

Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency

By Sebastien Marchio

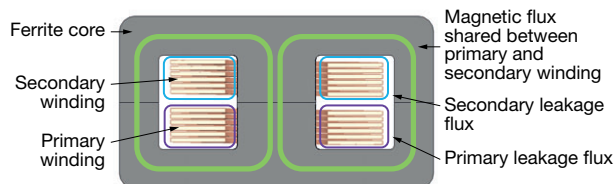
1. GENERAL DEFINITION

Nowadays, with the emergence of new technologies like electrical vehicles and renewable energy, the need to develop power converters has quickly grown. Designers are looking for enhanced power density and efficiency, as well as smaller dimensions and lower weight. A rise in switching frequencies is suited to meeting this target, but leads to other constraints that need to be managed in the design of magnetic components, such as proximity and skin effects. The main challenges with magnetic components are to minimize power losses and improve thermal management.

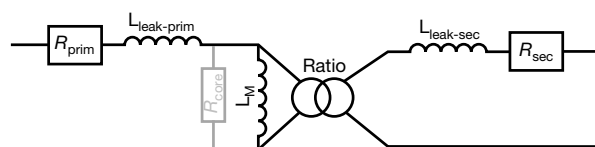
The PLA51 is a tropicalized planar transformer designed for converters from 1 kW to 3 kW. More compact than conventional transformers, the device's planar technology allows it to achieve better efficiency while providing a high power to size ratio. With the highly effective cross section of the planar ferrite core, the number of turns is minimized, as are the copper losses, while the magnetic core's low volume helps reduce core losses. The stacking of thin copper foil windings minimizes the influence of skin and proximity effects, while allowing for low leakage inductance values.

In addition, compared to conventional technology, planar technology is better suited to heatsink-cooled devices. With the extended surface of the core and flatter shape, it offers high contact areas to improve heat dissipation by conduction, thus increasing the transferable power density. The PLA51 can also withstand high temperatures because its insulation materials are rated to class H 180 °C. On the other hand, the core of the PLA51 - which envelops all the windings - works as a natural shield to limit radiation emissions and avoid EMI / EMC issues.

2. ELECTRICAL PARAMETER DEFINITIONS



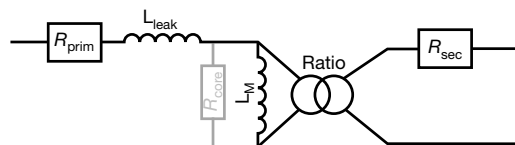
In converters, the purpose of transformers is to forward energy while providing the galvanic insulation between a primary and secondary grid, and to adapt voltage and current levels through the ratio. An electrical model of a power transformer with the location of its different parameters is shown below.



Where:

- R_{prim} = primary winding resistance
- R_{sec} = secondary winding resistance
- L_M = mutual inductance
- $L_{leak-prim}$ = primary leakage inductance
- $L_{leak-sec}$ = secondary leakage inductance
- R_{core} = core losses

This model is often simplified as in the following diagram, where the leakage inductances are gathered as one on the primary side (L_{leak}).



The main electrical parameters for power planar transformers are defined below. Unless otherwise indicated, the parameters are under 0.1 V_{RMS} and 10 kHz.

Primary Inductance

The primary inductance is the inductance value measured between primary winding terminals.

It reflects the sum of the magnetic flux shared between the primary and secondary windings and the primary leakage flux.

Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency

Leakage Inductance

The leakage inductance of one winding reflects the magnetic flux, which is not shared with the other windings. The measurement is carried out between the terminals of the winding while shunting the terminals of the other windings.

For direct power transmission (forward, bridge, push-pull, etc.), we often look to minimize the primary leakage inductance. So, the mutual inductance (reflecting the magnetic flux shared between the primary and secondary windings) can be considered as the primary inductance.

Other specific converter topologies need an inductor in series with the primary windings of the transformer to work. This inductor can be part of the transformer and match its leakage inductance, saving an additional component. Clever solutions can be designed upon request

Turn Ratio

The turn ratio reflects the ratio between the number of turns of the secondary and primary windings.

$$\text{Ratio} = \frac{N_{\text{sec}}}{N_{\text{prim}}}$$

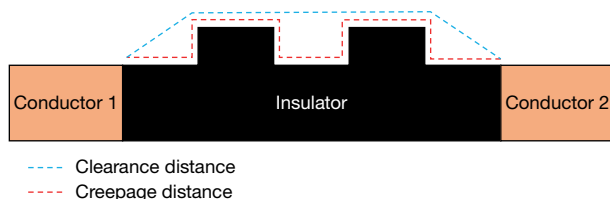
With the hypothesis of a perfect transformer (perfect coupling), the ratio can be seen as the ratio of instantaneous values of voltage or current, as defined below.

$$\text{Ratio} = \frac{V_{\text{sec}}}{V_{\text{prim}}} = \frac{I_{\text{prim}}}{I_{\text{sec}}}$$

Hipot Test

One of the main functions of the transformer is to guarantee insulation between primary and secondary grids. The main objective of the hipot test is to ensure that the construction rules for creepage and clearance distances have been met. The tester applies sinus wave voltage and measures the leakage current (designed for a 1 minute duration). The frequency could be 50 Hz or 60 Hz, depending on the equipment used (European or U.S. standard).

The creepage distance is the shortest distance along the surface of a solid insulating material between two conductive parts. The clearance distance is the shortest distance in the air between two conductive parts.



Insulation Test

The measurement of the insulation resistance is non-destructive under normal test conditions.

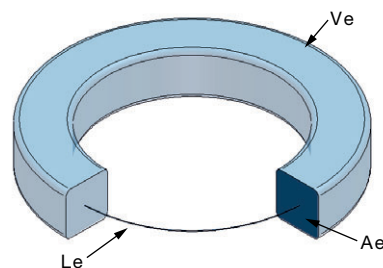
Performed by applying a DC voltage with a lower amplitude than for the dielectric test, the insulation test provides a result expressed in kΩ, MΩ, GΩ, or TΩ. This resistance indicates the quality of the insulation between two conductors.

3. MAGNETIC PARAMETER DEFINITIONS

The PLA51 has been designed with a manganese and zinc (MnZn) ferrite core to achieve the highest efficiency in the frequency range from 50 kHz to 400 kHz.

The function of the magnetic core is to lead the magnetic flux.

For a given core, the effective dimensions are those of a theoretical toroidal core with the equivalent magnetic properties.



For the PLA51, the effective core parameters of the ferrite are in the table below.

SYMBOL	DESCRIPTION	VALUE	UNIT
le	Effective path length	73.5	mm
Ae	Effective area	351	mm ²
Ve	Effective volume	25 798.5	mm ³

The main characteristics of the ferrite material to be followed to achieve the best performance of the transformer are defined below:

- The flux density B must be kept below the threshold of the saturation flux density Bs = 410 mT (100 °C)
- For the bipolar square wave voltage, the maximum flux density can be assessed with the formula:

$$B_{\text{peak}} = \frac{\hat{U}}{4 \times f \times N_{\text{prim}} \times A_e}$$

Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency

Where:

- $\hat{U}$ = maximum voltage applied to the primary winding
- N_{prim} = number of turns of the primary winding
- f (Hz) = switching frequency
- The core power losses can be assessed with the formula:

$$P_{\text{loss}} = 2.425 \times 10^{-6} \times (B_{\text{peak}})^{2.5891} \times (f)^{1.6677}$$

Where:

- P_{loss} (W) = ferrite core power losses
- B_{peak} (T) = peak flux density
- f (Hz) = switching frequency

Note

- Data are given for a core temperature of 100 °C

Example

- Primary input voltage = 50 V
- Switching frequency = 100 kHz

$$N_{\text{prim}} = 3$$

$$\rightarrow B_{\text{peak}} = 118.7 \text{ mT}$$

$$\rightarrow P_{\text{loss}} = 2.1 \text{ W}$$

- Primary inductance value: the inductance value is proportional to the square of the number of turns of the primary. It can be assessed with the following formula:

$$L = AL \times 10^{-9} \times N_p^2$$

Where:

- AL (nH) = inductance facto
- For PLA51, the $AL = 14\,230 \text{ nH/t}^2 \pm 25\%$ for an ungapped core
- Other lower AL values carried out with a gapped core can be provided upon request
- N_{prim} = number of turns of the primary winding

Example

$$N_{\text{prim}} = 3 \rightarrow L = 128 \text{ } \mu\text{H}$$

- Curie temperature: above the Curie temperature of 215 °C, the material loses its magnetic properties. The phenomenon is reversible

4. WINDING RESISTANCE AND COPPER LOSSES

The winding resistance is an important parameter in evaluating the copper losses due to the current flow through the windings. Winding resistance can be calculated with the following formula:

$$R_{\text{DC}} = \rho_{20\text{ }^\circ\text{C}} \times \frac{l}{A}$$

Where:

- R_{DC} (Ω) = winding resistance at 20 °C
- $\rho_{20\text{ }^\circ\text{C}}$ ($\Omega\cdot\text{m}$) = electrical resistivity of copper at room temperature
- l (m) = length of the winding
- A (m^2) = cross section of the conductor used for the winding

The electrical resistance is dependent on the working temperature of the winding. For windings made of copper, the resistance at T temperature can be approximated with the following formula:

$$R_{\text{DC}}^T = R_{\text{DC}} \times [1 + 3.90 \times 10^{-3} (T - 20)]$$

Where:

- R_{DC} (Ω) = winding resistance at 20 °C
- R_{DC}^T (Ω) = winding resistance at working temperature
- T (°C) = working temperature

Example

For PLA51LA32:

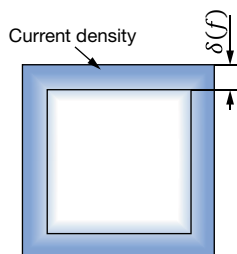
- $R_{\text{DC}}(1-2) = 1.35 \text{ m}\Omega$ max. (cannot be accurately measured)
- $R_{\text{DC}}(3-4) = 0.90 \text{ m}\Omega$ max. (cannot be accurately measured)

$$\rightarrow R_{\text{DC}}^{120\text{ }^\circ\text{C}}(1-2) = 1.88 \text{ m}\Omega$$

$$\rightarrow R_{\text{DC}}^{120\text{ }^\circ\text{C}}(3-4) = 1.25 \text{ m}\Omega$$

With the increase of switching frequencies above 50 kHz, to 100 kHz, other phenomenon like skin and proximity effects become significant. Unlike DC current, with high frequencies the current density becomes higher at the edge of the conductor due to the appearance of eddy current inside the conductor, leading to a rise in effective AC resistance.

Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency



63 % of the current is concentrated within the external part of the conductor (the so-called skin). The formula to define its depth is:

$$\delta = \sqrt{\frac{\rho}{\pi \times \mu \times f}}$$

With:

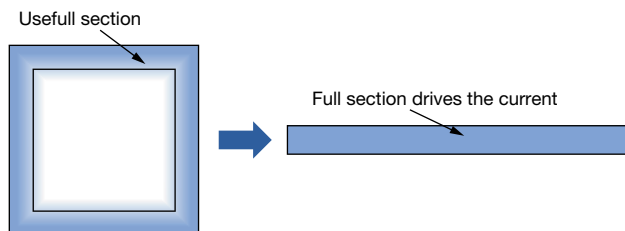
- ρ = electrical resistivity of the conductor
- μ = permeability of the conductor
- f (Hz) = frequency

f (Hz)	50	100	200	500
δ (mm)	0.34	0.24	0.17	0.11

Note

- For the copper at 100 °C

The windings of the PLA51 planar transformer are suited to work within this frequency range. The use of thin conductors and management of the stacking between primary and secondary windings allows for a reduction in the influence of skin and proximity effects, while optimizing the conductor cross section, dimensions, and weight.

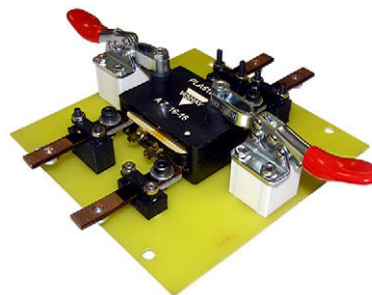


5. THERMAL MANAGEMENT

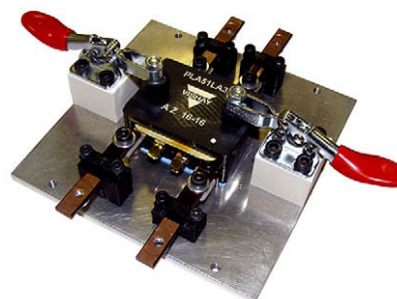
The raw insulation materials of the PLA51 are rated to class H 180 °C. Thermal management is an important parameter for the performance of transformers. Users must correctly size their cooling devices according to the real working conditions of their applications.

The PLA51 size has been characterized for several cooling methods:

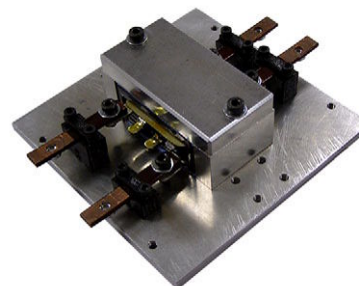
- Natural convection: horizontally oriented, the transformer is pressed upon a PCB



- Conduction with heatsink: the transformer has been mechanically fixed upon a heatsink with a water flow rate from 0.8 L/min to 1 L/min
 - Two layouts have been tested (with or without flange) with similar behavior
 - The transformer is pressed upon the heatsink. A thermally conductive pad gap filler [thickness: 0.04" (1.02 mm)] has been inserted between the bottom of the transformer and the heatsink



- The transformer is mechanically fixed as defined in the section "Precaution and Assembly Advised" below. One pad gap filler on each side of the transformer makes the thermal link with the heatsink as well as the flange, which has the function of a second heatsink



Natural convection	With heatsink
$R_{TH} \text{ (air / transformer)} = 4.5 \text{ °C/W}$	$R_{TH} \text{ (heatsink / transformer)} = 3 \text{ °C/W}$

Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency

The rise of temperature can be computed with the formula:

$$\Delta T\text{ }^{\circ}\text{C} = R_{TH} \times P_T$$

Where:

- $\Delta T\text{ }^{\circ}\text{C}$ = rise of temperature
- $R_{TH}\text{ }(^{\circ}\text{C}/\text{W})$ = thermal resistance
- $P_T\text{ (W)}$ = total power losses to be dissipated (copper and core losses)

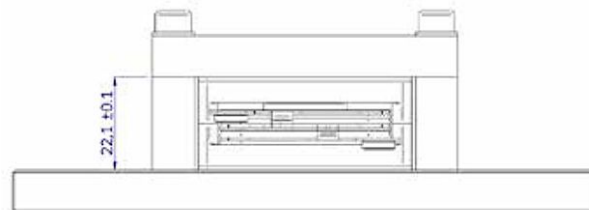
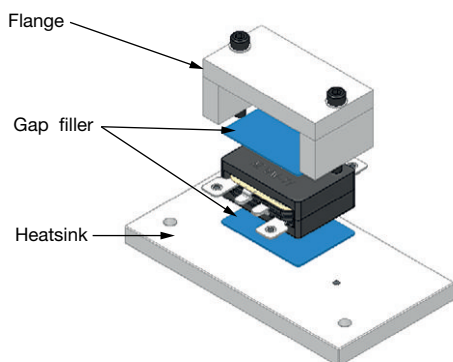
Example

- $P_T = 17\text{ W}$
- Heatsink water temperature = $80\text{ }^{\circ}\text{C}$
- Thermal management configuration: contact with the heatsink
 - $\Delta T\text{ }^{\circ}\text{C} = 51\text{ }^{\circ}\text{C}$
 - Transformer working temperature = $131\text{ }^{\circ}\text{C}$

6. PRECAUTION AND ASSEMBLY ADVICE

Ferrite cores are sintered materials. Like ceramics, they are brittle and sensitive to shocks and mechanical stress. It's very important to protect them throughout the entire life of the product (handling, as well as assembly processes and once the transformer is embedded into the final device). To protect the ferrite core and improve thermal flux dissipation through the heatsink, the transformer is stacked between two thermally conductive and soft pad gap filler [thickness: 0.04 inch (1.02 mm)].

The link between the top of the transformer and the flange allows for an increase in the dissipative area by conduction toward the heatsink, reducing the thermal resistance of the transformer and the rise in temperature while operating. The tightening must be performed alternatively and gradually on each screw until a torque of 3 N.m max. is reached. This will prevent cracks on the ferrite material due to an unbalanced pressure on the core during the fixing operation. It will also help the gap filler to perfectly match with the shape of the ferrite.



Advised height of the flange

To make the electrical connection and fixing with the electric busbars easier, the terminals of the PLA51 are fitted with crimped tapped M4 nuts. The advised tightening torque for electrical connection is 1 Nm (1.2 Nm max.).

The PLA51 transformer has been successfully tested for shock and vibration according to the above mechanical fixing and the following test conditions:

- **Vibration test:** according to MIL-STD-202, method 204
 - 5 g during 20 min
 - 12 cycles each following three orientations
 - Test from 20 Hz to 2000 Hz
- **Shock test:** according to MIL-STD-202, method 213, figure 1, condition C
 - 5 shocks following each direction

CAUTION: if the transformer falls down or an impact on the ferrite happens during handling, the transformer must be rejected.



Designing With the PLA51 Planar Transformer for Enhanced Power Density and Efficiency

GLOSSARY

R_{prim} :	primary winding resistance
R_{sec} :	secondary winding resistance
L_M :	mutual inductance
$L_{\text{leak-prim}}$:	primary leakage inductance
$L_{\text{leak-sec}}$:	secondary leakage inductance
B_s :	saturation flux density. It's the maximum intrinsic induction possible in a material
B_{peak} :	maximum flux density
P_{loss} (W):	ferrite core power losses
T_c (°C):	curie temperature is the transition temperature above which a ferrite loses its ferromagnetic properties
ρ :	electrical resistivity of the conductor
μ :	permeability of the conductor
f (Hz):	frequency
P_T (W):	total power losses to be dissipated
R_{TH} (°C/W):	thermal resistance
ΔT °C:	rise of temperature

Effective dimensions of a magnetic core:

A_e :	effective area
L_e :	effective path length
V_e :	effective volume