HOW TO DESIGN A TRANSFORMER WITH FRACTIONAL TURNS

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Fractional turns used in high frequency switching power supply transformers can reduce the number of turns otherwise needed to provide low voltage outputs and to obtain desired voltage resolution between several outputs. With fractional turns, half the number of turns or less may be required in all windings, significantly decreasing transformer size and cost. Unfortunately, fractional turns have inherently high leakage inductance, making their use impractical unless special techniques are employed. Several methods of accomplishing this are described.

The Need for Fractional Turns: The optimum number of turns in a transformer winding depends upon the maximum allowable flux swing and the operating frequency according to Faraday's Law (in SI units with dimensions in cm):

$$N_{(optimum)} = (V_N \Delta t / A_e \Delta B) \cdot 10^4$$

where ΔB is the flux swing (Tesla), A_e is the centerleg area (cm²), and Δt is the time (approaching 1/2 the period) that voltage V_N is across the winding.

In switching power supplies designed to operate at frequencies below 50 kHz, the optimum numbers of turns are so large that there is little need to use fractional turns. At higher frequencies, fractional turns become attractive for the following two reasons:

1. Optimum transformer design may call for less than one full turn for the lowest voltage secondary. This is likely to happen at high frequencies, high power levels, and especially with the 2 to 3 volt outputs required by the newer logic families.

2. With multiple secondaries, to obtain the desired output voltages with sufficient accuracy using integral turns may require several times the optimum number of turns. For example, with a 12 V and 5 V output, a turns ratio of 2.5:1 or 2.25:1 may be desired. If 1 turn is optimum for the 5 Volt output, 3 turns will provide too much voltage for the 12 Volt output, causing excessive losses in a linear post-regulator. Otherwise, 5 and 2 turns or 9 and 4 turns are necessary to achieve the desired voltage resolution.

In these examples, the actual number of turns required in all windings may be 2, 3,or 4 times greater than optimum. Slightly larger wire sizes are required because the larger transformer must operate at lower current density. This means the winding window area will be 2, 3, or 4 times larger and the core and transformer volume will be 2.8, 5.2, or 8 times larger, with a corresponding increase in cost. This can be a powerful incentive to use fractional turns!

Implementing a Fractional Turn: A fractional turn is really a full turn around a fraction of the total centerleg flux. With an E-E core shape having two outer legs of equal areas, each outer leg has 1/2 the total flux. A single turn around either outer leg will have an induced voltage equal to 1/2 the primary volts/turn. Such a turn is therefore equivalent to 1/2 turn. In

Figure 1A, winding A is 1/2 turn and winding B is 1 1/2 turns. (The half turns are both linked to leg #3). In the cross core shown in Figure 1B, the total flux divides into four equal portions in the four equal area outer legs. Windings A, B, and C are effectively 1 1/4, 1 1/2, and 1 3/4 turns.

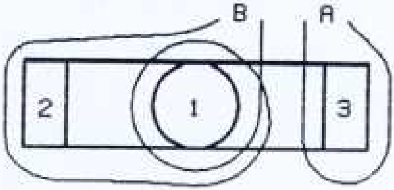


Figure 1A

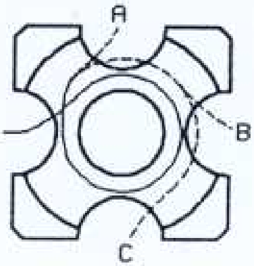


Figure 1B

Figures 2A and 2B show a transformer with multiple outer legs and its magnetic circuit equivalent. A single "fractional" turn is shown which encloses one or more (but not all) outer legs which are combined into leg #3 with magnetic cross-section area A_3 and permeance $P_3 = \mu A_3/\ell_3$. The remaining outer leg(s) are collectively leg #2 with area A_2 and permeance P_2.

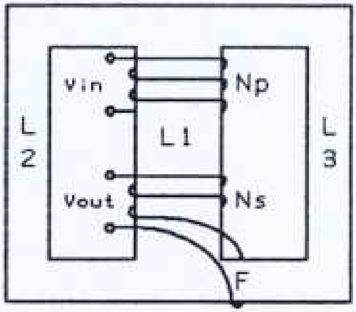


Figure 2A

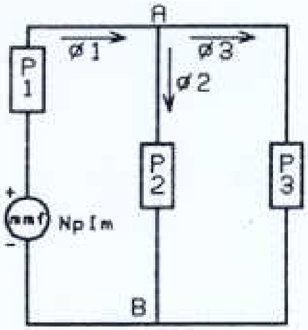


Figure 2B

With no secondary current, centerleg flux ϕ_1 divides between outer legs #2 and #3 in proportion to their permeances and their areas (assuming magnetic lengths ℓ_3 and ℓ_2 are the same). Let $F = P_3/(P_2+P_3) = A_3/(A_2+A_3)$, the fraction of the total outer leg area enclosed by the fractional turn. This turn encloses a corresponding fraction of the total flux, $\phi_3 = F\cdot\phi_1$, and $d\phi_3/dt = F\cdot d\phi_1/dt$. From Faraday's law, the induced volts/turn equals the rate of change of the enclosed flux, so the voltage induced in the fractional turn equals F times the primary volts/turn, V_{in}/N_p.

The full secondary turns around the centerleg and the primary turns link the same flux ϕ_1 so that their volts/turn are nearly identical: $V_s/N_s = V_{in}/N_p$. Thus:

$$V_{out}/V_{in} = (N_s+F)/N_p \qquad \text{(no load)}$$

Primary magnetizing ampere-turns N_pI_m provide the magnetic potential needed to support the flux level in the core.

The Leakage Inductance Problem: The full secondary turns are tightly coupled to the primary, although there is a small amount of leakage inductance in series with the full secondary turns due to stray flux between the windings. Unfortunately, the fractional turn has very high leakage inductance, and its induced voltage, $F \cdot V_{in}/N_p$, occurs only under no-load conditions.

When load current is drawn through the fractional turn, its voltage collapses. In fact, when a fractional turn is added to an otherwise stiff winding, the short-circuit current will probably be much less than the desired full load output current. Rather than helping matters, the performance of the winding is worsened by adding the fractional turn because of its leakage inductance.

As shown in Figure 3, secondary current through the full turns around the centerleg generates a magnetic potential, $N_S I_S$, which is cancelled by equal and opposite primary ampere-turns, $N_p I_p$. Magnetizing current, I_m, and centerleg flux, ϕ_1, do not change significantly. However, current through the fractional turn creates a magnetic potential in leg #3 which easily diverts flux ϕ_3 to leg #2. Because flux ϕ_3 is diminished, the voltage induced in the fractional turn is reduced. So the fractional turn voltage decreases rapidly with increasing load. At higher load current levels (usually well below desired full load), $d\phi_3/dt$ will reverse and the voltage induced in the fractional turn becomes negative. When this happens, the total secondary voltage is less than it would have been without the fractional turn.

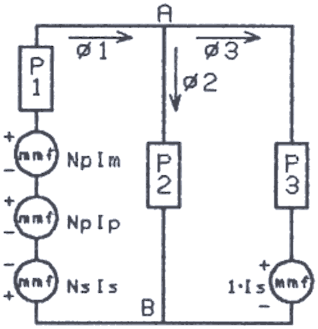


Figure 3

The leakage inductance of the fractional turn is:

$$L = F(1-F) \cdot P = F(1-F) \cdot \mu A/\ell \cdot 10^{-2} \qquad \text{Henrys}$$

ℓ (cm) - length of the outer legs

$A = A_2 + A_3$ (cm^2) - combined areas of all outer legs

$F = A_3/A$ - fraction of total outer leg area linked to fractional turn

$\mu = \mu_o \mu_r = 4\pi \cdot 10^{-7} \cdot \mu_r$ - absolute permeability of the outer leg material

$P = P_2 + P_3 = \mu A/\ell$ - permeance of all outer legs combined

This inductance of the fractional turn is equivalent to the inductance of a single turn wound on a core consisting of legs #2 and #3 in series. (Leg #1 has no effect.) The worst case is when the fractional turn links half the total outer leg area (effectively 1/2 turn). Whether the fractional turn is in series with one or more full turns around centerleg #1, or whether it is the entire secondary winding, it has the same leakage inductance. However, when the fractional turn is in series with several full turns, the power taken from it is only a small portion of the total transformer power. The adverse effect of the leakage inductance is then proportionately less, but it is more than enough to badly hurt cross-regulation in a multi-output supply.

The Solution to the Problem: The solution is simple -- maintain the flux in outer leg portions #2 and #3 in exactly the same ratio regardless of secondary current; in other words prevent the flux from escaping from leg #3 to leg #2 when the load current increases.

One technique used to keep the flux balanced in the two outer legs of an E-E core is to put one turn around each outer leg as shown in Figure 4. The two outer core legs have the same area (and permeance). Each of these turns links half the centerleg flux and acts like a half turn. If these turns were connected in series with the correct polarity, together they would become a full turn. But connected in parallel (with the same polarity) they act together like a single half-turn. Because of the parallel connection, the voltages induced across each turn must be identical, forcing equal flux in the two outer legs. This requires the opposing magnetic potentials in each outer leg to be the same ampere-turns which means the secondary current is shared equally by the two turns.

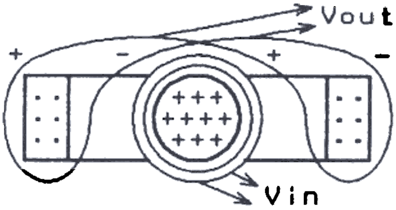


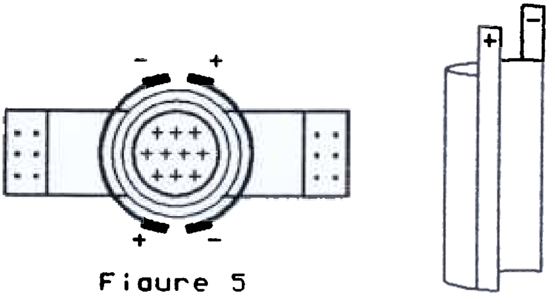
Figure 4

If the two outer legs had unequal flux, the voltages induced in the two paralleled turns would differ. This would cause a differential current to flow between these turns, applying magnetic potentials to each leg in a direction to eliminate the original flux inequality. Essentially, the cross-connection between the two turns forces the flux to divide equally between the two outer legs.

Note that even if the two outer legs have different areas, the flux in each leg is forced to be half the total flux, so that the paralleled turns still act like half turns.

While this technique eliminates the huge leakage inductance of a single half turn, it is far from ideal because there is much stray flux outside the core which is linked to the primary but not to the windings around the outer legs. This results in significant leakage inductance. Normally, to minimize leakage inductance caused by stray flux, good practice dictates the secondaries should be wound as intimately as possible with each other and with the primary.

Figure 5 shows a big improvement on the above technique which provides much better coupling to the primary, minimizing the leakage inductance of the half turn secondary. Two half cylinders of copper foil or strip are placed directly over the primary winding, separated only by the minimum insulation required for primary-secondary isolation. The half cylinders must not directly contact each other. They are paralleled by means of a pair of tabs off one end of each half cylinder, cross-connected over the outside end of the core. Output from the winding may be taken from across this pair of tabs.



Fiaure 5

The series inductance of this half turn approach is not quite as good as one full turn of copper strip because of the inductance of the cross-connected tabs. Further reduction in series inductance may be obtained by putting cross-connected tabs at both ends. The ultimate improvement is to divide the primary into two portions and interleave the secondary structure between the two primary portions.

Because the cross-connected half turns in Figure 5 force equal flux division, the outer legs are "stiffened", so that a half turn added to any other secondary(s) will also have low leakage inductance.

Using a Separate Flux Balancing Winding: Any windings that cross-connect the two outer legs will force the flux to divide equally between the two outer legs. It is not even necessary for the flux balancing winding to be one of the output windings. As shown in Figure 6, it may be a completely separate winding dedicated to the sole purpose of flux equalization between the outer legs. This enables a single wire half-turn to be added to any secondary with minimal series inductance by forcing the total flux to remain equally divided between the two outer legs.

This technique is useful when fractional turns are added to more than one secondary, and especially with the center-tapped secondaries used in push-pull converters, where a fractional turn must be added each side of center-tap. These situations are difficult to implement by the method shown in Figure 5.

Figure 6

As shown in Figure 6, the flux balancing winding has two coils with equal numbers of turns cross-connecting the two outer legs at the point where they join the centerleg. Actually, this winding can be a single turn on each outer leg or many turns. It is better to use multiple turns because finer wire can then be used. By laying these fine wire turns side by side along the outer legs, interference with the bobbin is minimized, and eddy current problems are eliminated.

The ampere-turns of the flux balancing winding will be 1/2 the unbalanced amperes of the secondary half-turns. For example, assume two secondaries, 12 V, 3 A and 24 V, 2 A, each having a half turn in series with several other full turns. If the 3 A and 2 A half turns link the same outer leg, the worst case ampere-turns in the flux balancing winding will be (3+2)/2 = 2.5 A. With five turns on each outer leg, the current in each turn is 2.5/5 = 0.5 A. On the other hand, if the 2 A and 3 A half turns link to opposite legs, the worst case is with the 3 A secondary at full load and the 2 A secondary at no load. The maximum flux balancing ampere-turns will be half of 3, or 1.5 A-t, resulting in only 1.5/5 = 0.3 A in the five turn flux balance windings.

For this method of flux balancing to be the most effective in reducing leakage inductance, the flux balancing winding must have good coupling to the secondary half turn(s):

> Wind the flux balancing coils on the outer legs as close as possible to where the flux divides - close to the centerleg. If they are located further out on the outer legs, coupling to the secondary half turns on the centerleg is reduced.

2. With a secondary half turn in series with several full turns wound helically along the centerleg, make sure this half turn is at the end of the centerleg adjacent to the flux balancing winding.

3. When the half turn is foil or strip along the length of the centerleg, put a flux balance winding at <u>both</u> ends of the centerleg.

4. When a secondary handles most of the total transformer power and has only 1/2 turn or 1 1/2 turns total, the method of Figure 5 works the best.

<u>Diverse Fractional Turn Values:</u> It is certainly possible to obtain fractional turn values other than 1/2. Referring back to Figure 1B, a cross core with four outer legs can provide 1/4, 1/2, or 3/4 turns. A slightly different technique is required to keep the flux divided equally among all <u>four</u> legs--a single flux balancing turn is put around each of the four legs and these four turns are paralleled. Because of the parallel connection, the voltages induced across each turn must be equal, which forces equal rates of flux change in each leg. Otherwise, current would flow in the flux balancing turns which would bring the flux changes back into equality.

In reference (1), the author cleverly provides the flux balancing winding by means of a double sided printed circuit board at one end of the centerleg where it interferes minimally with the transformer windings. Although this is a very simple and low cost method, the flux balancing turns are not close to the centerleg and the coupling to the secondary half turns is not as good as it might be. Also, cross cores are generally not optimally designed for high frequency power applications where a long narrow winding window is desirable to minimize leakage inductance and eddy current losses.

<u>Obtaining Any Fractional Value with an E-E Core:</u> It was stated earlier that the flux balancing winding would force equal flux in the outer legs even if they have unequal areas. Conversely, *it is easy to obtain any desired induced voltage in the fractional turn by forcing unequal flux division between the two outer legs*, even though their areas are equal. This makes it possible to take advantage of the better performance and cost available with modern E-E cores.

Unequal flux division between two outer legs of equal area is obtained by *using unequal turns in the flux balancing windings*. Suppose there are twice as many turns on leg #3 as on leg #2. The induced voltage across both windings must be equal because they are in parallel. This means the volts/turn and $d\phi_3/dt$ of leg #3 must be 1/2 of leg #2. Therefore 1/3 of the total flux goes to leg #3 with twice the turns, while 2/3 goes to leg #2.

Any secondary fractional turn linked to leg #3 will have only 1/3 of the primary volts/turn induced, while a fractional turn linked to leg #2 will have 2/3 of the primary volts/turn. Similarly, a 1:3 turns ratio in the flux balancing winding will result in a 1/4 : 3/4 flux division and corresponding fraction of the primary volts/turn induced in a fractional turn. Depending upon which leg is linked by the fractional turn, 1/4 turn or 3/4 turn is obtained. It is possible to obtain 1/2 turn in this configuration by putting one additional turn around the 1/4 turn leg!

When the flux division is made unequal between two outer legs of equal area, obviously one outer leg has greater flux density (and flux swing) than the other, and probably greater flux density than the centerleg, as well. This could theoretically force a reduction in the operating flux level and reduce the core utilization to avoid saturating the high flux density leg. However, fractional turns will normally be used above 50-100 kHz, where the flux density swing is limited by core losses, not saturation. The only adverse result is that one outer leg will have greater core loss, the other leg less, for a net small increase in core loss.

Experimental Results: The data given in Table I was taken with a 20 turn primary winding over the centerleg of an EC41 ferrite core. Secondaries were placed directly over the primary (not interleaved) with 5 mil insulation in between. Leakage inductance was measured on the primary side with the various secondary configurations shorted because it is difficult to obtaining accurate measurements on the 1/2 turn low impedance secondary side. Equivalent secondary leakage inductance with the primary shorted was calculated from the measured primary values.

TABLE I

Description	Measured Primary	Calculated Secondary	
(1) Primary only (20 turns) -- no secondary	1480. µH	--	
(2) 1 Full turn copper strip secondary	1.6 µH	1 nH	(Ideal)
(3) 1 Half turn strip - no flux bal. wdg.	944 µH	885 nH	
(4) Same with flux bal. opposite tab end	144 "	91 "	
(5) Same with flux bal. wdg. at tab end	38 "	24 "	
(6) 2 Par. half turns, outer leg (Figure 4)	42 µH	26 nH	
(7) 2 Par. half turns over primary (Figure 5)	8 "	5 nH	
			Measured Secondary
(8) 5 turn wire sec. spread across centerleg	2.9 µH	181 nH	185 nH
(9) 5 1/2 turn secondary - no flux bal. wdg.	17.5 "	1320 "	1580 "
(10) Same with flux bal. opposite end	4.2 "	317 "	307 "
(11) Same with flux bal. same end	2.8 "	211 "	207 "

Line (1) of Table I shows the open circuit primary inductance of 20 turns on the EC41 core. Line (2) demonstrates the lowest leakage inductance that can be obtained without interleaving the secondary between two primary half-sections. Dividing the 1.6 µH measured primary value by $(20/.5)^2$ gives 1 nH lowest possible leakage inductance for 1/2 turn - the ideal goal. (3) shows how bad a single half turn strip is without a flux balancing winding. Adding flux balancing opposite the tab end of the half turn (4) provides much improvement, but at the tab end (5) coupling between flux balance winding and the half turn is much better. Still, 24 nH is a long way from the 1 nH goal. It is just not possible for the flux balance winding at the one end of the centerleg to couple more effectively to the half turn along its entire length.

Line (6) shows the technique of Figure 4, with one turn of strip around each outer leg. The large amount of stray flux between these turns and the primary cause high leakage inductance. Best is (7), with the two half-cylindrical strips directly over the primary. Most of the 5 nH is in the cross-connected tabs at one end, and this could be further reduced by putting tabs at both ends. This is the best approach when most of the transformer power is in the half-turn (or 1 1/2 turn) winding.

Lines (8) - (11) show the results of adding a half turn to several full secondary turns, using wire instead of strip. The secondary impedance levels are high enough to take measurements from the secondary side as well. (8) shows that the 5 full turn secondary does not couple as tightly to the primary as the shorted strip in (2). This is because the 5 turns were spread across the centerleg with large spaces between turns (but this is much better than bunching the 5 turns in the center of the primary). Several parallel wires should have been used to fill the centerleg. The 185 nH is almost twice what it should be compared to (2). Note that with the additional half turn placed at the same end of the centerleg as the flux balance winding (11) the coupling is good and the additional leakage inductance of the half turn is only 22 nH. This compares to the half turn secondary alone in (5), but in (11) it is small by comparison to the leakage inductance of the 5 full secondary turns.

References:

1. G. Perica, "Elimination of Leakage Effects Related to the Use of Windings with Fractions of Turns," Proceedings of Power Electronics Specialists Conference (PESC), 1984, pp. 268-278

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