switching frequency f_{sw}=500kHz.
Further definitions:
B_{max}: Maximum magnetic flux density in the ferrite within the winding
A_{fe}: Cross-sectional area of the ferrite
A_N: Cross-sectional area of the winding
Φ: Magnetic flux
S: Current density in the winding
N: Number of turns
T: Period of the switching frequency f_{sw}
Subscripts 1 and 2 stand for primary and secondary

Fig. 8: primary phase-element voltage

Fig.8 shows the voltage between the output of the transistor bridge and the primary star point.

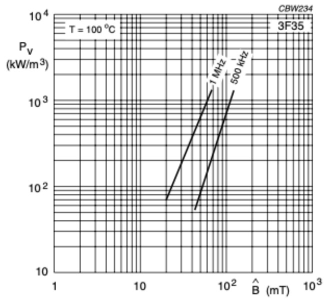


Fig.9: Power losses within the ferrit 3F35 (Ferroxcube) at 500kHz, $\hat{B}$ corresponds to B_{max}

For the calculation, we assume a current density S=5A/mm^2 in the copper and a B_{max}=100mT in the ferrite. B_{max}=100mT results in approximately 1mW/mm^3 in the aforementioned ferrite (1kW/m^3=1mW/mm^3). We consider this acceptable with respect to transformer heating with slightly forced ventilation.

The basis for further calculation is the Faradays Law of Induction:

(Formel 2): $$V = N \cdot \mathrm{d}\Phi / dt.$$

From this it can be seen that the voltage and the number of turns determine the suitable cross-section of the ferrite core.

It follows: (Formel 3) $\frac{1}{N}\int V\,dt = B \cdot A_{fe}$. The integral (Formel 3a) $\int V\,dt$ describes the voltage-time area, which determines the magnetic flux or magnetic flux density (see Fig. 9). For positive voltage, the flux increases; for negative voltage, it decreases.

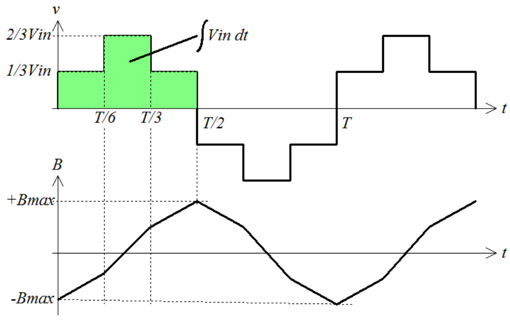


Abb. 10: Phase-element voltage and corresponding magnetic flux density B

With a free star point, the phase-element voltages describe a step function, each step of which is $V_{in}/3$ for each $T/6$. The voltage-time area per half-cycle is $4 \cdot V_{in}/3 \cdot T/6$, see Figs. 9 and 10. This causes the magnetic flux density to run from $-B_{max}$ to $+B_{max}$ and vs. in the steady state.

Applying Faradays Law of Induction now leads to:

(Formel 5) $\frac{1}{N} \cdot 4 \cdot \frac{V_{in}}{3} \cdot \frac{T}{6} = \frac{1}{N} \cdot \frac{1}{3} \cdot \frac{V_{in}}{f} = 2B_{max} \cdot A_{fe}$

Since the voltages in the transformer are proportional to the number of turns, this calculation applies equally to the input voltage V_{in} and the output voltage V_{out}:

(Formel 6)

$$\frac{1}{N_1} \cdot \frac{2}{9} \cdot \frac{V_{in}}{f} = 2B_{max} \cdot A_{fe} = \frac{1}{N_2} \cdot \frac{2}{9} \cdot \frac{V_{out}}{f}$$

Due to the high frequency, the secondary number of turns in our example can be very small. The number of turns must also be an integer. Therefore, we first choose N2 to calculate the required cross-sectional area of the core.

(Formel 7)

$$A_{fe} = \frac{1}{N_2} \cdot \frac{2}{9} \cdot \frac{V_{out}}{f} \cdot \frac{1}{2B_{max}}$$

Now you can iteratively determine which number of turns seems suitable:

a) N_2=1 leads to (Formel 8) $A_{fe} = \frac{1}{N_2} \cdot \frac{2}{9} \cdot \frac{V_{out}}{f} \cdot \frac{1}{2B_{max}} = 53\ mm^2$
b) N_2=2 leads to 27 mm^2 or
c) N_2=3 leads to 18 mm^2

The primary number of turns is then $N_1/N_2=V_{in}/V_{out}$ for:

a) $N_2=1 \rightarrow N_1=16$
b) $N_2=2 \rightarrow N_1=32$
c) $N_2=3 \rightarrow N_1=48$

Next, the required winding space can be determined.
The current determines the wire cross-section; the more turns, the larger the winding cross-section. The number of turns should be as small as possible to minimize copper losses. On the other hand, the winding space should be proportionate to the core volume. In the example, N_2=1 and N_1=16 are selected. A secondary number of 1 turn is particularly favorable for the layout of the subsequent rectifier stage.

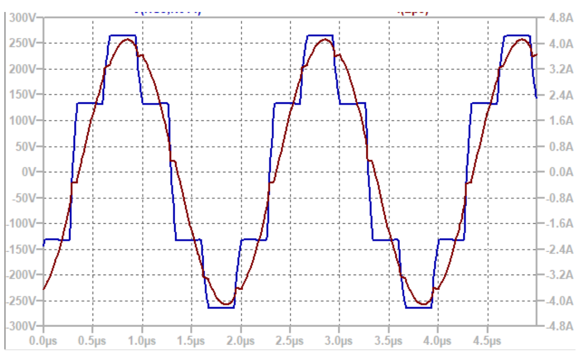


Abb. 11: primary phase-element voltage (blue) and phase current (red)

The phase-element voltages on the primary side are approximately V_{1peak} =270V and V_{1RMS} = 190V.
Each phase delivers P_{phase} = 500W.
This results in a primary phase current of I_1= 500W/190V = 2.65A (slightly higher in the simulation because the voltage drop in the inverter stage and the power loss of the secondary rectifier are taken into account).

The phase currents on the secondary side are therefore $I_2 = N_1/N_2 \times I_1$ = 42.5A.

The current density S = 5A/mm² should not be exceeded. A fill factor of 0.7 is assumed for the windings. The primary and secondary windings require the same winding cross-section.

This results in the following for the primary and secondary windings:

a) N_1=16, N_2=1: (Formel 9) $A_N = 2 \cdot \frac{N_2 \cdot Is_{Str}}{S} \cdot \frac{1}{0{,}7} = 2 \cdot \frac{42{,}5A}{5^A/_{mm^2}} \cdot \frac{1}{0{,}7} = 25mm^2$

b) N_1=32, N_2=2: A_N=50mm^2

c) N_1=48, N_2=3: A_N=75mm^2

Note: The winding windows in the core must accommodate the primary and secondary windings twice.

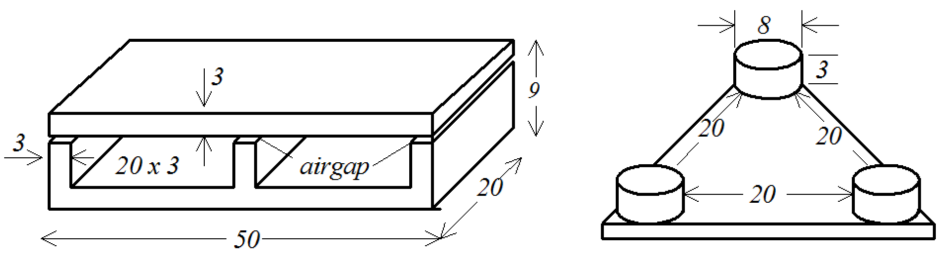


Fig.12: Two possible core-designs for N_1=16 und N_2=1

Fig. 12 shows two core designs. Fig. 12 left shows the traditional three-phase transformer design, right a symmetrical triangular core design (cover plate not shown). The windings count 16 and 1. The windings would protrude at the sides, creating an entire transformer area of 70 x 40 mm² on the left design and a triangular area with 56 mm edges on the right one. With the triangular solution, the base and cover plates could be reduced to 1.5 mm thickness because the magnetic fluxes would partially cancel each other out due to their phase shift.

An air gap can be inserted between the cover plate and the lower core.

6. Summary

LLC and CLLC converters are currently state-of-the-art when it comes to high efficiency and compact size. However, both converters have the problem that the output capacitor (or battery) is charged in a pulsating manner, placing a high load. Likewise, the input is subjected to a pulsating current.

The three-phase circuit in LLC and CLLC technology ensures a nearly continuous energy flow. This is particularly advantageous when the converters are powered by DC sources, such as batteries or solar cells, and/or have batteries as a load.

At the same time, the three-phase transformer is a particularly advantageous design because the three magnetic fluxes in the legs cancel each other out, so that the flux from one leg is absorbed by the other two. The transformer therefore has a smaller footprint than a single-phase converter of the same power and frequency.

The transformer must be connected in a star configuration with a free star point. The stepped voltage curve supports the sinusoidal current.

Notes:
- A patent for the LLC and CLLC three-phase solution has been filed.
- The simulation file for LTSpice is available upon request.