Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

Introduction

In a Flyback topology, the selection of the transformer core is fairly straightforward. The Flyback transformer has a dual function: it not only provides step-up or step-down ratio based on the Primary to Secondary turns ratio, but it also serves as a medium for energy storage. The Flyback is a derivative of the Buck-Boost, and shares its unique property that not just part, but *all,* the energy that is delivered to the output, must have previously been stored (as magnetic energy) within the core. This is consistent with the fact that the Secondary winding conducts only when the Primary winding stops, and vice versa. We can intuitively visualize this as the windings being "out of phase". So we have an endless sequence of energy store-and-release, store-and-release…, and so on. The core selection criterion is thus very simply as follows: the core must basically be capable of storing each packet of energy (per cycle) passing through it. That packet is equal to P_{IN} / f = $\Delta\mathcal{E} \approx \mathcal{E}_{PEAK}/1.8 = (L \times I_{PEAK}^2)/3.6$, in terms of Joules. Here f is the switching frequency and $\mathcal{E}$ is energy (see Figure 5.6 of Switching Power Supplies A-Z for a derivation of the above). Equivalently, we can just state that the peak current, I_{PEAK}, should not cause "core saturation", though that approach gives us no intuitive understanding of the fact that if we double the switching frequency, the energy packets get reduced in half, and so in effect the same core can handle twice the input/output energy. But that is indeed always true whenever we use an inductor or transformer as an energy-storage medium in switching power conversion.

But coming to a Forward converter, at least two things are very different right off the bat.

a) All the energy reaching the output does not necessarily need to get stored in any magnetic energy storage medium (core) along the way. Keep in mind that the Forward converter is based on the Buck topology. We realize from Page 208 of Switching Power Supplies A-Z, that only 1-D times the total energy gets cycled through the core in a Buck topology. So, for a given P_O, and a given switching frequency, the Buck/Forward core will be roughly half the size of a Buck-boost/ Flyback handling the same power (assuming D ≈ 1-D ≈ 0.5).

b) Further, in a Forward converter, the energy storage function does not reside in the transformer. The storage requirement, however limited, is fulfilled entirely by the Secondary-side choke, not the transformer. So we can well ask: what does the transformer do in a Forward converter anyway? It actually only provides "transformer action", i.e., voltage/current step-up/down function based on the turns ratio --- which is in a way, half the function of a Flyback transformer. Once it provides that step-up/down ratio, there is an additional step-down function provided by simply running the Secondary-side choke in a chopped-voltage fashion, as in any regular (non-isolated) Buck. That is why we always consider the output rail of a Forward converter, as having been derived from the input rail, with two successive step-down factors applied, as shown

$$V_O = \underbrace{\left(D \times V_{IN}\right)}_{\Uparrow \text{ Buck}} \quad \times \quad \underbrace{\frac{N_S}{N_P}}_{\Uparrow \text{ Transformer action}}$$

The perceptive will notice that the Forward converter's transformer action could be such that we use the transformer turns ratio to give an intermediate step-up instead of a step-down function, and then follow it up with a step-down function accruing from the inherent Buck stage based around the Secondary-side choke. That could in effect give us another type of (overall) Buck-Boost converter --- but not based on the classic inductor-based Buck-Boost anymore. And that is what we, in effect, usually do in the LLC resonant topology.

The Secondary-side choke selection criterion is straightforward too: it is simply sized so that it does not saturate with the peak current passing through it (typically 20% more than the load current). We see that it is the same underlying criterion as in a Flyback, Buck, a Buck-Boost, and even a Boost. So that does leave us the basic question: how do we pick the Forward converter *transformer*? What does its size depend on? What is/are its selection criteria?

There are two major factors affecting the Forward converter transformer selection. First we need to understand that the Primary and Secondary windings conduct *at the same time*. So they are intuitively "in phase". The observed "transformer action", i.e., the simple turns-ratio based current flow of the Secondary winding, is in fact just a direct result of induced EMF (electromotive force, i.e., voltage based on Faraday's/Lenz's law). The induced EMF in the Secondary, in response to the changing flux caused by the changing current in the Primary, tries to oppose the change of flux, and since both windings can conduct current at the same time in a Forward converter, the two voltages (applied and induced) lead to simultaneous currents in the windings, which create equal and opposite flux contributions in the core, cancelling each other out. Yes, completely so! In effect, the "core" of the Forward converter's transformer does not "see" *any* of the flux associated with the transfer of power across its isolation barrier. Note that this flux-cancellation "magic" was physically impossible in a Flyback, simply because, though there was induced EMF in the Secondary, the output diode was so pointed, that it blocked any current flow arising from this induced voltage --- so there was no possibility of having two equal and opposite flux contributions occurring (at the same time).

This leads to the big question: if the "core" of the Forward converter's transformer does not see any of the flux related to the ongoing energy transfer through the transformer, can we transfer limitless energy through the transformer? No, because the DC resistance of copper comes in the way. This creates a *physical limitation* based on the available window area "Wa" of the core. We just cannot stack endless copper windings in a restricted space to support any power throughput. Certainly not if we intend to keep to certain thermal limits….because though the core may be totally "unaware" of the actual currents in the windings (because of flux cancellation), the windings themselves do see I^2R (ohmic) losses. So eventually, for thermal reasons, we have to keep to within a certain acceptable *current density*. That in effect, restricts the amount of power we can transfer through a Forward converter transformer. We intuitively expect that if we have double the available window area Wa, we would be able to double the currents (and the power throughput) too, for a given (acceptable) current density. In other words, we expect roughly (intuitively)

$$P_O \propto Wa$$

Truth does in fact support intuition in this case. But there is another key factor too: a transformer needs a certain excitation (magnetization) current to function to be able to provide transformer action in the first place. So there is a certain relationship to the core itself, its "ferrite-related" dimensions, not just the window area (air dimensions) that it provides. A key parameter that characterizes this aspect of the core is the area of its center limb, or Ae (often just called "A" in this chapter). Finally we expect the power to be related to both factors: the air-related component Wa and the ferrite-related component Ae:

$$P_O \propto Wa \times Ae$$

The product Wa × Ae is generically called "AP", or area product of the core. See Figure 1.

As indicated, we intuitively expect that doubling the frequency will allow double the power too. So we expect

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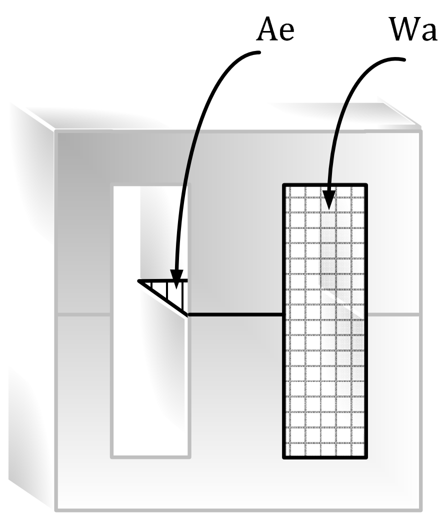
$P_O \propto AP \times f$

Or better still, since in the worst-case (losses after the transformer), the transformer is responsible for the entire *incoming* power, it makes more intuitive sense to write

$P_{IN} \propto AP \times f$



AP=Wa x Ae

Figure 1: Basic definition of Area Product

Finer Classes of Window Area and Area Product (finer terminology)

As we can see from Figure 2 and Figure 3, we can actually break up the window area into several windows (with associated Area Products). We should actually try to distinguish between them for the subsequent analysis, since typically, this becomes a source of major confusion in literature, with innumerable equations and fudge factors abounding (fudge factors rather generically called “Kx” usually), being apparently used to fit equations somehow to empirical data, rather than deriving equations from first principles then seeing how they match data. So we are creating some descriptors here.

a) Wac: This is the core window area. Multiplied by Ae, we get APc.

b) Wab: This is the bobbin window area. Multiplied by Ae, we get APb.

c) Wcu: This is the window available to wind copper in (both Primary and Secondary windings). Multiplied by Ae, we get APcu.

Note: In a safety approved transformer for AC-DC applications, we typically need 8 mm creepage between Primary and Secondary windings (see Fig. 2), so a 4 mm margin tape is often used (but sometimes 2.5 to 3 mm nowadays). For telecom applications, where only 1500VAC isolation is required, a 2 mm margin tape will suffice and provide 4 mm of creepage. The bobbin, insulation etc, significantly lowers the available area for copper windings --- to about 0.5 × (half) the core window area Wac.

d) Wcu_P: This is the window available for the Primary winding. Multiplied by Ae, we get $APcu_P$. For a safety approved AC-DC transformer, for example, this area only may be 0.25 times Wac (typically assuming Wcu is split equally between Primary and Secondary windings).

e) Wcu_S: This is the window available for the Secondary winding. Multiplied by Ae, we get $APcu_S$.

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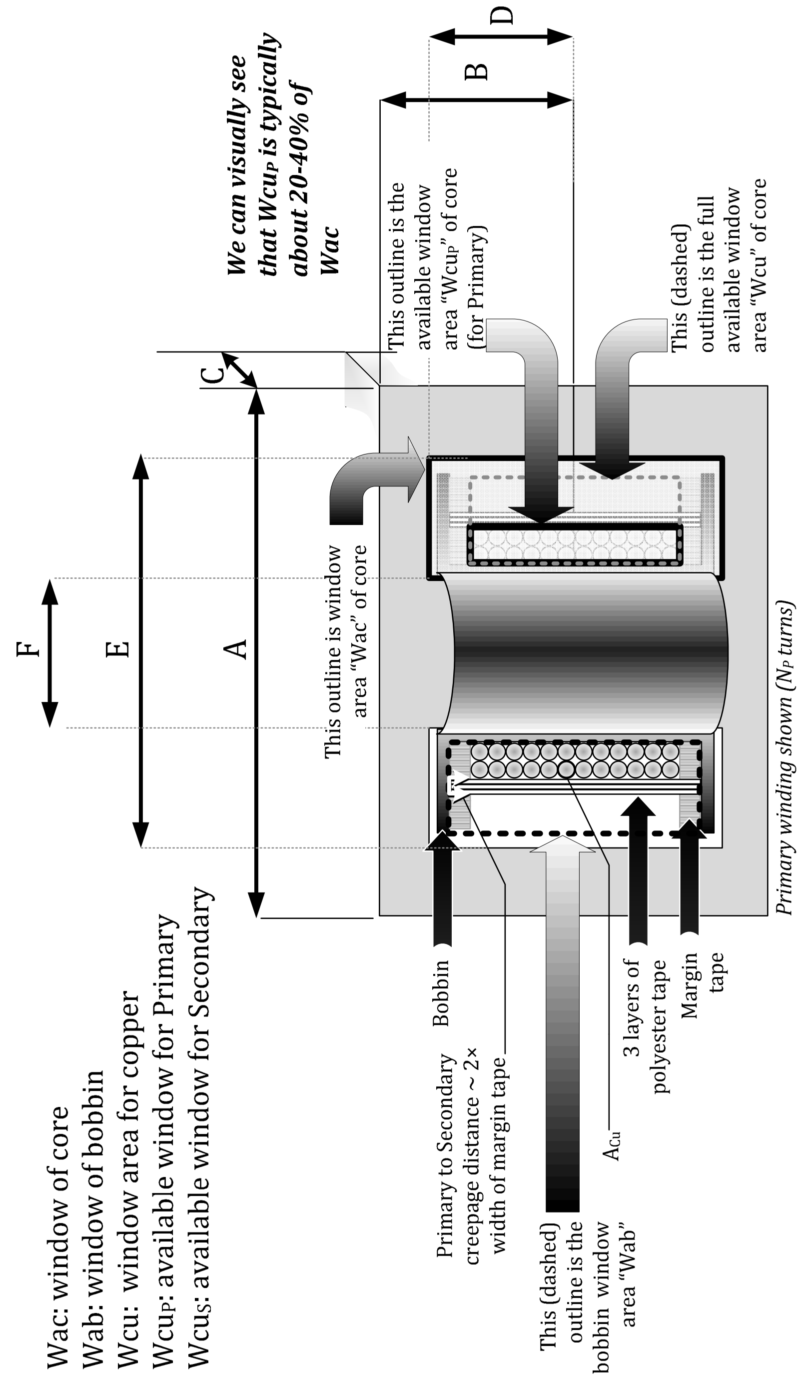

Figure 2: Finer divisions of window area and Area Product

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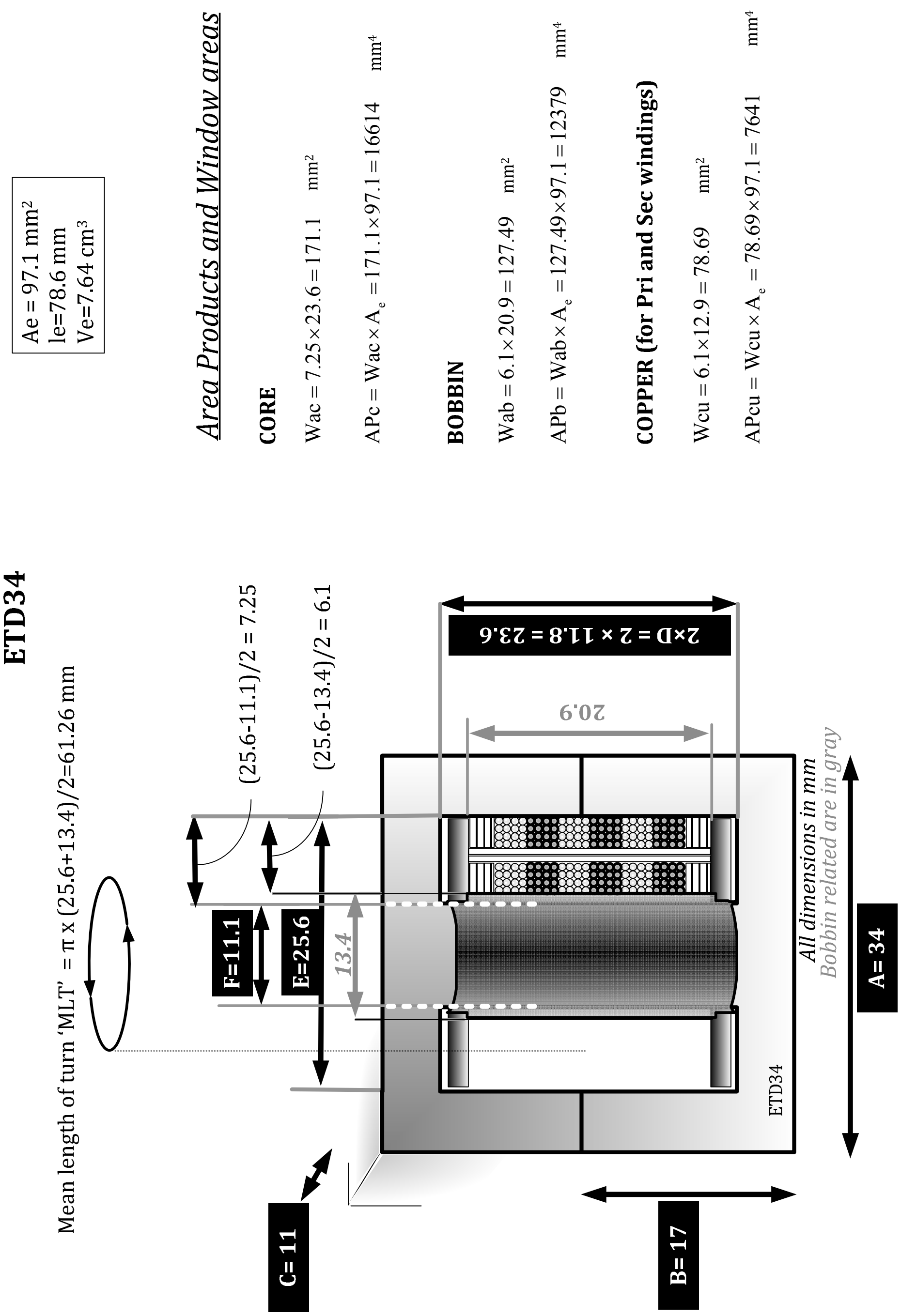

Figure 3: Numerical example showing popular dimensions' nomenclature, and also various window areas and Area Products

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Power and Area Product Relation

We remember that since the voltage across the inductor during the ON-time, V_{ON}, equals the input rail V_{IN} in *almost* all topologies (though not in the half-bridge for example), from the original form of the voltage-dependent (Faraday) equation

$$\Delta B = \frac{V_{IN} \times t_{ON}}{N_P \times A} \text{ Tesla}$$

Here "A" is the effective area of the core (same as "Ae"), expressed in m^2. (To remember try this: "voltseconds equals NAB"). Note that

$$N_P \times A_{Cu} = 0.785 \times Wcu_P$$

This is because a round wire of cross-sectional area "A_{Cu}" occupies only 78.5% (i.e., $\pi^2/4$) of the physical space (square of area D^2) that it physically occupies within the layer. Here Wcu_P is the (rectangular) physical window area available to wind copper in ---- but reserved only for the Primary turns. We are typically assuming that the available copper space "Wcu" is split equally between Primary and Secondary windings. That is a valid assumption mostly.

Solving for N_P, the number of Primary turns

$$N_P = \frac{0.785 \times Wcu_P}{A_{Cu}}$$

Using this in the voltage dependent equation, we get

$$\Delta B = \frac{V_{IN} \times t_{ON} \times A_{Cu}}{0.785 \times Wcu_P \times Ae} \text{ Tesla}$$

Performing some manipulations

$$\Delta B = \frac{V_{IN} \times t_{ON} \times A_{Cu}}{0.785 \times Wcu_P \times Ae} = \frac{V_{IN} \times {}^{I_{IN}}\!/_{I_{IN}} \times {}^{D}\!/_{f} \times A_{Cu}}{0.785 \times Wcu_P \times Ae}$$

$$= \frac{P_{IN} \times D \times A_{Cu}}{I_{IN} \times 0.785 \times Wcu_P \times Ae \times f} = \frac{P_{IN} \times D \times A_{Cu}}{(I_{SW} \times D) \times 0.785 \times Wcu_P \times Ae \times f}$$

$$\Delta B = \frac{P_{IN}}{{}^{I_{SW}}\!/_{A_{Cu}} \times 0.785 \times Wcu_P \times Ae \times f} = \frac{P_{IN}}{(J_{A/m^2}) \times 0.785 \times APcu_P \times f}$$

where J_{A/m^2} is the current density expressed in A/m^2, and '$APcu_P$' is the *'area product'* for the copper allocated to the Primary windings ($APcu_P = A_e \times Wcu_P$). Note that ***$I_{SW}$ here is the center of ramp ("COR") of the switch current (its average value during the ON-time). The current density is therefore based on that, not the RMS current*** as is often erroneously interpreted. Let us now convert the above into CGS units for convenience (writing units explicitly in the subscripts to avoid confusion). We get

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$$\Delta B_{Gauss} = \frac{P_{IN}}{\left(J_{A/cm^2}\right) \times 0.785 \times APcu_{P\_cm^4} \times f_{Hz}} \times 10^8$$

where $APcu_P$ is expressed in cm^2 now. Finally, converting the current density into "cmil/A" by using

$$J_{cmils/A} = \frac{197353}{J_{A/cm^2}}$$

we get

$$\Delta B_{Gauss} = \frac{P_{IN} \times J_{cmils/A}}{197353 \times 0.785 \times f_{Hz} \times APcu_{P\_cm^4}} \times 10^8 \text{ Gauss}$$

Solving for the area product

$$APcu_{P\_cm^4} = \frac{645.49 \times P_{IN} \times J_{cmils/A}}{f_{Hz} \times \Delta B_{Gauss}} \text{ cm}^4$$

Let us do some numerical substitutions here. Assuming a typical target current density of 600 cmil/A (based on *center of ramp* current value as explained above), a typical allowed ΔB equal to 1500 Gauss (to keep core losses down and to avoid saturation), we get the following core selection criterion

$$APcu_{P\_cm^4} = 258.2 \times \frac{P_{IN}}{f_{Hz}} \text{ cm}^4 \text{ (for 600 cmil/A, based on center of switch current ramp)}$$

Keep in that so far this is an exact relationship. It is based on the window area available for the Primary winding, because, with the target current density in mind (600 cmil/A), this determines the Ampere-turns and thus the flux.

In Switching Power Supplies A-Z, on Page 153, we derived the following relationship in a similar manner, almost the same as above

$$P_{IN} = \frac{AP_{cm^4} \times f_{Hz}}{675.6}$$

Equivalently

$$AP_{cm^4} = 675.6 \times \frac{P_{IN}}{f_{Hz}}$$

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This too was based on a *COR current density* of 600 cmil/A. The real difference with the equation we have just derived is that the Area Product in the A-Z book used the entire core area. In other words we had derived this

$$APc_{cm^4} = 675.6 \times \frac{P_{IN}}{f_{Hz}}$$

Compared to what we just derived (based on estimated area reserved for Primary winding)

$$APcu_{P\_cm^4} = 258.2 \times \frac{P_{IN}}{f_{Hz}}$$

In effect we had assumed in the A-Z book that that APcuP/APc=258.2/675.6 = 0.38. (Note: the reason it seems to be set to 0.3 in the A-Z book is this: 0.3/0.985 = 0.38! Think about it. The factor 0.785 was not factored into the current density).

In the A-Z book, as in most literature, the utilization factor "K" is just a fudge factor, applied to make equations fit data (with some physical reasoning to satisfy the critics). But in our ongoing analysis, we are actually trying to avoid all inexplicable fudge factors. So we should assume the equation we have come up with (immediately above) is accurate.

Keep in mind that though the max flux swing of 1500 Gauss is a very fair assumption to still make, in most types of practical Forward converters (to limit core losses and avoid saturation during transients), the current density of 600 cmil/A (COR value) needs further examination. And till we do that, let us stick to the more general equation connecting Area Product and power (make no assumptions yet).

$$APcu_{P\_cm^4} = \frac{645.49 \times P_{IN} \times J_{cmils/A}}{f_{Hz} \times \Delta B_{Gauss}} \text{ cm}^4 \text{ (most general)}$$

In terms of A/cm^2, this is

$$APcu_{P\_cm^4} = \frac{645.49 \times P_{IN} \times 197353}{f_{Hz} \times \Delta B_{Gauss} \times J_{A/cm^2}}$$

Or

$$APcu_{P\_cm^4} = \frac{12.74 \times P_{IN}}{f_{kHz} \times \Delta B_{Tesla} \times J_{A/cm^2}} \text{ (most general)}$$

Keep in mind that J here is based on the COR value.

Current Density and Conversions based on D

Keep in mind that in the derivation above, when we set $I_{IN} = I_{SW} \times D$, in effect the current density was a "COR" current density, not an RMS value. That is how we "eliminated D" from the equation. But heating does not actually depend directly on COR value, but on the

RMS. So, in effect, looking at it the other way, our Area Product equation actually implicitly *depends on D*, through the COR current density value we picked. If we make an assumption about D, we can convert it to an equivalent RMS current density value
The 600 cmil/A value we used to plug in numerically into the equation, should perhaps be written out more clearly as 600 cmil/A_{COR} , where "A_{COR}" is the center of ramp value of the current in Amps. We ask: what is 600 cmil/A in terms of RMS current? As indicated, that actually depends on duty cycle. Assuming a ball-park nominal figure of D=0.3 for a Forward converter, a current pulse of height 1A, leads to an RMS of 1A × √D = 1A × √(0.3) = 0.548 A. In other words, 600cmil/A_{COR} means that 600 cmil is being allocated for 0.548 A_{RMS}. In other words, this is equivalent to allocating 600 / 0.548 = 1095 cmil per A_{RMS}. So we get the following conversions

$$600 \text{ cmil/A}_{\text{COR}} \equiv 600/0.548 = 1095 \text{ cmil/A}_{\text{RMS}}$$

OR

$$197353/600 = 330 \text{ A}_{\text{COR}} / \text{cm}^2 \text{ (in terms of COR current)}$$

OR

$$197353/1095 = 180 \text{ A}_{\text{RMS}} / \text{cm}^2 \text{ (in terms of RMS current)}$$

These conversions are for a typical Forward converter with D=0.3. Note that we were in effect asking for a current density of 180 A/cm^2, which is rather low (conservative) than usually accepted. But let us discuss this further.

Optimum Current Density

What really is a good current density to target in an application? Is it 600 cmil/A_{COR} (i.e. 180 A_{RMS}/cm^2 for D=0.3), or something else? Actually, 600 mil/A_{COR} is a tad too conservative. But this is a topic of great debate, much confusion, and widely dissimilar recommendations in the industry. We need to sort it out.

As a good indication of the industry-wide dissonance on this subject, see the 40W Forward converter design from an engineer at Texas Instruments, at **http://www.ti.com/lit/ml/slup120/slup120.pdf**. He writes that

> *"The transformer design uses the Area Product Method that is described in [3]. This produced a design that was found to be core loss limited, as would be expected at 200 kHz. The actual core selected is a Siemens-Matsushita EFD 30/15/9 made ofN87 material….The area-product of the selected core is about 2.5 times more area-product than the method in [3] recommended. We selected the additional margin with the intention of allowing additional losses due to proximity effects in a multi-layer foil winding that is required for carrying the large secondary currents."*

The engineer is referring to his reference [3] which is: Lloyd H. Dixon, Jr., "Power Transformer Design for Switching Power Supplies," Rev. 7/86, SEM-700 Power Supply Design Seminar Manual, Unitrode Corporation, 1990, section M5.

This means that Unitrode (now TI) has a recommendation on core size of Forward converters, that was almost 250% off the mark, as reported by another TI engineer who actually tried to follow his own company's design note to design a practical converter.

It therefore seems it is a good idea to stay conservative here, as no one in the commercial arena, will appreciate or reward a thermal issue holding up safety approvals and production at the very last moment.

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Let us start with the basics: it has been widely stated and seemingly accepted that for most E-core type Flyback transformers, a current density of **400 cmil/A_{RMS}** (equivalent to 197353/400 ≈ **500 A_{RMS}/cm^2**), is acceptable. This seems to have served engineers making evaluation boards for controller ICs and FETs well at least. But is it acceptable in trying to achieve a maximum 55°C rise (internal hot-spot temperature), so as to qualify as a safety-approved Class A transformer (max 105°C)?

The problem is, a current density of 500A_{RMS}/cm^2 may serve well for low-frequency sine waveforms, as used by most core vendors, but when we come to Forward converters in particular, because of the skin and proximity effects, as best described by Dowell historically, the ratio F_R (AC resistance divided by DC resistance) is much higher than unity. Note that Dowell used high frequency waves for a change, but assumed sinusoidal waves. After that, a lot of Unitrode app notes invoked the original form of Dowell's equations, with sine waves, and arrived at achievable F_R values slightly greater than 1, with proper high-frequency winding techniques, and so on. However, in modern days, when we include the high-frequency harmonics of the typical "square waveforms" of switching power conversion, ***the best achievable AC resistance ratio F_R is not a little over 1, but about 2***. In other words, mentally we need to think of this as windings made with a new metal which has double the resistivity of copper. Now, to arrive at the same acceptable value of heating and temperature rise as regular (low-frequency) "copper transformers", a good target in a Forward converter would be to allocate twice the area (i.e., target half the current density as expressed in A/cm^2). That means we want to target 800 cmil/A_{RMS} for a Forward converter, comparable with 400 cmil/A_{RMS} for a Flyback. So, assuming a Forward converter with D = 0.3, we actually want to target

$$800\ \text{cmil/A}_{RMS} \equiv 800\times 0.548 = 440\ \text{cmil}/\text{A}_{COR}$$

OR

$$197353/800 \approx 250\ \text{A}_{RMS}/\text{cm}^2\ \text{(in terms of RMS current)}$$

OR

$$197353/440 = 450\ \text{A}_{COR}/\text{cm}^2\ \text{(in terms of COR current)}$$

If the duty cycle was D=0.5 (as in a Forward at lowest line condition), since √(0.5)=0.707, we could write the target current density as

$$800\ \text{cmil/A}_{RMS} \equiv 800\times 0.707 = 565\ \text{cmil}/\text{A}_{COR}$$

OR

$$197353/800 \approx 250\ \text{A}_{RMS}/\text{cm}^2\ \text{(in terms of RMS current)}$$

OR

$$197353/565 = 350\ \text{A}_{COR}/\text{cm}^2\ \text{(in terms of COR current)}$$

We see that for both duty cycles above, what remained constant was the following design target: a Forward converter transformer current density of ***250 A_{RMS}/cm^2***, exactly half the "widely accepted" current density target.
But keep in mind that the equation we have derived above for a Forward converter is exact, but uses COR current density (to mask D)

$$\text{APcu}_{P\_cm^4} = \frac{645.49\times P_{IN}\times J_{cmils/A_{COR}}}{f_{Hz}\times\Delta B_{Gauss}}\ \text{cm}^4$$

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If we plug in our recommended COR current density of 440 cmil/A (for D = 0.3), and also assume (quite valid) that we have a utilization factor of 0.25 (ratio of Primary winding area to core winding area, see Fig. 2), we get our basic (Maniktala) recommendation to be

$$APc_{cm^4} = \frac{645.49 \times P_{IN} \times J_{cmils/A_{COR}}}{f_{Hz} \times \Delta B_{Gauss}} = \frac{645.49 \times P_{IN} \times 440}{0.25 \times f_{Hz} \times \Delta B_{Gauss}} = 11360624 \times \frac{P_{IN}}{f_{Hz} \times \Delta B_{Gauss}}$$

Or

$$\boxed{APc_{cm^4} = 113.6 \times \frac{P_{IN}}{f_{Hz} \times \Delta B_{Tesla}}}$$ (Maniktala, for D=0.3, J = 250 A_{RMS}/cm^2, K = 0.25)

Plugging in a typical value of ΔB=1500 Gauss, we get

$$APc_{cm^4} = \frac{645.49 \times P_{IN} \times 440}{f_{Hz} \times 1500 \times 0.25} = 755 \times \frac{P_{IN}}{f_{Hz}}$$

Or equivalently (using kHz)

$$\boxed{APc_{cm^2} = 0.75 \times \frac{P_{IN}}{f_{kHz}}}$$ (Maniktala, for D=0.3, ΔB=0.15T, J = 250 A_{RMS}/cm^2, K=0.25)

As we can see, this equation asks for a slightly larger core than we had suggested in the numerical example A-Z book. In the A-Z book, though we had used a little more generous (conservative) current density, but we also set a much more optimistic “utilization (fudge) factor”. In that book we had derived

$$APc_{cm^4} = 675.6 \times \frac{P_{IN}}{f_{Hz}}$$

Or equivalently

$$APc_{cm^4} = 0.676 \times \frac{P_{IN}}{f_{kHz}}$$ (Maniktala old, for D=0.3, ΔB=0.15T, J = 180 A_{RMS}/cm^2, K = 0.38)

We conclude that the new equation we have now derived

$$APc_{cm^2} = 0.75 \times \frac{P_{IN}}{f_{kHz}}$$ (Maniktala new, for D=0.3, ΔB=0.15T, J = 250 A_{RMS}/cm^2, K = 0.25)

is a tad more realistic (and conservative in terms of available window area) than the older one in the A-Z book. This one asks for slightly higher Area Product (for a given power).

This slight modification of the A-Z book recommendation is a little more helpful for designing a safety-approved Class A Forward converter transformer running at a nominal D = 0.3.

Note that the underlying assumptions in our new equation include a ***max flux swing of 1500 Gauss, a current density of 250 A_{RMS}/cm^2, and a utilization factor (ratio of Primary winding area Wcu_P to the full core window area Wac) of 0.25***.

If we have a core with a certain prescribed core area product, we can also flip it to find its power capability as follows

$$P_{IN} = \frac{APc_{cm^4} \times f_{Hz}}{754} = 1.33 \times 10^{-3} \times \left(APc_{cm^4} \times f_{Hz}\right)$$

$$\boxed{P_{IN} = 1.33 \times APc_{cm^4} \times f_{kHz}}$$ (Maniktala, for D=0.3, ΔB=0.15T, J = 250 A_{RMS}/cm^2, K = 0.25)

For example, at f = 200 kHz, the ETD-34 core-set, with a core area product of 1.66 cm^4, is suitable for

$$P_{IN} = \frac{1.66 \times 200000}{754} = 440W$$ (Recommendation example based on Maniktala)

With an estimated efficiency of say 83%, this would work for a converter with P_O = 365W.

Having understood this, we would like to compare with the equations others are espousing in related literature, to see where we stand vis-à-vis their recommendations. Here is a list of other “similar” equations in literature.

Industry Recommended Equations for Area Product of Forward converter

A) **Fairchild Semi recommendation:**

(for example, see “The Forward-Converter Design Leverages Clever Magnetics by Carl Walding” in http://powerelectronics.com/mag/Fairchild.pdf**)**:

$$AP_{mm^4} = \left(\frac{78.72 \times P_{IN}}{\Delta B \times f_{Hz}}\right)^{1.31} \times 10^4$$

This was alternatively expressed in Application Note AN-4134 from Fairchild as

$$AP_{mm^4} = \left(\frac{11.1 \times P_{IN}}{0.141 \times \Delta B \times f_{Hz}}\right)^{1.31} \times 10^4$$

But it is the same equation. It seems to be assuming that the Area Product refers to the entire core. The field is in Tesla. We can also rewrite this in terms of cm^4 as

$$APc_{cm^4} = \left(\frac{78.72 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.31}$$ (Fairchild)

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Compare with our equation

$$APc_{cm^4} = \frac{113.6 \times P_{IN}}{f_{Hz} \times \Delta B_{Tesla}} \text{ (Maniktala)}$$

We can simplify the Fairchild equation and set ΔB = 0.15 T (the usual typical optimum flux swing to avoid saturation and keep core losses small). We get

$$APc_{cm^4} = \left(\frac{78.72 \times P_{IN}}{0.15 \times f_{kHz}}\right)^{1.31}$$

$$APc_{cm^4} = 0.43 \times \left(\frac{P_{IN}}{f_{kHz}}\right)^{1.31} \text{ (Fairchild, with ΔB=0.15T,)}$$

We can compare this with our equation

$$APc_{cm^4} = 0.75 \times \left(\frac{P_{IN}}{f_{kHz}}\right) \text{ (Maniktala, with ΔB=0.15T)}$$

For example, for 440W input power, we know at 200 kHz, we recommend the ETD-34 with APc=1.66 cm^4 (see Fig 3.). What does the Fairchild equation recommend? We get

$$APc_{cm^4} = 0.43 \times \left(\frac{440}{200}\right)^{1.31} = 1.21 \text{ cm}^4 \text{ (Fairchild recommendation example)}$$

ETD-29 has an Area Product (core) of 1.02 cm^4. So we will still end up using ETD-34. But in general, at least for lower powers and frequencies, the Fairchild equation can ask for up to half the Area Product, thus implying much smaller cores. It seems more aggressive, and unless forced into a default larger core size, it will likely require either forced air cooling, or better (more expensive) core materials to compensate higher copper losses by much lower core losses. Or the transformer will be either non-safety-approved, or Class B safety-approved.

We can also solve the Fairchild equation for the power throughput from a given (core) Area Product (using typical ΔB=1500 Gauss)

$$APc_{cm^4} = \left(\frac{78.72 \times P_{IN}}{0.15 \times f_{kHz}}\right)^{1.31}$$

$$P_{IN} = APc_{cm^4}^{0.763} \times \frac{0.15 \times f_{Hz}}{78.72} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.763}$$

$$\boxed{P_{IN} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.763}} \text{ (Fairchild, for ΔB=0.15 Tesla)}$$

B) **TI/Unitrode recommendation:**

For example see **http://www.ti.com/lit/ml/slup126/slup126.pdf** and **http://www.ti.com/lit/ml/slup205/slup205.pdf** :

$$APc_{cm^4} = \left(\frac{11.1 \times P_{IN}}{K \times \Delta B_{Tesla} \times f_{Hz}}\right)^{1.143}$$

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

In this case "K" is a fudge factor related to both window utilization and topology. Unitrode asks to fix this at 0.141 for a single-ended Forward, and at 0.165 for a bridge/half-bridge. So with that, we get (for a single-ended Forward, assuming core Area Product)

$$APc_{cm^4} = \left(\frac{11.1 \times P_{IN}}{0.141 \times \Delta B_{Tesla} \times f_{Hz}} \right)^{1.143} = \left(\frac{78.72 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}} \right)^{1.143}$$

$$APc_{cm^4} = \left(\frac{78.72 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}} \right)^{1.143} \quad \text{(Unitrode)}$$

Which is almost identical to the Fairchild equation, except that the exponent is 1.143, leading to a much slower "rise" with power (and a "fall" with frequency), as compared to the exponent of 1.31 in the Fairchild equation. Note that this equation too (as the Fairchild equation) is said to be based on a high current density of 450 A_{RMS}/cm^2 --- far more aggressive than the 250 A_{RMS}/cm^2 which we are recommending. But in Unitrode application notes, the best achievable F_R was calculated to be just slightly larger than 1, *because it was based on sinusoidal waveforms*, whereas in reality, we have the best-case F_R closer to 2. Hence our more conservative current density target. But it seems the fudge-factor K takes care of that somehow, in the TI/Unitrode notes.

We can also solve the Unitrode equation for the power throughput from a given (core) Area Product (using typical ΔB=1500 Gauss)

$$P_{IN} = APc_{cm^4}^{0.875} \times \frac{0.15 \times f_{Hz}}{78.72} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.875}$$

$$\boxed{P_{IN} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.875}} \quad \text{(Unitrode, for } \Delta B\text{=0.15 Tesla)}$$

C) **Basso/On-Semi recommendation:**

For example see http://www.onsemi.com/pub_link/Collateral/TND350-D.PDF:

$$APc_{cm^4} = \left(\frac{P_O}{K \times \Delta B_{Tesla} \times f_{Hz}} \right)^{4/3}$$

It is suggested that K= 0.014 for a Forward converter. This is another inexplicable fudge factor really. Simplifying we get

$$APc_{cm^4} = \left(\frac{71.43 \times P_O}{\Delta B_{Tesla} \times f_{Hz}} \right)^{1.33}$$

This is indeed very close to the Fairchild equation too, though this one unfortunately implicitly assumes 100% efficiency. If we assume say 90% efficiency, we actually get

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

$$APc_{cm^4} = \left(\frac{71.43 \times 0.9 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.33} = \left(\frac{64.3 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.33}$$

$$APc_{cm^4} = \left(\frac{64.3 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.33} \quad \text{(On-Semi)}$$

Note that On-Semi says this is based on a window utilization factor of 0.4, and a current density of 420 A/cm^2. We assumed a 90% efficiency to get to the above equation.

The On-Semi equation can also be written out for power throughput in term of (core) area product as follows

$$APc_{cm^4} = \left(\frac{71.43 \times P_O}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.33} \Rightarrow \left(APc_{cm^4}\right)^{\frac{1}{1.33}} = \left(\frac{71.43 \times P_O}{\Delta B_{Tesla} \times f_{Hz}}\right)$$

$$P_O = \frac{\Delta B_{Tesla} \times f_{Hz}}{71.43} \times APc_{cm^4}^{0.752}$$

For a flux swing of 1500 Gauss

$$P_O = APc_{cm^4}^{0.752} \times \frac{0.15 \times f_{Hz}}{71.43} = 2.1 \times f_{kHz} \times APc_{cm^4}^{0.752}$$

$$\boxed{P_{IN} = 2.1 \times APc_{cm^4}^{0.752} \times f_{kHz}} \quad \text{(On-Semi, for ΔB=0.15 Tesla, 100\% efficiency)}$$

D) **ST Micro recommendation:**

For example, see AN-1621 at **http://www.st.com/internet/com/TECHNICAL_RESOURCES/TECHNICAL_LITERATURE/APPLICATION_NOTE/CD00043746.pdf** :

$$APc_{cm^4} = \left(\frac{67.2 \times P_{IN}}{\Delta B_{Tesla} \times f_{Hz}}\right)^{1.31} \quad \text{(ST Micro)}$$

$$P_{IN} = APc_{cm^4}^{0.763} \times \frac{0.15 \times f_{Hz}}{67.2} = 2.23 \times f_{kHz} \times APc_{cm^4}^{0.763}$$

$$\boxed{P_{IN} = 2.23 \times f_{kHz} \times APc_{cm^4}^{0.763}} \quad \text{(ST-Micro, for ΔB=0.15 Tesla)}$$

E) **Keith Billings/Pressman recommendation and Explanation:**

(for example see "Switching Power Supply Design, 3rd Ed. by Abraham Pressman, Keith Billings and Taylor Morey", and "Switchmode Power Supply Handbook" by Keith Billings.)

Billings actually derives the requisite equation in a similar manner to what have done. But lands up with a Unitrode-type equation. This leads us to the origin of the odd exponent we are seeing in almost all the industry-wide equations. Where did that come from? It seems that almost all the equations are based on an old empirical equation found in "Transformer and Inductor Design Handbook" by Colonel Wm. T. McLyman. The reason for the odd exponent stems from a *completely empirical statement*, that says the target current density is not a constant as we assumed, but is a function of area product. The paradox is that everyone (including Billings) still writes out the current density target as a fixed number anyway: 420 or 450 A/cm^2. But the origin of the odd exponent is indirectly explained by Billings himself in his own derivation, courtesy McLyman --- thst derivation parallels ours, except that Billings writes

$$J_{A/m^2} = 450 \times 10^4 \times AP^{-0.125}$$

So current density (target?) is a function of Area Product.

Continuing the derivation as per Billings, (ignoring fudge factors etc., and replacing them with just an "X" here)

$$AP = \frac{X \times P_{IN}}{AP^{-0.125} \times \Delta B \times f}$$

$$AP^{1-0.125} = AP^{0.875} = \frac{X \times P_{IN}}{\Delta B \times f}$$

$$(AP)^{\frac{0.875}{0.875}} = AP = \left(\frac{X \times P_{IN}}{\Delta B \times f}\right)^{\frac{1}{0.875}} = \left(\frac{X \times P_{IN}}{\Delta B \times f}\right)^{1.143}$$

$$AP = \left(\frac{X \times P_{IN}}{\Delta B \times f}\right)^{1.143}$$

That is the underlying logic how the strange exponent of 1.14 (or something else very close) appears in almost all equations, especially the early TI/Unitrode notes.

Historically there was less recognition of safety issues (margin tape etc) and the *correct* AC resistance calculations to use. As mentioned, Dowell's equations were for sinusoidal waveforms originally.

It is likely that since smaller transformers have a larger exposed surface area to volume, they cool better (smaller thermal resistance), and so inaccuracies in setting more aggressive current densities for smaller cores were not noticed, till larger cores appeared for testing. In that case, temperatures rose much higher than expected. So now, empirically, it was decided to adjust core size down for a give power requirement, just to get a larger surface area to allow it to cool, and of course a larger window area for allowing improved current density too. That is likely how the term "-0.125" in the current density versus Area Product equation appeared, which in turn led to the odd exponents we see: such as 1.14, 1.31, and so on.

Disregarding where they all came from, we can certainly plot them all out for comparison, to see if our guess about the historical sequence and the resulting “equation adjustments” as described above, seems plausible.

Plotting Industry Recommendations for Forward Converter

For a typical flux swing of 1500 Gauss, we have plotted out the following recommendations

a) $P_{IN} = 1.33 \times f_{kHz} \times APc_{cm^4}$ (Maniktala)

b) $P_{IN} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.763}$ (Fairchild)

c) $P_{IN} = 1.9 \times f_{kHz} \times APc_{cm^4}^{0.875}$ (Unitrode/TI)

d) $P_{IN} = 2.1 \times f_{kHz} \times APc_{cm^4}^{0.752}$ (On-Semi)

e) $P_{IN} = 2.23 \times f_{kHz} \times APc_{cm^4}^{0.763}$ (ST Micro)

We see from these that indeed, doubling the frequency will double the power (so we really do not need to plot out curves for 300 KHz, 400 kHz, and so on --- it is obvious how to derive the results for different frequencies).

On plotting these out in Fig. 4 and Fig. 5., we see that our recommendation is more conservative for smaller output powers, but is in line with others at higher power levels. We know that ours is based on a constant current density target of 250 A_{RMS}/cm^2. The other recommendations do seem to be using a variable current density target, though that is never explicitly defined in literature. They may “get away” with their more aggressive core size recommendations *for small cores*, based on the empirical fact that smaller cores have improved thermal resistances on the bench, because of their higher surface-area-ratio- to-volume. And that fact may admittedly allow us also to also judiciously increase the current density in small cores, say up to 350-400 A_{RMS}/cm^2. But it is quite clear that for larger cores, we do need to drop down to 250 A_{RMS}/cm^2 --- because all other recommendations do coincide with ours at high power levels, and our recommendation was based on a fixed 250 A_{RMS}/cm^2.
We can confirm from Fig. 5 that our recommendation is ETD34 (APc = 1.66 cm^4) for up to 440 W input power at 200 kHz, whereas the others typically allow 100W to 200W more than that.
We can also compare with another set of curves historically available from **www.mag-inc.com**. These are shown in Fig. 6. These are clearly the most aggressive, and they also do not seem to spell out clearly if the topology is a single-ended Forward converter, or say, a Push-Pull (where due to symmetrical excitation, most engineers claim it will give exactly twice the power reflected by the curves in Fig. 4 and Fig. 5). Keep in mind that the mag-inc curves seem to be based on low-frequency sine waves applied to test cores. But these were widely “referred to” in most of the prevailing Forward converter design notes around us even today.
Our conclusion is we should use the equations proposed here, as these are more conservative and less likely to run into thermal recalls.

More Accurate Estimate of Power Throughput in Safety Transformers

All recommendations so far have been based on an assumption of a certain window utilization factor. All the curves we have shown in Fig. 4 and Fig 5, have some such underlying assumption. At least, in our case we have rather clearly assumed (and announced) that the Primary windings will occupy exactly $1/4^{th}$ the total available *core* window area (i.e., K=0.25). Most others typically either provide rather vague utilization numbers, seeming applied to somehow fit empirical data, but provide almost no physical explanation usually.

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

We also opined that for smaller transformers, we may be able to target higher current densities very judiciously. Keep in mind that if (exposed) area of a core was proportional to its volume, then even assuming that the coefficient of convection ("h") was constant with respect to area (it isn't perfectly), we would expect the thermal resistance, which is assumed inversely proportional to surface area, to be inversely proportional to the volume (size of core) too. So, we would expect Rth to vary as per 1/Ve. But that does not happen. The actual thermal resistance is much worse *than expected*, for larger cores, and is based on the following well-known empirical formula. See Fig. 7 for how a "wishful situation" was tempered with reality. So, the accepted empirical equation is

$$\mathrm{Rth} = \frac{53}{\mathrm{Ve}^{0.54}} \ {}^{\circ}\mathrm{C/W}$$

However, we should also keep in mind that in smaller cores, less and less window utilization occurs, because the margin tape is of a fixed width (and also with a constant bobbin wall thickness), and does not decrease proportionately with core window area. So we will likely struggle even to maintain the same fixed current density. We just may not have enough winding width available, once we subtract the margin tape width on either side.

To more accurately judge what is the *real utilization factor* to plug in (instead of the default value of 0.25 we have used so far*), we need to actually compute the physical dimensions*, making some assumptions about bobbin wall thickness too. We start with some popular core sizes listed in Table 1, and then use that to arrive at the detailed results in Tables 2 to 5, cranked out by a spreadsheet, for the following cases: no margin tape, 2mm margin tape (telecom), 4 mm margin tape (AC-DC with no PFC), 6.3 mm margin tape (AC-DC with Boost PFC front end). As we can see, certain core sizes result in "NA" (non-applicable), because after subtracting the margin tape from the available bobbin width, we get either almost no space for any winding, or worse, we have negative space. We also see that the utilization factor Kcu_P, is all over the place. Even our assumption of K=0.25 was clearly a broad assumption, not really valid for small cores in particular. From these tables we can do a much more detailed and accurate calculation, as we will carry out shortly.

Number of Primary Turns

The correct equation to use is the more basic form of Faraday's law ("voltseconds = NAB")

$$V_{IN} \times \frac{D}{f_{Hz}} = N_P \times Ae_{m^2} \times \Delta B_{Tesla}$$

$$N_P = \frac{V_{IN} \times D}{f_{Hz} \times Ae_{m^2} \times \Delta B_{Tesla}} = \frac{V_{IN} \times D \times 10^4}{f_{Hz} \times Ae_{cm^2} \times \Delta B_{Tesla}}$$

We will use this in the numerical example.

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

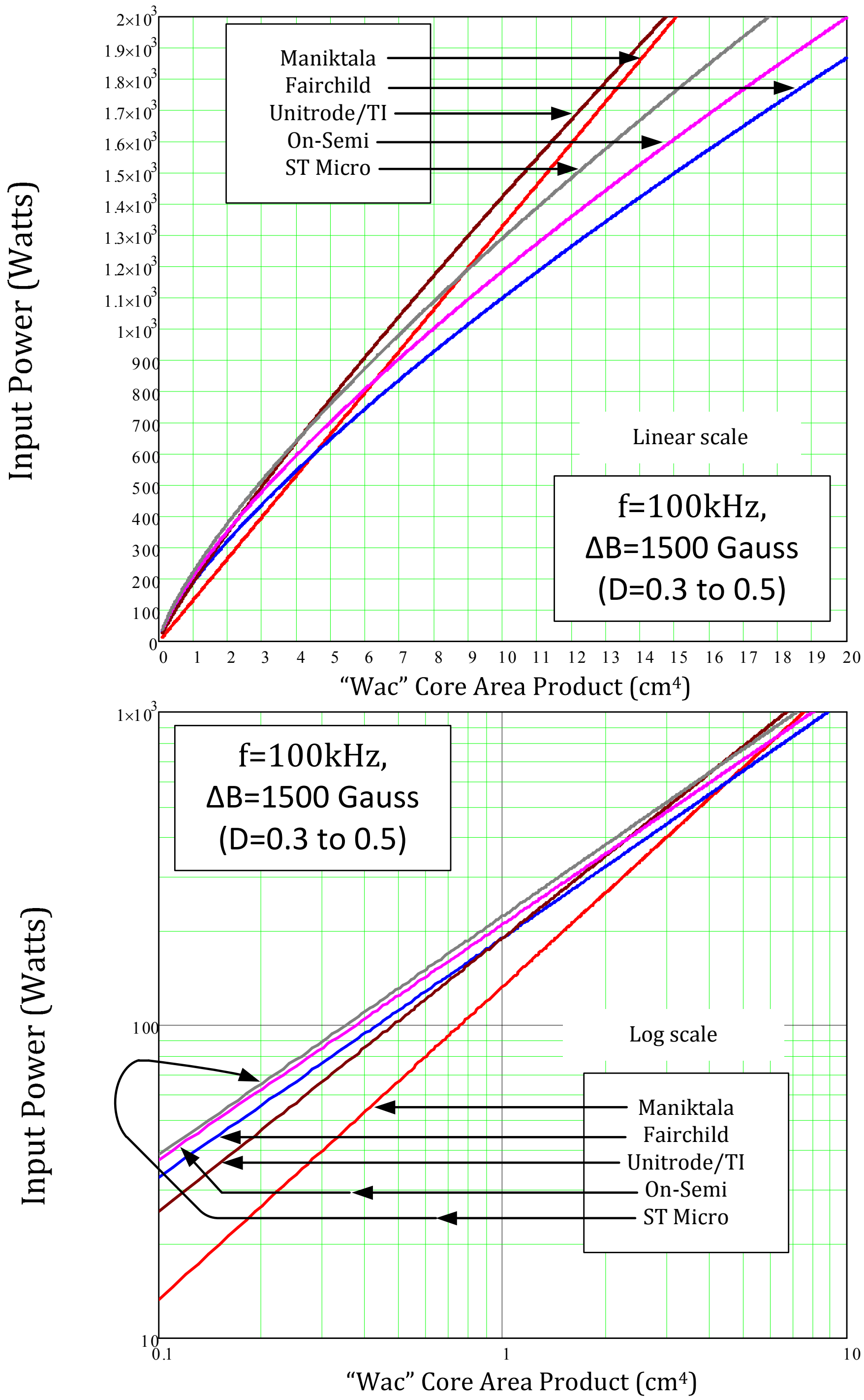

Figure 4: Comparing Industry Recommendations through plots of Power versus Core Area Product, assuming typical flux swing of 1500 Gauss (at 100kHz)

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

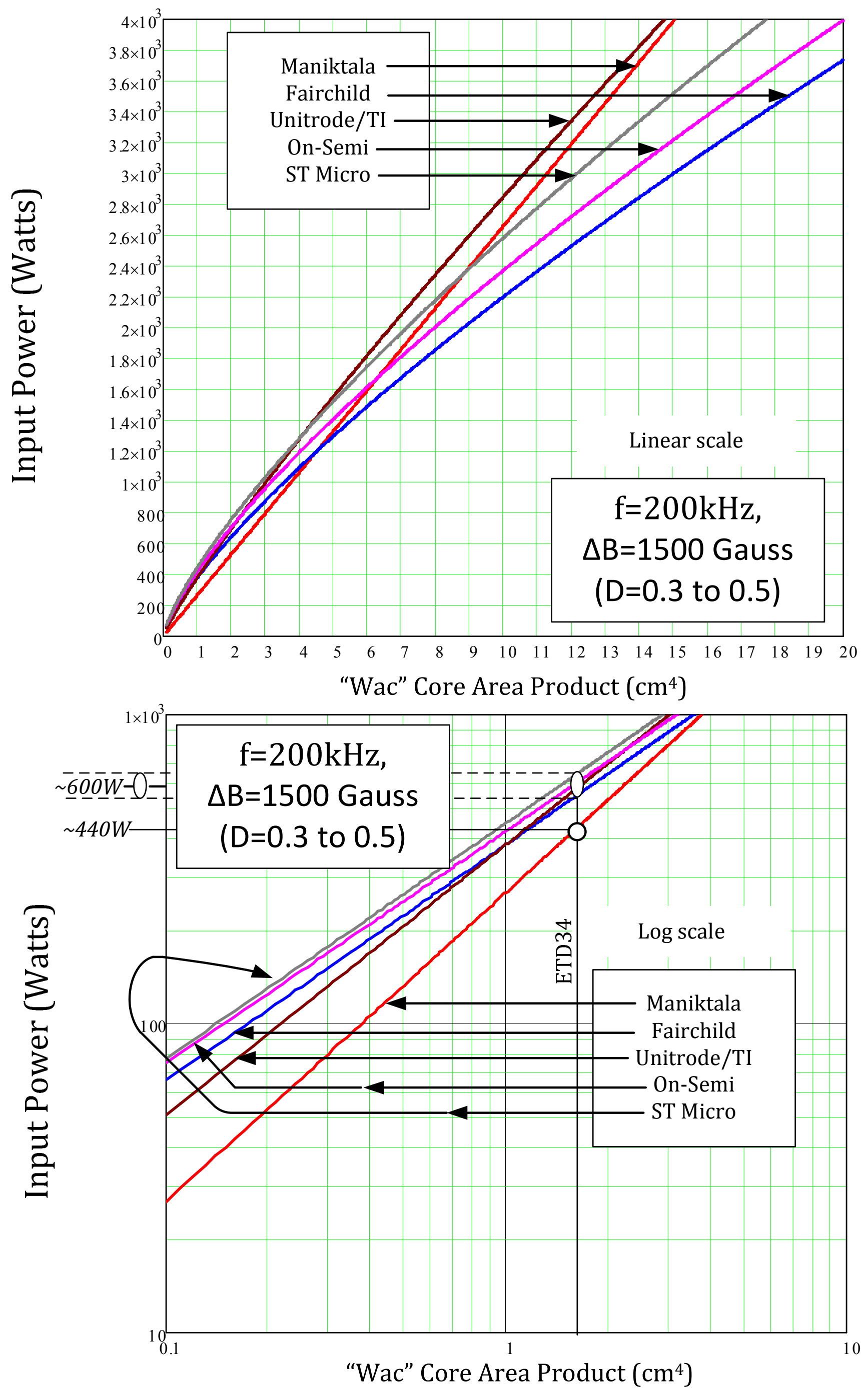

Figure 5: Comparing Industry Recommendations through plots of Power versus Core Area Product, assuming typical flux swing of 1500 Gauss (at 200kHz)

These say that even at 100 kHz, we can get 600 W from ETD34!

Curves from www.mag-inc.com

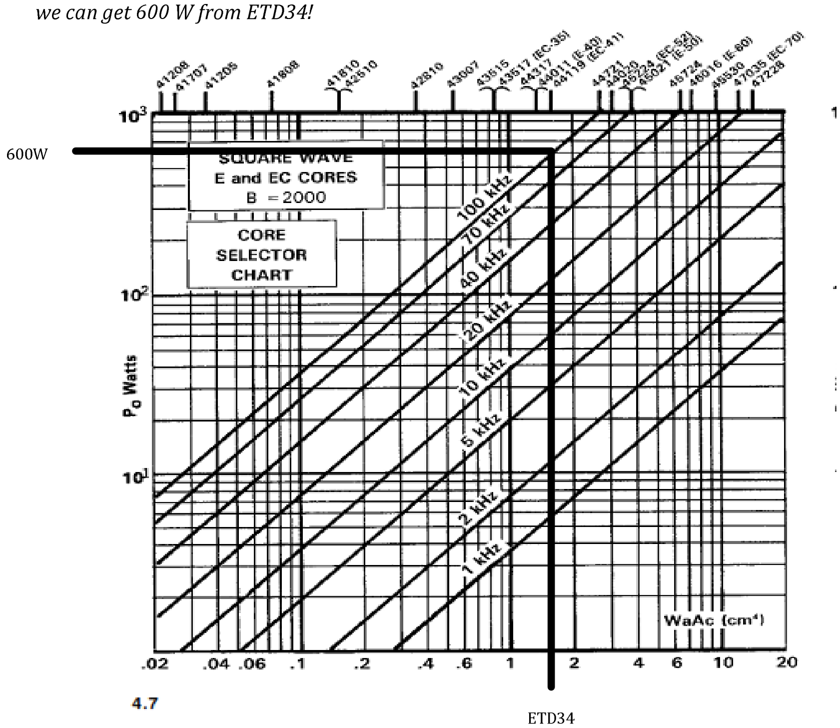

Figure 6: Historically available recommendations from Magnetics Inc.

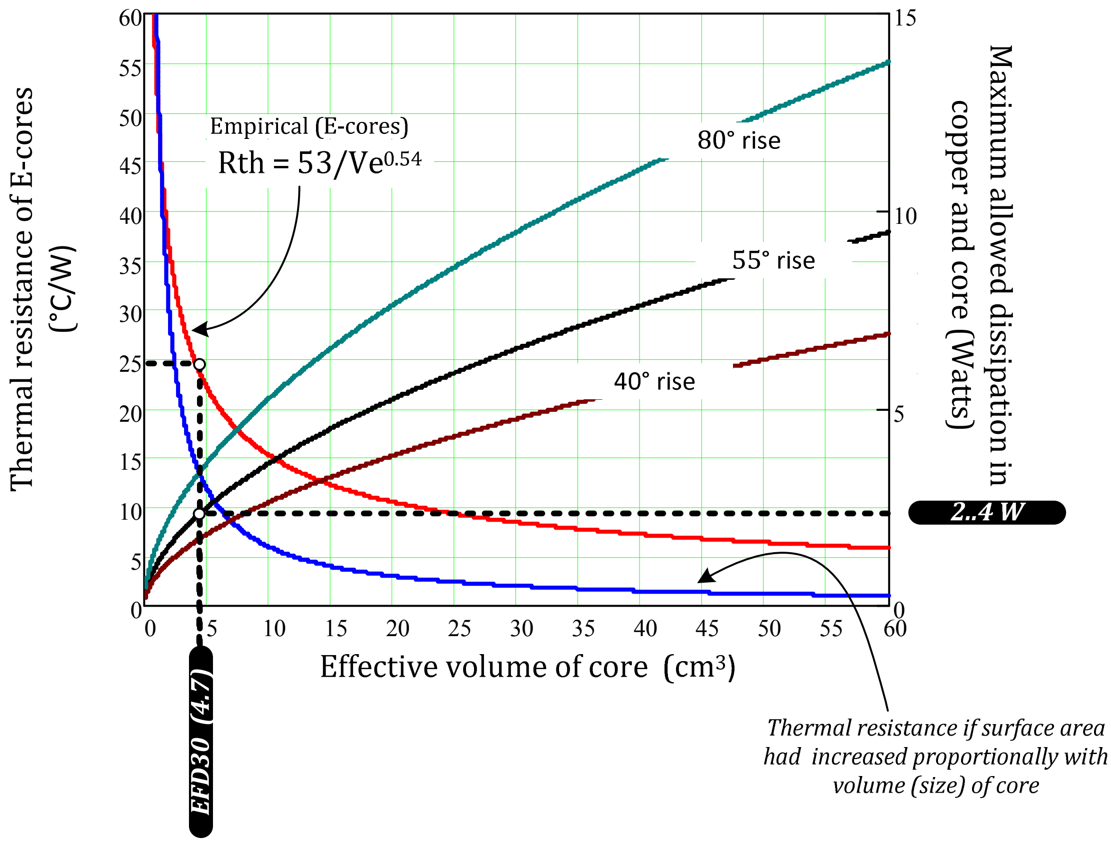

Figure 7: Thermal Resistance of E-cores and maximum allowed dissipation (in windings and core)

Worked Example: Flyback and Forward Alternative Design Paths

In a telecom application, such as PoE, we have an input voltage of 36-57V. We want to design a 200 kHz, 12V@11A (132W) Forward converter (LX7309 controller is limited to a max duty cycle of 44% as in a typical single-ended type). Select the transformer core, and calculate the Primary and Secondary number of turns on it. Also select a Secondary choke. If the same application and the same control IC was used for a Flyback, what would be the required core size and the number of turns?

Forward Converter Core Selection

Core Selection:

Assume the efficiency will be close to 85%. So for an output of 132W, the input will be 132/0.85 = 155.3W. We target a flux swing of 0.15T max, and a current density of 500 A/cm^2 as discussed previously. So

$$APcu_{P\_cm^4} = \frac{12.74 \times P_{IN}}{f_{kHz} \times \Delta B_{Tesla} \times J_{A/cm^2}}$$

$$APcu_{P\_cm^4} = \frac{12.74 \times 155.3}{200 \times 0.15 \times 500} = 0.132\ \mathrm{cm}^4$$

This is the required Area Product in terms of the Primary winding. We expect to use 2 mm margin tape. Therefore we look at Table 3. We see that $APcu_P$ of 0.13 cm^4, is available from EFD 30/15/9, almost exactly what we need here (0.132 cm^4). That is the selected core.

Primary Turns:

We assume the turns ratio will be fixed such that at minimum input, the duty cycle is 0.44. So

$$N_P = \frac{V_{IN} \times D \times 10^4}{f_{Hz} \times Ae_{cm^2} \times \Delta B_{Tesla}} = \frac{36 \times 0.44 \times 10^4}{200000 \times 0.69 \times 0.15} = 7.65\ \mathrm{turns}$$

Magnetization Inductance and Peak Magnetization Current:

What is the magnetization inductance? The EFD30 with no air gap, made of 3F3 from Ferroxcube, has a datasheet A_L value of 1900 nH/turns^2. So if we use 8 turns, we get an inductance of 1900nH×8^2 = **121 µH.**
Note that an alternative calculation in literature uses

$$L = \frac{\mu\mu_0 N^2 \times Ae}{z \times le}\quad \text{(MKS units)}$$

Plugging in our values, we get for Primary inductance

$$L = \frac{2000 \times \left(4\pi \times 10^{-7}\right) \times 8^2 \times 0.69 \times 10^{-4}}{1 \times 6.8 \times 10^{-2}} = 1.63 \times 10^{-4}\quad \text{(MKS units)}$$

This is 163µH.

The difference between the two results is based on the fact that the AL value provided by the vendor is more practical: it includes the small default air gap since, it is not possible to eliminate all air gaps when clamping two separate halves together. So in theory, if there was zero air gap (i.e., a air gap factor “z” of 1, see the A-Z book), we would get 163µH. In reality, the magnetization peak current will be higher than expected, because of the minute residual air gap, which has reduced the measured inductance to 121 µH.

So the actual peak magnetization current component in the switch will be a little higher than anticipated (though this will be the same at any input voltage as explained earlier)

$$I_{MAG} = \frac{V_{IN} \times D/f}{L} = \frac{36 \times 0.44/200000}{121 \times 10^{-6}} = 0.655\ \mathrm{A}$$

Turns Ratio:

The turns ratio is derived from

$$D = \frac{V_O}{V_{INR}} = \frac{n \times V_O}{V_{IN}}$$

$$D = \frac{V_O}{V_{INR}} = \frac{n \times V_O}{V_{IN}}$$

$$n = \frac{D \times V_{IN}}{V_O} = \frac{0.44 \times 36}{12} = 1.32$$

Secondary Turns:

The number of Secondary turns is

$$N_S = \frac{N_P}{n} = \frac{8}{1.32} = 6.06 \approx 6 \text{ turns}$$

Choke Inductance and Rating:

We have to design this at max input because, as in any regular Buck, the maximum peak current occurs at max input. At that point we want a total swing ΔI equal to about 40% times the average value (11A). This is 20% above and 20% below the center at I_O.

We need the duty cycle at max input from above step. So, setting a current ripple ratio of 0.4, using the standard Buck equations

$$L_{\mu H} = \frac{V_O}{I_O \times r \times f_{Hz}} \times (1 - D) \times 10^6 = \frac{12}{11 \times 0.4 \times 200000} \times (1 - 0.28) \times 10^6 = 9.82$$

So we pick an inductance of 10µH. It must have a minimum saturation rating of 12A.

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

Flyback Converter Core Selection

Here the requirements are the same as for the Forward converter above. This exercise will give us insight into how a Flyback compares with a Forward, in terms of design methodology and component selection, especially at these high power levels.

Choosing V_{OR}:

Once again, assume the efficiency will be close to 85%. So for an output of 132W, the input will be 132/0.85 = 155.3W. This is to compare apples to apples, though a Flyback will have much lower efficiency at these power levels, largely due to the huge pulsating current into the output caps, and leakage inductance dissipation.

We need to set the reflected output voltage (the effective output rail as seen by the Primary side). This is also based on max duty cycle limit condition at low line. We have

$$V_{OR} = V_{INMIN} \times \frac{\eta_{VINMIN} \times D_{MAX}}{1 - D_{MAX}} = 36 \times \frac{0.85 \times 0.44}{1 - 0.44} = 24.04 \text{ V}$$

Turns Ratio:

Therefore turns ratio must be

$$n = \frac{V_{OR}}{V_O} = \frac{24.04}{12} = 2$$

Core Selection:

$$Ve_{cm^3} = \frac{31.4 \times P_{IN} \times \mu}{z \times f_{MHz} \times Bsat_{Gauss}^2}\left[r \times \left(\frac{2}{r} + 1\right)^2\right] = \frac{31.4 \times 155.3 \times 2000}{10 \times 0.2 \times 3000^2}\left[0.4 \times \left(\frac{2}{0.4} + 1\right)^2\right] = 7.8$$

Here we have used the equation derived in Switching Power Supplies A-Z (Page 225). We have set relative permeability to 2000, maximum saturation flux density to 3000 Gauss (0.3 Tesla), an air gap factor (z) of 10 and a current ripple ratio of 0.4. We need a core volume of 7.8 cm^3. Looking at Table 1 we see that the EFD30 we selected for the Forward converter, has a volume of 4.7 cm^3. We need almost twice that here. From Table 1 we see that a close fit is ETD34 with a volume of 7.64 cm3 and an effective area of 0.97 cm^2.

Primary Turns:

As derived in A-Z book (Page 236)

$$N_P = \left(1 + \frac{2}{r}\right) \times \frac{V_{INMIN} \times D_{MAX}}{2 \times Bsat_{Tesla} \times Ae_{m^2} \times f_{Hz}}$$

$$= \left(1 + \frac{2}{0.4}\right) \times \frac{36 \times 0.44}{2 \times 0.3 \times 0.97 \times 10^{-4} \times 200000} = 8.2 \approx 8 \text{ turns}$$

Secondary Turns:

$$N_S = \frac{N_P}{n} = \frac{8}{2} = 4 \text{ turns}$$

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

Note that the turns ratio is 8/4 = 2, as compared to 1.33 for the Forward converter. This helps pick lower voltage components on the Secondary side since the reflected input voltage is lower.

Primary Inductance:

From the A-Z book (see Page 139)

$$L_{P\_\mu H} = \frac{V_{OR}}{I_{OR} \times r \times f_{Hz}} \times \left(1 - D_{MAX}\right)^2$$

$$L_{P\_H} = \frac{24.04}{\frac{11}{2} \times 0.4 \times 200000} \times \left(1 - 0.44\right)^2 = 1.714 \times 10^{-5}$$

So we need a Primary inductance of 17.14 µH.

Industry-wide Current Density Targets in Flyback Converters

In the A-Z book, we suggested 400 cmil/A as a recommended current density for the Flyback. See its nomogram and contained explanation on Page 145. That was based on the COR (center of ramp) value. To make that clearer here, as per our current terminology, we prefer to write it as 400 cmil/A_{COR}.

Assuming D ≈ 0.5, we have √D = 0.707, so the conversions are

$$400 \text{ cmil/A}_{COR} \equiv 600 / 0.707 = 565 \text{ cmil/A}_{RMS}$$

OR

$$197353/400 = 493 \text{ A}_{COR} / \text{cm}^2 \text{ (in terms of COR current)}$$

OR

$$197353/565 = 350 \text{ A}_{RMS} / \text{cm}^2 \text{ (in terms of RMS current)}$$

In other words, we were recommending somewhere between 250 A_{RMS}/cm^2 (conservative) to 500 A_{RMS}/cm^2 (overly aggressive). But a lot depends on core losses too, because we should remember, the flux swing in a typical Flyback is always fixed at around 3000 Gauss, not 1500 Gauss as in a Forward converter. So core losses can be 4 times (since for ferrites, we can have B^2 dependency in the core los equation). However, we are also using a (Flyback) core size which twice that in a Forward converter. So it is better exposed to cooling. But at the same time, everything else is scaling to. For example, we first calculate core loss per unit volume, then multiply that with volume to get the total core loss. So if volume is doubled, for the same flux density swing, we will get double the core losses! And so on. The picture is really murky. We do need to depend a lot on industry (and our own) experience here. In the case of this author, it was 400 cmil/A_{COR}, just for achieving Class A transformer certification (and barely so). So it is probably best to target 350 A_{RMS}/cm^2 at worst. Lower density is even better (say 250 A_{RMS}/cm^2). But what do others' say?

a) AN-4140 from Fairchild asks for 500 A_{RMS}/cm^2, suggesting up to 600 A_{RMS}/cm^2

b) Texas Instruments, **http://www.ti.com/lit/an/slua604/slua604.pdf** asks for 600 A_{RMS}/cm^2

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

c) International Rectifier, **http://www.irf.com/technical-info/appnotes/an-1024.pdf**, suggests 200 – 500 cmil/A_{RMS}. This translates to 400 A_{RMS}/cm^2 to 1000 A_{RMS}/cm^2

d) AN017 from Monolithic Power asks for 500 A_{RMS}/cm^2

e) AN-9737 from Fairchild, **http://www.fairchildsemi.com/an/AN/AN-9737.pdf** asks for 265 A_{RMS}/cm^2, very close to our conservative suggestion of 250 A_{RMS}/cm^2.

f) On-Semi, **http://www.onsemi.com/pub_link/Collateral/AN1320-D.PDF** asks for 500 A_{RMS}/cm^2

g) Power Integrations recommends 200 to 500 cmil/A, but in calculations often uses the COR value without necessarily pointing it out, and typical values used are 500 A_{COR}/cm^2. That is 19737/500 = 400 cmil/A_{COR}, same as what was suggested in the A-Z book.

Keep in mind there is a big difference in making a small and "attractive" transformer for the evaluation board of a chip vendor, and between a commercial product that meets safety approvals (Class A transformer).

Comparison of Energy Storage Requirements in Forward and Flyback

Irrespective of efficiency considerations, the most basic question is: by going from a Flyback to a Forward, do we end up requiring more magnetic volume or less?

We saw above, that when we went to the Flyback, its *transformer volume was twice that of the Forward converter*. But the Forward converter has an additional magnetic component, its energy storage element, i.e. its Secondary-side choke. Generally we pick an off-the shelf inductor for that. But we can ask: if we use a gapped ferrite for the choke, how will its volume compare with the transformer of the Flyback? Keep in mind that in a Flyback, its transformer is also the energy storage element.

The answer to this is on Page 225 of the A-Z book, where we show that for a Buck, the volume is (1-D)× the volume of a Buck-boost, for the same energy, current ripple ratio etc. So for a duty cycle of about 0.5, the volume of a Buck choke will be half that of a Buck-Boost.

We this learn that the transformer of a Forward is half the size of a Flyback, but then we need a Secondary-side choke for it, equal to half the size of the Flyback transformer. The total gain or *loss is virtually zero*. Both the Forward and the Flyback need almost the *same total volume* of magnetic components. Yes in a Forward, the heat gets split into two components and their total exposed area is more than that of a single component of the same net volume. This is one of the reasons a Forward is preferred at higher powers.

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

Basic Core Parameters (see Fig. 3)									
A (mm)	B (mm)	C (mm)	D (mm)	E (mm)	F (mm)	le (cm)	Ae (cm^2)	Ve (cm^3)	CORE
20.00	10	5	6.3	12.8	5.2	4.28	0.312	1.34	**ee20/10/5**
25.00	10	6	6.4	18.8	6.35	4.9	0.395	1.93	**ee25/10/6**
35.00	18	10	12.5	24.5	10	8.07	1	8.07	**ee35/18/10**
42.00	21	15	14.8	29.5	12.2	9.7	1.78	17.3	**ee42/21/15**
42.00	21	20	14.8	29.5	12.2	9.7	2.33	22.7	**ee42/21/20**
55.00	28	20	18.5	37.5	17.2	12.3	4.2	52	**ee55/28/20**
28.00	14	11	9.75	21.75	9.9	6.4	0.814	5.26	**er28/14/11**
35.00	20.7	11.3	14.7	25.6	11.3	9.08	1.07	9.72	**er35/21/11**
42.00	22	16	15.45	30.05	15.5	9.88	1.94	19.2	**er42/22/16**
54.00	18	18	11.1	40.65	17.9	9.18	2.5	23	**er54/18/18**
12.00	6	3.5	4.55	9	5.4	2.85	0.114	0.325	**efd12/6/3.5**
15.00	8	5	5.5	11	5.3	3.4	0.15	0.51	**efd15/8/5**
20.00	10	7	7.7	15.4	8.9	4.7	0.31	1.46	**edf20/10/7**
25.00	13	9	9.3	18.7	11.4	5.7	0.58	3.3	**efd25/13/9**
30.00	15	9	11.2	22.4	14.6	6.8	0.69	4.7	**efd30/15/9**
29.00	16	10	11	22	9.8	7.2	0.76	5.47	**etd29/16/10**
34.00	17	11	11.8	25.6	11.1	7.86	0.97	7.64	**etd34/17/11**
39.00	20	13	14.2	29.3	12.8	9.22	1.25	11.5	**etd39/20/13**
44.00	22	15	16.1	32.5	15.2	10.3	1.73	17.8	**etd44/22/15**
49.00	25	16	17.7	36.1	16.7	11.4	2.11	24	**etd49/25/16**
54.00	28	19	20.2	41.2	18.9	12.7	2.8	35.5	**etd54/28/19**
59.00	31	22	22.5	44.7	21.65	13.9	3.68	51.5	**etd59/31/22**
74.00	29.5	NA	20.35	57.5	29.5	12.8	7.9	101	**pm74/59**
87.00	35	NA	24	67	31.7	14.6	9.1	133	**pm87/70**
114.00	46.5	NA	31.5	88	43	20	17.2	344	**pm114/93**
35.00	17.3	9.5	12.3	22.75	9.5	7.74	0.843	6.53	**ec35**
41.00	19.5	11.6	13.9	27.05	11.6	8.93	1.21	10.8	**ec41**
52.00	24.2	13.4	15.9	33	13.4	10.5	1.8	18.8	**ec52**
70.00	34.5	16.4	22.75	44.5	16.4	14.4	2.79	40.1	**ec70**

Table 1: Selection of popular cores with basic characteristics

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

2 mm margin tape on either side

Default values: 1.15mm bobbin wall along direction of "A", 1.35 mm bobbin wall along direction of "D", additional 0.35mm minimum clearance to the ferrite on the outside of the copper winding.

Wac (cm^2)	Wab (cm^2)	Width (mm)	Height (mm)	APb (cm^4)	APc (cm^4)	Width _tape (mm)	Wcu (cm^2)	$APcu_P$ (cm^4)	Kcu_P	MLT (cm)	CORE
0.48	0.23	9.90	2.30	0.07	0.15	5.90	0.14	0.02	0.14	4.02	**ee20/10/5**
0.80	0.48	10.10	4.73	0.19	0.31	6.10	0.29	0.06	0.18	5.42	**ee25/10/6**
1.81	1.28	22.30	5.75	1.28	1.81	18.30	1.05	0.53	0.29	7.36	**ee35/18/10**
2.56	1.92	26.90	7.15	3.42	4.56	22.90	1.64	1.46	0.32	9.36	**ee42/21/15**
2.56	1.92	26.90	7.15	4.48	5.97	22.90	1.64	1.91	0.32	10.36	**ee42/21/20**
3.76	2.97	34.30	8.65	12.46	15.77	30.30	2.62	5.50	0.35	11.96	**ee55/28/20**
1.16	0.74	16.80	4.43	0.61	0.94	12.80	0.57	0.23	0.25	5.33	**er28/14/11**
2.10	1.51	26.70	5.65	1.61	2.25	22.70	1.28	0.69	0.31	6.16	**er35/21/11**
2.25	1.63	28.20	5.78	3.16	4.36	24.20	1.40	1.36	0.31	7.52	**er42/22/16**
2.53	1.93	19.50	9.88	4.81	6.31	15.50	1.53	1.91	0.30	9.56	**er54/18/18**
0.16	0.02	6.40	0.30	0.00	0.02	2.40	0.01	0.00	0.02	2.68	**efd12/6/3.5**
0.31	0.11	8.30	1.35	0.02	0.05	4.30	0.06	0.00	0.09	3.23	**efd15/8/5**
0.50	0.22	12.70	1.75	0.07	0.16	8.70	0.15	0.02	0.15	4.24	**edf20/10/7**
0.68	0.34	15.90	2.15	0.20	0.39	11.90	0.26	0.07	0.19	5.22	**efd25/13/9**
0.87	0.47	19.70	2.40	0.33	0.60	15.70	0.38	0.13	0.22	5.89	**efd30/15/9**
1.34	0.89	19.30	4.60	0.67	1.02	15.30	0.70	0.27	0.26	5.36	**etd29/16/10**
1.71	1.20	20.90	5.75	1.17	1.66	16.90	0.97	0.47	0.28	6.13	**etd34/17/11**
2.34	1.73	25.70	6.75	2.17	2.93	21.70	1.46	0.92	0.31	6.97	**etd39/20/13**
2.79	2.11	29.50	7.15	3.65	4.82	25.50	1.82	1.58	0.33	7.85	**etd44/22/15**
3.43	2.68	32.70	8.20	5.66	7.25	28.70	2.35	2.48	0.34	8.66	**etd49/25/16**
4.50	3.64	37.70	9.65	10.19	12.61	33.70	3.25	4.55	0.36	9.80	**etd54/28/19**
5.19	4.24	42.30	10.03	15.61	19.09	38.30	3.84	7.06	0.37	10.78	**etd59/31/22**
5.70	4.75	38.00	12.50	37.53	45.01	34.00	4.25	16.79	0.37	14.03	**pm74/59**
8.47	7.32	45.30	16.15	66.58	77.10	41.30	6.67	30.35	0.39	15.87	**pm87/70**
14.18	12.66	60.30	21.00	217.80	243.81	56.30	11.82	101.68	0.42	20.94	**pm114/93**
1.63	1.12	21.90	5.13	0.95	1.37	17.90	0.92	0.39	0.28	5.43	**ec35**
2.15	1.56	25.10	6.23	1.89	2.60	21.10	1.31	0.79	0.31	6.43	**ec41**
3.12	2.42	29.10	8.30	4.35	5.61	25.10	2.08	1.87	0.33	7.65	**ec52**
6.39	5.37	42.80	12.55	14.99	17.84	38.80	4.87	6.79	0.38	9.93	**ec70**

Wac is window area of core; **Wab** is window area in side bobbin; **Width** is the width of any layer inside bobbin if no margin tape were present; **Height** is the height available for winding copper; **APb** is the area product of the bobbin; **APc** is the area product of the core; **Width_tape** is the actual width available for the copper layer with margin tape present; **Wcu** is the net window area available to wind copper in (Pri mary and Secondary) with margin tape and bobbin considered; **$APcu_P$** is the area product available for Primary winding alone, assuming it is half the total available; **Kcu_P** is the actual utilization factor for the Primary winding (ratio of $APcu_P$ to APc), **MLT** is the mean (or average) length per turn with the bobbin wall thickness and required minimum clearance considered.

Table 2: Popular cores with Area Product, window area, utilization factor with 2mm margin tape

Forward and Flyback Core Selection using the LX7309 and Industry Recommendations

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