more than you expect

Midcom

WÜRTH ELEKTRONIK

Cookbook

for Discontinuous Conduction Mode Flyback Converters

Content

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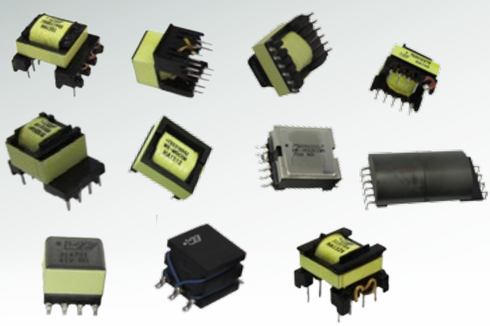
Product overview



Power Magnetics

Transformers for AC/DC Converters

Transformers for DC/DC Converters

Power Inductors

Sense Transformers

Signal and Communications

Analog Modem Transformers

xDSL Transformers

ISDN Transformers

Metering Signal & Communications Transformers

EMC Components

Power Common Mode Chokes

Signal Common Mode Chokes

Filter Chokes

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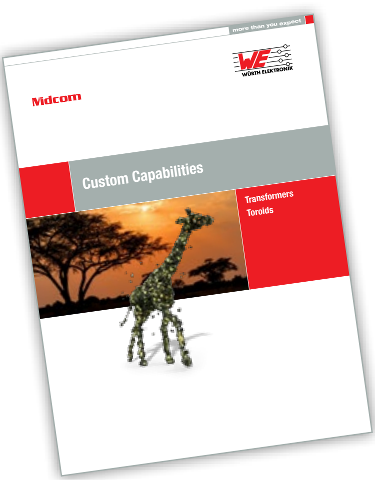
Introduction

This cookbook shows you an example of how to design and wind a transformer. We hope it helps you to understand the foundation of transformer design. When you're ready to move forward, we'll design it for you and offer free samples.

CUSTOM SOLUTIONS *Possible* Midcom

Refer to our Custom Capabilities Catalog to find out what packages we offer for manufacturing. Ask for a copy of the Custom Capabilities Catalog or browse the electronic version at **www.we-online.com/customcapabilities**.



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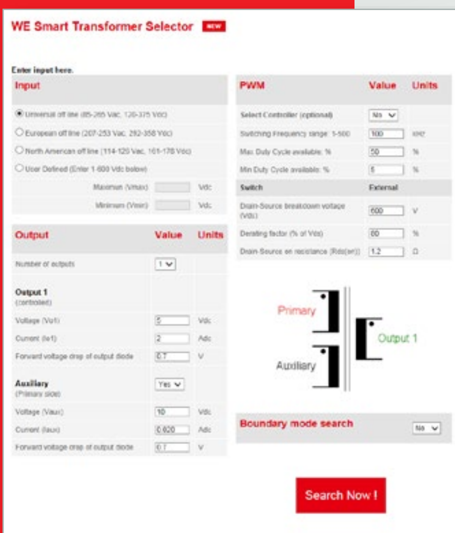
All appropriate material is only valid for low power applications. For applications with $60V_{DC}/48V_{AC}$ or more, please refer to relating safety regulations.

Smart Transformer Selector

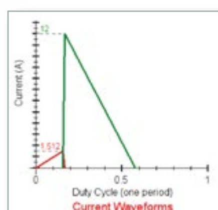


Benefits

- Smart search for all flyback transformers on the website
  - Discontinuous Mode
  - Boundary Mode
- Simple search needs only power supply parameters
  - Input voltage and switching frequency
  - Output voltages and current
- Finds all parts for your application that will:
  - Not saturate
  - Provide acceptable output voltages
- Samples available

Features

- Analyzes transformer in defined application
  - Voltage levels
  - Current wave forms



- Losses & temperature rise
- Compare multiple parts at once
- Schematic showing how to connect

Samples Available

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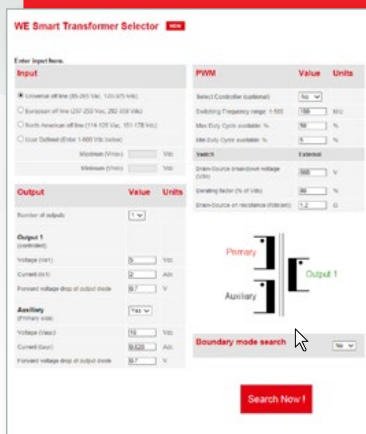
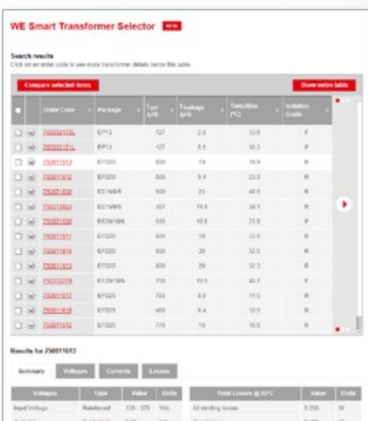
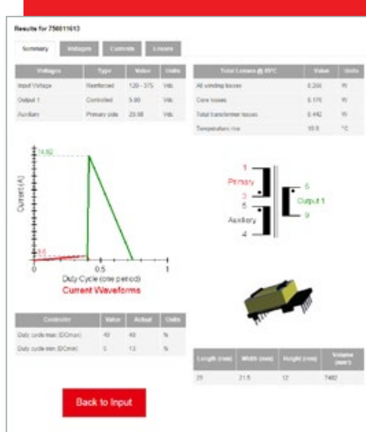
Easy as 1 ▪ 2 ▪ 3!



STEP 1 Enter power supply input and output criteria and click on "Search Now".



STEP 2 From the resulting list of parts, click on the transformer of choice.



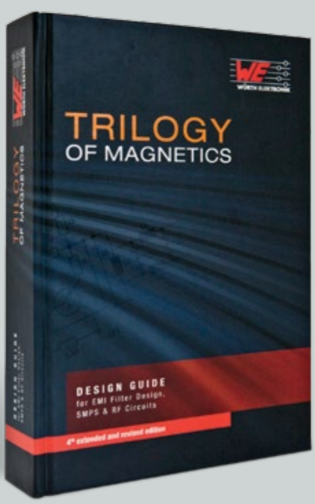
STEP 3 Review transformer performance in either summary tab or any of the other three tabs, which provide more detail.

Transformer design

The following example gives you an idea how to design a transformer for a flyback converter.

Fig. 1 shows a flowchart for the approach in designing a DCM flyback transformer. As you can notice, designing a transformer is a highly iterative process.

Further transformer designs for forward converters and push-pull converters are integrated in Würth Elektronik's design guide, Trilogy of Magnetics.



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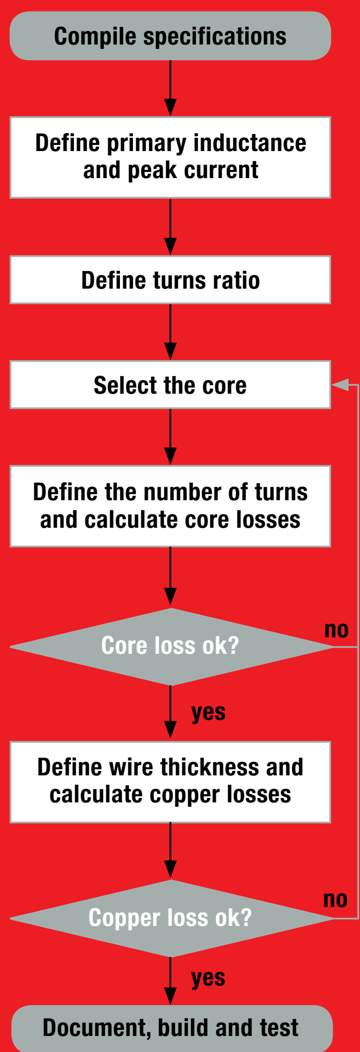

Fig. 1: Flow chart for the approach to design a DCM flyback transformer

Step-by-step to flyback converter design

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Fig. 2 shows the basic schematics of a flyback converter. The switch S1 is a controlled switch, e.g. a MOSFET. To understand the basic function of the flyback converter, the switching processes are described as follows:

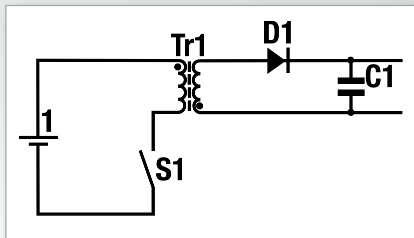


Fig. 2: Circuit diagram of a flyback converter

1. Switch closed
The closed switch applies the input voltage on the transformer´s primary winding. As a result of the inductance, a current rises linearly on the primary side. The polarity of the transformer is that the diode blocks the current on the secondary side. The energy fed is stored in the gap of the transformer.

2. Switch open
With the switch open, the current is interrupted on the primary side. The inductance of the transformer tries to maintain the flow of energy, so that the polarity of the secondary side changes. The diode becomes conducting, and a linear declining current flows on the secondary side.

Fig. 3 shows the current and voltage profile on the primary and secondary sides of the transformer.

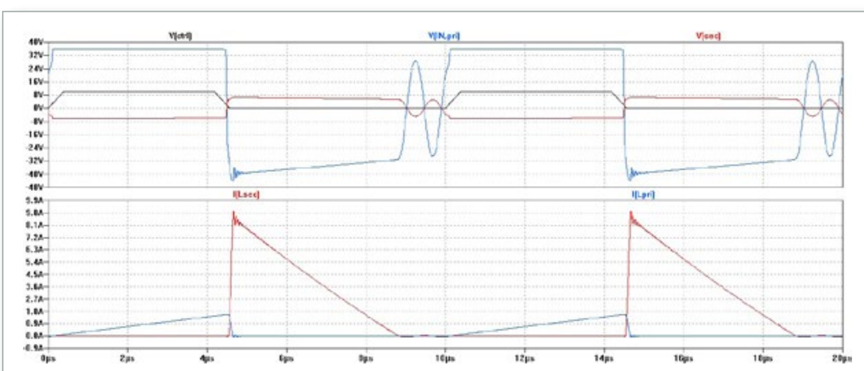


Fig. 3: Current and voltage profiles of a DCM flyback converter

Step-by-step to flyback converter design

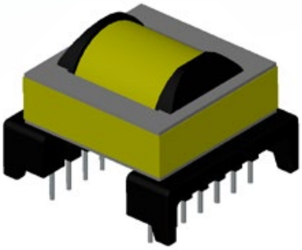
Two flyback converter operating modes are distinguished depending on the current profile.

1. Continuous mode:
In continuous mode (trapezoid operation or continuous conduction mode, CCM) energy is still stored at the end of the switching cycle. The linear decline in current does not return to zero.

2. Discontinuous mode:
In discontinuous mode (triangular operation or discontinuous conduction mode, DCM) the current on the secondary side will be zero at the end of the cycle. There are current gaps in which no current flows, neither on the primary nor on the secondary side.

Prior to design, the following parameters must be known.

- Input voltage range
- Output voltage
- Output power or output current
- Switching frequency
- Operating mode
- Maximum duty cycle of the IC
- Safety requirements
- Ambient temperature
- Size requirements



Safety requirements such as dielectric withstand voltage, creepage distance and clearance distance should be especially considered in the design phase, as a transformer requires a larger package if these requirements are considered. Special care should be taken for offline applications.

An idea about the creepage distance and clearance distance and the dielectric withstand voltages are given in **Tab. 1** and **Tab 2**. The values, therein, are based on IEC 60950.

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Creepage distances for working voltages according to IEC 60950 for pollution degree 2						
RMS working voltage	Creepage distance pollution degree 2 (mm)					
	Basic insulation			Reinforced insulation		
	CTI>600	400<CTI<600	CTI<400	CTI>600	400<CTI<600	CTI<400
50	0.60	0.85	1.20	1.20	1.7	2.4
63	0.63	0.90	1.25	1.26	1.8	2.5
80	0.67	0.90	1.30	1.34	1.8	2.6
100	0.71	1.00	1.40	1.42	2.0	2.8
125	0.75	1.05	1.50	1.50	2.1	3.0
160	0.80	1.10	1.60	1.60	2.2	3.2
200	1.00	1.40	2.00	2.00	2.8	4.0
250	1.25	1.80	2.50	2.50	3.6	5.0
320	1.60	2.20	3.20	3.20	4.4	6.4
400	2.00	2.80	4.00	4.00	5.6	8.0
500	2.50	3.60	5.00	5.00	7.2	10.0
630	3.20	4.50	6.30	6.40	9.0	12.6
800	4.00	5.60	8.00	8.00	11.2	16.0
1000	5.00	7.10	10.00	10.00	14.2	20.0

**CTI (Comparative Tracking Index)*
Tab. 1

Dielectric withstand voltages according to IEC 60950		
Operating voltage peak value or DC	Dielectric withstand voltage (V)	
	Basic insulation	Reinforced insulation
50	1000	2000
100	1000	2000
125	1000	2000
150	1000	2000
200	1000	2000
250	1500	3000
300	1500	3000
400	1500	3000
600	1893	3000
800	2164	3000
1000	2399	3000

Tab. 2

1st Step
Compile specifications

We will now show the step-by-step design process for a DCM flyback converter. The following example will help to illustrate the design steps.

Input voltage range ($V_{IN\ MIN}$ – $V_{IN\ MAX}$):	**36 - 57V**
Output voltage V_{OUT}:	**5V**
Output current I_{OUT}:	**2A**
Operating mode:	**DCM**
Maximum duty cycle D_{MAX}:	**48% (use 45%)**
Switching frequency:	**100kHz**
Safety requirements:	**Functional insulation**

Output diode drop voltage: $V_D = 0.5V$
Assume transformer efficiency, $\eta = 0.9$. The on time will be $T_{ON} = \frac{D_{MAX}}{f}$

Output transformer power:
$P_{OUT} = (V_{OUT}+V_d) \cdot I_{OUT} = (5+0.5) \cdot 2 = 11W$ (including output diode loss V_d)

Input power:
$P_{IN} = P_{OUT} / \eta = 11/0.9 = 12.22W$

2nd Step
Define primary inductance and peak current

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In a discontinuous mode, all of the energy stored in the transformer is delivered to the output during each cycle.

So, for each cycle, to make sure that the stored energy is delivered, we need to calculate the maximum inductance as:

$$L_{MAX} = \frac{V^2_{IN,\,MIN} D_{MAX}^2 \eta}{2fP_{OUT}}$$

$$L_{MAX} = \frac{36^2 \cdot 0.45^2 \cdot 0.9}{2 \cdot 100{,}000 \cdot 11} = 107.36\mu H$$

Consider 10% inductor tolerance + 5% safety margin = 15%. The new value of L is:

$$L_{MAX} = 91.25\mu H$$

(Choose primary inductance $L = 91\mu H$)

The Primary Peak Current is determined from:

$$I_{PK,PRI} = \sqrt{\frac{2 \cdot P_{OUT}}{L \cdot f \cdot \eta}}$$

$$I_{PK,PRI} = \sqrt{\frac{2 \cdot 11}{91x10^{-6} \cdot 100000 \cdot 0.9}} = 1.64A$$

3rd Step
Definition of turns ratio

Turns ratio and duty cycle determine each other; i.e. if one of the parameters is defined, so is the other.

The maximum duty cycle and the highest currents are occurring at the minimum input voltage. This is the worst case. In fast transient response, the duty cycle can be higher for a short time.

Design Tip 1: Keep a little safety margin to the maximum allowed duty cycle of the IC.

The relationship between maximum duty cycle and turns ratio is given by the following formula:

$$\frac{N_S}{N_P} = \frac{(V_{OUT} + V_D)(1 - D_{MAX})}{V_{IN,MIN} D_{MAX}}$$

D_{MAX}	*Maximum duty cycle:* $D_{MAX} = T_{ON}/(T_{ON}+T_{OFF})$
$V_{IN,MIN}$	*Minimum input voltage*
$T_{ON,\ OFF}$	*MOSFET ON time, OFF time*
N_P, N_S	*Primary and secondary number of turns*
V_{OUT}	*Output voltage*
V_D	*Output diode drop off voltage*

For our example, we calculate a turns ratio of:

$$\frac{N_S}{N_P} = \frac{(5 + 0.5)(1 - 0.45)}{36 \cdot 0.45} = 0.187$$

Care should be taken on the breakdown voltage of the MOSFET. The voltage between drain and source of this MOSFET during the off time is:

$$V_{DS} = V_{IN} + \frac{N_P}{N_S} \cdot V^*_{OUT} + V_{LEAKAGE}$$

$V_{LEAKAGE}$ *is the voltage spike resulting from leakage inductance (Typically add 20-30% of* V_{IN} *depending if a snubber is used or not)*

$V^*_{OUT} = V_{OUT} + V_D$ *output voltage including diode voltage drop*

Design Tip 2: Use a MOSFET with a sufficient safety margin in breakdown voltage, as the voltage spike from discharge of leakage inductance can destroy the MOSFET.

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4th Step
Selection of the core

For frequencies between 25 and 500kHz, the best choices for core material are so called power ferrites, MnZn ferrites with a permeability of 2400. The saturation flux density Bs of this material is 390mT at 100°C. **Fig. 4** shows the specific losses for given frequencies and flux densities.

The package type depends on the power to be transformed. A starting point is transformer indexes. **Tab. 3** shows a power table in the Custom Capabilities Catalog.

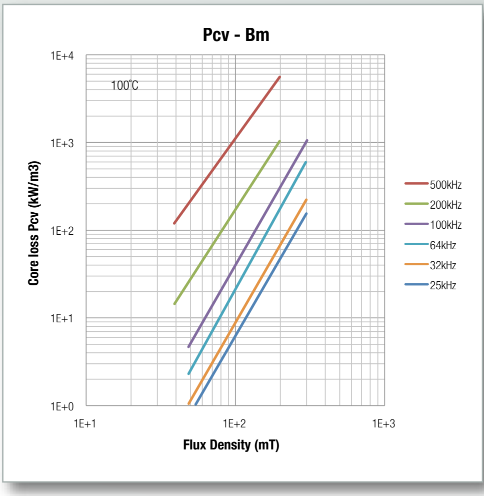

Fig. 4: Specific losses against the change in flux density

Power

DC/DC Flyback Power Level (W) at 100kHz	Offline Power Level (W) at 100kHz	Package Size	Mount	Pins	Safety	Length (mm)	Width (mm)	Height (mm)	Bobbin	Page Number
1		EP5	SMD-H	6		6.6	8.3	5.6	070-4426	51
2		ER9.5	SMD-V	8		10.0	12.1	6.0	070-6051	73
2		ER11.5	SMD-V	12		13.0	12.7	6.4	070-6058	74
3		EP7	SMD-H	6		10.2	13.4	8.6	070-5801	52
3		EP7	TH-H	6		10.2	8.3	9.8	070-2150	53
3		EP7	SMD-H	8	⚡	9.8	9.1	10.5	070-4436	54
4		EPX7	SMD-H	8	⚡	10.2	9.1	12.3	070-4434	64
5		ER14.5	SMD-V	12		16.0	16.8	7.6	070-4477	75
6		EPX9	SMD-H	8		10.2	10.2	12.7	070-5103	65
6		RM4	TH-V	6		11.4	11.4	11.2	070-5754	88
8		EP10	SMD-H	8		13.3	15.2	11.4	070-6052	55
8		EP10	TH-H	8		13.3	11.7	12.6	070-2365	57
8		EP10	SMD-H	8	⚡	13.3	15.2	11.6	070-4410	56
8		EPC13	TH-H	10		14.6	14.7	8.5	070-5483	66
8		EPC13	SMD-H	10		14.6	20.9	8.3	070-4887	67
10		EE13/7/4 (EF12.6)	TH-H	8		14.7	16.8	12.7	070-4849	22
10		EE13/7/4 (EF12.6) NEW	SMD-H	9	⚡⚡	13.8	23.7	11.0	070-6258	24
10	5	EE13/7/4 (EF12.6)	TH-H	9	⚡⚡	13.7	20.5	10.2	070-5662	23
10		EE13/7/4 (EF12.6)	SMD-H	10		13.7	19.7	10.5	070-4820	25
10		RM5	TH-V	6		14.0	14.0	11.2	070-2250	89
14		EFD15	SMD-H	12		17.2	22.2	8.9	070-4265	41
14	7	EE13/7/6	TH-H	8	⚡⚡	15.0	15.8	18.5	070-5449	26
14		EFD15	TH-H	8		16.8	16.8	8.9	070-2745	39

Tab. 3: Core geometries and typical transformable power at 100kHz DC/DC

For the total needed power of 12.22W, in our example we choose EFD15 core size, with SMD-H, 10-pin bobbin, as the estimated power level for this package (100KHz DC/DC Flyback) is 14W.

5th Step
Define the number of turns and calculate core losses

The minimum number of turns is defined by the saturation flux density for a given core. The ferrite material 1P2400 has a saturation flux density of 312mT (B_{MAX} derated to 80%). Thus, the minimum number of turns is:

$$N_P > \frac{L_{PRI} \cdot I_{PK,PRI}}{B_{SAT} \cdot A_E} = \frac{91\mu H \cdot 1.64A}{0.312T \cdot 15mm^2} = 31.88, \text{ choose } 32$$

$$N_S = N_P \cdot n = 32 \cdot 0.187 = 5.98$$

As we need a complete number of turns, and to have a little safety margin, we choose $N_S = 6$:

$$N_P = {}^{N_S}/_{n} = {}^{6}/_{0.187} = 32.08 \qquad N_P = 33$$

Calculate the core loss due to change of the flux density as following:

The flux variation is:

$$\Delta B = \frac{L_{PRI} \cdot I_{PK,PRI}}{N_P \cdot A_E} = \frac{91\mu H \cdot 1.64A}{33 \cdot 15mm^2} = 301mT$$

Divide ΔB by 2 for a unipolar waveform to calculate Bpk from which we will determine the core loss. Out of **Fig. 4** we can determine the specific loss, and together with effective volume of **Tab. 4**, we can calculate the core losses. Please use only half of ΔB to calculate the specific core loss.

$$\begin{aligned} Bpk &= \Delta B / 2 \\ &= 301mT / 2 \\ &= 150.5mT \end{aligned}$$

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Core geometries and parameters					
Core geometry	A_E (mm²)	L_E (mm)	V_E (mm³)	R_{TH} (K/W)	winding window height (mm)
ER11/5	11.00	14.70	161.70	134	1.60
ER14.5	17.30	19.00	328.70	99	2.74
EFD15	15.00	34.00	510.00	75	1.80
EFD20	31.00	47.00	1457.00	45	2.25
EE13/7/4 (EF12.6)	12.40	29.60	367.04	94	1.80
EE16/8/5 (EF16)	20.10	37.60	755.76	76	2.51
EE20/10/6 (EF20)	32.00	46.00	1472.00	46	3.15
EE25/13/7 (EF25)	51.40	57.80	2970.92	40	4.01

Tab. 4

Calculating core loss (using **Fig. 4** and **Tab. 4**):

From Fig. 4, P_V = 120kW/m³ (at 100kHz and 100°C)

Core loss = V_E x P_V = 510mm³ x 120kW/m³ = 62mW

Thermal resistance of an EFD15 SMD-H 10 pin, **Rth = 75K/W**
If we set a temperature rise limit of 40°C then the maximum power loss (P_{MAX}) of the transformer is:

P_{MAX} = °C_{RISE}/R_{TH} = 40/75 = 533mW

Dividing half of the losses to the core and half to the coil that is 533mW/2 = 266mW.

The calculated core loss of 62mW is well below 266mW which suggests that our core is too large for this application but we're not done yet.

6th Step

Define wire thickness and calculate copper losses

Select the wire cross section that the total power loss and the resulting temperature rise remain within reasonable bounds.

Design Tip 3: For small parts the temperature rise should be less than 40°C.

Design Tip 4: A good starting point is to select a current density of 4A/mm².

The copper losses are calculated by Ohm´s law. For the thin wires, it is reasonable to disregard eddy current losses in the first step.

Check if the selected wire fits into the winding build of the bobbin. By using **Fig. 5** you can determine the number of layers you need. Note that this figure is only valid if you don´t need creepage and clearance distances.

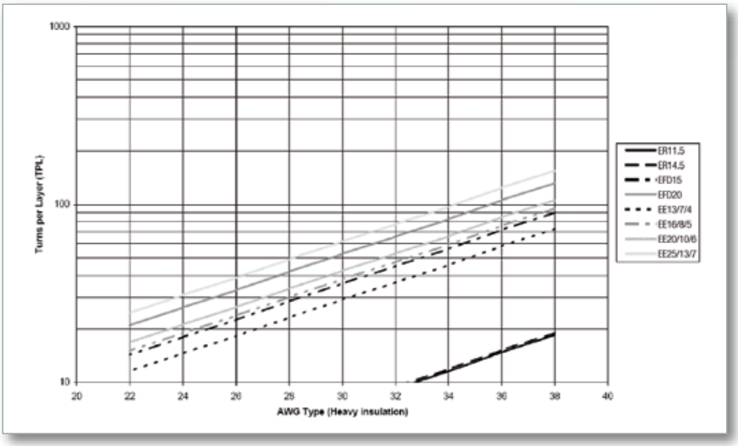

Fig. 5: Number of turns per layer for different packages and wires

By multiplying the number of layers with the outer wire diameter (**Tab. 5**) we calculate the winding build. Calculate the total winding build by adding the winding heights of all windings. Check if the total winding build is less than the build of the winding window (**Tab. 4**)

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Wire diameter (mm)	AWG	Outer diameter (mm)	DCR/Turn (mΩ/Turn)							
			ER11.5	ER14.5	EFD15	EFD20	EE13/7/4	EE16/8/5	EE20/10/6	EE25/13/7
0.1	38	0.125	57.18	71.47	69.62	90.26	63.53	92.65	103.23	139.76
0.15	34	0.177	24.00	30.00	29.22	37.89	26.66	38.89	43.33	58.66
0.2	32	0.239	13.10	16.38	15.96	20.69	14.56	21.23	23.66	32.03
0.28	29	0.329	6.55	8.19	7.98	10.34	7.28	10.62	11.83	16.01
0.3	28	0.337	5.68	7.10	6.91	8.96	6.31	9.20	10.25	13.88
0.35	27	0.387	4.13	5.16	5.03	6.52	4.59	6.69	7.46	10.10
0.4	26	0.459	3.14	3.92	3.82	4.95	3.49	5.09	5.67	7.67
0.5	24	0.566	1.97	2.47	2.40	3.12	2.19	3.20	3.57	4.83

Winding wires and parameters

Tab. 5

As with storage chokes, first the currents have to be calculated. The effective current, the average current and the peak current can be distinguished by examining the current curves.

The effective or RMS current is that with which the copper losses are calculated. It is the current averaged over the period. For the secondary side we calculate:

$$I_{RMS,\,SEC} = I_{PK,\,SEC}\sqrt{\frac{1-D_{MAX}}{3}}$$

$I_{RMS,SEC}$ effective current on secondary winding

$$\text{where } I_{PK,\,SEC} = \sqrt{\frac{2 \cdot P_{OUT}}{L_{SEC} \cdot f}}$$

$$\text{we know, } L_{SEC} = \left(\frac{N_s}{N_p}\right)^2 \cdot L_{PRI} = (0.187)^2 \cdot 91\mu H = 3.182\mu H$$

$$I_{PK,\,SEC} = \sqrt{\frac{2 \cdot 11}{3.182 \times 10^{-6} \times 100000}} = 8.31A$$

$$\text{Hence, } I_{RMS,\,SEC} = 8.31 \cdot \sqrt{\frac{1-0.45}{3}} = 3.56A$$

For the effective current on the primary winding we calculate:

$$I_{RMS,\,PRI} = I_{PK,\,PRI}\sqrt{\frac{D_{MAX}}{3}} = 1.64\sqrt{\frac{0.45}{3}} = 0.635$$

In our example, we have an RMS current of 0.635A on primary and 3.56A on secondary side. At 4A/mm², we need cross sections of 0.158mm² and 0.89mm² on primary and secondary, the corresponding diameters of which are 0.44mm and 1.06mm respectively. We choose a wire diameter of 2 strands of 0.28mm on primary side and 2 strands of 0.5mm wire on secondary side. These results in a resistance of 132mΩ for primary winding and about 7mΩ maximum for the secondary side (see Tab 5). According to Ohm´s law, we calculate winding losses of 53mW and 88mW on primary of secondary windings respectively.

Now we have fixed the design and can start with the winding of the transformer:

1. Core and bobbin: EFD15
2. Primary 2 * 33 turns ø 0.28mm wire
3. Insulation tape between primary and secondary
4. Secondary: 2 * 6 turns ø 0.5mm wire

Transformer construction

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Now that the steps are completed, you can begin the construction of the transformer. Review the following questions 1-9 to see if anything was missed in the steps leading up to the construction process.

Q1: Is the transformer required to meet safety agency standards that are intended to reduce risks of fire, electric shock or injury to personnel?

What Material Group/CTI rating is required for the materials?

What are the creepage/ clearance distances?

Q2: Is the transformer required to meet an insulation system?

Q3: In what environment will the transformer operate?

Q4: What power supply and transformer topology will be used?

Q5: How much space is allowed for the transformer on the printed circuit board?

Q6: What is the lowest and highest frequency of operation?

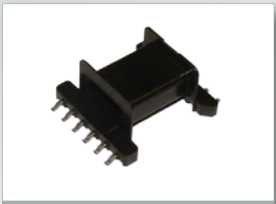
Q7: What is the wattage rating of the transformer?

Q8: What are the input and output voltages and currents of the transformer, and how many windings are needed?

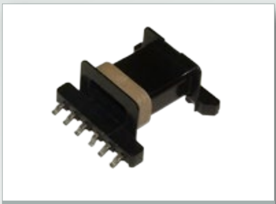
Q9: Are the materials suitable for a lead-free solder reflow process?

Here are some basic guidelines to follow when building a transformer. By following these guidelines, you will minimize the manufacturing costs, while optimizing the electrical performance. Note these guidelines are not intended to show all possible methods of construction. The accompanying photographs show an example of a surface mount construction.

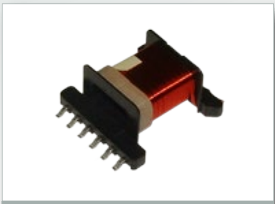
General example of step-by-step construction of a transformer



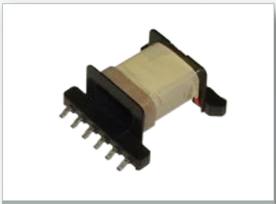
Step 1 – Bare Bobbin



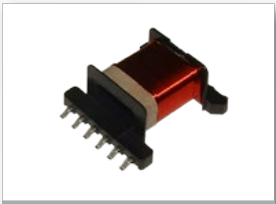
Step 2 – Shelf Tape



Step 3 – Wind 1

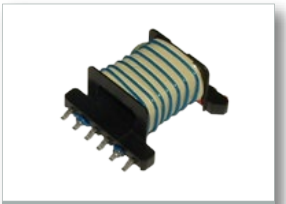


Step 4 – Wrapper Tape 1



Step 5 – Wind 2

Step 6 – Wrapper Tape 2

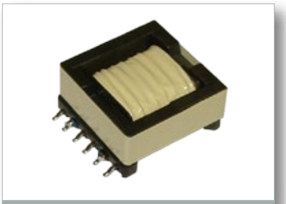


Step 7 – Wind 3

Step 8 – Finish Tape

Step 9 – Solder

Step 10 – Core



Step 11 – Core Tape

Glossary

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Margin (Shelf) Tape – Determine if a safety isolation barrier is required and where that barrier will be located. In the example, margin (shelf) tape is applied to one side of the bobbin (coil former). The number and placement of margin tape will affect magnetic coupling and leakage inductance. An alternative to margin tape is double or triple insulated wire. This wire may be cost prohibitive on high turn windings.

Wire Strands/Wire Gauge – Choose the type of wire, number of strands, and wire gauge based on the frequency of operation and current carrying ability. Be aware that heavy gauge or multi-stranded wire may solder bridge together on adjacent terminals.

Turns Per Layer (TPL) – Pick a turns per layer of wire that fills the winding area of the bobbin. On low turns per layer windings, it may be necessary to space the turns of wire evenly across the bobbin. This also applies to high turn, multilayered windings where the last layer does not entirely fill the bobbin. Minimize the number of layers of wire to reduce leakage inductance and eddy current losses.

Pinout – A number of factors will affect the bobbin pinout, including safety agency requirements and circuit board layout. Typically, the primary windings are terminated on one side of the bobbin, and the secondary windings are terminated on the other. Ideally, the pinout for a particular winding will be dictated by the number of layers of wire, whether odd or even, although other factors will also affect it. If the winding ends on the side of the bobbin that is opposite from the intended finish terminal, bring the wire across the coil at a 90˚ angle. Place the wire in an area where it will be the least disruptive to subsequent windings and the ferrite core set. Tape can be used to hold the wire down at the bend. It may be necessary to place a piece of tape under this wire to insulate it from its own winding to prevent cut-through and subsequent shorted turns. Pulling this wire across the coil at an angle other than 90˚ will cause the subsequent windings to not lay uniformily and evenly.

Interlayer Insulation – Interlayer tape may be required if there is a high voltage potential between each layer of wire within the same winding.

Wrapper Tape/Finish Tape – Select a wrapper tape that is slightly wider than the distance between the bobbin flanges. This extra width allows the tape to lap up the sides of the flanges without folding over. This ensures isolation between the windings, minimizing the risk of wire-to-wire contact and potential dielectric breakdown. The higher temperatures associated with a lead-free solder reflow process may cause the standard polyester tapes to shrink. Also, smaller transformer packages will absorb more heat, causing more tape shrinkage. This tape shrinkage will have a direct affect on dielectric breakdown strength and the integrity of the safety isolation barrier. High temperature polyamide tapes are available, but their comparative tracking index (CTI) is lower with a resulting change in the material group. This results in a greater creepage/clearance distance requirement.

Core Set/Core Tape/Insulation Tape – Choose the appropriate core set and AL inductance factor. Secure the core set to the coil with 2 layers of tape. Do not stretch the tape during the application process. It may be necessary to apply insulation tape to one or both sides of the core set to insulate the core from the terminals. Additionally the core set may be bonded to the coil (bobbin) with an adhesive or varnish coating.

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