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How planar magnetics improve performance in power electronics

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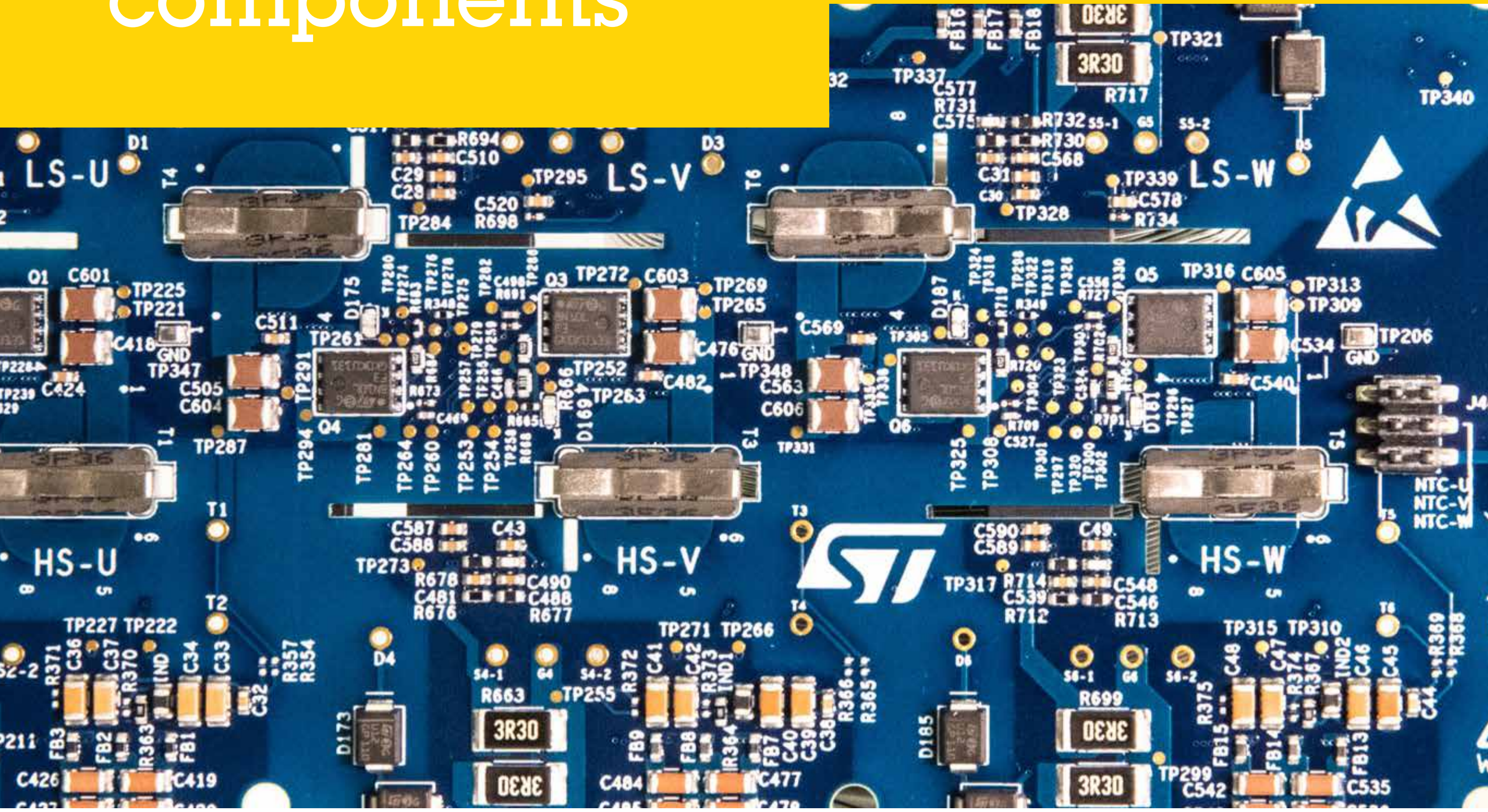
History of planar magnetic components



In today's competitive marketplace, renewables, energy storage, power adapters, power chargers, and data processing applications require cost-saving, high-efficiency solutions with higher power density for improved performance to meet the demands of the constantly growing telecommunication, automotive, healthcare, and aerospace industries.

Compound semiconductor devices such as gallium nitride (GaN) and silicon carbide (SiC) transistors limit switching losses at high frequencies and accelerate the trends for increasingly smaller circuits. In fact, high-frequency operation leads to the shrinkage of electronic circuits, thanks to their reduced magnetic size and increased power density. This is very important for electronic power converters which include magnetic components such as transformers for power transfer and inductors for energy storage.

This article explains how planar magnetics can significantly improve power electronics in terms of efficiency, cost, and space requirements as well as heat dissipation.

The first studies on planar magnetic components date back to the 1960s. However, these studies emerged predominantly with the research on design, modeling, and optimization in the 1990s.

More recently, the planar magnetic technology has gained a worldwide interest thanks to the spread of printed circuit board technologies.

A planar component is a transformer or an inductor consisting of planar copper windings. The planar components are usually flat copper sheets wound around a rigid or flex PCB, but can also be a hybrid. They are inserted in a low-profile magnetic core made from a "soft" ferrite. Their copper tracks have rectangular cross-sections, different from conventional wire-wound components that have circular cross-sections.

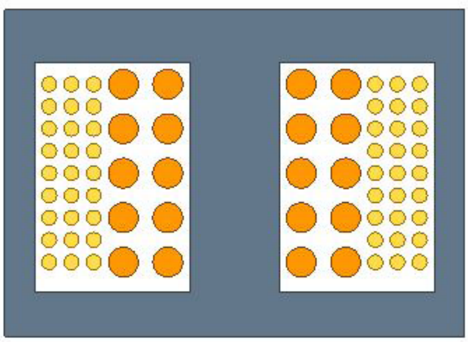


Figure 1. Standard transformer cross-section structures

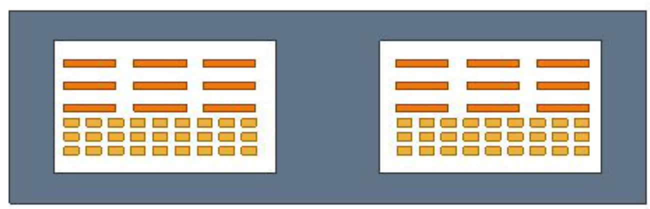


Figure 2. Planar transformer cross-section structures

> Planar magnetics significantly improve power electronics in terms of efficiency, cost, and space requirements as well as heat dissipation.

As this technology leads to more compact solutions with improved overall system performance and increased efficiency, planar magnetics are generating a growing interest in semiconductor companies and power conversion research groups. For instance, controlling and fine-tuning the leakage inductance increases a system's efficiency. The leakage inductance can be reduced, as required by the majority of systems, or increased using appropriate techniques as is the case of resonant circuits. This technology applies to several fields, from high-power application magnetics to low-power supply circuits.

But before applying planar magnetics to any project, it is important to consider the advantages and drawbacks of this technology. The following pages will take an in-depth look at how an efficient design workflow can help you get the most out of planar magnetics and include useful design recommendations and application examples.

Advantages and drawbacks

The main advantages of planar magnetics technology [1] are:

- **a low profile:** planar magnetic components are up to one-half or even less the height of conventional ones;
- **optimized thermal characteristics:** planar magnetic cores feature better thermal characteristics to conduct heat and maintain the device to temperatures lower than the wire-wound ones. The planar magnetic cores make this possible as they have a surface area to volume ratio higher than conventional ones, generating an efficient heat exchange with the surrounding environment.

For a reliable comparison, we have chosen two transformer designs, one conventional and one planar. They are designed for a flyback converter, whose technical specifications are listed in the table below.

V_{IN}	12V
V_{OUT}	24V
Power	50W
Switching frequency	100 kHz

Table 1. Flyback specifications

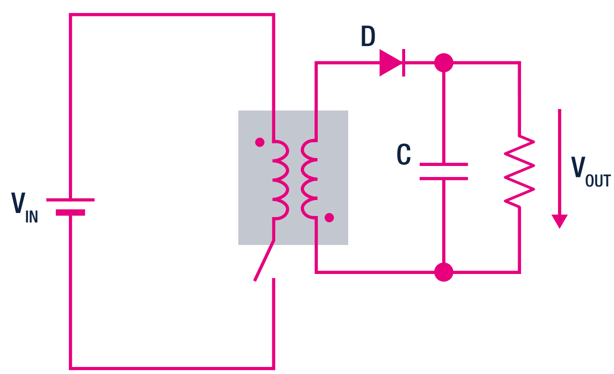


Figure 3. Flyback converter topology

We have compared two transformers with the same inductive value at the primary $L_{prim} = 20\mu H$ and $n = 2$, approximately the same volume, and the same materials.

The designs have the following characteristics.

Core Type	E38/8/25
Core Material	3C92
Volume	8477 mm^3
Window fill factor	34.37

Table 2. Planar transformer design specifications

Core Type	R12/I
Core Material	3C92
Volume	8264 mm^3
Window fill factor	41.69

Table 3. Concentric transformer design specifications

A power loss of 348 mW is dissipated in the planar transformer and a power loss of 434 mW is dissipated in the concentric transformer. They have the same boundary conditions: an ambient temperature of 20°C and a natural heat convection and radiation. They reach different thermal values.

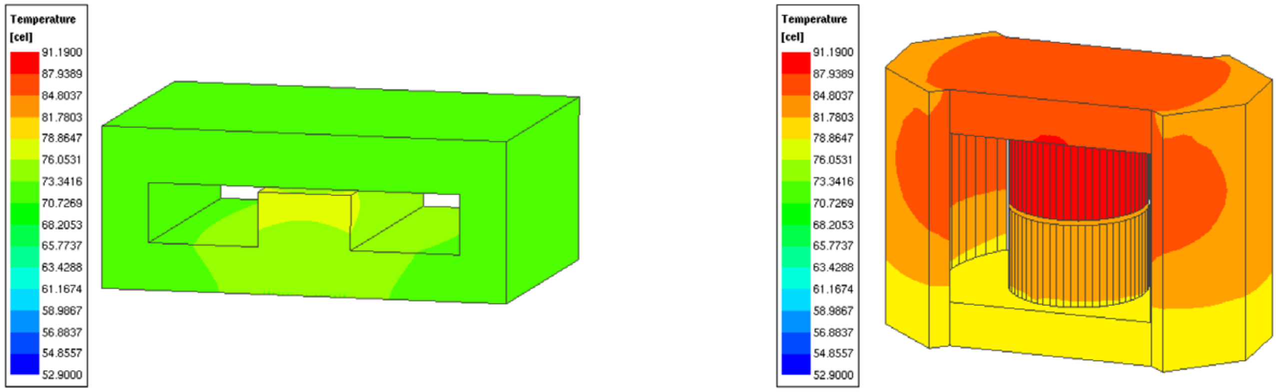


Figure 4. Planar vs concentric temperature profiles comparison

By adding an aluminum dissipation plane, we obtain the following results.

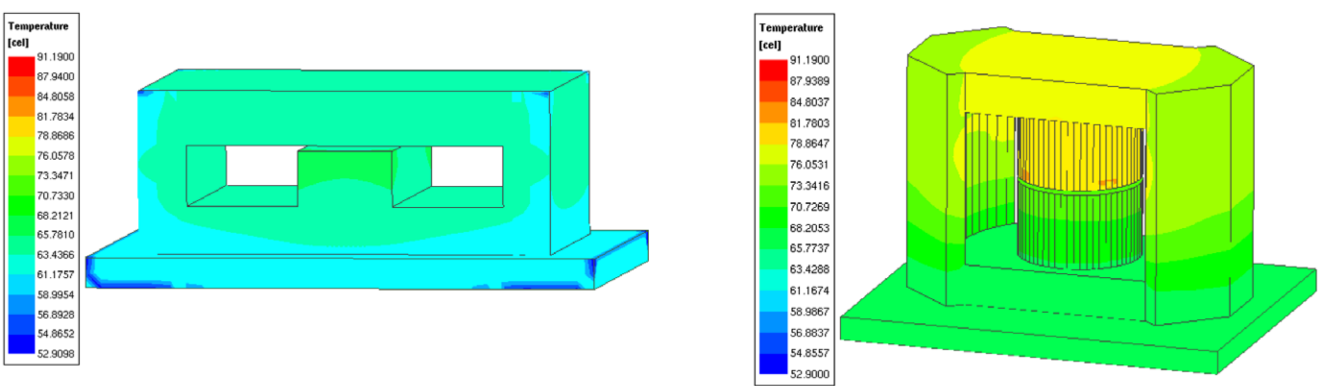


Figure 5. Planar vs concentric temperature profiles comparison with aluminum plate

The heat dissipation plane further improves the thermal dissipation when applied to a planar geometry, with respect to a conventional one.

Other advantages are :

- **automation, ease of manufacturability, and cost reduction:** the conventional assembly process allows manufacturing the planar magnetic components with an incomparable repeatability and accuracy. In fact, it is difficult to automate the winding of conventional inductors and transformers. On the contrary, the production and assembly processes used in the planar magnetics are linked to innovative technological tools, which simplify the automation. In particular, PCB technologies are suitable for global manufacturing;
- **PCB modularity:** can also be assembled without extra connections. The different core shapes and the PCB construction generate different form factors;
- **predictable parasitic effects:** the planar winding layout is easy to control and achieve an interleaved solution, which means lower leakage effects and lower windings capacitance. In wire-wound components, it is more complicated and not always possible to achieve this goal.

The main drawbacks of the planar technology are :

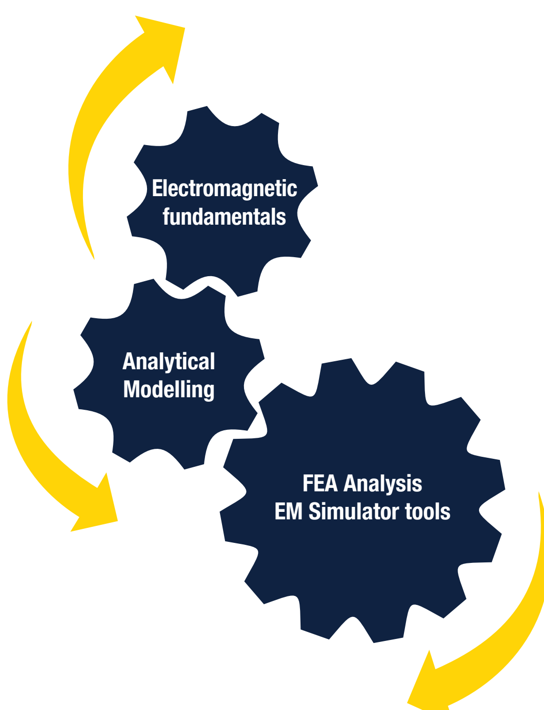
- **a large footprint:** the occupied area is larger than the area of a conventional one, whereas the height is lower;
- **a low copper fill factor:** the copper fill factor is generally low if the PCB is used to carry out planar windings. This is due to some structural limitations of the PCB technology; that is, the minimum inner turn spacing is twice the copper thickness plus 50 µm and the minimum dielectric thickness among layers (equivalent to about 100 µm for a standard board);
- **a limited number of turns:** designs have to use a limited number of turns as the increase in the number of turns leads to a greater number of PCB layers, raising the PCB manufacturing costs. The winding width could be decreased to gain more space, causing the DC resistance to rise and the current capability to decrease;
- **a high interwinding capacitance:** structurally, the windings made with PCB technology pile up and occupy more space than the conventional ones, increasing the parasitics effect capacitance;
- **a lack of accurate analytical models** for typical structures;
- **a longer mean turn length (MLT)** and, consequently, **higher DC resistances** due to the core shape;
- **EMI to be evaluated** for some structures with coils partially outside of the core, as this can create noise to the surrounding devices.

The design of a planar component requires an in-depth knowledge of the laws of electromagnetism, magnetic materials for power electronics, losses in magnetic components, magnetic phenomena like skin and proximity effects, airgap fringing effects, leakage inductance, stray capacitance, etc.

It is necessary to start from an analytical approach, mastering the theory behind the design and using a design verification tool. Offering different levels of complexity, verification tools help designers determine the correct solver to use and facilitate the creation of a magnetic model by defining its material, creating a region, assigning boundary conditions, excitations, parameters, and meshing. These tools also help designers decide how to best set up a solution, define the required post-processing, and interpret the results in a user-friendly way.

Required knowledge

- Laws of electromagnetism
- Magnetic materials for power electronics
- Losses in magnetic components
- Skin effect
- Proximity effect
- Airgap
- Fringing effects around airgap
- Leakage inductance
- Stray capacitance



Design check and correction, if necessary

- Dealing with the problem and choosing the most suitable tool
- Choice of the correct solver
- Model creation and material assignment
- Excitations and parameter assignement
- Meshing and solution setup
- Post processing and interpretation of results

Analytical approach

- Formulas and rules

Figure 6. Mastering planar magnetics design

Planar magnetics design

This section describes a simple design workflow for a flyback converter coupled inductor, which operates with an isolation between primary and secondary inductances. For a deeper understanding of the technical concepts of magnetic equations and parameters, please read a dedicated book, for example, [2].

A magnetic device is characterized by its magnetizing or primary inductance, the core shape and material, the number of turns and, for the planar devices based on multilayer PCBs, by copper tracks dimensions and placement on the PCB stack-up.

Once the power converter (in this example, the flyback) characteristics have been fixed (the power, voltage, and current ratings, the operating frequency and duty cycle, the maximum temperature admitted for the magnetic device, etc.), select a core candidate, in terms of material and dimensions. In this phase, the designer experience plays an important role, often supported by the design guidelines provided by the core manufacturer documentation.

The core selection impacts the magnetizing inductance (or primary inductance for a flyback converter), according to the following formula:

$$L_m = \mu_0 \mu_r N_p^2 \frac{A_e}{l_e} = N_p^2 A_l \qquad (1)$$

where μ_r is the relative permeability of the core material, N_p is the number of turns on the primary side, A_e is the core cross-sectional area, and l_e is the core magnetic path length.

When the core shape, size, and material are identified, the manufacturer datasheet can provide an additional magnetic parameter, the inductance factor A_l, often referred to the ungapped core (sometimes, A_l is provided for the available variants of the same core at different gaps). Once the inductance has been established, this value allows setting the minimum required number of turns at the primary winding, by reverting the last term of (1):

$$N_{p,MIN} \geq \sqrt{\frac{L_m}{A_l}} \qquad (2)$$

Then, the selected core geometry must satisfy the relation between the core product area, capable of handling the required energy, and the core material properties. The following formula can be used for this purpose:

$$A_e \times A_w \geq \frac{L_{PRI} \times I_{PRI,PK} \times I_{PRI,RMS}}{K_w \times B_{MAX} \times J} \qquad (3)$$

where A_w is the core window area, K_w is the window factor, $I_{PRI,PK}$ is the primary peak current, $I_{PRI,RMS}$ is the primary RMS current, B_{MAX} is the peak flux density, and J is the copper wire current density.

The core material choice is then driven according to the inductance factor A_l and the converter switching frequency.

As the core constitutes one of the most significant parts of magnetic device, its temperature plays an important role in the overall operating temperature. [3] reports some formulas for planar E-shaped cores, which allow estimating the temperature rise of the transformer as a function of flux density in the core. The latter needs to be maximized to balance the limited available winding space (an intrinsic characteristic of the planar magnetics based on multilayer PCBs).

Assuming that the core is responsible for half the total planar transformer losses, it is possible to express the maximum core loss density P_{core} as a function of the maximum allowed ΔT:

$$P_{core} = \frac{12\ \Delta T}{\sqrt{V_e\ (cm^3)}} \qquad (mW/cm^3) \qquad (4)$$

where V_e is the effective core volume.
Core losses density can be approximated by the Steinmetz equation [4]:

$$P_{core} = C_m \cdot f^x \cdot B_{MAX}^y \cdot (ct_0 - ct_1 T + ct_2 T^2) = C_m \cdot C_T \cdot f^x \cdot B_{MAX}^y \qquad (mW/cm^3) \qquad (5)$$

where all the parameters x, y, C_m, C_T depend on the ferrite material and are provided by the core manufacturer.

From equation (5), B_{MAX} can be expressed as a function of P_{core}:

$$B_{MAX} = \left(\frac{P_{core}}{C_m \cdot C_T \cdot f^x}\right)^{1/y} \ (T) \qquad (6)$$

By replacing P_{core} calculated in (4) in relation (6), it allows estimating the maximum value of B at a given temperature T.

The actual number of turns N_p at the primary winding depends on the primary inductance, the peak current, and the peak flux density for a given core cross-sectional area [3]:

$$N_p = \frac{L_{PRI} \times I_{PRI,PK}}{B_{MAX} \times A_e} \qquad (7)$$

If the turns ratio n is given by the application constraints, the number of secondary winding turns can be easily determined:

$$N_s = n \times N_p \qquad (8)$$

For the actual values of N_p and N_s, usually, the nearest whole number is assumed to be the best choice.

To determine the cross-sectional area of the PCB copper tracks that constitute the primary and secondary coils, the following formulas apply, assuming that the RMS values of the primary, secondary current and the specifications on the current density values are known:

$$A_1 = \frac{I_{PRI,RMS}}{J_{PRI}} \quad \text{and} \quad A_2 = \frac{I_{SEC,RMS}}{J_{SEC}} \qquad (9)$$

It is important to determine how to distribute the primary and secondary coils among a pre-assigned number of PCB layers. Two major factors affect this choice: the temperature rise due to the current flowing on the PCB tracks and the available winding window width. The latter depends on the selected core geometry.

An additional fundamental design constraint applies to reduce the proximity effects of the winding currents (that greatly affect the AC resistance), by strategically stacking the primary and secondary layers (interleaving technique). The choice of the copper track thickness and width, according to the target PCB stack-up, is often constrained by the host application and the core size.

Another important aspect concerns compliance with certain standards. For instance, the Safety Standards IEC 950 require 400 *μm* through the PCB material (FR4) for the mains insulation between the primary and secondary windings.

The track width of a winding depends on (9), once the PCB copper thickness is given. This happens when the PCB stack-up is established in advance by the host application and the planar device must be integrated in the board. The spacing *s* between the turns is affected by the PCB production capabilities and costs. The rule of thumb for a copper layer thickness of 35 *μm* is a track width and spacing of >150 *μm* and for layers of 70 *μm* >200 *μm* [2].

For a given winding width W_w, a simple formula provides the track width T_w, once the number of turns per layer N_{PL} and the spacing s are given:

$$T_w = \frac{W_w - (N_{pl} + 1) \times s}{N_{pl}} \qquad (10)$$

This calculation is made to accommodate the maximum turns per layer in a given winding width.

The allowable temperature rise given by the RMS current, as a first approximation, can be determined by following the IPC-2221 standards, once the copper track thickness and width have been calculated. However, it should be considered that these indications refer to DC currents, whereas in power converter applications, the high frequency AC current causes Eddy current effects, which can be subdivided in the well-known skin and proximity effects. These effects significantly impact the actual winding resistance, their losses, and the actual temperature rise.

Then skin depth δ depends on the material properties, such as conductivity and permeability. It is inversely proportional to the square root of the frequency. When the track width T_w is less than 2δ, the skin effect is negligible. If a wider track is required, a solution could be to split the track up into parallel tracks.

The fields due to other conductors in the vicinity cause the proximity effects. When the primary and secondary layers are interleaved, this effect strongly decreases.

Once a planar magnetic device design has been completed, it can be modeled and verified through the finite element analysis (FEA). 2-D and 3-D FEA simulations support the design process to ensure that the design requirements and specifications are matched. Moreover, they accurately evaluate the leakage inductance and self-capacitance. Analytical methods can calculate these parameters approximately. These tools can also perform thermal profiling, given that the electrical waveforms of current and voltage are provided to the component terminals (transient analysis).

The following section describes a tool by Ansys dedicated to magnetics design. The tool effectively supports the entire development cycle, including design and validation.

Ansys workflow for planar design and verification

Virtual prototyping for electronics transformer-type devices is gaining importance for a well-tuned and efficient design workflow. This requires design and modelling skills and the use of multiple solvers and tools to address all the relevant phenomena regarding different physical domains.

The Ansys portfolio offers a complete workflow for the magnetic, multiphysics, and system analysis of multi-winding electronic transformers as shown in the figure below.

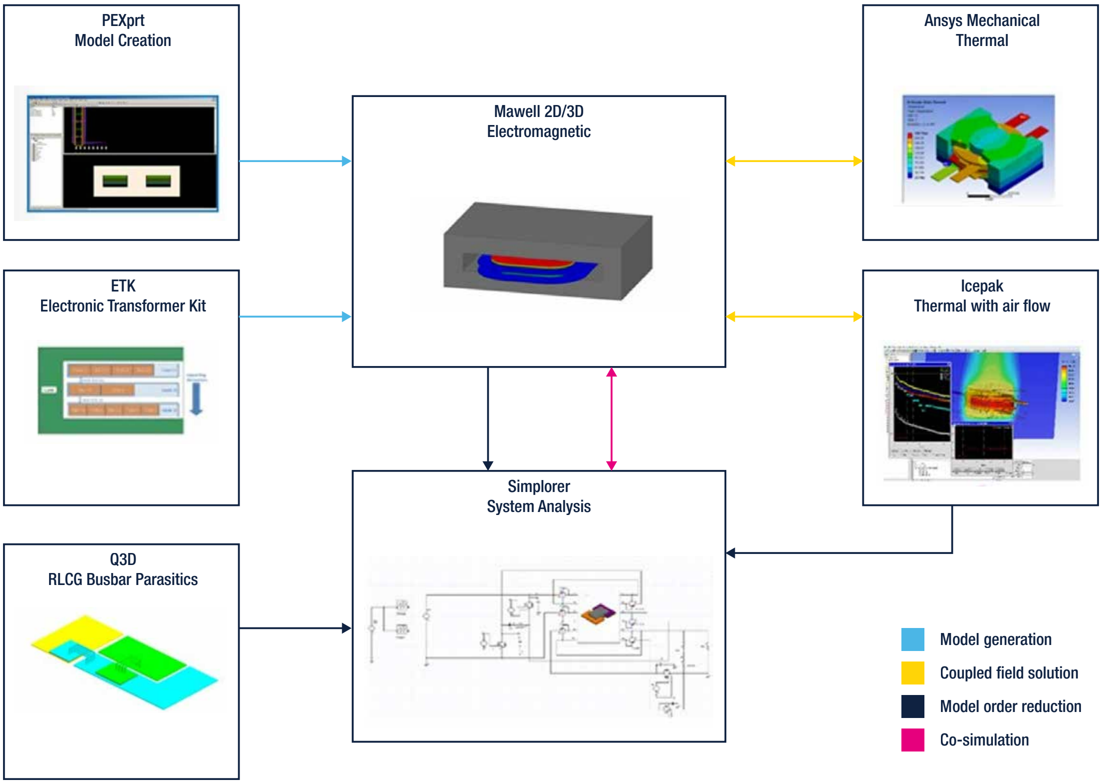


Figure 7. Ansys workflow for magnetic components for power electronics

Different options are offered to the user at each stage. To simplify the workflow, we differentiate its stages as follows:

- design/preprocessing
- device parameter identification/equivalent circuit
- low frequency electromagnetic analysis
- coupled field analysis: thermal management
- system simulation/digital twin

We recommend relying on Ansys Maxwell field simulation capabilities for an accurate parameter identification and the equivalent circuit generation in the frequency domain. Then, investigate the transient behavior at system level. In this way, the influence of the surrounding circuit elements and parasitic effects is also taken into account. Moreover, the system approach better captures the challenging behavior of the waveform with steep derivatives, which is typical of these kinds of components.

DESIGN/PREPROCESSING

A first design sketch or device layout model is needed to start the workflow. This can be generated in different ways depending on the project phase (design specification, detailed design, or validation).

Defined geometry layout

If the design is already defined in terms of geometry and materials, a 2D or 3D model can be generated through the Ansys tools shown in the figure below, where the recommended input sources are noted with the green check mark.

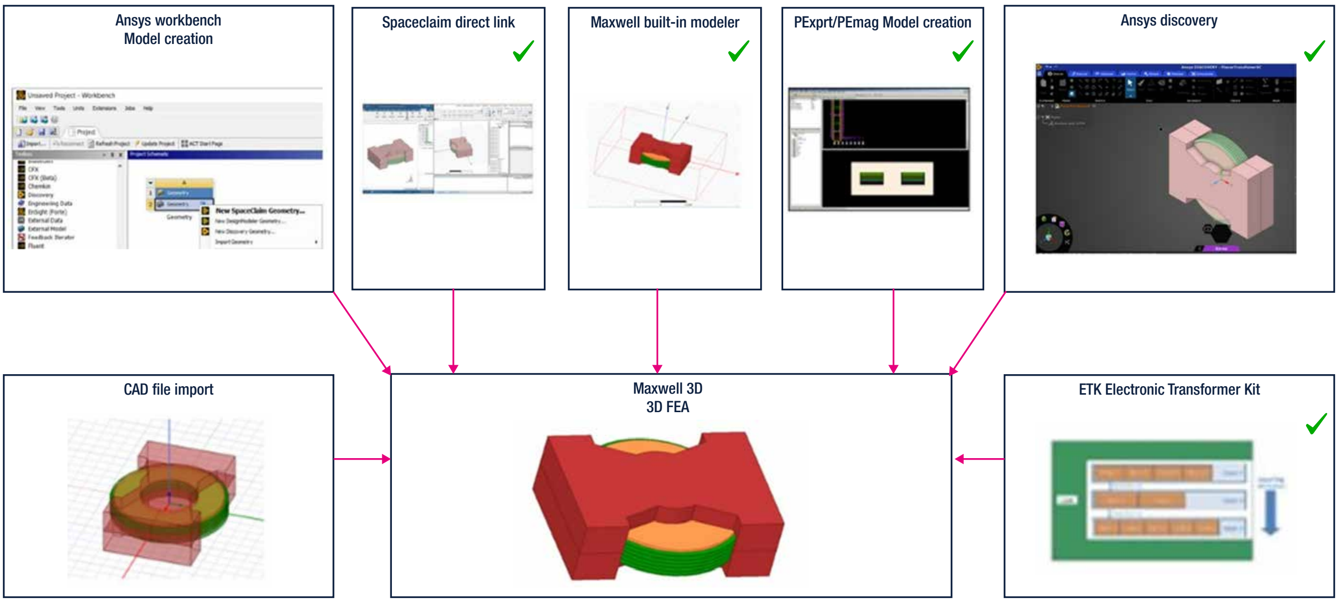


Figure 8. Ansys Maxwell input geometry

Undefined geometry layout

If the design does not exist yet, you can build an analytics-based first design via the Ansys PExprt tool.

PExprt is an analytical tool for the design of different topologies of small converters for power electronic applications. It includes standard libraries for cores, wires, bobbins, insulators, and materials. It creates potential designs that can be automatically analyzed and modeled for different types of devices, such as inductors, multi-winding transformers, and flyback converters.

The full list of available templates is shown in Figure 9. The converter chosen for the design can be waveform-based or converter-based. In each case, you can insert the corresponding design specification.

PExprt also includes the PEmag module, which allows editing of the device layout that results from the chosen design, as well as generating a full Ansys Maxwell model.

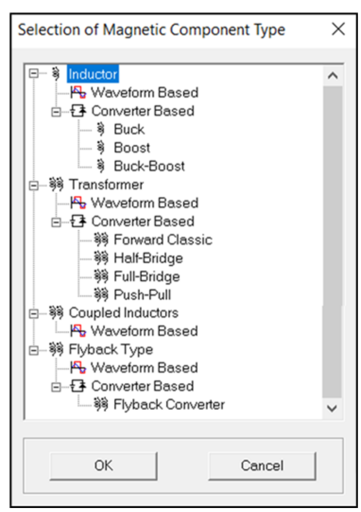


Figure 9. PExprt available templates

DEVICE PARAMETER IDENTIFICATION/EQUIVALENT CIRCUIT

The parameter identification stage is performed within Maxwell, generating:

• an impedance matrix for all the needed frequency points through a frequency sweep FEM simulation run within the Eddy Current solver (in this case, a direct link to Ansys Simplorer/Ansys Twin Builder with a good quality fitting of the parameters)

• if needed, a capacitance matrix obtained through an electrostatic simulation, which is imported into the system simulator as a separate block, as shown in the figure below.

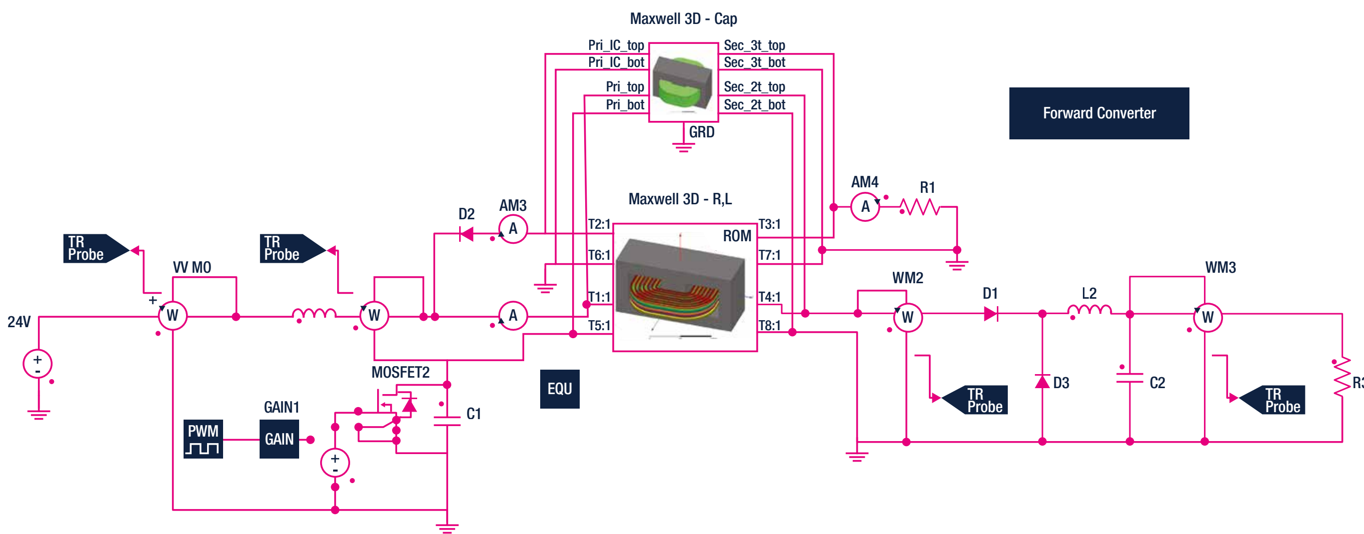


Figure 10. Electronic transformer Simplorer system simulation, reduced-order models (ROMs) created with Maxwell

LOW FREQUENCY ELECTROMAGNETIC ANALYSIS: BEST PRACTICES

For electronic transformer applications (mW-W power), where the analysis over a wide frequency range is needed (DC-MHz), the Eddy Current solver is mainly used.

Through the Eddy Current solver, it is possible to extract the device impedance matrix vs. the frequency as mentioned above. Through the simulation, with a proper excitation setting, it is also possible to evaluate the losses that result from the sinusoidal excitations. These device challenges also include nonlinear materials, eddy currents, proximity effects, and time diffusion of magnetic fields. Therefore, to perform a complete and accurate study for an electronic transfomer, we suggest the following simulations:

• **no-load analysis:** the primary windings are fed at rated conditions (usually at a rated voltage) and the secondary windings are open circuit;

• **full-load analysis:** the primary windings are fed at rated conditions (usually at a rated voltage) and the secondary windings are closed on the rated load;

• **short-circuit analysis:** the primary windings are fed at rated conditions and the secondary windings are short-circuited (closed on a very small resistance); the secondary windings are short-circuited (closed on a very small resistance) while the primary windings are fed at reduced conditions so that the rated currents are flowing (laboratory test);

• **in-rush analysis (transient only):** startup due to a sudden change in the supply during turn-on.

In addition:

• a magnetostatic run can be useful to evaluate the operating point on the B-H curve of the core material at no load. Usually, a good design should prevent operating points in the nonlinear region of the B-H curve and a scalar value can used;

• a transient run is used in case of a nonsinusoidal excitation to study losses; according to the geometry layout, this simulation can be performed either in 2D or 3D. In the transient case, it is also possible to capture nonlinear phenomena occuring in the cores.

COUPLED FIELD ANALYSIS: THERMAL MANAGEMENT

The Ansys Electronics Desktop Platform (AEDT) can also perform multiphysics analysis. The most useful analysis for an electronic transformer is the coupled electromagnetic-thermal simulation, which takes advantage of the built-in coupling capability among AEDT Maxwell, AEDT Icepak, and AEDT Mechanical Thermal as shown in the figure below.

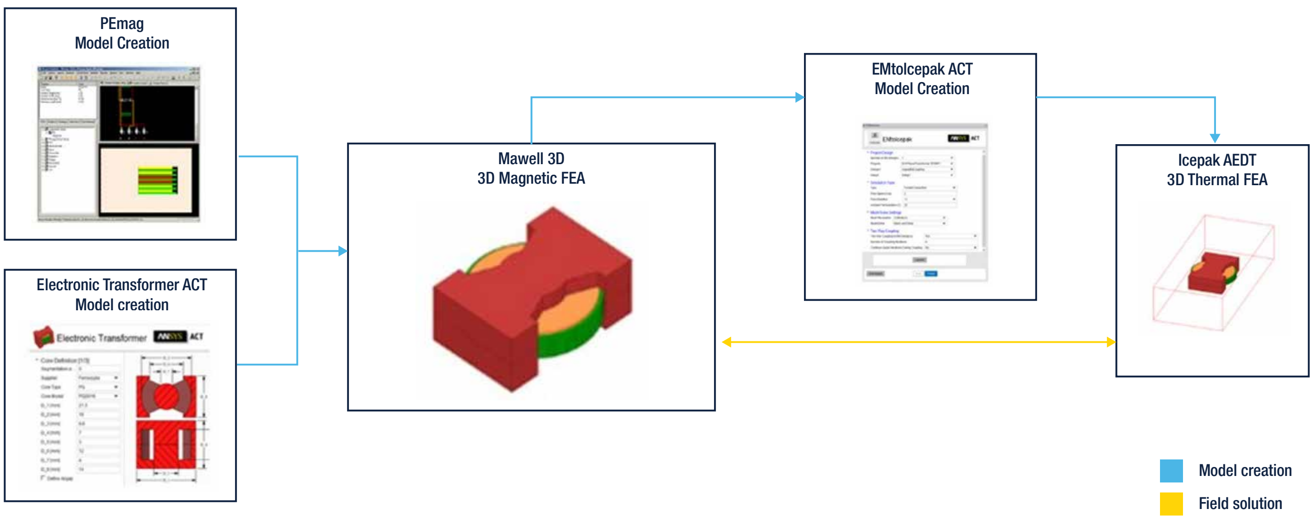


Figure 11. Electromagnetic-thermal coupling via Ansys Application Customization Toolkit (ACT)

In the shown example, Maxwell Eddy Current can be used to simulate losses at a sinusoidal frequency. Then, the EM-to-Icepak Application Customization Toolkit (ACT) can be used to create and automatically solve an Icepak AEDT model, including a two-way coupling.

Application examples

Planar transformers and inductors represent the ideal solution for efficient SMPS applications. The following sections show some examples of these applications: flyback, iso-buck, and LLC converter topologies.

Flyback topology

One of the most used topologies for a power range of few watts to 150 W is the flyback converter.

During the power transistor on-time, some energy is stored in the transformer while the output capacitors supply the load. When the transistor is turned off, the energy stored in the transformer is used to feed both the load and the output capacitors.

The figure below shows an application example.

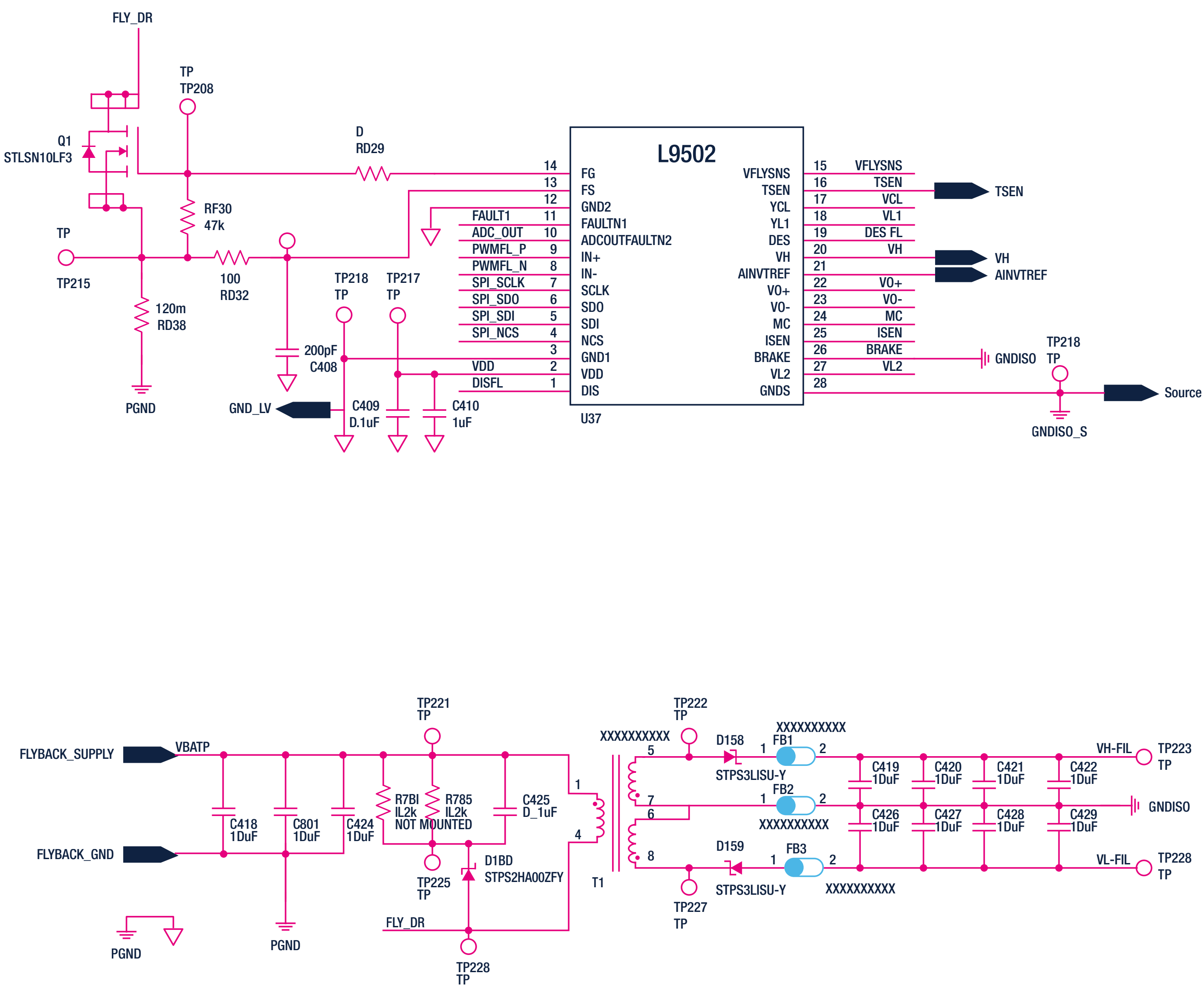


Figure 12. Electrical schematic of a flyback converter based on the L9502 driver

The converter is supplied by 12 V_{DC} that provides an output of +18/-5 volts for a total power of 3 watts with an operating frequency at 400 kHz.

The core used is E14/3.5/5 + I 14/1.5/5 by Ferroxcube. A clamp is used for the assembly as shown in the figure below based on ST's L9502 single-channel, isolated gate driver for traction inverters.

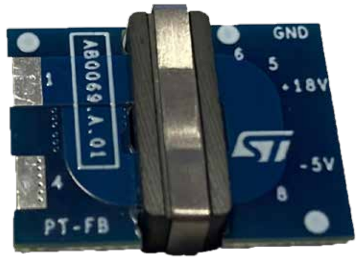


Figure 13. Planar transformer of a flyback based on the L9502 driver

The transformer has a power of 3 W, with a primary inductance with four turns distributed over four layers and a secondary inductance with four turns distributed over two layers.

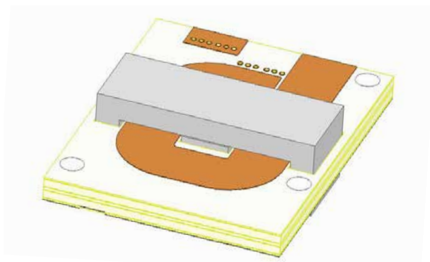


Figure 14. 3D planar transformer model for a simulation tool based on the L9502 driver

Therefore, the overall number of layers is six. The thickness of the copper used is 35 µm.

The planar transformer has a very low profile compared to the wired transformer, as shown below.

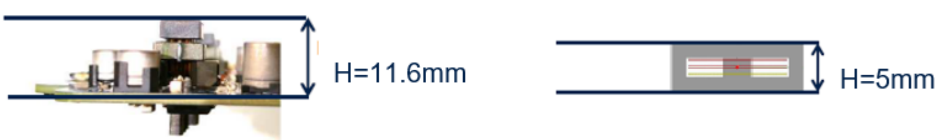


Figure 15. Height comparison: conventional transformer vs. planar transformer

Iso-buck topology

The isolated buck topology (iso-buck) is becoming a very popular solution for low-power isolated DC-DC applications. It combines the advantages of flyback and synchronous buck converter topologies to achieve a simple, isolated design with a smaller size and lower BoM cost.

The iso-buck converter shown in Figure 16 is based on ST's **L6986I synchronous iso-buck converter** which consists of:

- a primary side: the regulation loop of the peak current mode architecture regulates the primary voltage (light blue box)
- a two-winding transformer (in the grey area)
- a secondary side, which generates the isolated output voltage (yellow box) given the selected transformer ratio

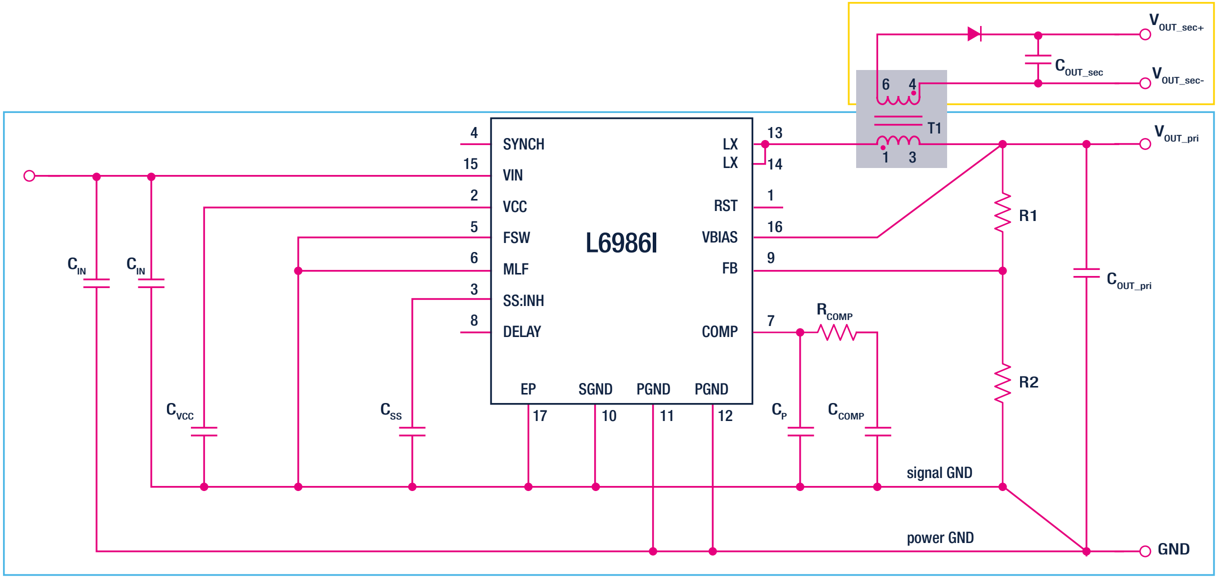


Figure 16. Isobuck general schematic with the L6986I controller

The transformer is the key component for the iso-buck. It ensures the desired isolation and allows transferring the energy to the secondary side, generating the secondary isolated output voltage.

Thanks to its customization as a planar magnetic device, the application board reaches new limits in terms of space reduction, low profile, EMI reduction, and overall solution costs.

The transformer has a power of 3 W, with a primary side that has five turns distributed over two layers and a secondary side that has 11 turns distributed over four layers.

Therefore, the total number of layers is six. The thickness of the copper used is 35 μm.

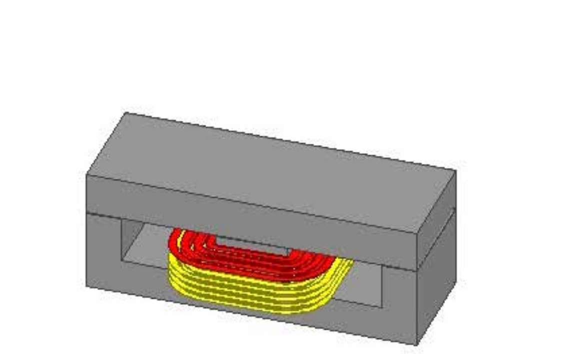


Figure 17. 3D planar transformer model for simulation tool – L6986I

The core used is E14/3.5/5 + I 14/1.5/5 by Ferroxcube. A clamp is used for the assembly.

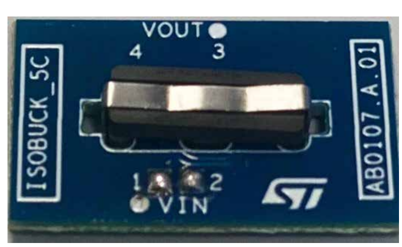


Figure 18. Planar transformer of an isobuck based on the L6986i

LLC topology

The LLC is the most used type of resonant converter. This topology can work from few watts and, theoretically, can reach any desired output power.

The figure below shows an example of LLC circuit.

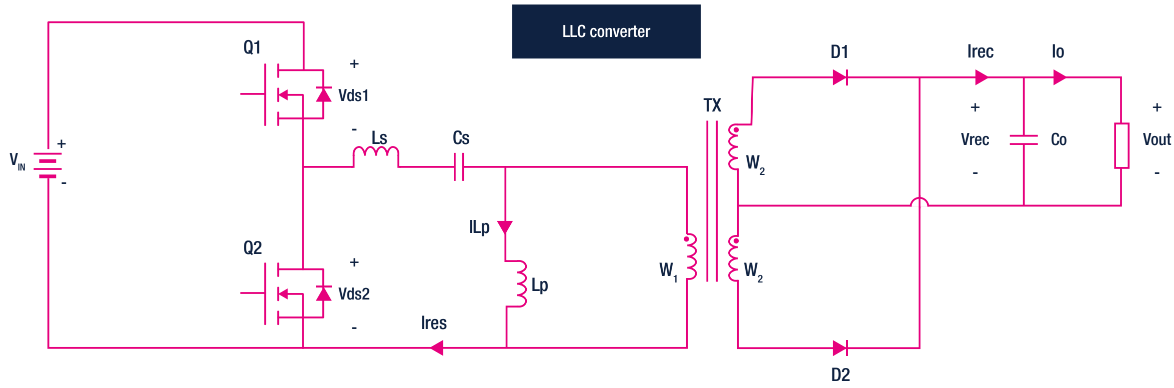


Figure 19. LLC converter schematic

A key characteristic of the resonant converters is the high efficiency they can achieve as well as the high frequency operation with a wide soft switching operative range.

A conventional resonant converter consists of three sections: a switch network, a resonant tank, and a rectifier network. The switch network generates pulses from a DC bus that feeds the resonant tank. Through the transformer, the tank transfers the power to the secondary side where a rectification network generates a DC source from the received pulses.

The resonant tank, which consists of the two inductors and the capacitor for the LLC, is tuned to resonate at a given frequency (resonance frequency).

In the following example, a PFC bus at 400 V_{DC} supplies the LLC converter which provides an output of 22.5 volts up to 420 W.

The transformer has nine turns distributed over three layers on the primary side and a secondary side with two turns distributed over two layers. The thickness of the copper used is 105 µm.

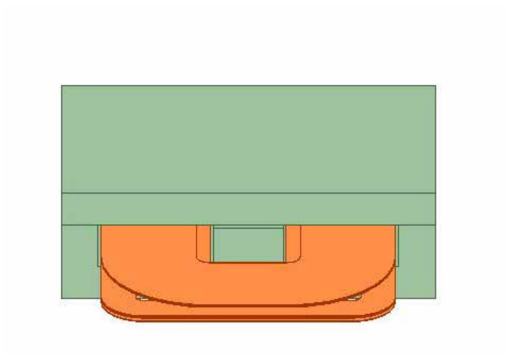
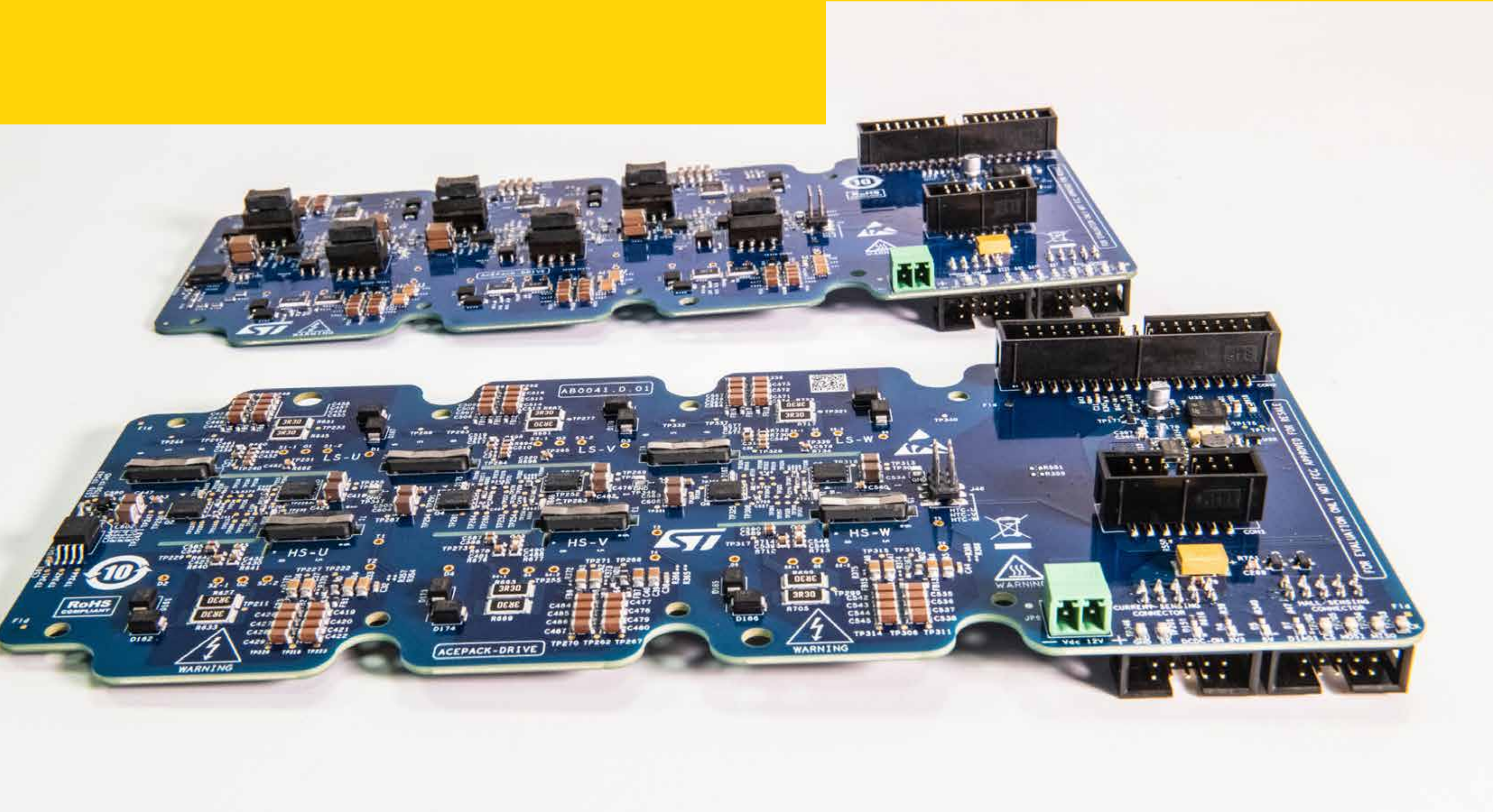


Figure 20. 3D planar transformer model for simulation tool – LLC

The core used is ELP 43/10/28+I43/1.5/28 by TDK.

Figure 21. Planar transformer for LLC

Conclusion



After reading this whitepaper, you should have a good understanding of the advantages of planar magnetic technology and how an automated workflow can easily help engineers optimize their power electronics designs. We specifically looked at Ansys Maxwell 3D software, a user-friendly solution that can accurately conduct electromagnetic analysis in the frequency and time domains.

In conclusion, the combination of planar magnetic technology with fine engineering provides a higher power density and more cost-effective solution tailored to your specifications in a unique way.

Planar transformers and inductors are the ideal solution for efficient SMPS applications

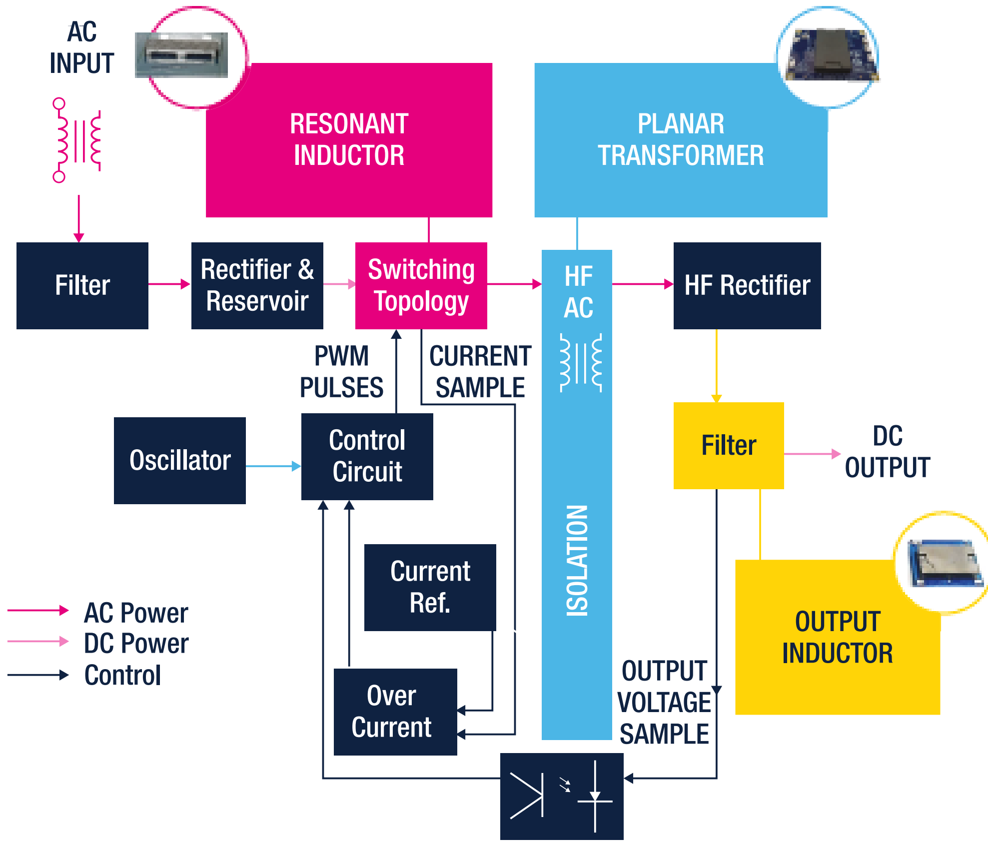


Figure 22. Switch mode power supply planar magnetic applications

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ADDITIONAL RESOURCES

Power Supply Design Tool (part of our eDesignSuite set of easy-to-use design-aid utilities) [Design tool page]

Silicon-Carbide STPOWER MOSFETs and diodes [SiC device portfolio page]

L6986I 38 V, 5W synchronous iso-buck converter [Product page]

Power supplies and converters [Application page]

Industrial motor control [Application page]

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