# ISOLATED FULL BRIDGE DC/DC CONVERTER

## 1 Abstract

The aim of the work is desinging 96W full-bridge isolating converter with $V_{in} = 12V$ and $V_{out} = 48V$ with 1% output voltage ripple. Switching frequency of the converter is 100kHz.

Contents

## 2 Circuit Parameters

a) Assuming operating duty cycle is 0.4, find the turns ratio of the transformer.

b) Find the required inductance value so that the filter inductor current ripple is 10% of the average inductor current.

c) Find the output capacitor value to meet the output voltage ripple requirements. Do not just use the formula, show derivaton.

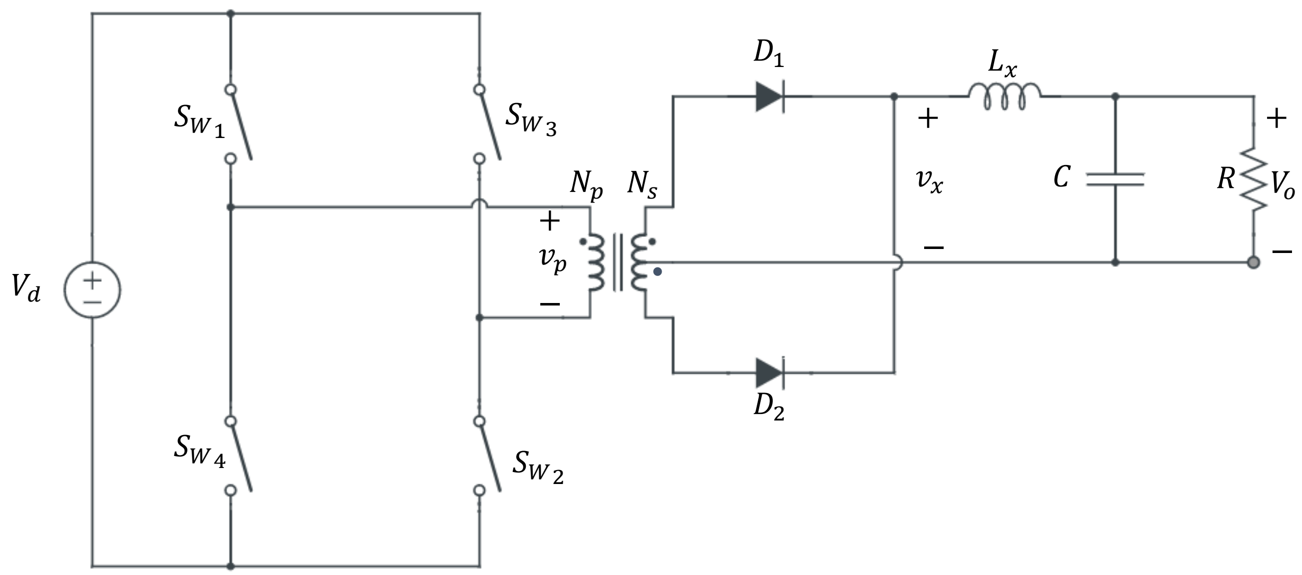



*Figure 1. Isolated Full-Bridge Converter*

$S_{W_1}$ & $S_{W_2}$ are operating in simultaneously. Besides, $S_{W_3}$ & $S_{W_4}$ are operating in simultaneously.

When $S_{W_1}$ & $S_{W_2}$ are ON and $S_{W_3}$ & $S_{W_4}$ are OFF:

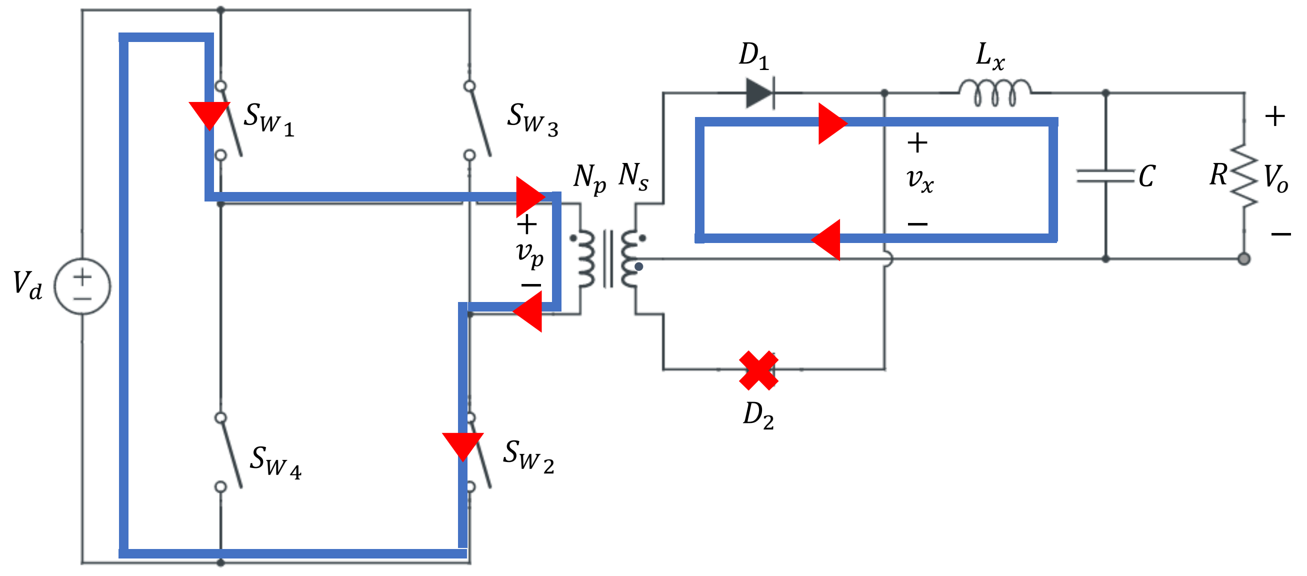



*Figure 2. Isolated Full-Bridge SW1 & SW2 ON, SW3 & SW4 OFF*

When $S_{W_1}$ & $S_{W_2}$ are OFF and $S_{W_3}$ & $S_{W_4}$ are ON:

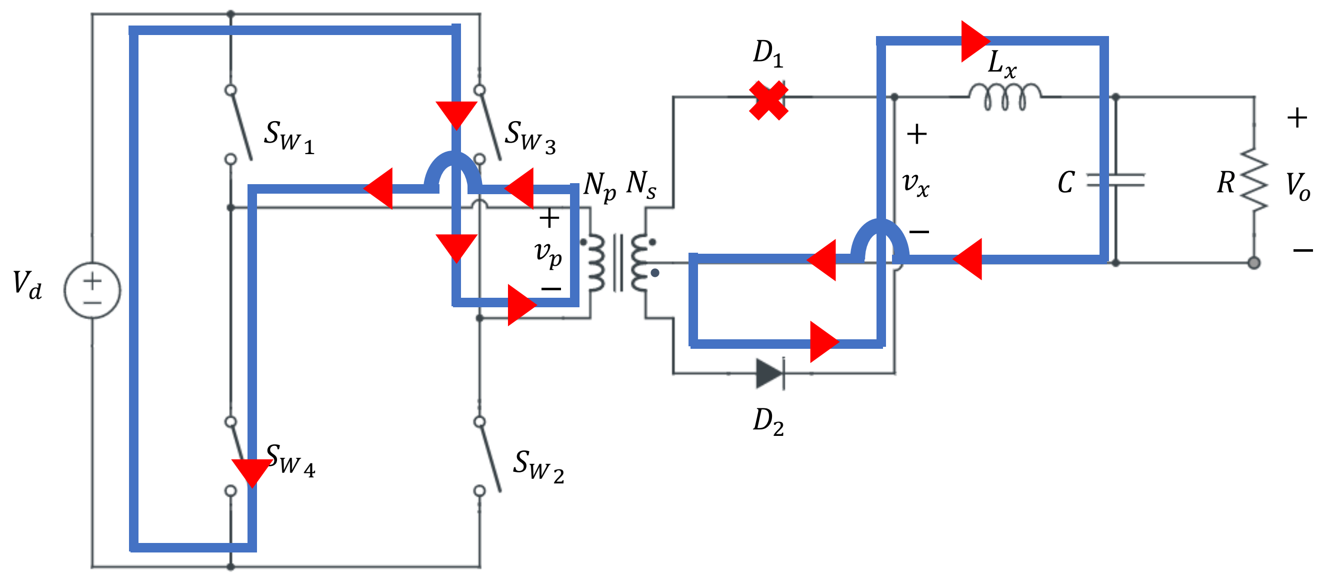



*Figure 3. Figure 2. Isolated Full-Bridge SW1 & SW2 OFF, SW3 & SW4 ON*

As it can be observed from the figures above, inductor voltage is positive in the both cases, therefore; the third case should be added and it should let discharge the inductor.

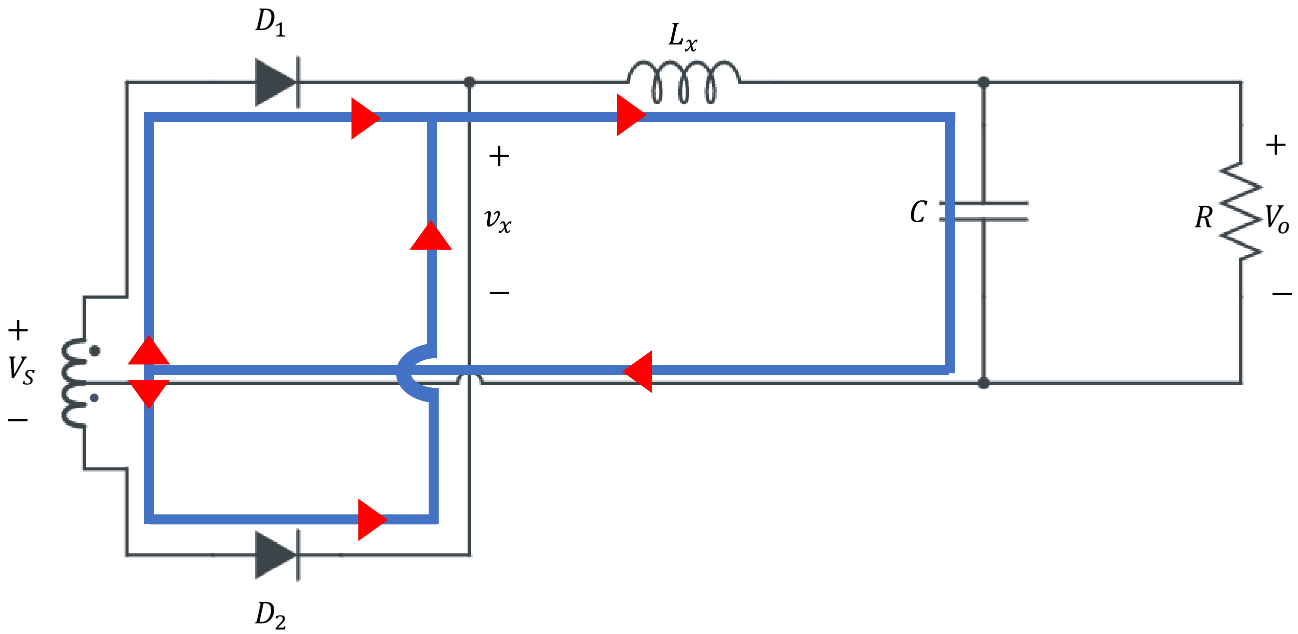
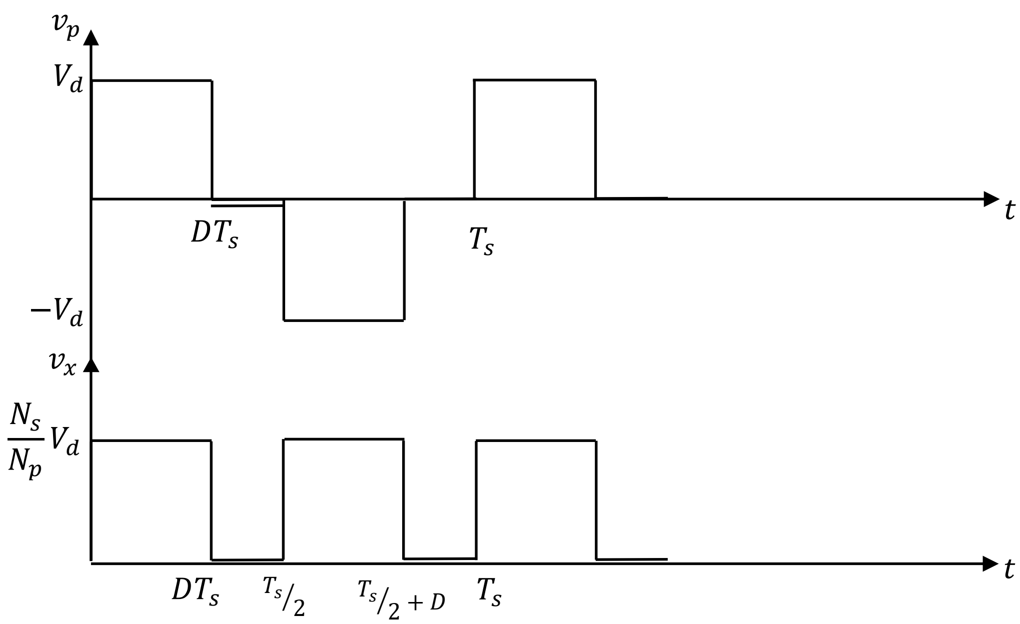



*Figure 4. Isolated Full-Bridge SW1, SW2, SW3 & SW4 OFF*

Here, voltage induced on secondary side cancels each other and $v_{L_x}$ is being discharged.

$$v_{L_x} = \cancelto{0}{V_S} - V_o$$

$$v_{L_x} = -V_o$$




Ripple frequency of inductor current is twice of the main frequency.

As the ripple frequency is twice of main signal.

$$V_o = 2V_d \left(\frac{N_s}{N_p}\right) D$$

The inductor must discharge its energy to not charging up continuously and damage to circuit eventually. There are 2 charge period in the inductor like it can be seen on the graph above. Therefore, duty cycle can't be larger than D=0.5. However, there is no discharging period/time; so, D must be smaller than half of the period (D<0.5) to discharge properly.

As it is given:

$$V_{in} = 12V$$

$$V_{out} = 48V$$

$$P = 96W$$

$$f_s = 100kHz$$

a) Assuming operating duty cycle is 0.4, find the turns ratio of the transformer.

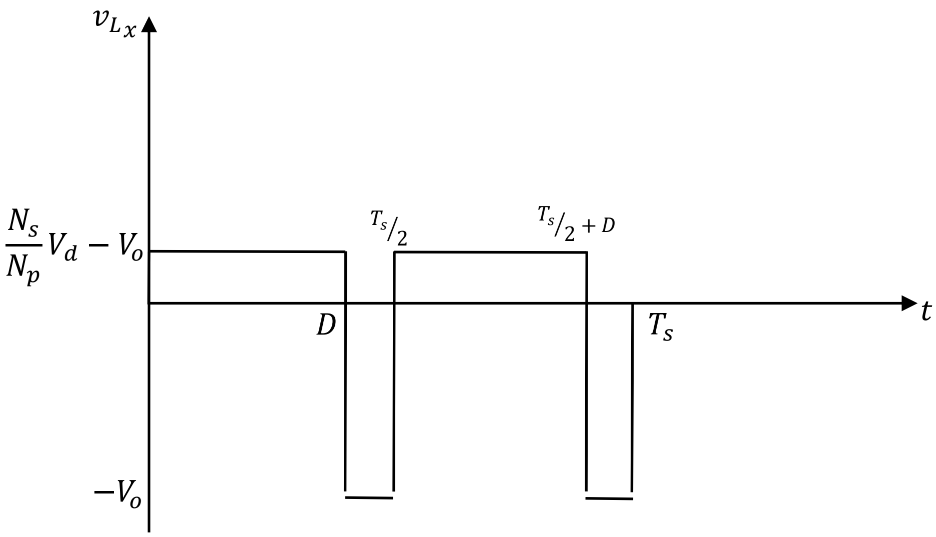
$$V_o = 2V_d \left(\frac{N_s}{N_p}\right) D$$

$$48 = 2 \times 12 \times \left(\frac{N_s}{N_p}\right) \times 0.4$$

$$\frac{N_s}{N_p} = \frac{48}{9.6} = 5$$

b) Find the required inductance value so that the filter inductor current ripple is 10% of the average inductor current.

To get required inductance value, we need to have voltage waveform of the inductor:




$$v_{Lx} = L\frac{di_{Lx}}{dt} = L\frac{\Delta i_{Lx}}{\Delta T}$$

$$L = \frac{v_{Lx} \times \Delta T}{\Delta i_{Lx}}$$

From the negative portion of the inductor voltage:

$v_{Lx} = -V_o$ and $\Delta T = (0.5 - D)T_s$

Average inductor current is

$$I_{Lx} = I_o = {}^{P_o}/_{V_o} = {}^{96W}/_{48V} = 2A$$

$$\Delta i_{Lx} = 0.1 \times 2A \ = \ 0.2$$

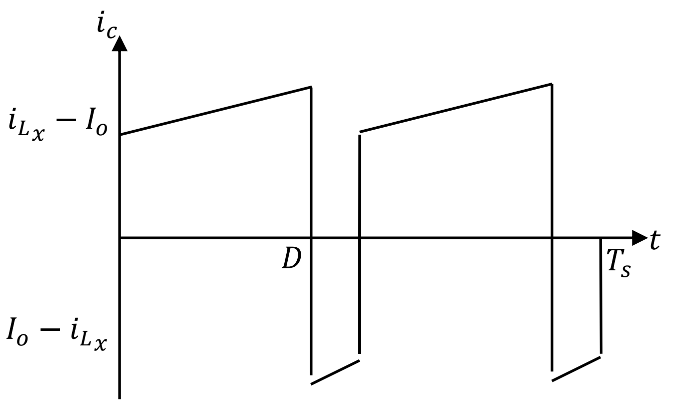
$$L = \frac{V_o \times (0.5 - D)T_s}{0.2}$$

$$L = \frac{V_o \times (0.5 - D)}{0.2 \times f_s} \ where \ f_s = 100kHz, and \ D = 0.4$$

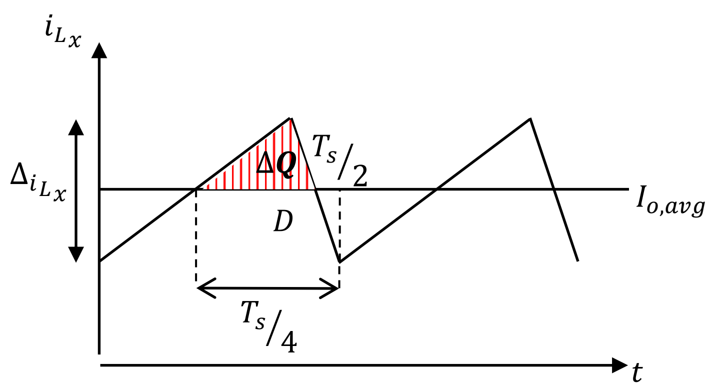
$$L = \frac{48 \times (0.5 - 0.4)}{0.2 \times 100k} = 240\mu F$$

c) Find the output capacitor value to meet the output voltage ripple requirements. Do not just use the formula, show derivaton.

To get required capacitance value, we need to have current waveform of the capacitor:




It is not easy to calculate capacitance value from this graph. Therefore, it is possible to derive capacitance value from the technique is used in buck converter.




Electrical capacitance says $Q = CV$

$\Delta Q = C\Delta V$

$$\Delta Q = \frac{{\Delta i_{L_x}}/{2} \times {T_s}/{4}}{2} = \frac{\Delta i_{L_x} \times T_s}{16}$$

$$\Delta V = \frac{\Delta Q}{C}$$

$$\Delta V = \frac{\Delta i_{L_x} \times T_s}{16C}$$

$$\Delta i_{L_x} = \frac{V_{L_x} \times \Delta T}{L_x}$$

Using off-time $\Delta i_{L_x}$ equation:

$$\Delta i_{L_x} = \frac{V_o \times (0.5 - D)T_s}{L_x}$$

$$\Delta V = \frac{V_o \times (0.5 - D)T_s \times T_s}{16 L_x C}$$

$$\Delta V_o = \frac{V_o \times (0.5 - D){T_s}^2}{16 L_x C} = \frac{V_o \times (0.5 - D){T_s}^2}{16 L_x C} = \frac{V_o \times (0.5 - D)}{16 L_x C {f_s}^2}$$

$$\frac{\Delta V_o}{V_o} = \frac{(0.5 - D)}{16 L_x C {f_s}^2} \; or \; \frac{1 - 2D}{32 L_x C {f_s}^2}$$

It is given that we have 1% ripple at the output voltage.

$$0.01 = \frac{1 - 2D}{32 L_x C {f_s}^2} \quad , where \; D = 0.4, L_x = 240\mu F, f_s = 100kHz$$

$$C = 260nF$$

## 3 Magnetic Design

The total loss of magnetic components -transformer and inductor- should not exceed 15 W and fill factor of the cores should not be less than 30%.

It is strongly advised to use programs such as Matlab or Excel, since magnetic design can be a tedious job which may require a few iterations to find the optimum parameters. A simple script would save you from losing your precious hours.

a) Design your transformer with cores which can be found on Magnetics. Clearly indicate the reasoning behind choosing the core. Find the primary and secondary number of turns. Calculate the magnetizing inductance of the transformer. (Hint: Magnetics has some great design guides for inductor and transformer designs. Please have a look at those guidelines.)

b) With current density being 4 A/mm2, find an AWG cable according to the switching frequency and current value. Firstly, calculate the fill factor of the transformer with the chosen cable. Is it a reasonable value? Then, calculate the cable DC and AC resistances and copper loss of the transformer (Proximity can be ignored).

c) Calculate the core loss of the transformer using core loss formulas given by the manufacturer and compare it with previously found copper loss value. Does your design require new iterations?

d) Design the output inductor with cores on Magnetics. Find the required number of turns and make sure that core is not saturated by checking the DC bias curves of the material.

e) Choose appropriate AWG cable for the design with 4 A/mm2 current density and calculate the fill factor. Is it a reasonable value? Then, calculate the cable DC and AC resistances and copper loss of the inductor.

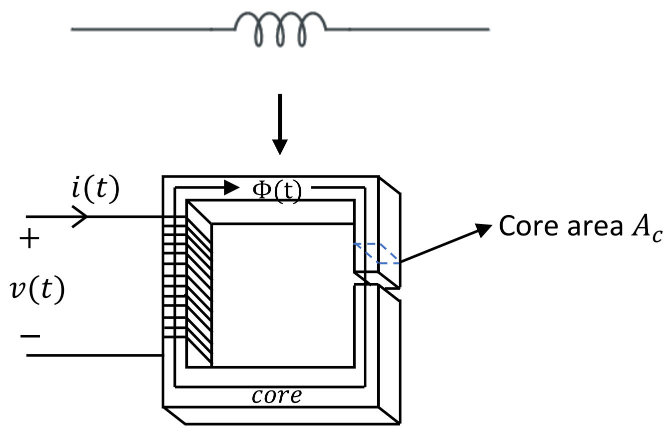
f) Calculate the core loss of the inductor and compare it with previously found copper loss value. Does your design require new iterations?

**3.1 Design your transformer with cores which can be found on Magnetics. Clearly indicate the reasoning behind choosing the core. Find the primary and secondary number of turns. Calculate the magnetizing inductance of the transformer. (Hint: Magnetics has some great design guides for inductor and transformer designs. Please have a look at those guidelines.)**

First, let's try to understand basics:

Faraday's law:

For each turn of wire:




$$v_{turn}(t) = \frac{d\Phi}{dt}$$

Total winding voltage is

$$v(t) = N\frac{d\Phi}{dt}$$

Express flux ($\Phi$) in terms of flux density $\Phi = B_{ac}A_c$

$$V_{pri} = N_{pri}A_c\frac{dB_{ac}(t)}{dt}$$

$$V_{pri} = N_{pri}A_cB_{ac}2\pi f\frac{2}{\pi}$$

$$V_{pri}I_{pri} = 4N_{pri}A_cB_{ac}fI_{pri}$$

$I_{pri}$ is not one of the specificationsof transformer, therefore we can write instead:

$I = JA_w$ *where $A_w$ is the area of copper (wire)*

$$V_{pri}I_{pri} = 4N_{pri}A_cB_{ac}fJ_{rms}A_w$$

However, $A_w$ is still not related to the transformer specifications, therefore, we can write instead:

$$K_u = \frac{2NA_w}{W_A}$$

$$A_w = \frac{K_u W_A}{2N}$$

Fill factor $K_u$

Copper area $A_w$

Window area $W_A$

We are using constant 2 because having 2 winding in the transformer

Insert $A_w$ into the equation:

$$V_{pri} I_{pri} = 4N_{pri} A_c B_{ac} f J_{rms} A_w$$

$$V_{pri} I_{pri} = 4N_{pri} A_c B_{ac} f J_{rms} \frac{K_u W_A}{2N_{pri}}$$

$$V_{pri} I_{pri} = 2f K_u B_{ac} J_{rms} A_c W_A$$

$$A_c W_A = \frac{V_{pri} I_{pri}}{2K_u J_{rms} B_{ac} f}$$

To simplify the equation, following equation can be used which is taken from Magnetics.Inc:

$$\boldsymbol{W_A A_c = \frac{P_o D_{cma}}{K_t B_{max} f}}$$

*Where $K_t$ = Topology constant*

*Forward converter = 0.0005*

*Push-Pull = 0.001*

*Half-bridge = 0.0014*

*Full-bridge = 0.0014*

*Flyback = 0.00033 (single winding)*

*Flyback = 0.00025 (multiple winding)*

$$W_A A_c = \frac{P_o D_{cma}}{K_t B_{max} f}$$

Our specifications:

$$P_o = 96W$$

$$K_t \ for \ full-bridge = 0.0014$$

$$f = 100kHz$$

Suggested interval for $D_{cma}$ is between 500 to 750 cir. mils/amp

$$D_{cma} = 750 \text{ cir. mils/amp}$$

$$D_{cma} = {}^{1}/_{J}$$

$$D_{cma} = \ Current \ density \ (cir.mils/amp)$$

Current density can be selected depending upon the amount of heat rise allowed. 750 cir. mils/amp is conservative; 500 cir. mils is aggressive.

$B_{max}$ = Flux Density (gauss) selected based upon frequency of operation. Above 20kHz, core losses increase. To operate ferrite cores at higher frequencies, it is necessary to operate the core flux levels lower than ± 2 kg. The Flux Density vs. Frequency chart shows the reduction in flux levels required to maintain 100 mW/cm³ core losses at various frequencies, with a maximum temperature rise of 25°C. for a typical power material, Magnetics' P material. From [transformer design with magnetics ferrite cores](transformer design with magnetics ferrite cores) (Mag. Inc)

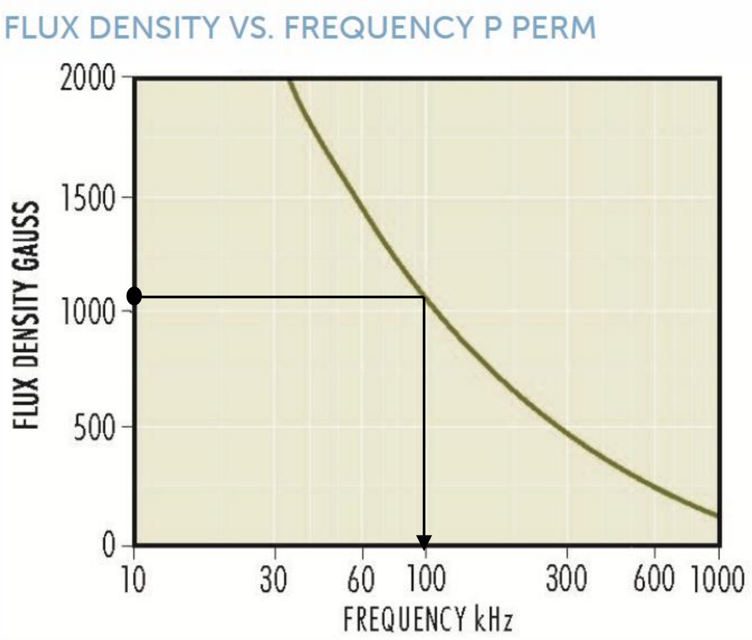



*Figure 6. Flux density (gauss) vs frequency (kHz)*

From the graph above, it is suitable for using the value $B_{max} = 1000\ (gauss)$

$$[Tesla\ (T)\ =\ 10{,}000\ Gauss]$$

$$W_A A_c = \frac{P_o D_{cma}}{K_t B_{max} f}$$

$$W_A A_c = \frac{96 \times 750}{0.0014 \times 1000 \times 100000} = 0.52\ (cm^4)$$

Now, it is time to choose suitable core for the design of transformer,

It is important that our core is able to handle power of 96W and meet $W_A A_c\ =\ 0.52\ (cm^4)$.

When we check Area Product Distribution ($W_A A_c$) Chart (Mag. Inc) and Typical Power Handle Chart (Mag. Inc)

$W_A A_c (cm^4)$

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **0.5** | | 42520 EE<br>43007 EE | 42814 EER | | 43021 EE | | | | 42207 TC | |
| **0.6** | 43019 DS HS | 42515 EE<br>43009 EE | | | | 43618 EE | 42823 UG | 42625 UG | | 42220 UU<br>42515 UU |

*Figure 7. WaAc chart*

Suitable cores are 43019 DS HS, 42515 EE, 43009 EE.

| 20 kHz | 50 kHz | 100 kHz | 250 kHz | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 70 | 94 | 183 | 43019 HS | | 42625 PQ | | | 43618 EE | |
| 48 | 75 | 108 | 210 | 42823 PC<br>43019 RS DS PC | 43009 EE | | 42512 UU<br>42515 UU | 42929 ETD | 44008 EE | 42507 TC |

*Figure 8. Typical power handle chart*

We are working on 100kHz. We need at least 96W power ratings for our system. Hence, it is better to choose the bottom row.

Suitable cores are 42823 PC,43019 RS DS PC, 43009 EE.

43009 EE meets the requirements for $W_A A_c$ and handles the requirement power rating.

Now let's check 43009 EE core in detail. It is a E core with part number 3009.

| Part # | AL nH/T2 (nominal) L 750μ | R 2300μ | P 2500μ | F 3000μ | T 3000μ | J 5000μ | W 10000μ | Le Path Length mm | Ae Cross Section mm2 | Ve Volume mm3 | WaAc cm4 | Length mm | Leg Length mm | Height mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3009 | | 2,893 | 3,147 | 3,780 | | 5,893 | | 61.9 | 83.2 | 5,150 | 0.59 | 30.95 | 13.1 | 9.4 |

*Figure 9. Magnetics Inc. material list*

As it is decided that system will be working on 100mT (1,000 Gauss) and 100kHz.

According to Magnetics Inc. Ferrite Core Material Summary

The cores have types like L, R, P, F, T

| | MATERIAL | | | L | R | P | F | T |
|---|---|---|---|---|---|---|---|---|
| Power Loss (PL) Sine Wave, in mW/cm$^3$ (typical) | | 100 kHz 100 mT (1,000 G) | @25˚C | | 87 | 70 | 70 | 65 |
| | | | @60˚C | | 64 | 50 | 65 | 57 |
| | | | @100˚C | | 58 | 65 | 110 | 55 |
| | | | @120˚C | | 64 | 45 | 150 | 58 |

*Figure 10. Ferrite core material types*

Power loss of material types can be observed on figure above. To make losses minimize, P or T types are better to use.

The choose is: [P type 3009 E core].

### 3.1.1 Number of turns calculations:

Again from Faraday's law of induction:

$$v(t) = N\frac{d\Phi}{dt}$$

$$V_{pri} = N_{pri}A_c\frac{dB_{ac}(t)}{dt}$$

$$V_{pri} = N_{pri}A_cB_{ac}2\pi f\frac{2}{\pi}$$

$$V_{pri} = 4N_{pri}A_cB_{ac}f$$

$$N_{pri} = \frac{V_{pri}}{4A_cB_{ac}f} \longrightarrow$$

To simplify the equation, following equation can be used which is taken from Magnetics.Inc:

$$\boldsymbol{N_p = \frac{V_p}{4BA_cf}10^8}$$

$V_p = 12V$

$\mathrm{B} = 1000\ \mathrm{Gauss}\ (100\ \mathrm{mT})$

$f = 100\ kHz$

Effective cross-sectional area $A_e = 83.2\ mm^2$

$$N_p = \frac{12}{4 \times 1000 \times 83.2 \times 100000} 10^8 = 3.6\ \cong\ 4\ turns$$

$$\frac{N_s}{N_p} = 5, hence\ N_s = 20\ turns$$

#### 3.1.2 Magnetizing Inductance Calculations:

$$L = \frac{N^2}{\mathcal{R}} = A_L N^2$$

$A_L$ = inductance factor $^1/_{\mathcal{R}}$

$$N = \sqrt{L\mathcal{R}} = \sqrt{\frac{L}{A_L}}$$

$$L = A_L N^2$$

$A_L$ value of 0P43009EC is 3147

$L_m = 50.4\mu H$

#### 3.1.3 With current density being 4 A/mm2, find an AWG cable according to the switching frequency and current value. Firstly, calculate the fill factor of the transformer with the chosen cable. Is it a reasonable value? Then, calculate the cable DC and AC resistances and copper loss of the transformer (Proximity can be ignored).

**Cable Selection:**

$$I_{sec,rms} = \sqrt{D{I_o}^2 + 2D(I_o/2)^2} = 1.55\ A$$

$$I_{pri,rms} = 12\ A$$

Current density $J$ is specified as $4A/mm^2$

Therefore;

$$A_{pri} = 12A/4A/mm^2 = 3mm^2$$

$$A_{sec} = 1.55A/4A/mm^2 = 0.4mm^2$$

Let's check American Wire Gauge(AWG) table:

| AWG gauge | Conductor Diameter Inches | Conductor Diameter mm | Conductor cross section in $mm^2$ | Ohms per 1000 ft. | Ohms per km | Maximum amps for chassis wiring | Maximum amps for power transmission | Maximum frequency for 100% skin depth for solid conductor copper | Breaking force Soft Annealed Cu 37000 PSI |
|---|---|---|---|---|---|---|---|---|---|
| 0000 | 0.46 | 11.684 | 107 | 0.049 | 0.16072 | 380 | 302 | 125 Hz | 6120 lbs |
| 000 | 0.4096 | 10.40384 | 84.9 | 0.0618 | 0.202704 | 328 | 239 | 160 Hz | 4860 lbs |
| 00 | 0.3648 | 9.26592 | 67.4 | 0.0779 | 0.255512 | 283 | 190 | 200 Hz | 3860 lbs |
| 0 | 0.3249 | 8.25246 | 53.5 | 0.0983 | 0.322424 | 245 | 150 | 250 Hz | 3060 lbs |
| 1 | 0.2893 | 7.34822 | 42.4 | 0.1239 | 0.406392 | 211 | 119 | 325 Hz | 2430 lbs |
| 2 | 0.2576 | 6.54304 | 33.6 | 0.1563 | 0.512664 | 181 | 94 | 410 Hz | 1930 lbs |
| 3 | 0.2294 | 5.82676 | 26.7 | 0.197 | 0.64616 | 158 | 75 | 500 Hz | 1530 lbs |
| 4 | 0.2043 | 5.18922 | 21.1 | 0.2485 | 0.81508 | 135 | 60 | 650 Hz | 1210 lbs |
| 5 | 0.1819 | 4.62026 | 16.8 | 0.3133 | 1.027624 | 118 | 47 | 810 Hz | 960 lbs |
| 6 | 0.162 | 4.1148 | 13.3 | 0.3951 | 1.295928 | 101 | 37 | 1100 Hz | 760 lbs |
| 7 | 0.1443 | 3.66522 | 10.6 | 0.4982 | 1.634096 | 89 | 30 | 1300 Hz | 605 lbs |
| 8 | 0.1285 | 3.2639 | 8.37 | 0.6282 | 2.060496 | 73 | 24 | 1650 Hz | 480 lbs |
| 9 | 0.1144 | 2.90576 | 6.63 | 0.7921 | 2.598088 | 64 | 19 | 2050 Hz | 380 lbs |
| 10 | 0.1019 | 2.58826 | 5.26 | 0.9989 | 3.276392 | 55 | 15 | 2600 Hz | 314 lbs |
| 11 | 0.0907 | 2.30378 | 4.17 | 1.26 | 4.1328 | 47 | 12 | 3200 Hz | 249 lbs |
| 12 | 0.0808 | 2.05232 | 3.31 | 1.588 | 5.20864 | 41 | 9.3 | 4150 Hz | 197 lbs |
| 13 | 0.072 | 1.8288 | 2.63 | 2.003 | 6.56984 | 35 | 7.4 | 5300 Hz | 150 lbs |
| 14 | 0.0641 | 1.62814 | 2.08 | 2.525 | 8.282 | 32 | 5.9 | 6700 Hz | 119 lbs |
| 15 | 0.0571 | 1.45034 | 1.65 | 3.184 | 10.44352 | 28 | 4.7 | 8250 Hz | 94 lbs |
| 16 | 0.0508 | 1.29032 | 1.31 | 4.016 | 13.17248 | 22 | 3.7 | 11 k Hz | 75 lbs |
| 17 | 0.0453 | 1.15062 | 1.04 | 5.064 | 16.60992 | 19 | 2.9 | 13 k Hz | 59 lbs |
| 18 | 0.0403 | 1.02362 | 0.823 | 6.385 | 20.9428 | 16 | 2.3 | 17 kHz | 47 lbs |
| 19 | 0.0359 | 0.91186 | 0.653 | 8.051 | 26.40728 | 14 | 1.8 | 21 kHz | 37 lbs |
| 20 | 0.032 | 0.8128 | 0.519 | 10.15 | 33.292 | 11 | 1.5 | 27 kHz | 29 lbs |
| 21 | 0.0285 | 0.7239 | 0.412 | 12.8 | 41.984 | 9 | 1.2 | 33 kHz | 23 lbs |
| 22 | 0.0253 | 0.64516 | 0.327 | 16.14 | 52.9392 | 7 | 0.92 | 42 kHz | 18 lbs |
| 23 | 0.0226 | 0.57404 | 0.259 | 20.36 | 66.7808 | 4.7 | 0.729 | 53 kHz | 14.5 lbs |
| 24 | 0.0201 | 0.51054 | 0.205 | 25.67 | 84.1976 | 3.5 | 0.577 | 68 kHz | 11.5 lbs |
| 25 | 0.0179 | 0.45466 | 0.162 | 32.37 | 106.1736 | 2.7 | 0.457 | 85 kHz | 9 lbs |
| 26 | 0.0159 | 0.40386 | 0.128 | 40.81 | 133.8568 | 2.2 | 0.361 | 107 kHz | 7.2 lbs |
| 27 | 0.0142 | 0.36068 | 0.102 | 51.47 | 168.8216 | 1.7 | 0.288 | 130 kHz | 5.5 lbs |

*Figure 11. American Wire Gauge (AWG) table*

$A_{pri} = 12A/4A/mm^2 = 3mm^2$

$A_{sec} = 1.55A/4A/mm^2 = 0.4mm^2$

In normal conditions, 12AWG for primary, 21AWG for secondary is suitable. But, we have a constraint of skin depth δ. The system switching frequency is 100kHz. As it can be seen on the above list, for both 12AWG and 21AWG, skin depth δ reach maximum value below 100kHz. Therefore, we need to use strands of small gauge which has skin depth δ is above 100kHz. For this purpose, 26AWG cable with having cross-sectional area $0.128mm^2$ is good solution. To get same cross-sectional area, for example, 24×26AWG in parallel for primary winding, 4×26AWG in parallel for secondary windings is necessary.

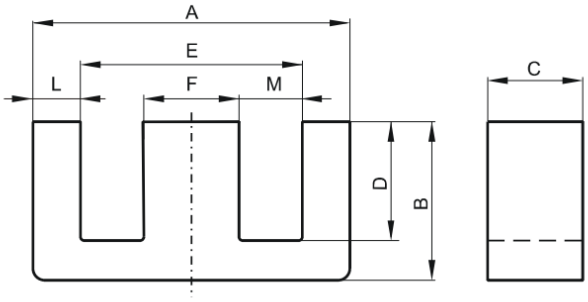
### 3.1.4 Fill factor calculation:

$$K_u = \frac{Total\ copper\ area}{Window\ area}$$

$$K_u = \frac{A_{w,primary} + 2A_{w,secondary}}{W_A}$$

$$K_u = \frac{3 \times (4\ turns) + 2 \times 0.4 \times (20\ turns)}{83.2} = 0.34$$

### 3.1.5 Copper loss calculation:




| (mm) | Nominal: | Tol. min.: | Tol. max.: |
|---|---|---|---|
| **A** | 30.95 | -0.5 | + 0.5 |
| **B** | 13.1 | -0.25 | + 0.25 |
| **C** | 9.4 | -0.3 | + 0.3 |
| **D** | 8.5 Min. | | |
| **E** | 21.41 Min. | | |
| **F** | 9.4 | -0.13 | + 0.13 |
| **L** | 4.29 Nom. | | |
| **M** | 6.0 Min. | | |
| **Eff. Parameters** | | | |
| **Ae mm $^2$** | **Amin mm $^2$** | **le mm** | **Ve mm $^3$** |
| 83.2 | 83.2 | 61.9 | 5150 |

*Figure 11. 0P43009EC core dimensions*

$$(MLT) \ = \ 2\pi\frac{E-F}{2} = 2\pi\frac{21.41-9.4}{2} = 37.73\ mm$$

$$N_p = 4\ turns$$

$$N_s = 20\ turns$$

$$R_{pri} = \frac{N_{pri} \times (MLT) \times R_{one\ cable}}{(number\ of\ parallel\ cables)}$$

Number of parallel cables for pri = 24

$$R_{sec} = \frac{N_{sec} \times (MLT) \times R_{one\ cable}}{(number\ of\ parallel\ cables)}$$

Number of parallel cables for sec = 4

$$R_{pri} = \frac{4{\times}37.73{\times}10^{-3}{\times}133.85{\times}10^{-3}}{24} = 0.84m\Omega$$

$$R_{sec} = \frac{20 \times 37.73 \times 10^{-3} \times 133.85 \times 10^{-3}}{4} = 25m\Omega$$

$$P_{cu,total} = I_{pri,rms}{}^2 R_{pri} + 2 \times I_{sec,rms}{}^2 R_{sec}$$

$$P_{cu,total} = 12^2 \times 0.84m\Omega + 2 \times 2^2 \times 25m\Omega$$

$$P_{cu,total} = 0.32W$$

### 3.1.6 Calculate the core loss of the transformer using core loss formulas given by the manufacturer and compare it with previously found copper loss value. Does your design require new iterations?

To calculate core loss, we are using Steinmetz' equation:

$$P_{core} = \alpha f^{x} B^{y} V_{core}$$

The parameters depend on the material which is supplied by the manufacturer.

$$V_{core} = 5.150mm^{3}$$

$$B = 0.1T \; = \; (1000 \; Gauss)$$

Typically, $1 < x < 3 \; and \; 2 \; < y < 3$

$$P_{core} = 2 \times 3.53 \times 100000^{1.42} \times (0.1)^{2.88} \times 5.1 = 0.6W$$

$$P_{total} = P_{cu,total} + P_{core} = 0.32 + 0.6 \; = \; 0.92W$$

Our system design is not required further iterations. Losses are kind of valid.

## 3.2 Design the output inductor with cores on Magnetics. Find the required number of turns and make sure that core is not saturated by checking the DC bias curves of the material.

To design an inductor, two parameters must be known:

1. Inductance required with DC bias
2. DC current

Inductance was found as 240µH and DC average current of the inductor is equal to the output current $I_o = 2A$.

The procedure is:

### 3.2.1 Compute the product of $LI^2$ where

- L = inductance required with DC bias (millihenries)
- I = maximum DC output current + 1/2 AC Ripple

The ripple is specified as 10%. Therefore, we take I as $2 + (\%10 \times 2)/2 \; = 2.05A$

$LI^2 = 240 \times 10^{-6} \times 2.05^2 = 1\,mJ$

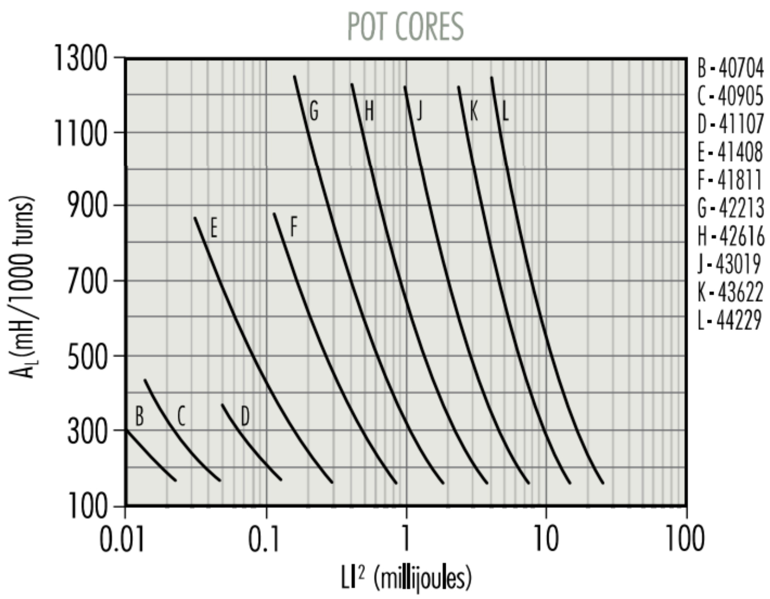



*Figure 12. Magnetics Inc. Ferrite core selection chart*

From above picture which shows ferrite core selection chart according to $LI^2$ value.

We found $LI^2 = 1mJ$. Put the value into the chart and follow the coordinate up to intersection point. $A_L(mH/1000\;turns) \; = \; 300$ and core type is G (42213) which can be found on [Magnetics Inc. Ferrite Pot Cores with part number 2213]

Required inductance L, core type and core nominal inductance $A_L$ are known.

### 3.2.2 Number of turns calculation:

$$N = 10^3 \sqrt{\frac{L}{A_L}}$$

Where L is in millihenries.

$$N = 10^3 \sqrt{\frac{240 \times 10^{-3}}{300}} = 28.28 \cong 29\, turns$$

Let's recheck

$$L = N^2 A_L \qquad (T^2 \times nH/T^2)$$

$$L = 28.28^2 \times 300 \times 10^{-9} = 240\mu H$$

d) Design the output inductor with cores on Magnetics. Find the required number of turns and make sure that core is not saturated by checking the DC bias curves of the material.

One of suitable core is Ferrite Pot Core part number 2213 with material type of P, having

$A_L = 315$

$\ell_e\, (path\ length) = 31.5mm$

$A_e\, (cross - sectional\ area) = 63.4mm^2$

To check saturation:

The maximum allowable H = 25 Oersted

$\ell_e\, (path\ length)\ in\ cm = 3.15cm$

$NI\ (maximum) = 0.8 \times H \times \ell_e$

$NI\ (maximum)\ = 0.8 \times 25 \times 3.15cm = 63\ A \bullet \mathrm{T}$

So, it is in safe region.

#### 3.2.3 Choose appropriate AWG cable for the design with 4 A/mm2 current density and calculate the fill factor. Is it a reasonable value? Then, calculate the cable DC and AC resistances and copper loss of the inductor.

We have 2.2A passing through the inductor.

$A_{inductor} = 2.2A/4A/mm^2 = 0.54mm^2$

From AWG list in page 16, 19AWG with $0.653mm^2$ is suitable; however, skin depth factor is occurs because our system is working on 100kHz.

Therefore, we can use parallel strands 26AWG with $0.128mm^2$ by the number of 5. Therefore, core losses can be minimized.

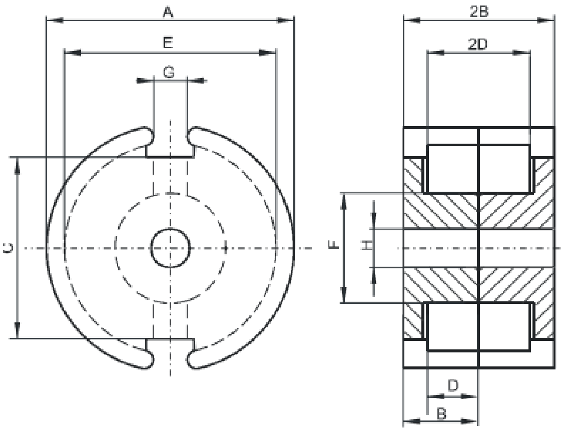
#### 3.2.4 Copper loss calculation of inductor:

$$R_{inductor} = \frac{N_{inductor} \times (MLT) \times R_{one\ cable}}{(number\ of\ parallel\ cables)}$$

$R_{one\ cable} = 133.8568 \times 10^{-3}\Omega$ for 26AWG

$N_{inductor} = 29\ turns$

**DIMENSIONS**




| (mm) | Nominal: | Tol. min.: | Tol. max.: |
|---|---|---|---|
| **A** | 22.0 | -0.8 | 0.0 |
| **B** | 6.7 | -0.1 | + 0.1 |
| **2B** | 13.4 | -0.2 | + 0.2 |
| **C** | 15.0 | -0.4 | + 0.4 |
| **D** | 4.6 | 0.0 | + 0.2 |
| **2D** | 9.2 | 0.0 | + 0.4 |
| **E** | 17.9 | 0.0 | + 0.6 |
| **F** | 9.4 | -0.3 | 0.0 |
| **G** | 3.8 | -0.6 | + 0.6 |
| **H** | 4.4 | 0.0 | + 0.3 |
| **Eff. Parameters** | | | |
| **Ae mm $^2$** | **Amin mm $^2$** | **le mm** | **Ve mm $^3$** |
| 63.4 | 50.9 | 31.5 | 2000 |

*Figure 13. POT core dimensions*

$$(MLT) = 2\pi \frac{E - G}{2} = 2\pi \frac{17.9 - 3.8}{2} = 44.3mm$$

$$R_{inductor} = \frac{29 \times 44.3 \times 10^{-3} \times 133.8568 \times 10^{-3}}{5} = 34.4m\Omega$$

Copper loss of inductor

$$P_{cu} = {I_L}^2 R_{inductor}$$

$$P_{cu} = 2.2^2 \times 34.4m\Omega = 0.17\mathrm{W}$$

**3.2.5 Calculate the core loss of the inductor and compare it with previously found copper loss value. Does your design require new iterations?**

**Core loss calculation of inductor:**

$P_{core}(mW) = \alpha f^x B^y V_e$

$V_e = 2000mm^3$

$f = 100kHz$

Typically, $1 < x < 3 \; and \; 2 < y < 3$

$P_{core} = 3.53 \times 100000^{1.42} \times 0.1^{2.9} \times 2 = 0.1W$

$P_{total} = P_{core} + P_{cu} = 0.17 + 0.1 = 0.27W$

All values seems to be valid.

# 4 SIMULATION

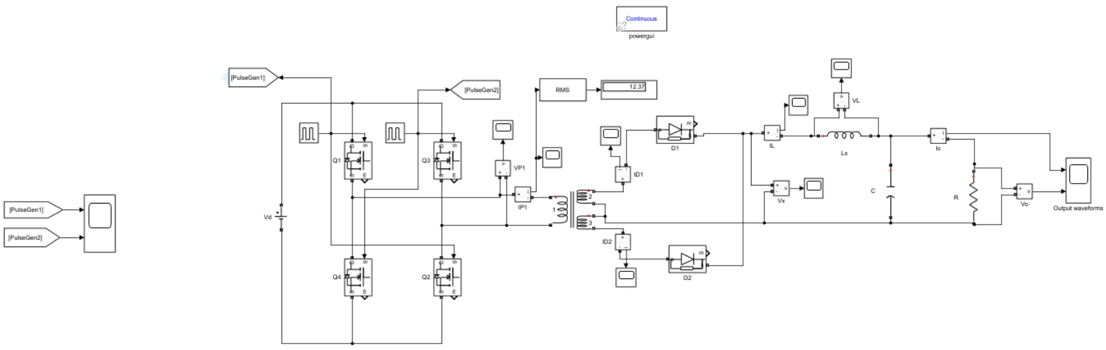



*Figure 14. Simulink schematic design of Full-Bridge DC-DC Converter*

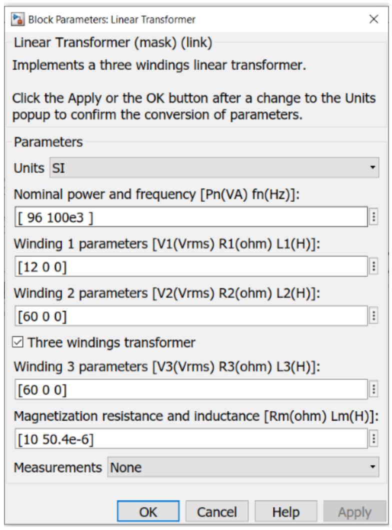



*Figure 15. Transformer parameters*

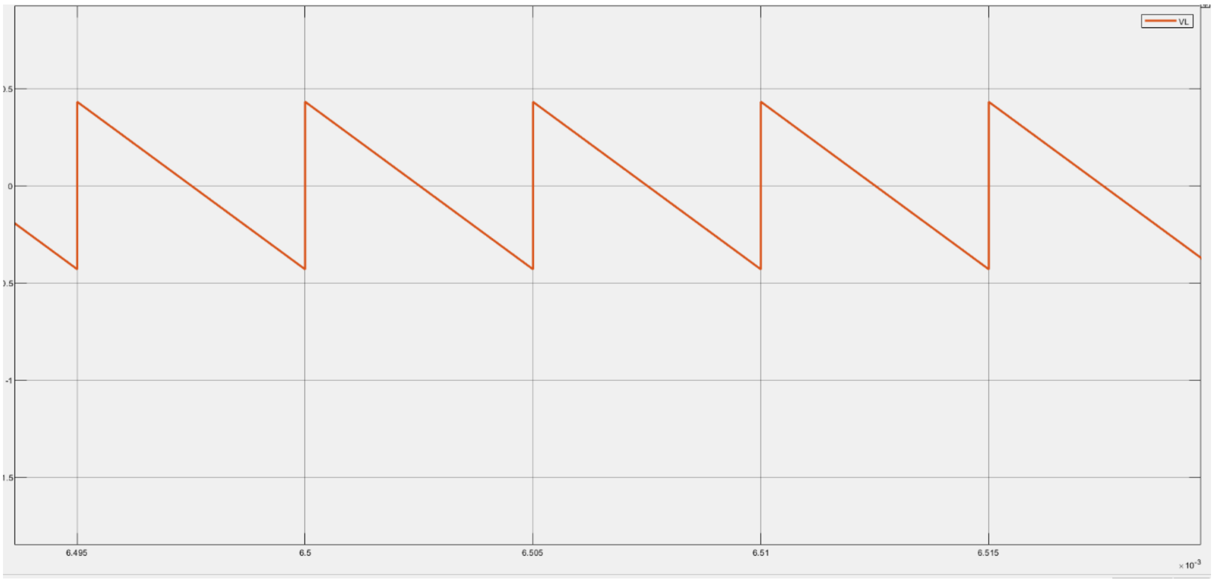



*Figure 16. Inductor voltage waveform*

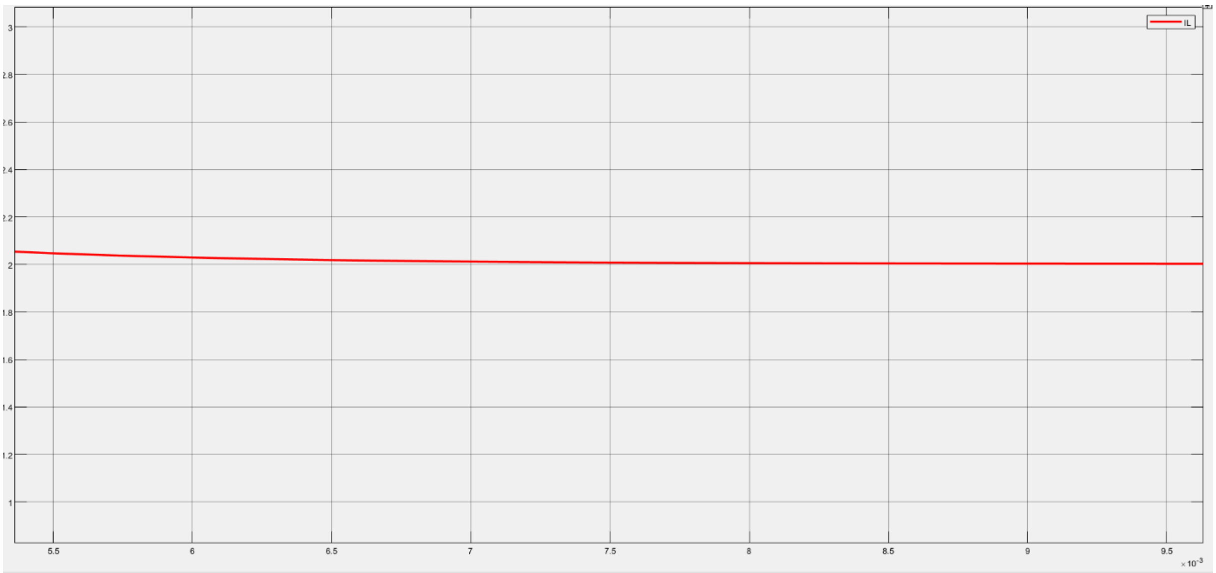



*Figure 17. Inductor current waveform*

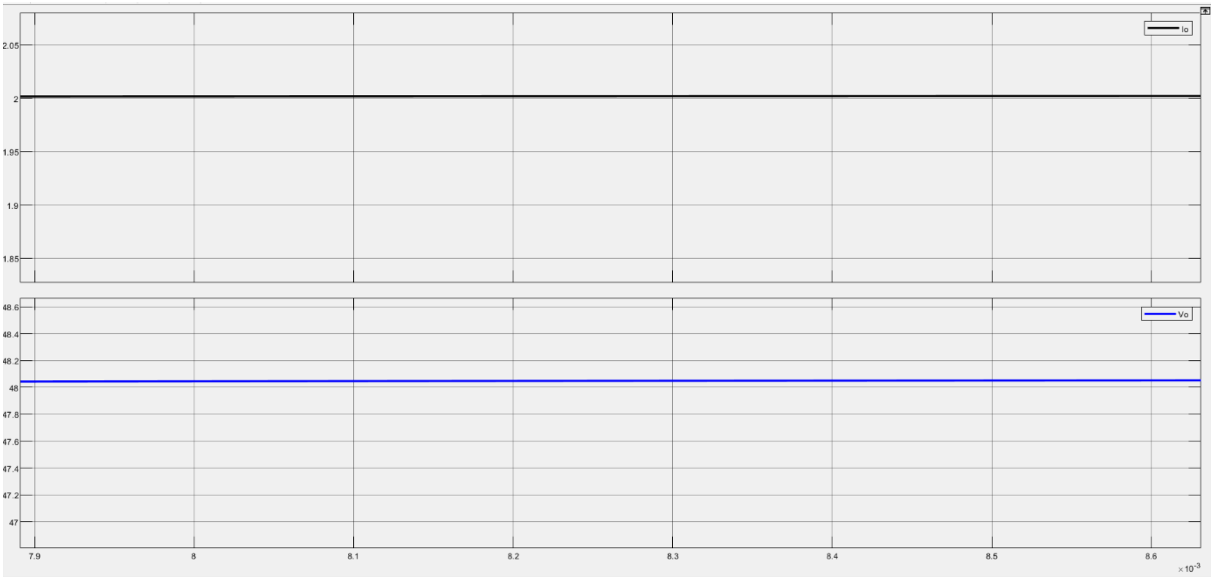



*Figure 18. Output parameters*

# 5 References

[1] (n.d.). *Magnetic Design Guides*. Magnetics. https://www.mag-inc.com/Design/Design-Guides