Simulation Analysis

Interleaved Flyback Converter with Integrated Magnetic Transformer:

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1、Integrated Magnetics Technology

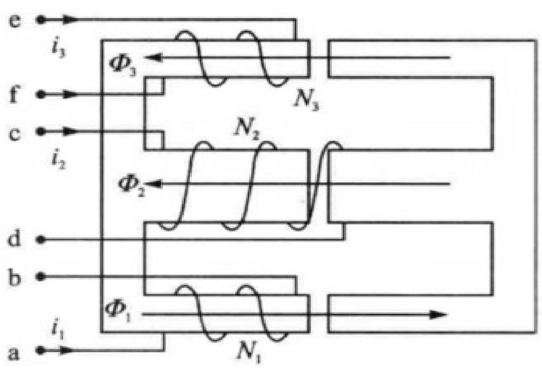
In power electronic converters, magnetic components serve as core elements for energy storage, conversion, filtering, and electrical isolation, playing a pivotal role in determining converter performance. Magnetic components remain one of the primary limiting factors in achieving miniaturization, weight reduction, and power density enhancement of converters. Integrated Magnetics (IM) technology enables the integration of two or more discrete magnetic components (e.g., inductors, transformers) onto a single magnetic core, significantly reducing component count, volume, weight, losses, and costs while improving operational efficiency and power density. Key objectives of IM technology include:

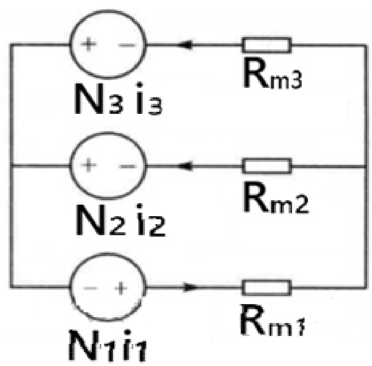
* Reducing magnetic component quantity
* Minimizing maximum magnetic flux density through flux superposition/destruction
* Suppressing magnetic flux ripple to reduce core losses
* Optimizing magnetic flux distribution for improved performance metrics (e.g., input/output current ripple reduction, transient response enhancement)

1.1 Magnetic Component Analysis Methodology

Theoretical analysis of magnetic components relies on fundamental magnetic circuit laws: Ampère's circuital law、Magnetic Ohm's law、Kirchhoff's laws for parallel/series magnetic circuits。Source transfer equivalence transformation is commonly employed for magnetic circuit analysis. This method involves redistributing windings across magnetic limbs while preserving magnetic flux direction and winding inductance relationships.

Consider the original magnetic structure and equivalent circuit:





The corresponding magnetic circuit equations are:

$$\begin{cases} N_1 i_1 - R_{m1}\Phi_1 = R_{m2}\Phi_2 - N_2 i_2 \\ N_2 i_2 - R_{m2}\Phi_2 = N_3 i_3 - R_{m3}\Phi_3 \end{cases}$$

Through source transfer transformation, the equivalent magnetic circuit becomes:

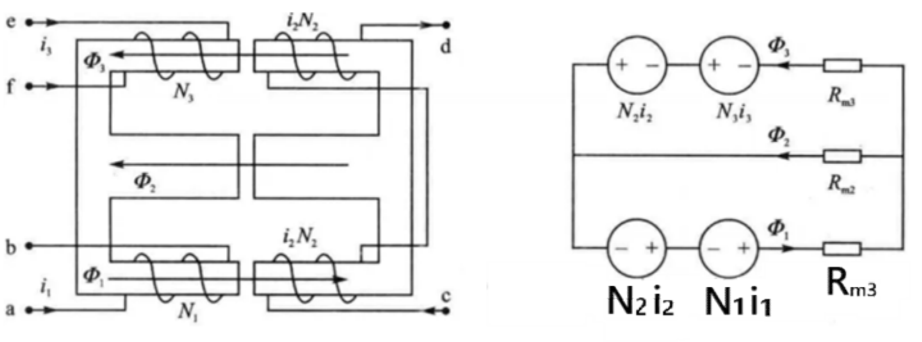
Before:

$$\begin{cases} N_1 i_1 - R_{m1}\Phi_1 = R_{m2}\Phi_2 - N_2 i_2 \\ N_2 i_2 - R_{m2}\Phi_2 = N_3 i_3 - R_{m3}\Phi_3 \end{cases}$$

After:

$$\begin{cases} N_1 i_1 - R_{m1}\Phi_1 + N_2 i_2 = R_{m2}\Phi_2 \\ R_{m3}\Phi_3 - N_3 i_3 + N_2 i_2 = R_{m2}\Phi_2 \end{cases}$$

Transformed Magnetic Circuit Diagram：



This transformation achieves equivalent winding-flux linkage relationships while redistributing magnetic potential distributions.

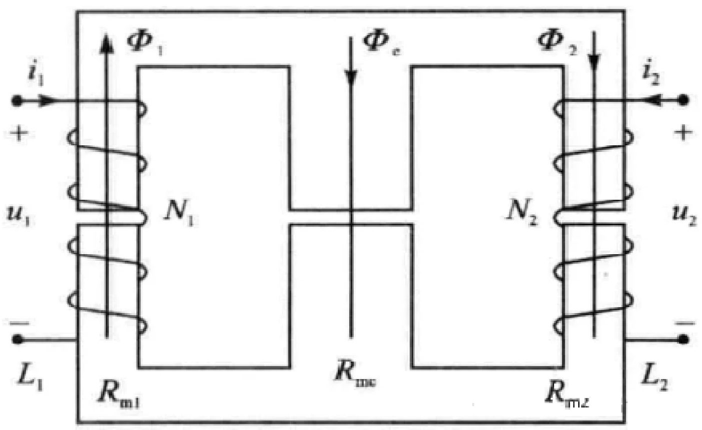
1.2 Magnetic Integration Topologies
Based on magnetic flux interaction mechanisms, IM techniques can be categorized into:

* DC flux superposition/annihilation (for high-frequency inductor-transformer integration)

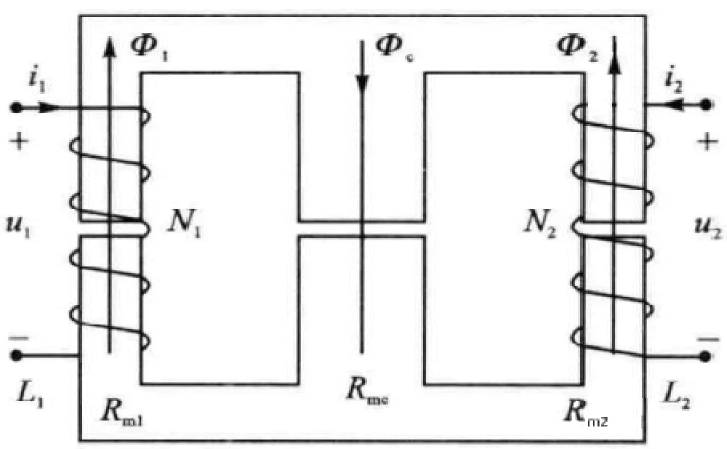
* AC flux cancellation (for general inductor-inductor integration)

* Phase-shifted AC flux coupling (for interleaved inductor-transformer systems)

* Positive/negative flux coupling (for voltage-aligned magnetic components)
Forward coupling increases net magnetic flux：



Reverse coupling suppresses magnetic flux：



As shown in the coupled inductor structures:Forward/Reverse Coupling Structures。Where forward coupling exhibits lower central limb DC flux density compared to reverse coupling.

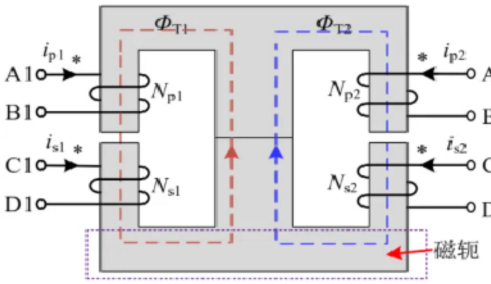
2、Two-Phase Interleaved Flyback Transformer Analysis

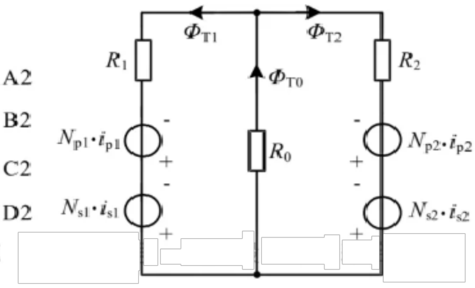
2.1 Decoupling Magnetic Integration Design

This topology integrates multiple magnetic components on a shared core without magnetic coupling. Key features include:

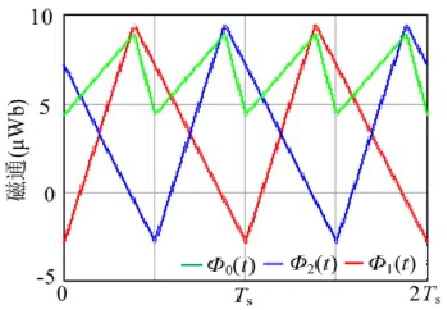
∗ Central limb free of air gaps
∗ Side limb flux decoupling via low-reluctance central path
∗ Optimized core volume utilization

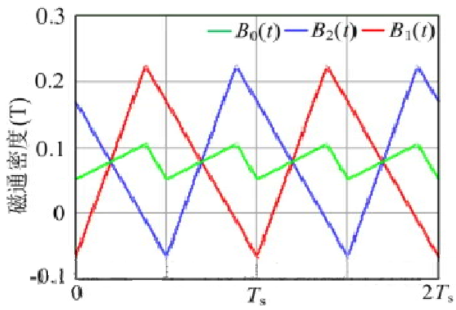
对The integrated transformer structure and equivalent magnetic circuit are shown below:





Magnetic flux and density waveforms demonstrate non-saturation operation with lower central limb flux density:



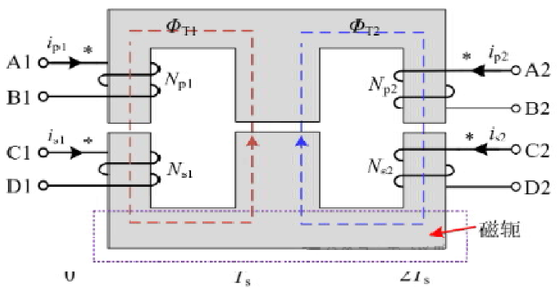


2.2 Coupling Magnetic Integration Design

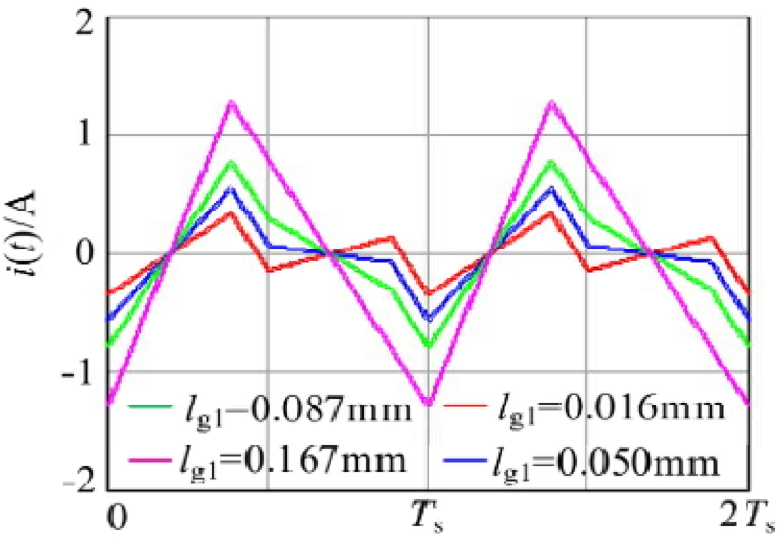
To achieve interleaved current ripple reduction, coupling-type integration is adopted:

∗ Central limb air gap adjustment for coupling coefficient control
∗ Side limb air gap optimization for current waveform shaping

The coupled transformer winding configuration and equivalent magnetic circuit are depicted as follows:



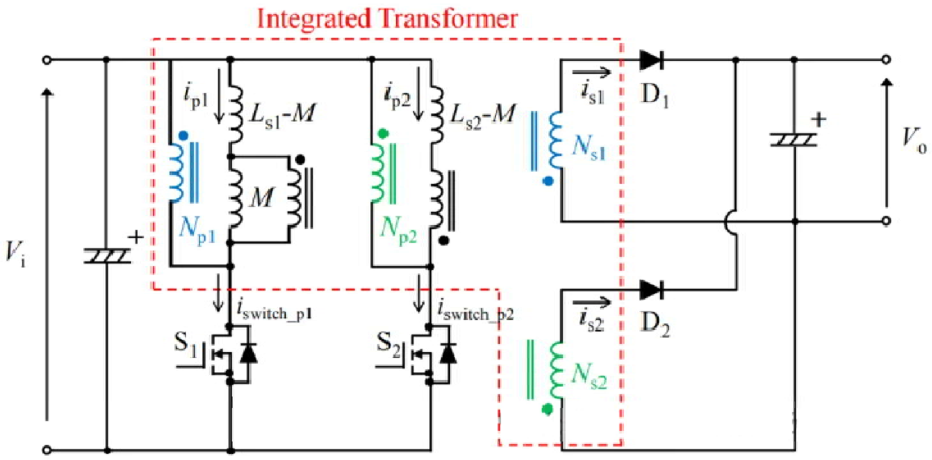
By adjusting the air gap ratio between center and side limbs, the AC component of phase currents can be modulated. Representative current waveforms under varying air gap configurations are shown:



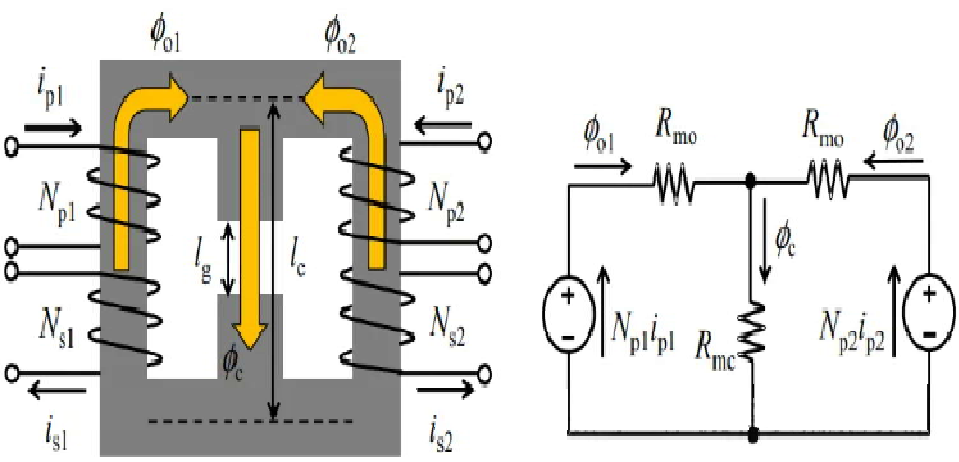
3、Simulation Analysis of Integrated Flyback Transformer

3.1 Simulation Model

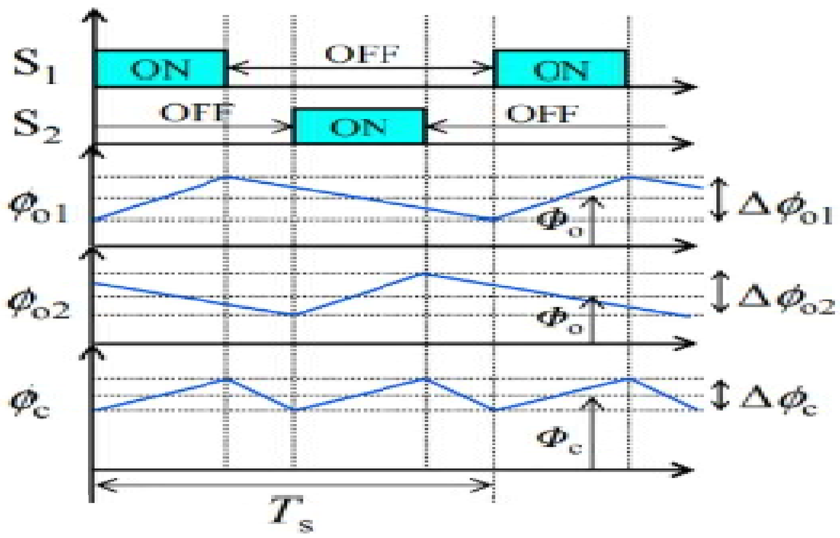
The circuit schematic of the two-phase interleaved parallel flyback converter and its magnetically integrated transformer—used in 3D finite element simulation—is shown below:



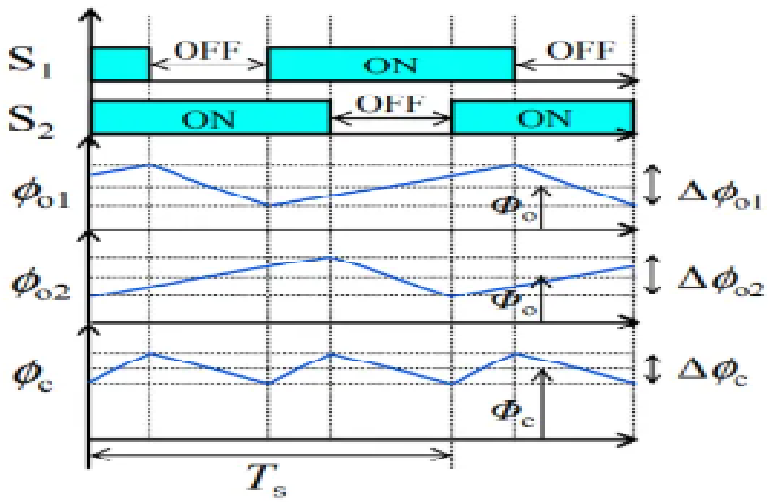
The flyback transformer adopts a coupled magnetically integrated structure, with its winding structure and equivalent magnetic circuit shown below:



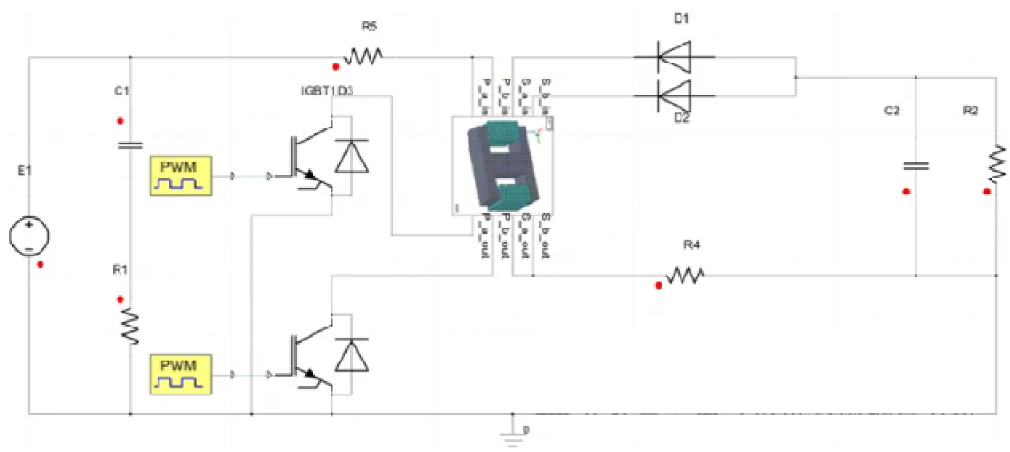
When the duty cycle D<0.5, the flux variations in the side and center legs of the magnetically integrated transformer are as follows:



When the duty cycle D>0.5, the flux variations in the side and center legs of the magnetically integrated transformer are as follows:

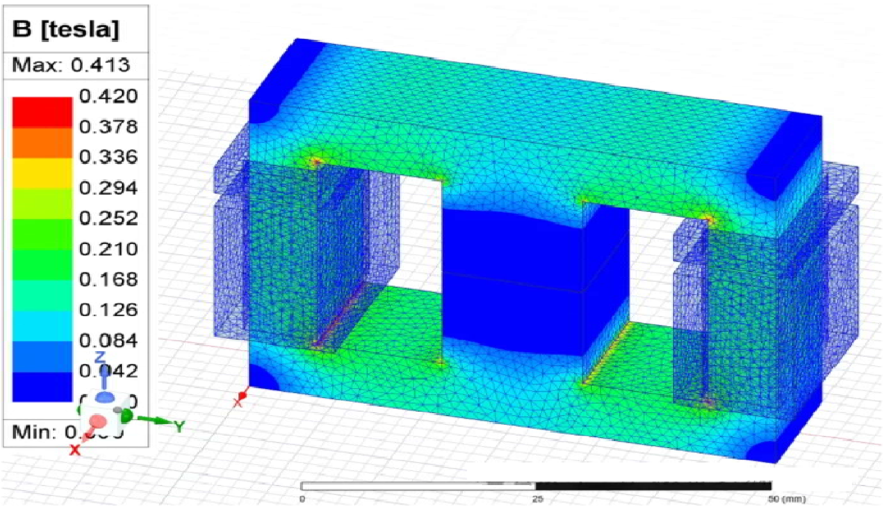


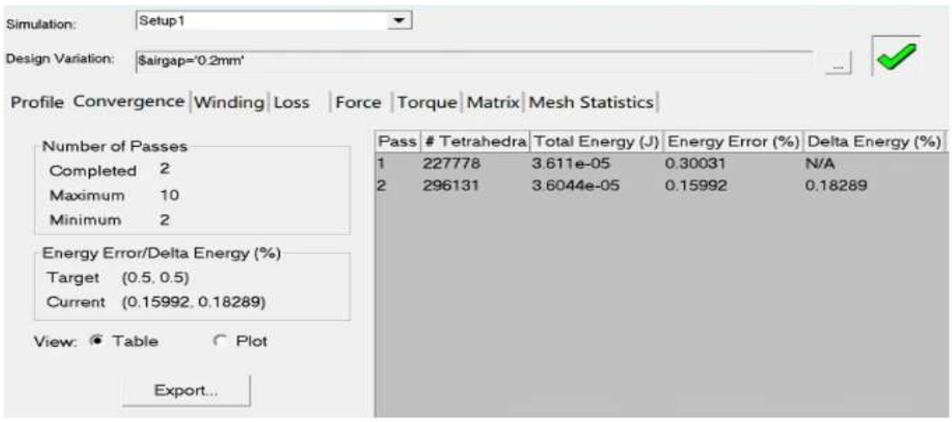
Given the converter's rated specifications: input voltage 48–60 V, output voltage 12 V, output current 5 A, switching frequency 100 kHz. The field-circuit coupled finite element simulation model of the two-phase interleaved parallel flyback converter—established in the Maxwell and Simplorer modules of ANSYS EDT—is shown



The parameter settings for materials, excitation, and boundary conditions in the electromagnetic finite element simulation are consistent with those of the discrete transformer simulation in the two-phase interleaved parallel flyback converter.

In a constant magnetic field, the magnetic flux density distribution and adaptive meshing grid of the magnetically integrated transformer are as follows:

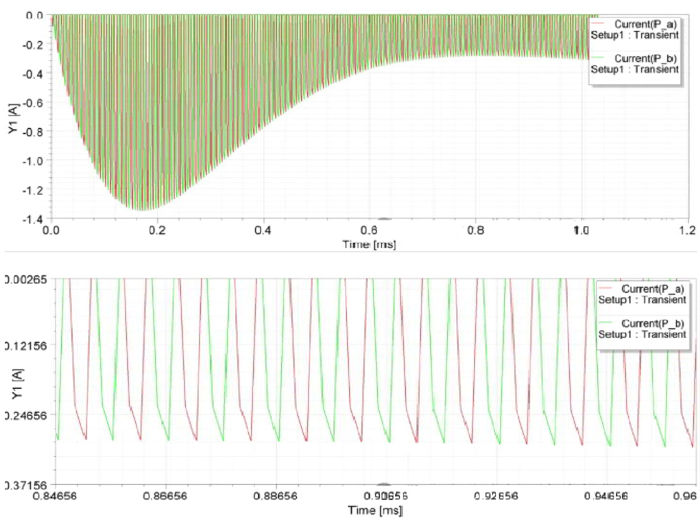




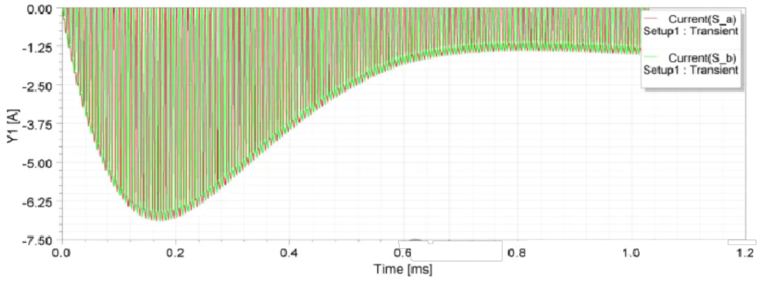
3.2 Magnetically Integrated Flyback Transformer Simulation Results

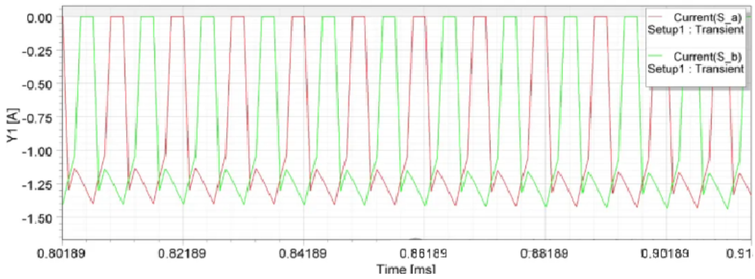
Assuming the converter's switching frequency is 100 kHz, simulation time step 1.5 μs, and total duration 1.4 ms. Various waveforms of the transformer's primary/secondary sides, along with transformer loss distribution, core magnetic flux density distribution, winding current density distribution, etc., are obtained.

Magnetically Integrated Flyback Transformer Primary Current Waveform:

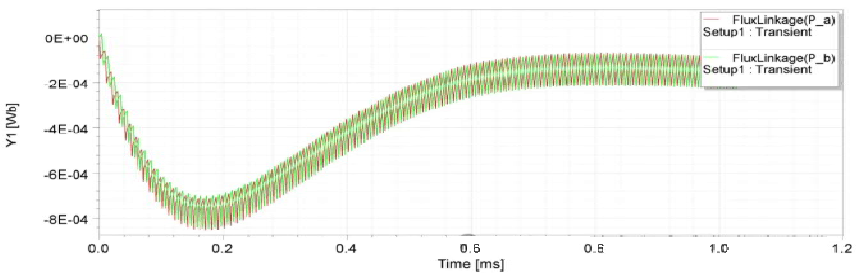


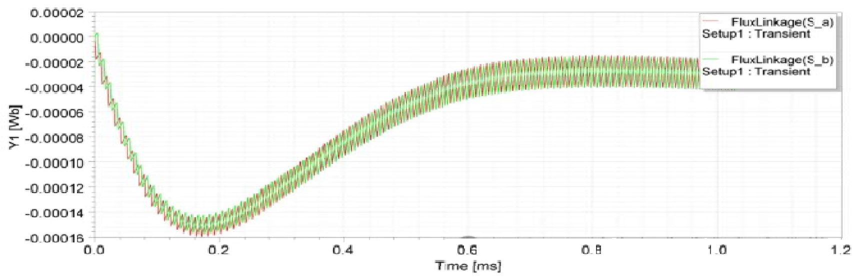
Magnetically Integrated Flyback Transformer Secondary Current Waveform:



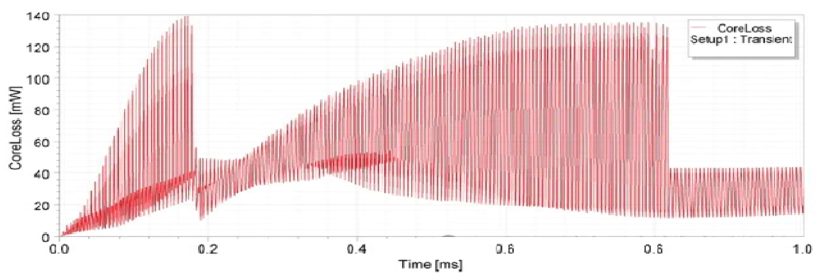


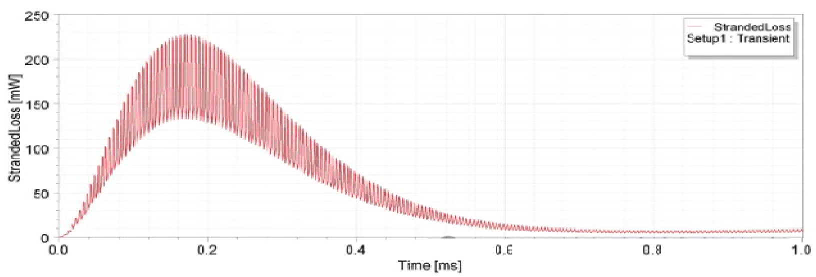
Magnetically Integrated Flyback Transformer Primary and Secondary Flux Linkage Waveforms:



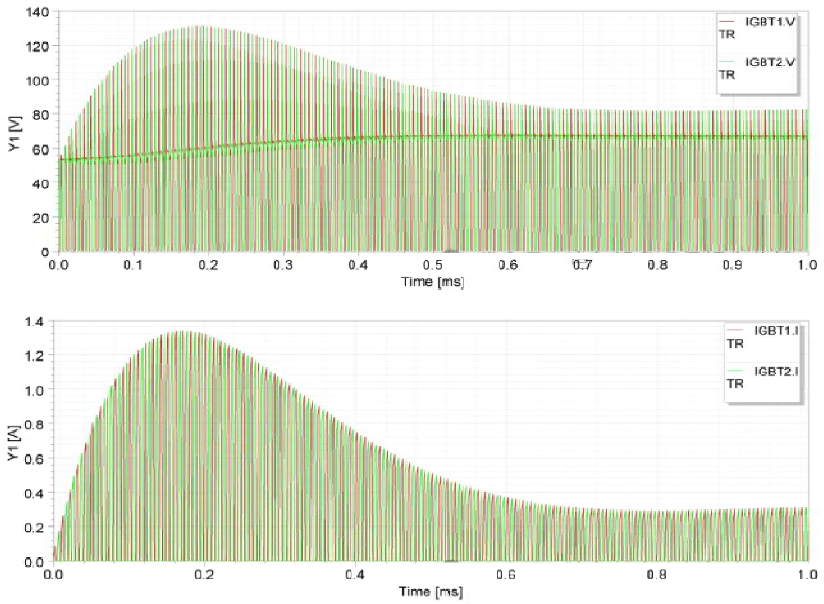


Magnetically Integrated Flyback Transformer Core and Winding Loss Waveforms:

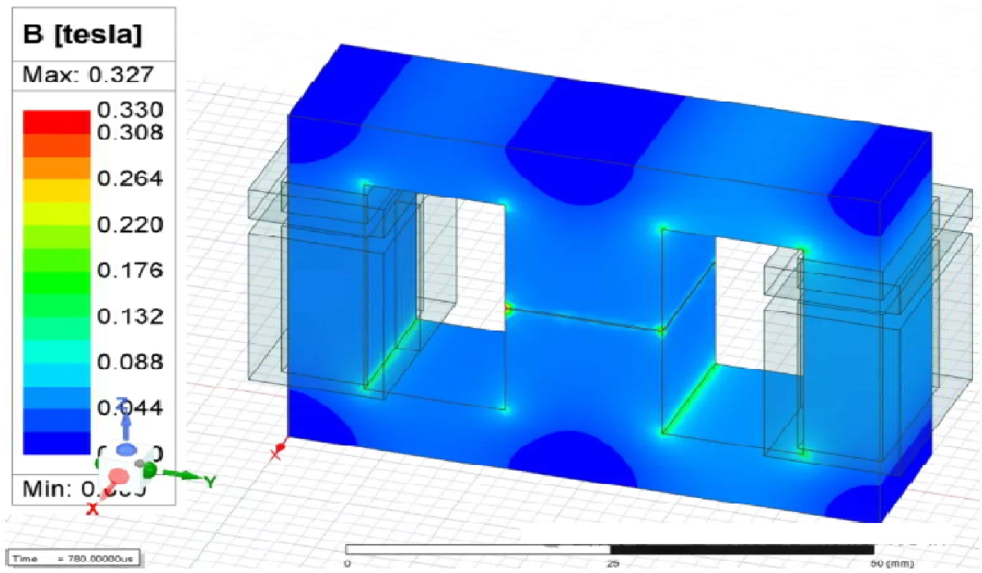


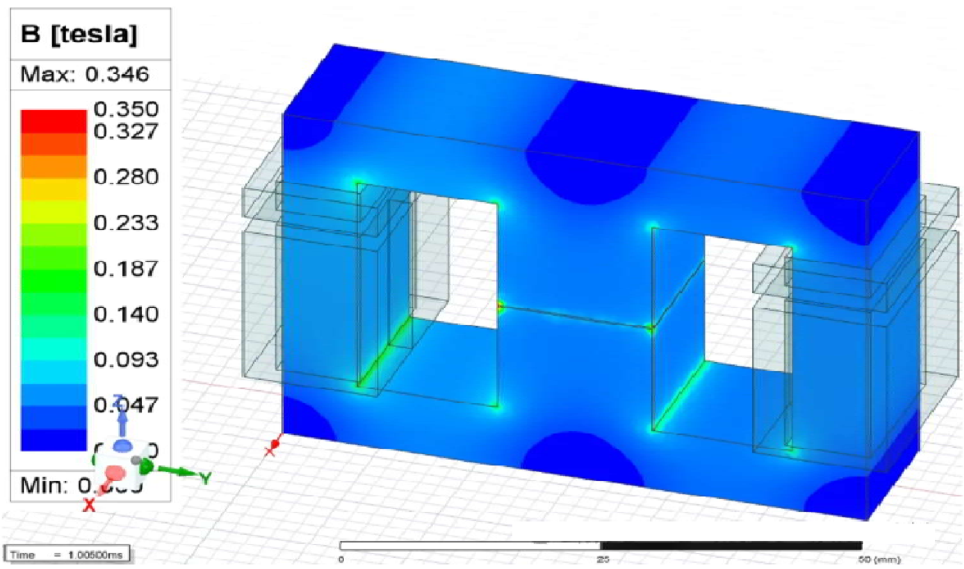


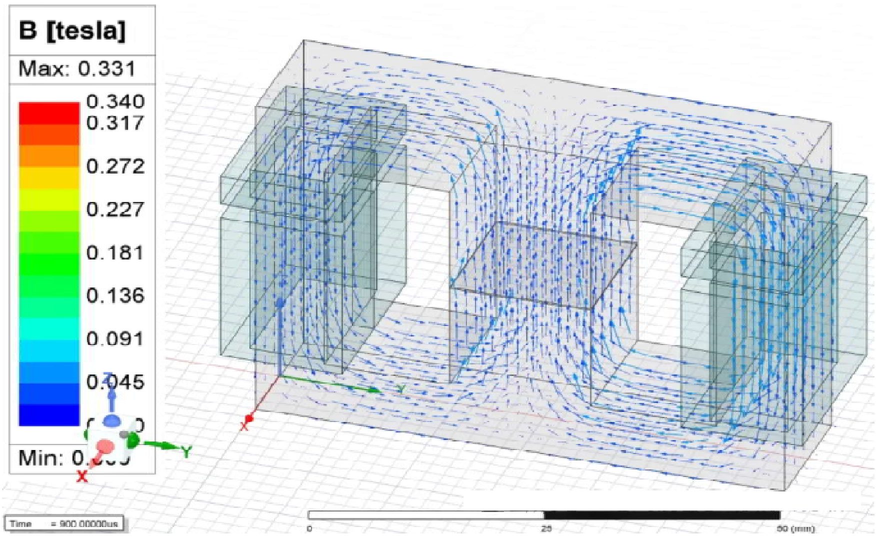
Interleaved Parallel Converter Primary Switch Terminal Voltage and Conduction Current Waveforms

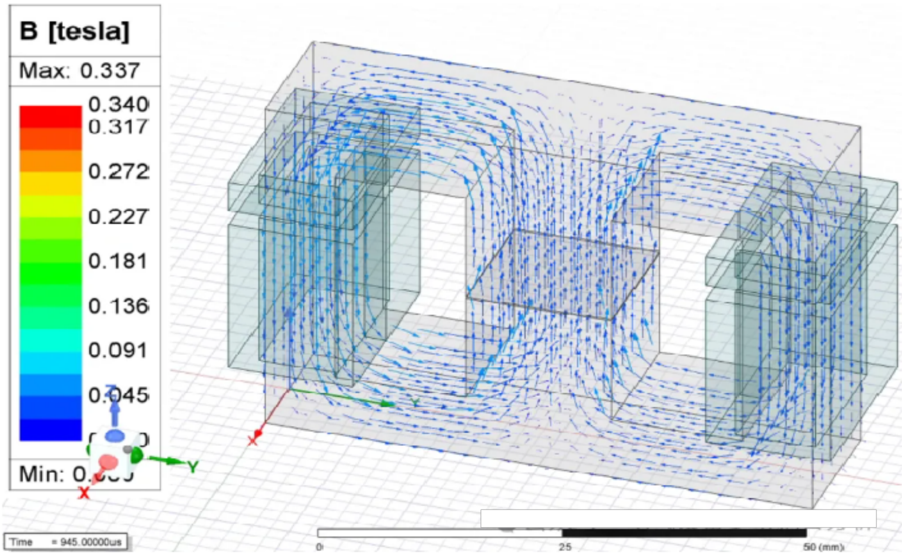


Transformer Core Magnetic Flux Density Distribution at Various Instants：

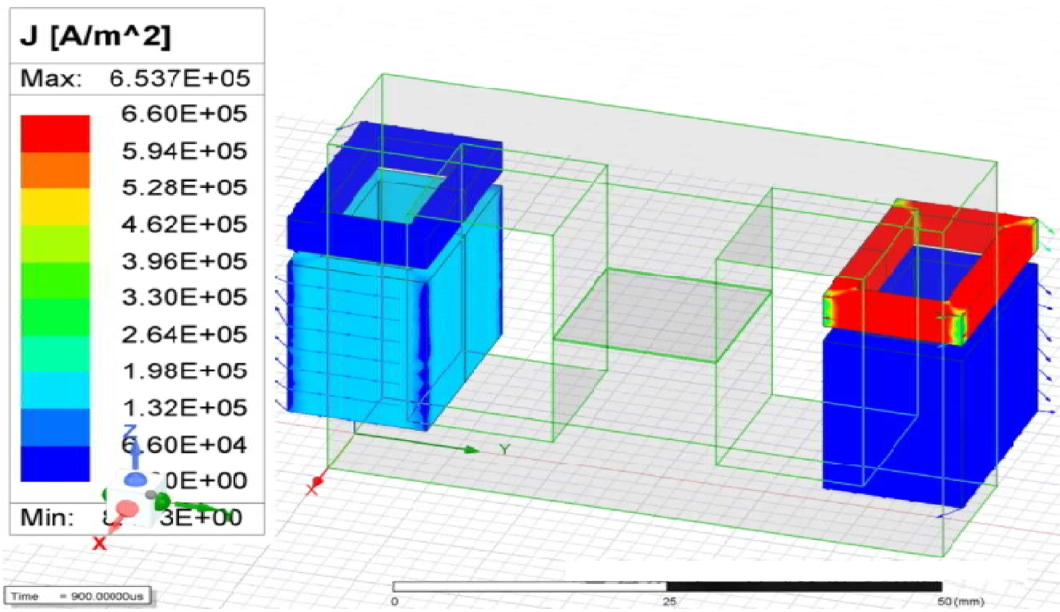


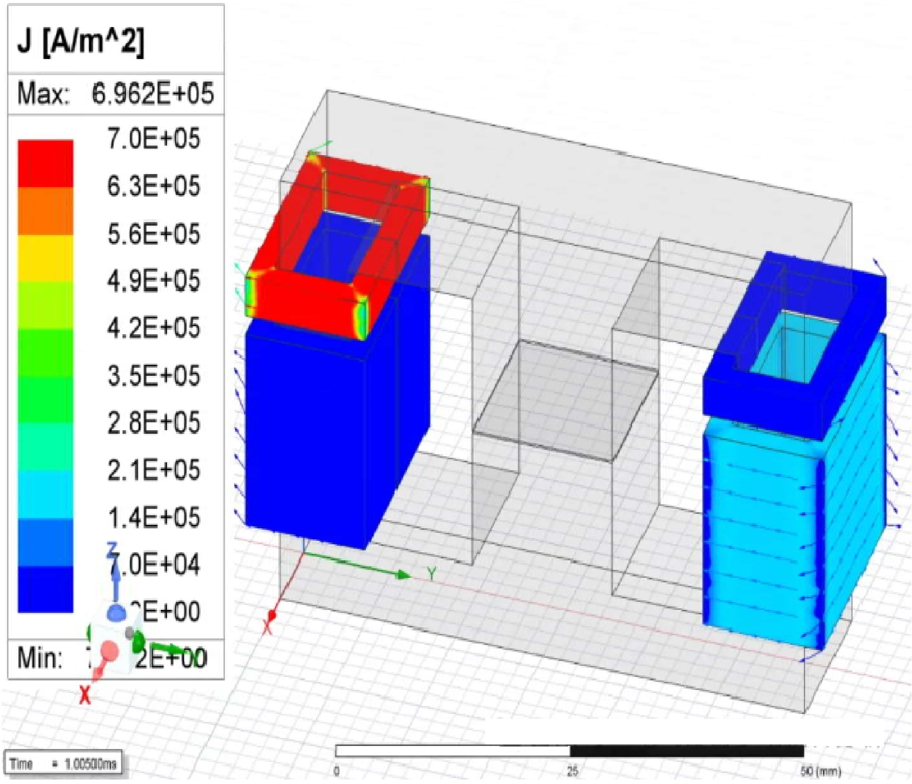






Transformer Winding Current Density Distribution at Various Instants：





Compared with the discrete flyback transformer, the losses, maximum magnetic flux density, and current density magnitude of the magnetically integrated flyback transformer are significantly reduced!