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Comparative Study Of Designing For Low Frequency And High Frequency Transformer

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Abstract

Transformer is a kind of device that can increase or decrease voltage at its output terminal. It is based on faraday's electromagnetic induction law. It is very popular and reliable device. However this is very old technology but still used is most of power devices like inverters, amplifiers and power stations. It is interesting to see a very old technique still very valuable. This paper is a review of technique used designing of low as well as high frequency transformers and compares them on the basis various design parameters .This paper will be helpful for students, new researchers, engineers and hobbyist.

Keywords: DCM, CCM, SMPS, CRGO, CRNGO, SMPS

Introduction

Transformer is a device that transmits electrical energy through magnetic flux from one part to other part of core. Primary coil of transformer generate magnetic field in core of transformer. Core are made of Silicon steel, ferrite, Permalloy, Molypermalloy Powder (MPP) etc. Mostly ferrite is used as core material as compare to silicon steel in high frequency transformer. After a certain magnetic field core get saturated and permeability goes to zero. This is called over excitation. Silicon steel has saturated magnetic field 1.5 T, Ferrite (Fe-Mn) has 0.4T, Permendur (Fe 49% Co 49% vanadium 2%) has 2.4T and Nickel Steel (Fe 50% Ni 50%) has 3T. (Flanagan, 1993; Waller, 1971). Low frequency transformer uses E-I, E-E, L-L and U-I shaped laminations to make core and high frequency transformer use block of ferrite material that form core type E-E,E-I,U-I, planer EI, pot, ETD, EFD etc. Cold Rolled Grain Oriented (CRGO) silicon steel and Cold Rolled Non-Grain Oriented (CRNGO) silicon steel are popular in making cores. Low frequency transformers are generally made from CRGO silicon steel. As current flows in winding some of power dissipates as heat is called copper loss. This should be minimizing for longer life and efficiency of transformer. Alternating magnetic field in core induces current in core. This is called eddy current. As core magnetized or demagnetized atoms of core material changes its orientation recursively. They feel friction from against each other in doing so. Hence energy of atoms dissipates in form of heat. This is called hysteresis loss. Eddy current loss is proportional to square of frequency so as frequency increases eddy loss began to dominant over hysteresis loss. To keep eddy current loss at lowest level laminated stripes are used. In making of core or shell Silicon in electrical sheet and manganese in ferrite is mixed with iron to increase resistivity and reduce eddy loss. Both hysteresis and eddy current loss cumulatively known as iron loss or core loss. An empirical formula is given as $kf^m (B_{max})^n$ describe dependency of magnetic field and frequency on core loss. If frequency of sinusoidal voltage is f, volume of magnetic material is V, magnetic field B then hysteresis loss in watts in given by $\mu B^{1.6}Vf$. μ is hysteresis coefficient depends on magnetic material, (also known as steinmetz constant). High frequency in conductor flows throw surface not in entire volume of conductor. This is called skin effect. This effect is taken as increased impedance for AC current. If f is operating frequency, μ relative permeability of wire and σ is conductivity of wire than skin depth will be $\frac{503}{\sqrt{\mu\sigma f}}$. Magnetic flux in not perfectly coupled between primary and secondary coils. Some of flux may get leak is called Leakage inductance. Capacitance between windings of transformer taken as distributed capacitance. These two factors play crucial role when transformer are designed to work at frequency more than 10 kHz. (Marcel Dekker, Inc., 2004; High Frequency Transformer: Working Principle, Design and Application_JRPanel, n.d.). Spikes cause by leakage inductance can be eliminated by snubber circuit. At higher frequency winding wire starts inducing eddy current in nearby winding wires. This cause heating loss in winding. This proximity effect can be reduced by making lesser layers of windings.

Methodology

Designing Procedure

1. Selection Of Wire: For low frequency transformer working on Vrms sinusoidal ac rms voltage desired output power Pout can be taken approximately equal to Pin due to its 95% percent efficiency. From power formula Pin=VrmsIp primary current Ip is determined. After it from Editor Engineeringtoolbox (2023) proper rated current wire in AWG number is selected. From diameter of wire (d) cross section area A_{wire} $3.14x(d/2)^2$ will be calculated. From this current density (J) described by $\frac{Ip}{Awire}$ will be calculated. For high frequency transformer wire used in

primary or secondary winding skin depth should be half of wire diameter. From Editor Engineeringtoolbox (2023) one can find wire specification and AWG number.

If high frequency transformer is working between minimum input voltage Vmin and maximum voltage Vmax peak current or pulsating current I_R can be determined an approximated formula given by Brown (2001, pp. 31–35) $\frac{kP_{out}}{Vmin}$; k value depends on topology given is as

1.4 For the Buck, Half-forward, and Full-Bridge.

2.8 For the Half-bridge, IT Forward

5.5 For the Boost, Buck-boost, and Flyback

There are two kind of flyback converter: discontinuous current mode (DCM) and continuous current mode (CCM).

Peak pulsating current I_R for DCM if efficiency of transformer µ and maximum duty cycle D will be $\frac{2P_{out}}{\mu VminD}$

For CCM peak pulsating current $I_r = \frac{1.4P_{out}}{\mu VminD}$. Sha et al. (2015, pp. 215-221)

2. Calculation Of Area Product: This is product of area of core (Ae) and window area (Aw) of transformer. Window of transformer has occupied only a fraction K_u called space factor or utilization factor. f is operating frequency. B is taken just half of saturated field. For sinusoidal low frequency transformer this is given by formula $A_p = \frac{P}{K_f K_u B f J}$ m^4

For high frequency flyback transformer area product changes due to triangular or trapezoidal current wave form.

For fly back discontinuous current mode transformer

Area product: $A_p = \frac{0.22P(10^4)}{K_u BfJD}$

$B = 0.5B_{max}$

For continuous current mode

$A_p = \frac{0.32P(10^4)}{K_u BfJD}$

D is maximum duty cycle. For designing purpose its value can be taken 0.4. Larger area product should be selected. 30-40 percent can be increased if multiple secondary windings needed.

Flyback transformer acts as choke so that inductance of transformer $L = \frac{Vmin\ D}{I_R f}$

There is critical inductance in primary coil Lcriti = $\frac{V_{out}^2}{2Poutf(\frac{Ns}{Np}+\frac{Vout}{Vin})^2}$; Inductance value should be less than Lcriti for discontinuous and greater than for continuous current mode. (De Gruttola et al., 2018) P_{prim} is maximum power stored during on period of input current with frequency f in primary coil $\frac{fLI_R^2}{2}$

Air gap in core prevents core's magnetic field get into saturation. This also enhances performance of converter. Np turns of primary coil have Lp inductance and core cross sectional area is Ae than air gap will be $\frac{0.0125N_{pA_e}^2}{L_P}$.

3. Selection Of Core Parameter: Generally low frequency transformer core is made of laminated silicon strips with different shapes like EI, EE, FF, and UI. Manufacturer makes these in some standard sizes. So that they give their dimensional parameters in the data sheet, from these data one can find size of laminations that would fit in calculated area product. From these parameter core area, stack height, window tongue, volume, mass etc. can be obtained.

4. Calculation Of Volt Per Turn: If cross section area of core is Ae, frequency of input voltage f and magnetic field in core in B than volts per turn can be calculated by K_fBAef. K_f is form factor: 4.44 for sine wave and 4 for square wave depends on duty cycle. From its inverse volt per turn primary and secondary coil turns can be calculated

5. Secondary Coil Current: Peak current in secondary coil (I_{ps}) = nI_R, here n is ratio of turns in primary (N_P) coil to turns in secondary coil (N_S).

If flyback transformer is working in continuous current mode than peak current will approx 0.7 times of DCM peak current.

If ("Design Limitations and Application Considerations for Power Inductors," n.d.) Imin is minimum non-zero current flowing in transformer during CCM and peak current is Ir then average current Iavg will be (Ir+Imin)/2

Idc=DIavg

Idc=$\frac{Ir}{2}$ DCM

Irms=$Ir\sqrt{\frac{D}{3}}$ for DCM

Irms=$Iavg\sqrt{D}$ for CCM

Here D is maximum duty cycle for secondary coil this will be 1-(maximum duty cycle at primary side)

Iac=$\sqrt{I_{rsm}^2 - I_{dc}^2}$

From these equations peak current, DC component and AC component of current can be determined.

6. Losses: Data sheet often gives core loss of material at particular magnetic field. Core loss for silicon laminations is given in watt per unit kilogram and for ferrite core, it is given watt per unit volume. From weight or volume of core material, core loss can be determined.

Copper loss can be determined by mean turn length (MLT), resistance per unit length, number of turns and current flowing in windings.

7. Voltage regulation depends on copper loss. Ratio of copper loss to total output power is called voltage regulation.

8. Temperature Rise: As transformer run it produces heat. This should be quickly absorbed by ambient. Core material should have lower thermal resistance. Resistance depends on geometry of core. Surface area A_S of transformer equal to K_S $(A_P)^{0.5}$ value of Ks depends on shape, type of magnetic material. Value of K_S value is given in Marcel Dekker, Inc.(2004a, Transformer Surface Area and the Area Product, and Transformer-Inductor Efficiency, Regulation,and Temperature Rise)

Temperature rise= $450(\frac{Pls}{As})^{0.826}$

K. H. Billings (1989, p.3.97-3.99) gives an approximate formula for ferrite core for 30-50 degree Celsius temperature rise.

Temperature rise=$\frac{23.5Pls}{\sqrt{A_P}}$ °C

Design

A. Low Frequency Transformer Design:

Specification of transformer: 50watt step down transformer; operating frequency 50 Hz; input voltage 220 Vrms

1. Selection Of Wire: From power formula P=VrmsIrms; 0.227A current should be flow in primary coil. From Editor Engineeringtoolbox (2023) 27 AWG wire have maximum rated current 0.288 and has 0.1021 mm^2 cross-sectional area so that current density will be $2.17x10^6$ $A/m^{2.}$

2. Selection Of Core: Since frequency is low and from trade point silicon steel laminated strips can be used for making core. Window area and other dimension can be determined from $A_p = \frac{P}{K_f K_u B f J}$ m^4.

P=100 watts; K_f =4.44 for sin wave; K_u=0.4, B=1.0 T (saturated magnetic field approximately 2T), f=50 Hz; J= 2.17×10^6 A/m^2

Ap=5.19×10^{-7} m^4 = 519000 mm^4 From this value, to find dimension of core we have to look data sheet of core provided by core manufacturer. Generally core manufacturer make different lamination like EI, EE, UI, F. Let we are using EI shaped lamination. According to data sheet of EI Core Dimension Manufacturer, Supplier in Delhi, India, n.d., for this area product EI lamination No.15 is suitable. Stack height to get required cross section area of core should be 45mm. stack height is under 1.5 time of tongue height of transformer. Core cross section area (Ae) =1143mm^2.

Volume of core is 174193 mm^3.

Ap=553000 mm^4

3. Calculation Of Iron Loss: If core strips are made of electrical sheet grade 35C360 (Indian standard (IS) 648) as described by manufacturer, it has density 7.65kg/dm3=7.65×10^{-6} kg/mm3. One can use data sheet of JFE Steel, n.d. for some grain oriented and non-grain oriented magnetic material.

Mass of transformer = 1.33 kg.

Iron loss (Pfe) = 4.78 watt

4. Number Of Turns In Primary And Secondary Coil: Volt per turn= K_fBAef let B=1.2 T for kept B-H curve in linear region.

V/N=0.304. This ratio is also true for secondary winding. If input voltage in rms is 230V then turns in primary coil (Np) = $\frac{220}{0.304}$=724

At ideal condition transformer runs with 100% efficiency. So for step down transformer turns in secondary winding (Ns), if we want 12volt at secondary winding will be $\frac{12}{0.304}$ = 40. Voltage regulation is important factor, this is depends on copper loss. So for good voltage regulation copper loss should be low.

5. Copper Loss Calculation: Again from power equation P=VI maximum current flowing in secondary winding when secondary winding connected to load will be= $\frac{50}{12}$ A= 4.16A

From Editor Engineeringtoolbox (2023) this current required an AWG 15 number wire. Current density in this winding will nearly equal to primary winding current density.

Mean turn length (MLT) approx = 160 mm

If AWG 27 has resistance per unit meter (r) $169x10^{-3}$ than primary coil dc resistance

Rpdc= rMLTNp

$169x10^{-3}$ x$160x10^{-3}$ x724 =19.57 ohm.

Power dissipation in primary coil (Ppcu)= Rpdc Ip^2 =0.94watt.

DC resistance of secondary coil Rsdc= rxMLTxNs

If AWG 15 has resistance per unit meter (r) $10.44x10^{-3}$ than secondary coil dc resistance

$10.44x10^{-3}$ x$160x10^{-3}$ x40=0.066 ohm.

Power dissipation in secondary coil (Pscu)= Rsdc Ip^2 =1.14watt.

Total copper loss (Pcu) = 0.94+1.14=2.08W

Puce = Pie condition for maximum efficiency.

Total loss Pls =2.08+4.78=6.86 W

6. Voltage Regulation: $\frac{Pcu}{P}$ 100%=$\frac{2.08}{50}$x100%= 4.16 %

7. Temperature Rise: area product Ap= 553000 mm^4 , Ks=41.3, then surface area of transformer A_s=30712 mm^2=307.12 cm^2

Temperature rise=$450(\frac{6.86}{294.14})^{0.826}$ == 19℃

B. High Frequency SMPS Transformer Design:

Design specifications are as follows

Output power 50 watt; output voltage 12V; input DC voltage range in =127V-340V; operating frequency 50 kHz. DCM flyback transformer

1. Selection Of Primary Wire: Peak current I_R= $\frac{2P_{out}}{\mu Vmin\ D}$ efficiency μ generally 80 percent its approaximate value I_R= $\frac{5.5P_{out}}{Vmin}$ from this equation peak pulsating current will be 2.16A.

Flyback converter transformer act like inductor that has inductance L= $\frac{Vmin\ D}{I_R f}$

From this maximum duty cycle D=0.4. Maximum inductance of primary coil of transformer 0.470mH.

#17AWG wire will be sufficient for 2.16A. Skin depth at 50 kHz is 0.3 mm so that wire diameter should be less than 0.6mm. So that three strand of #23 AWG should be used rather than single enameled copper wire at higher frequency. Cumulative diameter of this wire arrangement=1.72mm. However in view of rms current 0.788A two strands of wire would be enough.

Current density= $1.5x10^6$ A/m^2

2. Selection Of Core: Since frequency is high and ferrite core will be appropriate for very less core loss. Window area and other dimension can be determined from $A_p = \frac{0.223P}{K_u BfJD}$

For 80 percent efficiency P=50 watts; K_u=0.4, B=0.12T, f=50 kHz; J=$1.5x10^6$ A/m^2 maximum duty cycle=0.4, Ape = $0.774x10^{-8}$ m^4 = 0.774cm^4 but for multi windings, margin should be kept by increasing this area product by 30-40 percent. So that effective area product will be = 1.08cm^4. EI core E 34/14/9 and ETD 34 would be suitable. Other core may be matching this data. So one can use accordingly. Let ETD 34 is selected for example. From manufacturers MAGNETICS, n.d. data sheet various cores like EI, EE, ETD, RM, PQ, POT, UI etc. may be used for this area product.

Core cross section area (Age) =97.1 mm^2.

Volume of core is 7640 mm^3.

3. Calculation Of Core Loss:

Mass of transformer = 0.040 kg.

Core loss=0.7640 watt considering 100mW/ cm^3 loss from ferrite core.

4. Number Of Turns In Primary And Secondary Coil: Volt per turn (V/N) = K_fBAef Kf = 4 for square wave. Saturation magnetic field for R material as given in data sheet of MAGNETICS, n.d. approx 0.47 T. for maximum voltage 340V magnetic fields should stay lower than this. So that for this magnetic field V/N=4.85 for 0.25 T. This ratio is also true for secondary winding. If max input voltage is 340 then turns in primary coil (Np) = $\frac{340}{4.85}$ =71

For minimum DC voltage 127 V, V/N=1.78

However for getting inductance from primary coil turns (Np = 71) one can use formula $1000\sqrt{\frac{L}{AL}}$ given in Brown (2001, pp. 44-45), here AL inductance per 1000 turn^2. This value is often given in data sheet for R material. Ungapped AL value is 2707 so that gap should be provided to match primary coil turn number as derived above.

Gap prevent core to reach at saturation magnetic field and linearize B-H curve.

Secondary coil winding turns (Ns) = $\frac{VoutNp}{Vin}$,Vin will be minimum dc voltage and Vout voltage on secondary coil this also include diode voltages. Secondary coil turns will be 7.51 let 8 approx. for other winding voltage per turn will be same and can be calculated accordingly.

From this AL should be 90.

One can find gap from formula given in Brown (2001, pp. 44-45) $lg = \frac{.0125Np^2Ae}{L}$

Units of lg, Ae, and L are cm, cm^2, and μH, respectively.

This will be 1.3mm approx.

Approximate gap between each lag of core will be 0.65 mm.

At ideal condition transformer runs with 80% efficiency. So for step down transformer turns in secondary winding (Ns), if we want 12volt at secondary winding. If diode voltage and voltage drop in output circuit is considered than approx 1 voltage extra will be included in desired output voltage. So that turns in secondary winding $\frac{12+1}{1.73}$ =7.51 approx 8. Let for 5V out turns in that winding will be approx 4. Voltage regulation is important factor, this is depends on copper loss. So for good voltage regulation copper loss should be low.

5. Copper Loss Calculation: Average current in primary winding I_{av}= $\frac{1.25P_{out}}{Vmin}$ for 80 percent efficiency. Peak current flowing in secondary winding = $\frac{2I_{av}N_P}{DN_S}$, D max duty cycle. (Sha et al. 2015, p. 219)

Secondary coil peak current (I_{PS}) =2.16x8.87=19.15 A

DC current at secondary coil= (19.15/2) x (1-0.4) =5.74A

rms current at secondary coil= 8.83A

rms current (Irmsp) in primary coil=0.788A.

Peak current in primary coil=2.16A.

Looking rms value of current #12 AWG wire will be proper. But diameter of wire 2.05 mm will not fit for skin depth. So that a copper strip of length less nearly 1.8 cm and 0.6 mm thick can be used. Otherwise litz wire will be good. 40/27 diameter 3mm. Manufacturer data sheet shows that bobbin feature for ETD34/17/11 is as follows: (Ferroxcube, 2008) MLT=60mm; minimum winding width=20.9mm for CPH-ETD34-1S-14P bobbin.

Mean turn length (MLT) approx = 60 mm

If AWG 23 has resistance per unit meter (r) 66.78x10^{-3} than primary coil dc resistance

Rpdc= rMLTNp

$66.78x10^{-3}$ $x60x10^{-3}$ x71=0.29 ohms.

We have used two strands of wire. Total Power dissipation in both wires of primary coil (Ppcu)= 2xRpdc I^2rmsp =0.090watt.

DC resistance of secondary coil Rsdc= rxMLTxNs

$168.82x10^{-3}$ $x60x10^{-3}$ x8=0.081 ohms.

Total power dissipation in 40 wires of secondary coil (Pscu)= 40xRsdc Ip^2 =0.156watt.

Total copper loss (Pcu) = 0.156+0.090=0.247watt

Total loss=0.247+0.764=1.01watt

6. Voltage Regulation: $\frac{Pcu}{P}$ 100%=$\frac{0.247}{50}$x100%= 0.494 %

7. Secondary winding inductance L= $\frac{Vout\ Ds}{I_{PS}f} = \frac{12X0.6}{19.15X50000}$=7.51µH

8. Temperature Rise: Heat dissipation depends on thermal resistance of ferrite core. For 1.01watt total loss temperature rise $\frac{23.5Pls}{\sqrt{A_P}} = \frac{23.5X1.01}{\sqrt{0.744}}$=27 degree celcius.

Result And Conclusion

Low frequency power supply transformer is 23 times larger in size and 33 times heavier than high frequency transformer despite that they have same power capability. Total loss is 7 times higher in low frequency transformer but temperature rise is lower than high frequency transformer. High frequency transformer has higher current carrying capacity as peak current reaches up to 20 A. Low frequency power supply uses very little component like some diodes and a capacitor whereas higher frequency transformer uses complicated circuit consisted of filter, controller IC, MOSFETs so that it is not as robust as low frequency power supply. MOSFET is used as switch to provide high frequency current in transformer so that more than 30 percent power is wasted as heat. Large heat sink is often used in high frequency power supply or switch mode power supply (SMPS). From designing parameters we can conclude that kiloWatt rated low frequency power supply can only be made with big transformer. This may be too heavy to lift and expensive but high frequency power supply can be made with small, little weight and not too expensive transformer. But high frequency transformer can be made with medium size transformer. So that application where space, weight and money involve high frequency power supply is best choice. Now days high frequency power supply or SMPS are designed to work in MHz region. At this frequency leakage inductance and distributed capacitance became more significant. so some extra design parameter should be considered to minimize losses.

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