EEEE2046 Energy: Things to consider for the Gate Drive Transformer 22-23

1.0 Introduction

This document provides some basic information which should be considered when designing and constructing the transformer for the MOSFET gate drives of the two transistor Forward Converter in EEEE2046 (Energy Project). It is not a complete guide for the design of the transformers but instead should be used as a reference for the most important considerations.

Figure 1: Toroidal magnetic core

The gate drive transformer should be small as it only transfers a few Watts of power from the supply to the MOSFETS. As a result a toroidal core is chosen.

2.0 Core material selection

Below are a few core materials (there are many others) which are used in magnetic components in power electronics applications.

Laminated Silicon Steel- Used in low frequency AC applications where a “Soft Iron” core would suffer from high Eddy current losses. Has a high saturation flux density 1.5-1.8T.

Ferrite- Generally used in high frequency applications. The ceramic nature of the material means that it is highly resistive to electrical current and therefore has very low eddy current losses and does not need to be laminated. The saturation flux densities are in the 0.4-0.5T region.

Powdered Iron- Not generally used for transformers because powdered material has an inherent “Distributed air gap” which lowers the permeability of the core. They have a saturation flux density of around 1-1.5T.

Amorphous metal- These materials are non-crystalline or “glassy”. They can be used to produce highly efficient transformers (with a high saturation flux density) but are generally more expensive than other materials. There are many types, but, for example, “Metglas” cores have a saturation flux density of 1-1.5T.

We are using Ferrite. Research these materials and make yourself comfortable with the justification of this choice of material.

What type of Ferrite? There are many “grades” of Ferrite which are optimised for certain frequency ranges, flux densities, losses etc. We will use Ferroxcube (manufacturer) 3C90 ferrite. This is driven by the operational frequency range and the availability in bulk for the project.

3.0 Core Dimensions Selection

Selection of the required core for a transformer is usually done one of two ways:

a. The power rating of the required transformer is used as a design input and the correctly sized core is chosen from charts in manufacturer's datasheets.

b. The "Area Product" method is used- this considers the current density (i.e. the required cross sectional area of copper wire) and the required maximum operational flux density as constraints to decide how big the core needs to be. The closest core dimensions are used to select the appropriate core.

Two appropriately sized cores have been selected for you. They are both toroidal (very common when considering "small" magnetic components). Both cores are actually larger than an optimised design would consider but they were readily available in bulk from suppliers and are large enough to wind without needing magnifying equipment. The available choices are:

- TN 13/7.5/5
- TN 14/9/5

Both use 3C90 grade ferrite and the datasheets are available on Moodle.

4.0 Maximum Flux Density (B_{max})

Below is a typical BH curve for a typical grade of Ferrite (not 3C90). We need to ensure that our flux density does not saturate the core.

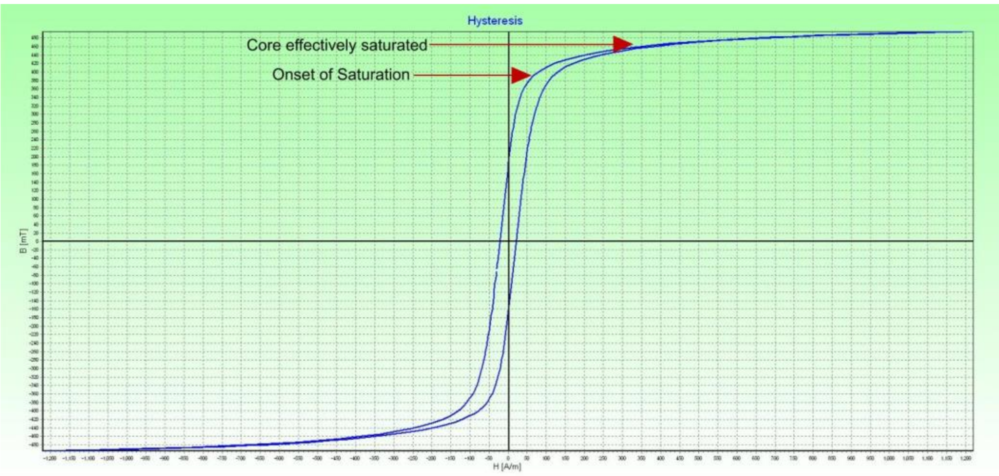

Figure 2: B (Flux Density), H (MMF) plot for a piece of Ferrite (Note: NOT 3C90)

Our peak operational flux density (B_{max}) must be lower than B_{sat} for the 3C90 material. It should also be noted that the peak operational flux density will affect the Hysteresis loss of the core- i.e. the energy dissipated every time we "travel" around a loop (or cycle) of the BH loop.

You need to decide what B_{max} will be for your 3C90 core.

5.0 Number of turns (N_1, N_2, N_3)

The gate drive transformer has three windings and a 1:1:1 ratio. We only need to calculate the number of turns (N) for one winding- and then apply it to all three.

Starting from Faraday's law:

$$V = N\frac{d\varphi}{dt} \qquad [1]$$

Where V is the voltage applied to the winding, N is the number of turns and φ is the flux created in the core. Rearranging this into the integral form gives:

$$\frac{1}{N}\int V\,dt = \varphi_1 - \varphi_0 \qquad [2]$$

Which can be converted to flux density (B) by considering that $B/A_{core} = \varphi$:

$$\frac{VTA}{NA_{core}} = B_1 - B_0 = \Delta B \qquad [3]$$

Where VTA is the "Voltage Time Area" (See Power Electronics analysis in EEEE2045), and A_{core} is the cross-sectional area of the core. Finally, ΔB is the change in flux density.

This can clearly be re-arranged and re-labelled to calculate the number of turns required for a winding:

$$\frac{VTA}{\Delta BA_{core}} = N \qquad [4]$$

You need to decide what the "Worst case" VTA that will be applied to the core- this will give the largest shift in flux density. $\Delta B = B_{max}$ i.e. the highest VTA must keep the flux density below the B_{max} chosen in the previous section. Clearly the calculated N must be a whole number.

Once N has been calculated, the number of turns for each winding is $N_1=N_2=N_3=N$.

6.0 Magnetising Inductance (L_{mag})

Calculation of the magnetising inductance of the transformer can be used to help deduce the magnetising current value which in turn is useful for calculating the required wire size. The inductance of the core can be calculated two main ways.

a. The first method considers the reluctance of the magnetic core and uses this and the number of turns to calculate the inductance from:

$$L_{mag} = \frac{N^2}{\Re} \qquad [5]$$

Where $\Re$ is the reluctance of the core which can be calculated using:

$$\Re = \frac{1}{A_{core}}\left[\frac{l_{core}}{\mu_r\mu_0}\right] \qquad [6]$$

Where μ_r and μ_0 are the relative permeability and the permeability of free space ($4\pi \times 10^{-7} Hm^{-1}$) respectively.

b. The alternative method for calculating the magnetising inductance is to use the A_L value given in the datasheet for the core (you must make sure that it considers the right grade of core material). A_L (in nH) is the inductance per turn squared. As such it is possible to calculate the magnetising inductance of the core from:

$$L_{mag} = A_L N^2 \qquad [7]$$

7.0 Size of wire (Cross Sectional Area, A_{cu})

Now we know how many turns that each winding of the transformer will have we need to determine the size of the wire. There are two main constraints

a. The RMS current density in the wire must be below around 3A/mm^2. This will ensure that the winding does not get too hot during operation- the worst case being that the insulation melts off the wires and all of the turns on the winding short circuit.

   The current density is unfortunately not straight forward. At high frequencies the current is concentrated in an outer “skin” on the conductor and as a result the current density is increased. You need to determine the “skin depth” and calculate the current density from this. The required information is readily available on the internet and in books [1].

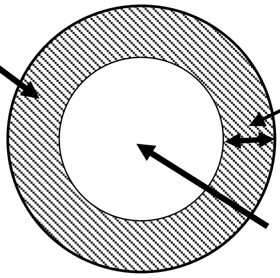

Figure 3: “Skin Effect” and its impact on current density of a circular conductor

b. The three windings clearly need to fit on the core. The available “window” for the winding can be calculated for the core (it’s the area in the middle of the toroid where we will put the winding). However, we also consider a “Fill Factor”, K_{fill}, as a result of the fact that it is impossible to fill the winding area in a practical magnetic component. For a toroid, the fill factor is between K_{fill}=0.2 and K_{fill}=0.4. Clearly:

$$K_{fill}A_{window} > 3NA_{cu} \qquad [8]$$

   Note: You must also consider that only certain sizes of wire are available in the lab and this adds a further constraint. These sizes are given in AWG (American Wire Gauge) -tables converting this to mm^2 are readily available online.

8.0 Losses

As for any wound magnetic component there are two main sources of loss. The first is the core loss. For Ferrite, Eddy currents can be neglected because the material is a good electrical insulator. Hysteresis loss can be considered using manufacturer datasheets or design software. For the gate drive transformer, the worst case VTA will determine the highest hysteresis loss (you need to think about why this is the case). The second source of loss is in the resistance of the windings of the transformer. The DC resistance of the wire can be calculated using the resistivity of copper (ρ_{cu}) and the dimensions of the wire, similarly to the forward converter output inductor [2]:

$$R_{DC} = \rho_{cu}l_{cu}/A_{cu} \qquad [9]$$

The AC resistance is more challenging to calculate as a result of the complication caused by the "Skin Effect" at high frequencies. Whether this needs to be considered or not depends on the size of the wire chosen for the gate drive transformer. Further information is available in [1].

9.0 Winding Techniques

We now have wire and the required number of turns for each winding. We need to think about how we are actually going to put the windings on core. There are three main options

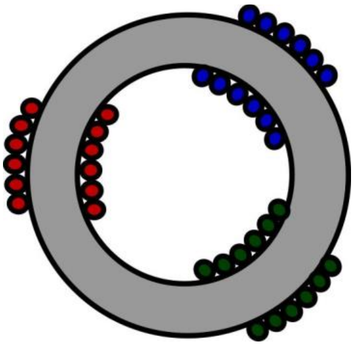

Figure 4a: Option 1: Put each winding separately spaced around the core

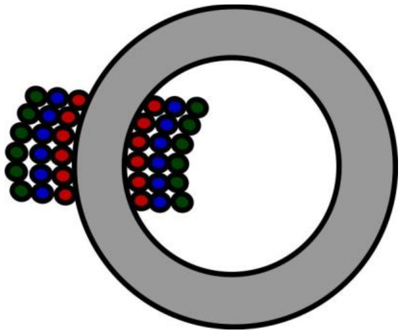

Figure 4b: Option 2: Put each winding on top of each other (note: turns could be distributed further around the transformer)

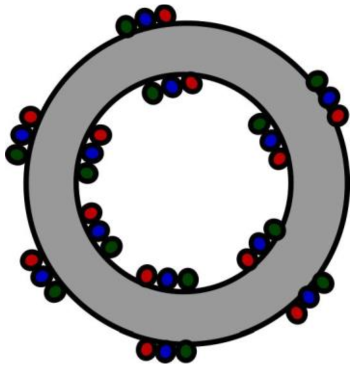

Figure 4c: Option 3: "Trifilar" wind the three windings together, next to each other at the same time

The choice of winding method is determined by consideration of two main points. The first is the insulation requirements i.e. do we need to separate the windings using insulating materials (note that the wires are already coated in a thin film of enamel- enough to prevent "turn to turn" short circuits). The second is the effect of the winding method on the circuit. For the latter, in particularly the winding method has an impact on the Leakage Inductance (see first year notes for Power and Energy) of the circuit- a winding method should be selected to minimise this. At high frequencies, the capacitance of the windings (remember that windings are two conductors separated by a dielectric insulator) can also create issues but this will not be considered in this project.

References

[1] Ron Lenk, "Practical Design of Magnetics," in *Practical Design of Power Supplies* , 1, Wiley-IEEE Press, 2005, pp.288- Available on campus on IEEEXplore
[2] Jon Clare, "EEEE2046 Energy Project: Designing an Inductor", November 2017, Available on Moodle.

Further Reading

[1] L. Warnes, "Electronic and Electrical Engineering Principles and Practice", 3rd Edition, Palgrave Macmillan, 2003
[2] P.T. Krein, "Elements of Power Electronics", Oxford University Press, 1998
[3] A. Van den Bossche, V. Valchev, "Inductors and Transformers for Power Electronics", CRC Press, 2005
[4] W.G. Hurley, W.H. Wölfle, "Transformers and Inductors for Power Electronics", Wiley, 2014
[5] https://kitsandparts.com/howtowindtoroidswithoutpain.php - a good source of information on how to wind a toroid.

Updated February 2023: Al Watson