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RESEARCH ARTICLE

DESIGN OF HIGH FREQUENCY POWER TRANSFORMER FOR SWITCHED MODE POWER SUPPLIES

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Abstract

Application of high frequency power transformers has become abundant in most of the power electronic switched mode power supplies. As the contextual idea behind the evolution of power electronic switched mode powers supplies against the general linear grid power supplies is, to convert and control the electrical power in accordance to the load requirements in an efficient way using power transformers, inductors, capacitors, and electronic switches which ideally do not dissipate any power. This paper will noticeably convey the step by step design strategy of high frequency power transformer distinguishing, how it is variant from normal fundamental frequency distribution & power transformers, its mathematical electrical circuit modeling, magnetic circuit modeling, mathematical relationship between various electrical and magnetic quantities to the geometry of the magnetics, some customer and designer specifications while processing the practical design, A practical design example to how one has to design high frequency transformer right from the core selection with the idea of mathematical power capacity derivations and data sheets considerations, number of turns calculation, wire gauge calculation considering the skin effect as it is high frequency operation, core loss calculations, calculation of some non-idealities that comes to picture like winding magnetizing inductances, energy stored in the transformer due to non-idealities, peak primary magnetizing current calculations and so on. Some of the practical design tips & safety tips are also included in path way of the design processing.

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INTRODUCTION

In most of the power electronic switch mode power supplies the high frequency power transformers plays a vital role in proving the voltage levels matching between the source and the sink and providing the electrical isolation, where the primary and secondary grounds are variant in concern to the safety, and in some cases as per the customer specifications. The conventional fundamental 50Hertz frequency distribution & power transformer is considerably different in regards with the application and geometry to high frequency transformer. The fundamental frequency transformers are basically classified depending on the core geometry as, shell and core type. In transmission and distribution wing the core type transformer geometries are commonly used. The magnetic core is made up of cold rolled grain oriented silicon steel ferromagnetic material and it is laminated to limit eddy current losses. Also in some distribution transformers amorphous magnetic cores are used for high distribution efficiency.
But, in the high frequency transformers which are used in power electronic switched mode supplies the core geometry of shell type is in common usage. The leading motive for opting shell type topology is, for high frequency applications the third harmonic components will circulate with in the primary without inflowing in to the secondary power circuit which is similar to advantage brought out by the three phase delta connection. Also as the magnetic flux divides in the outer limbs, these cores offers less magnetic core losses compared to conventional transformer. In high frequency transformers generally Ferrite Cores are used as magnetic medium. For frequencies less than

5megaHertz manganese-zinc ferrites are used above which nickel-zinc ferrites are of common application. These ferrites offer very low coercivity, which means the material magnetization can easily reverse the direction without dissipating much energy, which in common termed as hysteresis loss. Also these ferrite cores are not laminated to reduce eddy current losses as the Powder ferrite core itself offers High resistance. Only concern with ferrite cores is its operating Maximum flux density which is limited to maximum of 0.5Tesla typically. While for conventional ferromagnetic core it is maximum of 2.2Tesla & 1.8Tesla for amorphous magnetic cores.

The electromagnetic circuitry of a transformer can be categorized in to electrical circuit and magnetic circuit. The electrical equivalent circuit of a transformer is shown in Fig.1 where the primary is represented with a dependent current source, such a way that the primary current [I_1] is transformation ratio times secondary current [I_2]. It is given by,

$$I_1 = (N_2/N_1)^* I_2 \qquad [1]$$

Where, (N_2/N_1) is transformation ratio, N_2 is number of secondary turns and N_1 is number of primary turns.

While, the secondary is represented with a dependent voltage source, such a way that the secondary voltage [V_2] is transformation ratio times the primary voltage [V_1]. It is given by,

$$V_2 = (N_2/N_1)^* V_1 \qquad [2]$$

The magnetic circuit equivalent of a transformer can be represented as shown in Fig.2. Where the primary and secondary circuits are coupled magnetically through a torroidal core.

Where, V_1 is the primary voltage, V_2 is the secondary voltage, μ is the magnetic permeability, A_C is the core area and A_W is window area. Various core geometries are available like ETD cores, low profile EFD cores, pot cores and so on. Of which most popular geometry is EE cores as shown in the Fig.3, in various isometric views.

Where, $\mathbf{A_C}$ is the effective core area which is offered for the main flux to link both primary and secondary. $\mathbf{A_W}$ is the window area through which primary and secondary turns are wound.

2. EMF (Electro Motive Force) EQUATION FOR HIGH FREQUENCY POWER TRANSFORMER

Most commonly, all the switched mode power supply transformers are supplied through an electronic switch which operates at predefined switching frequency. Let the application be a D.C. to D.C. isolation power converter. Therefore the output voltage waveform from the input electronic switch will be a pulsating D.C. as shown in the Fig.4. This gets applied to the transformer.

DESIGN TIP:

While using a power transformer in a power electronic converter circuit, care must be taken to allow the core to **reset**. This means, as shown in the Fig.4 the output voltage waveform from the electronic switch is a pulsating D.C. If this output is directly fed to the transformer, it will lead to the core saturation. Because for a pulsating waveform the average value of the voltage over a full switching cycle is not zero, it has a finite value. Since the magnetic flux is integral of the voltage, a finite value of residual flux exists even after a complete switching cycle as shown in the Fig.5. In the next switching cycle the flux starts from that previous residual flux value and slowly the flux reaches its maximum value within few switching cycles and the core saturates.

To avoid that, a symmetrical square waveform is made to appear across the primary of a transformer through some auxiliary circuits or topologies**,** so that the average voltage over a switching cycle is zero which in turn makes the average value of magnetic flux to return zero after a switching cycle. In next switching cycle the flux starts from zero as shown in Fig.6. Thus protecting against core saturation. Therefore volt-second balance must be satisfied with the primary excitation to avoid core walking in to saturation.

Safety:

Even though a symmetrical waveform is made to appear across the primary of the transformer, if the sufficient turn-off time is not allowed for the core flux to return zero, this will again leave a finite value of residual flux after a switching cycle and slowly leads the core to walk in to saturation as shown in Fig.7. So care must be taken with the pulse width modulation controller to provide sufficient turn-off time for the transformer magnetizing flux to return zero within a switching cycle.

A typical transformer primary voltage & flux waveforms are as shown in the Fig.8. For which the EMF (Electro Motive Force) equation is derived.

From the faradays law of electromagnetic induction we have,

$V = N * \frac{d\emptyset}{dt}$; where $\emptyset$ is the magnetic flux in Webers, **V** is the excitation, **N** is the number of turns, let $\mathbf{T_S}$ is total switching time & $\mathbf{F_S}$ is total switching frequency.

V = N*(slope of the flux) ; $\frac{d\emptyset}{dt}$ = slope of the flux.

$V = N * \frac{\text{maximum flux} - \text{minimum flux}}{\text{time}} = N * \frac{\Phi m - (-\Phi m)}{Ts/2}$

V= (4*F_S* Φ_m *N) Volts. **[3];** where $\mathbf{Ts = \frac{1}{Fs}}$

Equation [3] can be rewritten as

($V = 4*F_S*B_m*A_C*N$) [4]; ($\Phi_m = B_m*A_C$)

Where, B_m = maximum, flux density in Tesla.

A_C = effective core Area.

From the equation [4] core area [A_C] is a function of applied voltage [V] and switching frequency [F_S].

3. DEDUCING RELATION FOR WINDOW AREA [A_W]

Let, $\mathbf{A_1}$ is cross sectional area of primary winding, $\mathbf{A_2}$ is cross sectional area of secondary winding, **J** is Current density of copper, $\mathbf{K_W}$ is window space factor. $\mathbf{N_1}$ is number of primary turns, $\mathbf{N_2}$ is number of secondary turns, $\mathbf{I_1}$ is primary current & $\mathbf{I_2}$ is secondary current.

As shown in the Fig.9. $\mathbf{A_W}$ is the window area through the primary and secondary turns are wound. But entire window area is not used for the winding, a portion of it is being used for insulation, therefore a factor $\mathbf{K_W}$ is introduced which is called window space factor or window utilization factor.

Volume of the conductor $=N_1A_1 + N_2A_2 = K_W*A_W$

$= (N_1*\frac{I1}{J} + N_2 *\frac{I2}{J}) = K_W*A_W$; $(J= \frac{I1}{A1} = \frac{I2}{A2})$

= (2*N*(I/J)) =K_W*Aw [5] ($N_1I_1=N_2I_2$=NI (say), from transformation ratio.

From equation [4] & [5],

$$A_C*A_W = \frac{V*I}{2*KW*J*Bm*Fs} \quad [6]$$

Therefore area product of core area [$\mathbf{A_C}$] and window area [$\mathbf{A_W}$] is directly proportional to power to be handled and inversely proportional to switching frequency. Thus higher the switching frequency less the transformer size.

4. DESIGN EXAMPLE

Let a DC-DC converter will be taken as an example. The customer or application specifications are as below:

Input dc voltage [V_1] = 48Volts,
Output dc voltage [V_2] = 400Volts,
Output dc current [I_2] = 3Amperes.

Designer Specifications:

1. ***Maximum flux density [B_m] = 0.2Tesla.***
2. ***Copper current density [J] = 3Amperes.***
3. ***Window utilization factor [K_W] = 0.35.***
4. ***Switching frequency [F_S] = 50kiloHertz.***

STEP 1: Selection of core

From equation[6], A relation for transformers core area[$\mathbf{A_C}$] and window area[$\mathbf{A_W}$] with respect to power handling capacity is deduced, therefore,

$$A_C*A_W = \frac{V*I}{2*KW*J*Bm*Fs}$$

$$A_C*A_W = \frac{400*3}{2*0.35*3*0.2*50000}$$

(Considering primary and secondary active power remains same)

$$\mathbf{A_C*A_W = 57142mm^4} \qquad \mathbf{[7]}$$

A typical ETD cores data with area product of core area [$\mathbf{A_C}$] and window area [$\mathbf{A_W}$] is as tabulated in Table.1.

From the Table.1 **ETD 49/25/16** core best suits for the application from the calculated core area [$\mathbf{A_C}$] and window area [$\mathbf{A_W}$] product.

STEP 2: Primary [N_1] and Secondary [N_2] number of turns

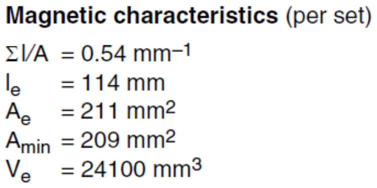
We know that, from [4],

$$\mathbf{N_1= V_1/ (4*B_m*Ac* F_S)}$$

$$\mathbf{N_1=48/ (4*0.2*211*10^{-6}*50000)}$$

$$\mathbf{N_1= 5.68 = 6(approximately)}$$

NOTE: *The Core Area[A_C] Value is taken from the ETD/49/25/16 Core data sheet magnetic characteristics as shown in the below Fig.10. Where* ***Ae = Ac*** *(effective core area). For worst case design, can consider* $\mathbf{A_{min}} = A_C$.



Magnetic characteristics (per set)

$\Sigma l/A = 0.54\ mm^{-1}$

$l_e = 114\ mm$

$A_e = 211\ mm^2$

$A_{min} = 209\ mm^2$

$V_e = 24100\ mm^3$

Fig.10

Similarly,

$$\mathbf{N_2= V_2/ (4*B_m*Ac* F_S)}$$

$$N_2= 400/ (4*0.2*211*10^{-6}*50000)$$

$$\mathbf{N_2= 47.39 = 47(approximately)}$$

Design tip: *For worst case design, add the secondary diode and devices voltage drops and transformer winding voltage drops, while calculating the turns.*

STEP 3: Primary [A_1] and Secondary [A_2] conductor gauge

We know that current density ($J= \frac{I1}{A1} = \frac{I2}{A2}$), therefore,

$$\mathbf{A_1 = \frac{I1}{J} = \frac{25}{3} = 8.33mm^2.}$$

($\frac{I1}{I2} = \frac{V2}{V1}$, $I1= (V_2/V_1)*I_2 = (400/48)*3 =$ **25A**)

Similarly,

$$\mathbf{A_2 = \frac{I2}{J} = \frac{3}{3} = 1mm^2}$$

Skin effect:

The current distribution through a conductor for an A.C. system will not be uniform throughout the conductor and the most of the charges will accumulate towards the surface of the conductor than the center portion, which literally know to be as **skin effect**. This skin effect will be more prominent at high frequencies and it is directly proportional to the switching frequency.

As a rule of thumb,

$$\text{Skin depth} = \frac{1}{\sqrt{\mu 0*\pi*\rho*Fs}}$$

Where **ρ=** resistivity of copper =$59.6*10^6$ per ohm-meter, μ_0=absolute permeability =$4\pi*10^{-7}$ Henry per meter, therefore,

$$\text{Skin depth} = \frac{1}{\sqrt{4\pi*10-7*\pi*59.6*106*50000}}$$

Skin depth = 0.291 mm = 0.26 mm^2 = 24 standard wire gauge (SWG) copper wire.

Therefore, considering skin effect,
For primary, 32 number of 24 SWG wires have to be used in parallel for A_1=8.33mm^2
For secondary, 4 number of 24 SWG wires have to be used in parallel for A_2=1mm^2

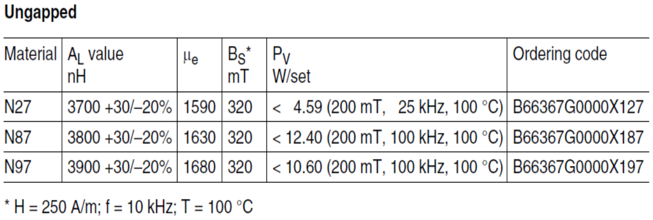
Design tip: *While calculating current density, use root mean square value of currents for the worst case conditions and also as this current is prime responsible for ohmic losses and temperature raise. Also check whether the selected gauge is going to accommodate in the window area [A_w] of the selected core by condition, product of (A_w*K_w) should be greater than (N_1*A_1+N_2*A_2)*

STEP 4: Primary [L_1] and Secondary [L_2] magnetizing inductances

Inductance = (Number of turns)^2/ (reluctance[S])
Reluctance[S] = le/ (μo*μr*Ac)

Where le = effective length of core
μ_0 = absolute permeability = 4π*10^{-7} H/m
μr = relative permeability of the magnetic medium
Ac = effective core area.

Note:
1. The value of [le] & [Ac] is taken from the core magnetic characteristics as shown in the Fig.10.
2. The value of [μr] that is [μe] in data sheet, is taken from core material characteristics for instant let the core material is ungapped N97 material. The data for ETD49/25/16 Core is shown below Fig.11.



Ungapped

Material	A_L value nH	μ_e	B_S* mT	P_V W/set	Ordering code
N27	3700 +30/–20%	1590	320	< 4.59 (200 mT, 25 kHz, 100 °C)	B66367G0000X127
N87	3800 +30/–20%	1630	320	< 12.40 (200 mT, 100 kHz, 100 °C)	B66367G0000X187
N97	3900 +30/–20%	1680	320	< 10.60 (200 mT, 100 kHz, 100 °C)	B66367G0000X197

* H = 250 A/m; f = 10 kHz; T = 100 °C

Fig.11

Therefore, $\mathbf{L_1 = (N_1^2)/ le/ (\mu o*\mu r*Ac)}$
$L_1 = (6^2)/ 114*10^{-3}/ (4\pi*10^{-7} *1680*211*10^{-6})$
$\mathbf{L_{1=}\ 0.14\ mH}$
Similarly, $\mathbf{L_2 = (N_2^2)/ le/ (\mu o*\mu r*Ac)}$
$L_2 = (47^2)/ 114*10^{-3}/ (4\pi*10^{-7} *1680*211*10^{-6})$
$\mathbf{L_2 = 8.63\ mH}$

STEP 5: Core loss

After selecting the core the material is selected depending on the designer switching frequency and power loss in the core. Let us consider **N97** as the core material and calculate core losses. From Fig.11 it is clear that power dissipation per set for N97 material is,
P_V/set = 10.6watts at 200mT, 100kHz, 1000C, therefore,
As the switching frequency is 50kHz, the core loss will approximate to be *5.3watts/set* (as core losses are directly proportional to switching frequency)

STEP 6: Peak primary magnetizing current and energy stored in the core

Peak primary magnetizing current [I_{1max}]:

We know that for an inductor, voltage applied [V] = L* $\frac{di}{dt}$ = L * (slope of the current), therefore considering the waveform shown in Fig.8.

$[V_1] = L_1 * \frac{dI1}{dT} = L_1 * \frac{4*I1max}{Ts} = L_1*4*I_{1max} *F_S$

$I_{1max} = V_1/ (L_1*4*F_S) = 48/0.14*10^{-3}*4*50000 =$ **1.71A.** This is very less than the rated primary current of **25A**.

Energy stored in the core:

Ideally transformers do not store any energy which is in contradictory to an inductor. Transformer reluctance is ideally zero and the magnetizing inductance is infinity, so that with very less magnetizing current the flux has to build up in the core. But, due to the non-ideality in the core reluctances it stores a finite energy which can be calculated as below,

Energy stored in a inductor, $E = \frac{1}{2}*L*I^2 = \frac{1}{2}*L_1*I_{1max}{}^2$

$= \frac{1}{2}*0.14*10^{-3}*1.71^2 =$ **0.2 mJ**

TEST RESULTS

LCR meter is used for measuring the primary and secondary inductances. Set frequency in the LCR meter =**1kHz.** Set voltage =**1V**.

Primary inductance [L_1] = 0.138 mH.

Secondary inductance [L_2] = 8.612 mH.

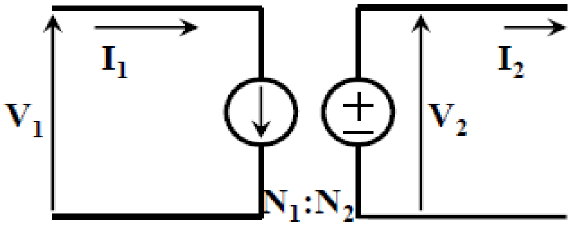


Fig.1.Electrical equivalent circuit

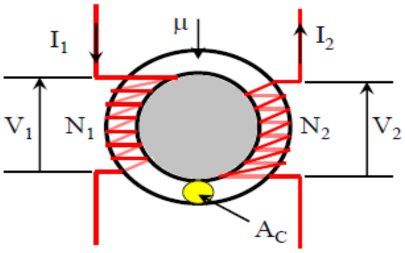


Fig.2.Magnetic equivalent circuit

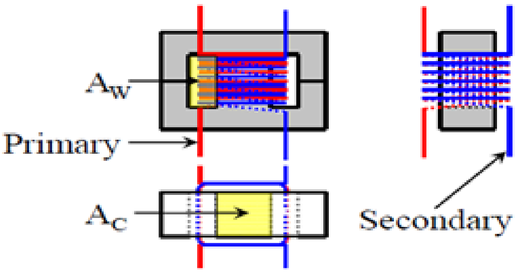


Fig.3.Goemetry of EE- Core

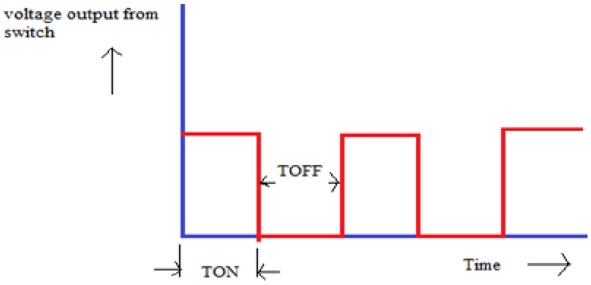


Fig.4.D.C.pulsating waveform

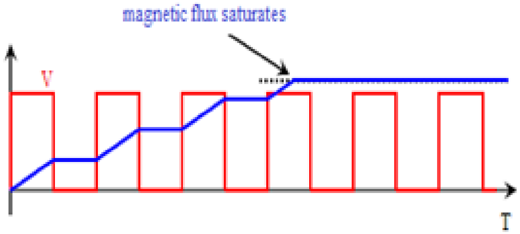


Fig.5.Core saturation with pulsating D.C.excitation

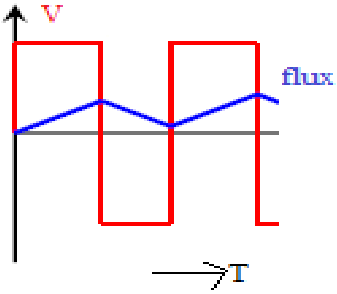


Fig.6.Symmetrical square wave excitation

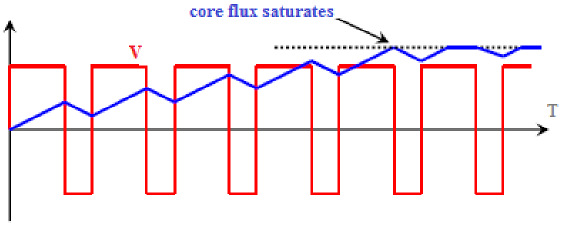


Fig.7.Core saturation with reduced turn-off time.

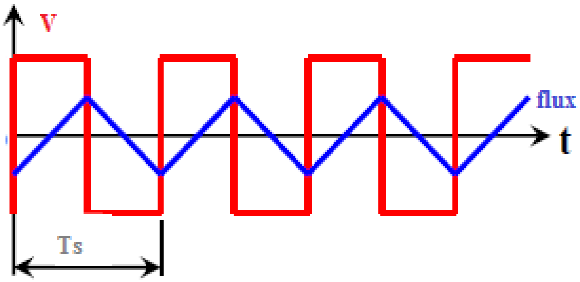


Fig.8. Typical voltage and flux waveforms

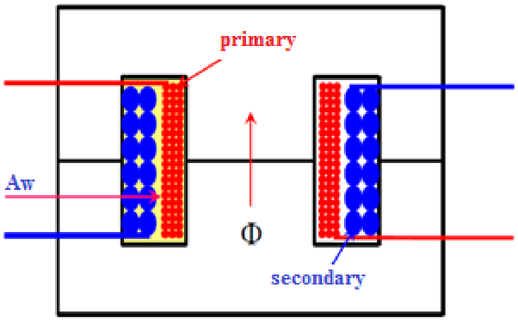


Fig.9.EE-Core geometry

Table.1.ETD Cores geometry data.

Type Number	A_C mm^2	A_W mm^2	A_CA_W mm^4
ETD 29/16/10	76	128	9728
ETD 34/17/11	97	171	16587
ETD 39/20/13	125	234	29250
ETD 44/22/15	173	279	48267
ETD 49/25/16	**211**	**343**	**72373**
ETD 54/28/19	280	412	115360
ETD 59/31/22	368	473	174064

CONCLUSION

This paper considerably addressed the step by step design strategy for high frequency transformer, Root from the mathematical modeling of electrical and magnetic equivalent circuits, transformer core selection, turns and wire gauge calculation, skin effect considerations, data sheets considerations, core loss, winding magnetizing inductances, peak magnetizing current and energy stored in a transformer calculations with intermediate design and safety tips.

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