EE 513

THEORY AND DESIGN

OF

ELECTRONIC POWER SUPPLIES

REPORT OF TERM PROJECT

"MULTI-OUTPUT FLYBACK DESIGN"

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Introduction

In this project, isolated AC-DC converter will be designed and its controller will be selected and observed. First part, we will obtain AC voltage from DC voltage PFC boost converter. In addition, we will design fly back converter. Then, we will design transformer and estimate equivalent circuit for our fly-back converter. Also, efficiency of converter will be observed different load conditions. Likewise, we will obtain same characteristic with using computer simulation program.

In this report includes five main parts. These parts are as follow;

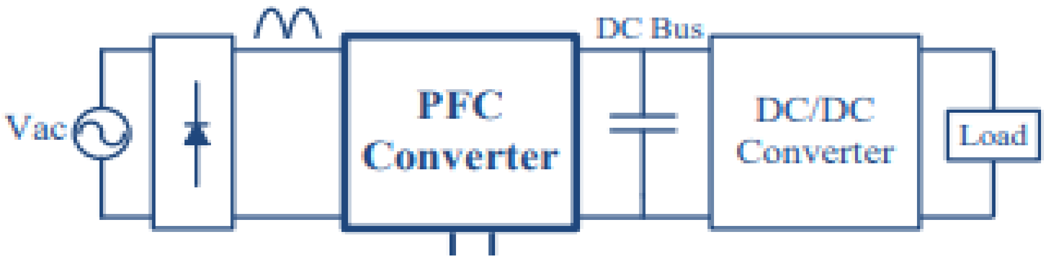
- theoretical information about converter,
- Design process (calculations, element selections, design of power circuit (rectifier and DC-DC converter) and magnetic elements.)
- simulations,
- theoretical calculations and comparison of simulation results,
- evaluation and conclusion

Theoretical Information

The system of AC-DC converter includes basically two parts. These are

-PFC part

-Fly back converter part



PFC

PFC is used for conversion of an alternating current to direct current and producing continuous current by power supply. For converting AC current to DC current, four diodes are used as seen from figure 1. Also, output side of the diodes are shown figure 2. For taking pure DC voltage and doing power factor correction, boost converter is used. Boost converter is most ideal converter for power factor correction.

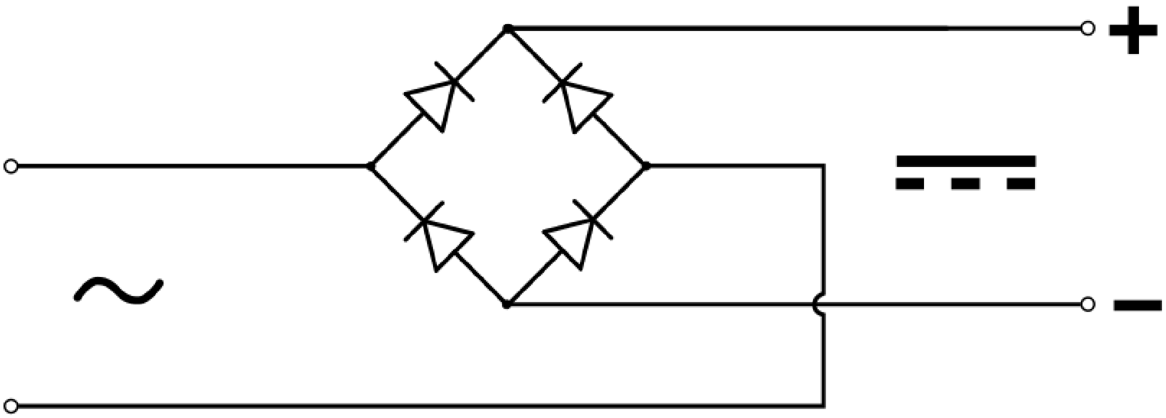


Figure 1. Full-Wave Rectifier

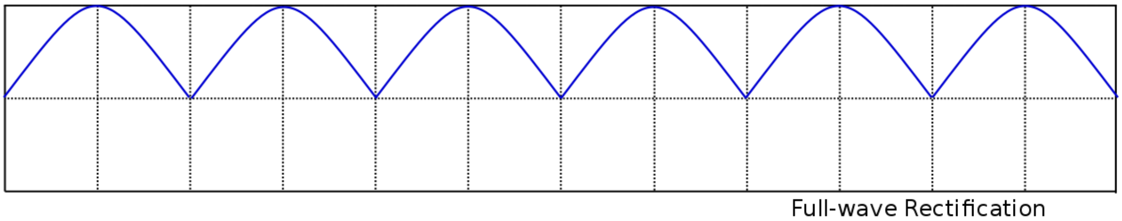


Figure 2. Full Wave Rectifier Output Voltage

The PFC circuit and output simulation are shown figure 3. Input voltage and current according to mode is given figure 4.

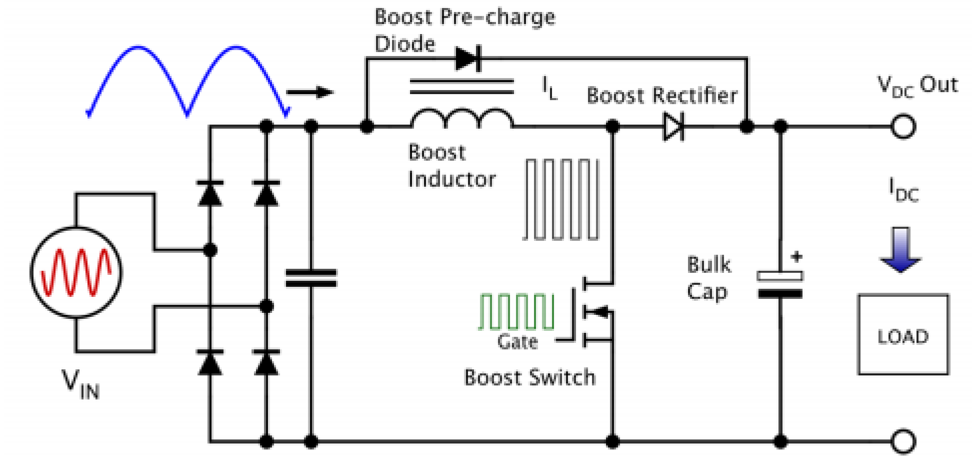


Figure 3.PFC Boost Converter Schematic

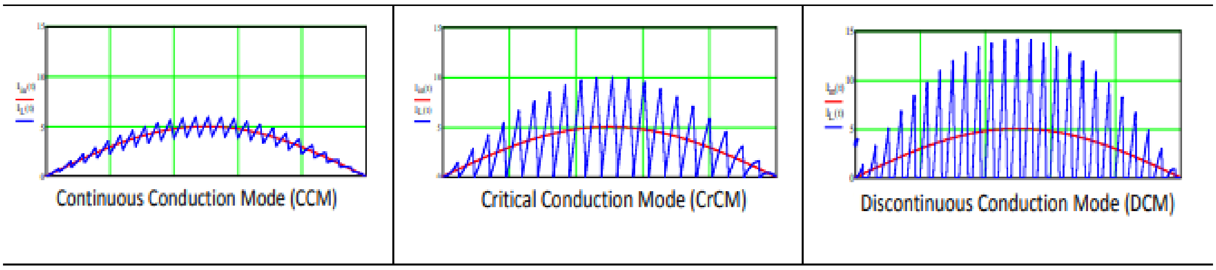


Figure 4.PFC Input Currents and Voltages

Ripple voltage changes according to size of capacitor and inductor. İnductor value are chosen according to output voltage and desiring ripple of output side. Inductance of PFC's inductor is calculated as follows;

$$L = \frac{1}{\%Ripple} \cdot \frac{{V_{ac.min}}^2}{P_o} \left(1 - \frac{\sqrt{2} \cdot V_{ac.min}}{V_o}\right) \cdot T$$

Maximum current on inductor is calculated as follows;

$$I_{L.max} = \frac{\sqrt{2} \cdot P_o}{V_{ac.min}} \cdot \left(1 + \frac{\%Ripple}{2}\right)$$

Inductor consist of two part copper and core. When we design inductor, we consider these two material features. Then, we have to choose most proper material for minimizing power loss. Power loss are defined as:

Inductor copper loss is calculated as follows;

$$I_{L.rms} \cong I_{in.rms} = \frac{P_o}{V_{ac.min}}$$

$$P_{L.cond} = {I_{L.rms}}^2 \cdot DCR$$

Inductor core losses are calculated as follows;

$$H_{max} = \frac{0.4 \cdot \pi \cdot N \cdot I_{L.max}}{l_e\ (in\ cm)}$$

$$I_{L.min} = \frac{P_o \cdot \sqrt{2}}{V_{ac.min}} \left(1 - \frac{\%Ripple}{2}\right)$$

$$H_{min} = \frac{0.4 \cdot \pi \cdot N \cdot I_{L.min}}{l_e\ (in\ cm)}$$

a,b,c,d are parameter of core selected by us;

$$B_{max} = \left(\frac{a + b \cdot H_{max} + c \cdot H_{max}{}^2}{a + d \cdot H_{max} + e \cdot H_{max}{}^2}\right)^x$$

$$B_{min} = \left(\frac{a + b \cdot H_{min} + c \cdot H_{min}{}^2}{a + d \cdot H_{min} + e \cdot H_{min}{}^2}\right)^x$$

The AC flux swing at the peak of the line cycle is:

$$\Delta B = \frac{B_{max} - B_{min}}{2}$$

$$P_{core.pk} = \Delta B^2 \cdot \left(\frac{f}{10^3}\right)^{1.46} \cdot V_e \cdot 10^{-6}$$

Average core loss across the line cycle is:

$$P_{core.av} = P_{core.pk} \cdot \frac{2}{\pi}$$

In addition MOSFET loss I also important. MOSFET is chosen according to Rds, frequency and maximum voltage capacity.

Total MOSFET loss is calculated as follows:

$$P_{S.total} = P_{S.cond} + P_{S.on} + P_{S.off} + P_{S.oss}$$

Conduction mode loss formula is this:

$$I_{S.rms} = \frac{P_o}{V_{ac.min}} \cdot \sqrt{1 - \frac{8 \cdot \sqrt{2} \cdot V_{ac.min}}{3 \cdot \pi \cdot V_o}}$$

$$P_{S.cond} = I_{S.rms}{}^2 \cdot R_{on(100℃)}$$

Turn on loss calculation is as follows;

$$I_{L.avg} = \frac{P_o}{V_{ac.min}} \cdot \frac{2 \cdot \sqrt{2}}{\pi}$$

$$t_{on} = C_{iss} * R_g \cdot ln\left(\frac{V_g - V_{th}}{V_g - V_{pl}}\right) + C_{rss} \cdot R_g \cdot \left(\frac{V_{ds} - V_{pl}}{V_g - V_{pl}}\right)$$

$$P_{S.on} = 0.5 \cdot I_{L.avg} \cdot V_o \cdot t_{on} \cdot f$$

Turn off loss calculation is as follows;

$$t_{off} = C_{rss} * R_g \cdot \left(\frac{V_{ds} - V_{pl}}{V_{pl}}\right) + C_{iss} \cdot R_g \cdot ln\left(\frac{V_{pl}}{V_{th}}\right)$$

$$P_{S.off} = 0.5 \cdot I_{L.avg} \cdot V_o \cdot t_{off} \cdot f$$

Output capacitance switching loss is defined as;

$$P_{S.oss} = E_{oss} \cdot f$$

Gate drive loss is defined as:

$$P_{S.gate} = V_g \cdot Q_g \cdot f$$

Boost diode selection:

One of the most important thing of designing boost converter is selecting proper diode for our system. Since, Boost diode cause the biggest part of energy loss of our system. Therefore, when we choose boost diode we consider open voltage of boost diode and maximum voltage of diode. In addition switching loss of diode is a big problem for us.

The loss calculation of switching loss and conduction loss are as follows;

$$P_{D.cond} = I_{D.avg} \cdot V_{f.diode}$$

$$P_{D.swit} = 0.5 \cdot V_o \cdot Q_C \cdot f$$

Total loss on boost diode is;

$$P_{D.total} = P_{D.cond} + P_{D.swit}$$

Output capacitor selection;

Output capacitor size changes according to desired ripple of output voltage. If desired ripple voltage is small, Capacitance has to be high as possible. To contrary, desired ripple is not important, we can use small capacitance.

Capacitance calculation of output capacitor is defined as follows;

$$C_o \geq \frac{2 \cdot P_o \cdot t_{hold}}{V_o^2 - V_{o.min}^2}$$

Hold up time is changes according to supply frequency.

$$C_o \geq \frac{P_o}{2 \cdot \pi \cdot f_{line} \cdot \Delta V_o \cdot V_o}$$

Capacitance have to obey these two conditions.

Capacitor ESR loss is calculated as follows;

$$ESR = \frac{DF}{2 \cdot \pi \cdot f \cdot C_o}$$

Capacitor rms current defined as;

$$I_{Co.rms} = \sqrt{\frac{8 \cdot \sqrt{2} \cdot P_o^2}{3 \cdot \pi \cdot V_{ac.min} \cdot V_o} - \frac{P_o^2}{V_o^2}}$$

Power loss is:

$$P_{Co} = I_{Co.rms}^2 \cdot ESR$$

Fly-back Converter

Fly-back converter is basically thought as isolated buck-boost converter. Different from basic fly-back converter we used multi output transformer for construct two different output voltage. The circuit of fly-back converter is given as follows;

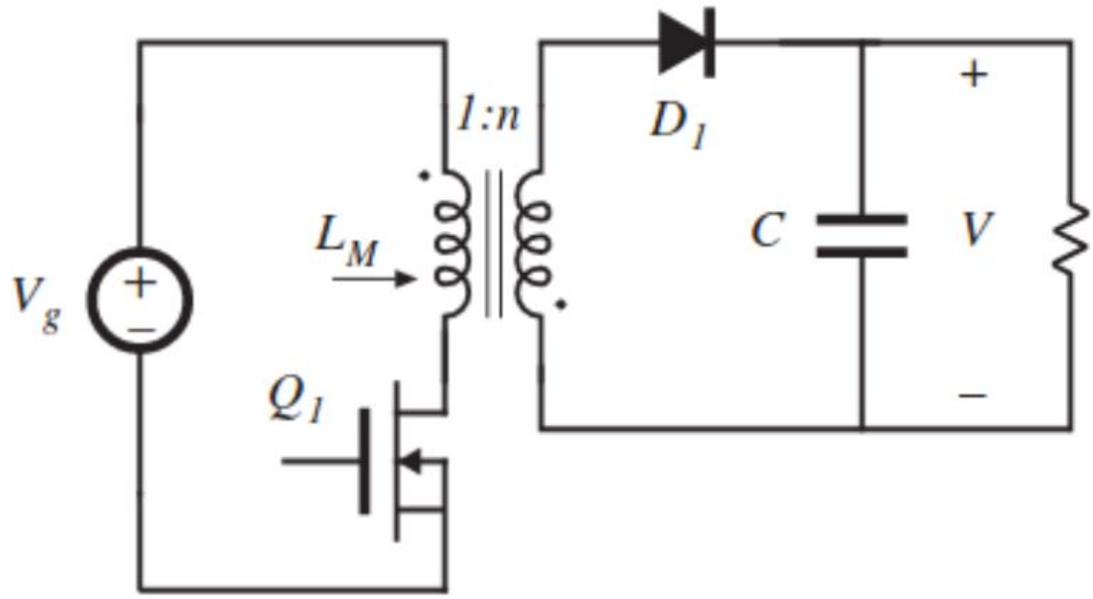


Figure 5. Fly-back Converter Circuit Schematic

The output voltage of converter is calculated assuming diodes are ideal as follows;

$$\frac{V_o}{V_d} = \frac{D}{(1-D)} \frac{N_2}{N_1}$$

The fly-back converter designed by us consists of 3 main parts.

- Controller
- Transformer
- Snubber and MOSFET

First part is transformer part. Transformer is using for isolation and increasing or decreasing coming voltage and current primary side. Second part is snubber. Snubber is used for decreasing voltage on MOSFET. Effects of snubber on circuit will be determined at snubber part. Last part is controller part. Controller is used for working on load types or different input voltages.

The sub-parts are given as follows;

Controller

Controller is used to receive constant output voltage without affecting the input voltage. Therefore, before selecting controller, we have to consider these things;

- Voltage on MOSFET
- Switching frequency
- Consuming maximum energy on controller.
- Maximum duty cycle
- Maximum output power

We have to consider that whether our controller fixed frequency or not. Voltage o MOSFET very important if our MOSFET voltage is integrated in controller.

Therefore, when we choose controller, we have to fore see these conditions.

Transformer

Transformer is used for isolation and changing voltage range. When designing transformer, the important things are

- Core size and type,
- Inductance of primary and secondary sides
- Thickness and type of cable used
- Turn ratios of two sides

Core size and type are determined according to Pout range. For fly-back converter, we choose EE type core. There are different material if we want to choose.

When designing transformer, we have to consider two voltage Vreflected and Vinmin. Determine Dmax based on Vreflected and Vinmin: The maximum duty cycle will appear during VDCmin, at this condition we will design the transformer to be at the boundary of DCM and CCM. In our design, we want to stay DCM side. Therefore, the given calculations and equations are according to DCM mode. Duty cycle here is given by;

$$Dmax = \frac{VR}{VR+VDCmin}$$

The calculation of primary inductance and primary peak current are as follows;

The primary peak current can be found by using following equations:

$$Pin_{max} = \frac{Pout_{max}}{n}$$

$$Ip = \frac{2 \times Pin_{max}}{VDCmin \times Dmax}$$

$$Lpri_{max} = \frac{VDCmin \times Dmax}{Ipri \times fsw}$$

After calculating primary inductance, core type, turn ratio and copper weight are calculated.

When choosing core, these are considered as follows;

- core geometry
- core size
- core material

There are different types of core geometry such as ETD, EE, etc. Most of the flyback application EE types are chosen.

Core size changes according to maximum power of transformer. Therefore, when output power increases, core size also increases. Core size is chosen according to datasheet of cores.

Minimum turn ratio is defined according to given formulas;

$$Np = \frac{Lpri \times Ipri}{Bmax \times Ae}$$

Determine the number of turns for the secondary main output (Ns) and other auxiliary turns (Naux): To get the secondary turns first determine the turn ratio as "n";

$$n = \frac{Np}{Ns}$$

$$n = \frac{VR}{Vout + VD}$$

Determining the wire size for each output windings: In order to determine the required wire size the RMS current for each winding should be determined. Primary winding RMS current:

$$Ip_{RMS} = Ip \times \sqrt{\frac{Dmax}{3}}$$

Secondary Winding RMS current:

$$Isec_{pk} = Ip \times \frac{Np}{Ns}$$

$$Isec_{RMS} = Isec_{pk} \times \sqrt{\frac{1 - Dmax}{3}}$$

Snubber and MOSFET

In the project, switching device is MOSFET. In the real life, used transformer is not ideal. This situation causes leakage inductance on the transformer. This can be called inductive load as well. When inductive load is used and switching is made, inductive current is cut suddenly. This sudden cut causes sharp voltage drop on MOSFET.

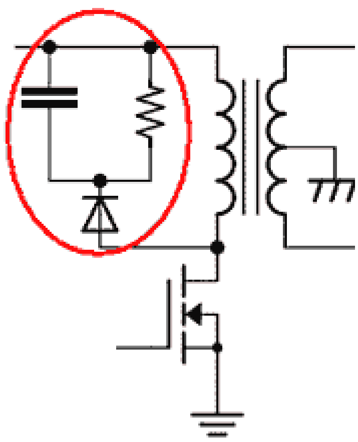


Figure 6.Schematic of snubber circuit

To prevent this sharp voltage drop, snubber circuits are used. Snubber circuit provides path for inductive current and prevent to sudden cut on the inductive load. This implies that sudden voltage drop on MOSFET does not occur. As seen from figure we can use capacitor, resistor and diodes. Also, if we do not have suitable area on our board, we can use zener and diode as snubber too. (Zener placed at capacitor and resistor area I used zener)

When we choose MOSFET, we consider following things;

- Rds resistance of MOSFET
- Max frequency of MOSFET
- MAX capacity of voltage

After determining these values, we can choose our capacitor at least %10 higher than these values.

Design Process

Input Voltage	90 – 250 V rms AC, 50 Hz
Outputs	1) 12 V, 100 W max. 2) 5 V, 10 W max.
Output Ripple (max):	% 4
No Load Power(maks)	100 mW
Conduction Mode	DCM
Efficiency	min 85%
Topology	Flyback
Switching freq.	100 kHz
Input Side	PFC Boost Converter

Calculations and Magnetic Elements Design

PFC design for our system;

We design PFC according to “Theoretical Information” part. We have to define inductor and capacitor size according to desired ripple and given information.

Firstly, PFC specifications are defined as;

Input voltage: 90-250 Vrms AC,50 hz

Output Voltage: 400V

Maximum Power: 130W for **%85 efficiency**

Switching Frequency: 100 kHz

Inductor Current Ripple: 25%

Output Voltage 100 Hz ripple: 10 Vp-p

Let's start to calculations;

For inductor, the calculation is follows as defined theory part;

$$L = \frac{1}{\%Ripple} \cdot \frac{{V_{ac.min}}^2}{P_o}\left(1 - \frac{\sqrt{2} \cdot V_{ac.min}}{V_o}\right) \cdot T :$$

Ripple=%25=0.25

$Vac\ min$=90V

f=100 kHz

Vo=400V

Po=130W

L=1.69 mH

$$I_{L.max} = \frac{\sqrt{2} \cdot P_o}{V_{ac.min}} \cdot \left(1 + \frac{\%Ripple}{2}\right) :$$

$I_{L,max}$ =2.29A .Therefore, inductor saturation current bigger than 2.29 A.

Copper Loss:

$$I_{L.rms} \cong I_{in.rms} = \frac{P_o}{V_{ac.min}}$$

$$P_{L.cond} = {I_{L.rms}}^2 \cdot DCR$$

$I_{L,rms}$ =1.44 A

We assume DCR around 0.2 ohm. Since, product which used commonly industry “Kool Mμ” 77083A7 toroids cores from Magnetics Inc. has 0.07 ohm for 0.68 mH inductor. I plan to use 3 inductor series. Therefore copper loss is as follows;

$P_{L,cond}$ =0.4W

Core Loss:

In order to calculate the core loss, we must calculate the minimum and maximum inductor current and the associated minimum and maximum magnetic force (H), then we can use the fitted equation of that magnetic material to calculate the minimum and maximum magnetic flux (B). I decided using Kool Mμ 77083A7 toroids.

Specifications are as follows;

$Path\ length\ le$ = 98.4 mm

$Cross\ section\ area\ Ae$ = 2 · 107 mm2

$Volume\ Ve$ = 2 · 10600 mm3

$$H_{max} = \frac{0.4 \cdot \pi \cdot N \cdot I_{L.max}}{l_e\ (in\ cm)}$$

Hmax=186 Oersteds

$$I_{L.min} = \frac{P_o \cdot \sqrt{2}}{V_{ac.min}} \left(1 - \frac{\%Ripple}{2}\right)$$

=1.787

$$H_{min} = \frac{0.4 \cdot \pi \cdot N \cdot I_{L.min}}{l_e\ (in\ cm)}:$$

=145.5 Oersteds

Flux density for 60μ Koolu material is:

$$B = \left(\frac{a + b \cdot H + c \cdot H^2}{a + d \cdot H + e \cdot H^2}\right)^x$$

Where a = 1.658e-2   b = 1.831e-3   c = 4.621e-3   d = 4.7e-3   e = 3.833e-5   x = 0.5

We can find maximum and minimum flux density according to H-max and H-min

Bmax= 8.52 kGauss

Bmin= 8.03 kGauss

$$\Delta B = \frac{B_{max} - B_{min}}{2}$$

=0.245 kGauss

$$P_{core.pk} = \Delta B^2 \cdot \left(\frac{f}{10^3}\right)^{1.46} \cdot V_e \cdot 10^{-6}$$

$$P_{core.av} = P_{core.pk} \cdot \frac{2}{\pi}$$

= 1.03*3=3W

Rectifier Bridge Loss and Diode Value Defination:

For calculating maximum loss, I choose min input voltage at input side for

$$I_{average} = \frac{2}{\pi} \cdot \frac{\sqrt{2} \cdot P_o}{V_{ac.min}}$$

=1.3A

I change Vf as 1V. Therefore;

$$P_{bridge} = 2 \cdot I_{average} \cdot V_{f.bridge}$$

=2.6W is total loss on Diodes

MOSFET loss:

I found that 45 mΩ CoolMOS™ C7 "IPW65R045C7" is the optimum device for my design because of low resistance and max frequency.

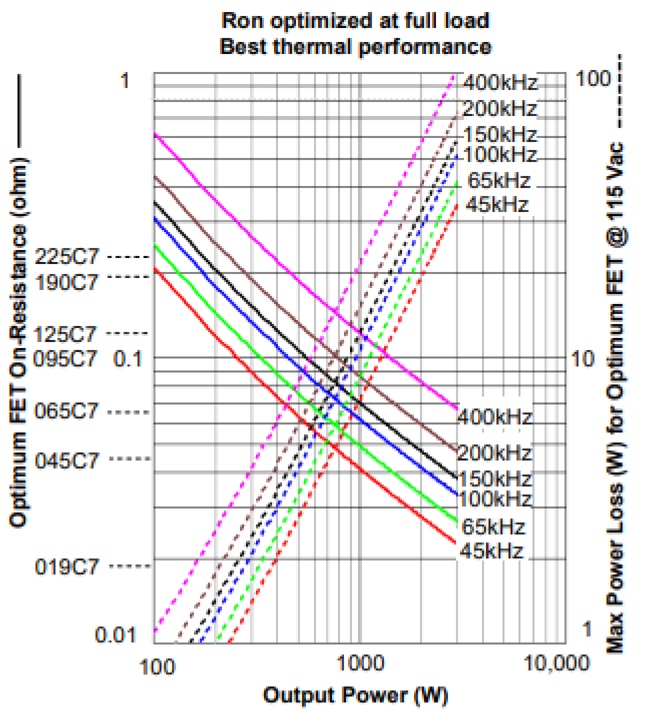


Figure 7.MOSFET Power vs Resistance Graphic

Switching loss is very low for 100 kHz for the selected MOSFET.

$$P_{S.cond} = I_{S.rms}{}^{2} \cdot R_{on(100°C)}$$

Therefore, we take 0.06 W for our system. Since, Rds=0.045 ohm and average current is equal to 1.4 A. There, we can neglect switching loss.

$$I_{L.avg} = \frac{P_o}{V_{ac.min}} \cdot \frac{2 \cdot \sqrt{2}}{\pi}$$

=1.3 A

I chose “IPW65R045C7” MOSFET. Vth=3.5V,Vpl=5.4V,Rg=1.8ohm,Ciss=4340*10^{-12} F, Crss=75*10^{-12} F for Vds equal to 400V . Vds =Vo=400V for PFC part.

$$t_{on} = C_{iss} * R_g \cdot ln\left(\frac{V_g - V_{th}}{V_g - V_{pl}}\right) + C_{rss} \cdot R_g \cdot \left(\frac{V_{ds} - V_{pl}}{V_g - V_{pl}}\right)$$

=10*10^{-9} s

$$P_{S.on} = 0.5 \cdot I_{L.avg} \cdot V_o \cdot t_{on} \cdot f$$

=0.25W

$$t_{off} = C_{rss} * R_g \cdot \left(\frac{V_{ds} - V_{pl}}{V_{pl}}\right) + C_{iss} \cdot R_g \cdot ln\left(\frac{V_{pl}}{V_{th}}\right)$$

=13.3*10^{-9} s

$$P_{S.off} = 0.5 \cdot I_{L.avg} \cdot V_o \cdot t_{off} \cdot f$$

=0.34W

$$P_{S.gate} = V_g \cdot Q_g \cdot f$$

=0.11 W

$$P_{S.total} = P_{S.cond} + P_{S.on} + P_{S.off}$$

= 0.7 W

Boost Diode Loss And Calculations:

Voltage capacitiy of diode is over 400 V, since output voltage of PFC part is equal to 400V. Therefore, I chose “IDH16G65C5” with Vf=1V and break voltage is bigger than 400V.

$$I_{D.avg} = \frac{P_o}{V_o}$$

=0.325 A

$$P_{D.cond} = I_{D.avg} \cdot V_{f.diode}$$

=0.325 W

Diode Loss=0.325 W

Output capacitor calculation and capacitor Loss:

We chose capacitor hold up time and voltage ripple. In our system voltage ripple can be around %2.5 equal to 10 V p-p. Hold up time is 16.6 ms.

Output capacitor meets following two conditions.

$$C_o \geq \frac{2 \cdot P_o \cdot t_{hold}}{V_o^{\ 2} - V_{o.min}^{\ \ 2}}$$

=97.59 μF

$$C_o \geq \frac{P_o}{2 \cdot \pi \cdot f_{line} \cdot \Delta V_o \cdot V_o}$$

=103μF

Therefore; Co>103μF

I chose my capacitor as "CBB60" run capacitor 450V 130 μF with 0.1 DF (dissipation factor).
Power loss and ESR calculations are as follows;

$$ESR = \frac{DF}{2 \cdot \pi \cdot f \cdot C_o}$$

=1.545 ohm

$$I_{Co.rms} = \sqrt{\frac{8 \cdot \sqrt{2} \cdot P_o^{\ 2}}{3 \cdot \pi \cdot V_{ac.min} \cdot V_o} - \frac{P_o^{\ 2}}{V_o^{\ 2}}}$$

=0.67A

$$P_{Co} = I_{Co.rms}^{\ \ 2} \cdot ESR$$

=0.7 W

Therefore, total loss on PFC part without controller part is equal to;

Ptotal=0.7+0.325+0.7+3+2.6=7.3W

7.3 watt total loss at PFC. PFC loss can be down half of the calculated value.

Fly back converter design part;

I used given transformer guide from gazi.lms web page. Lets start with Transformer design and calculation:

System is defined as follows;

1. Input voltage nominal Vnom = 400 V

2. Input voltage minimum Vmin = 384V

3. Input voltage maximum Vmax = 416 V

4. Output voltages are V_{O1} = 12 V and V_{O2} = 5 V

5. Output current I_{O1} = 8.3 A max, I_{O2} = 2 A

6. Frequency f=100 kHz

7. Efficiency h = 95 %

8. Maximum duty ratio Dmax = 0.5

9. Regulation a = 0.5 %

10. Operating flux density B_{AC} = 0.25 T

11. Diode voltage drop Vd = 1 V (Assumed before defining diode. Since, most of the diode has 1V forward voltage)

12. Window utilization K_u =0.3. Waveform factor K_f =4.0

14. Temperature rise T_r=30°C

I can choose 26 AWG for secondary side

Define the total period, T;

$T=1/f=10*10^{-6}$ s

Transistor on time defined as;

$t_{on} = TD_{MAX} * t_{on} = 10 * 10^{-6} * 0.5 = 5$ µs

Calculate the secondary load power, P_{01}

$$P_{o1} = I_{o1}\left(V_{o1} + V_d\right) \quad \text{[watts]}$$

=107.9 W

Calculate the secondary load power, P_{02}

$$P_{o2} = I_{o2}\left(V_{o2} + V_d\right) \quad \text{[watts]}$$

=12W

Calculate the total secondary load power P_{0max}

$$P_{o(\max)} = P_{o1} + P_{o2} \quad \text{[watts]}$$

=119.9W

Calculate the maximum input current, $I_{i(max)}$

$$I_{in(\max)} = \frac{P_{o(\max)}}{V_{in(\min)}\eta} \quad \text{[amps]}$$

=0.312A

Calculate the primary peak current, $I_{p(pk)}$

$$I_{p(pk)} = \frac{2\,P_{o(\max)}T}{\eta V_{in(\min)}t_{on(\max)}} \quad \text{[amps peak]}$$

=1.307A

Calculate the primary rms current, $I_{p(rms)}$

$$I_{p(rms)} = I_{p(pk)}\sqrt{\frac{t_{on}}{3T}} \quad \text{[amps]}$$

=0.53 A

Calculate the maximum input power, $P_{in(max)}$

$$P_{in(\max)} = \frac{P_{o(\max)}}{\eta} \quad \text{[watts]}$$

=125.7 W

Calculate the equivalent input resistance, $R_{m(equiv)}$

$$R_{in(equiv)} = \frac{\left(V_{in(\min)}\right)^2}{P_{in(\max)}}, \quad \text{[ohms]}$$

=1.18 kohm

Calculate the required primary inductance, L

$$L = \frac{\left(R_{in(equiv)}\right) T \left(D_{\max}\right)^2}{2} \quad \text{[henry]}$$

=1.48 mH

Calculate the energy-handling capability in watt-seconds, w-s.

$$\text{Energy} = \frac{L I_{p(pk)}^2}{2} \quad \text{[w-s]}$$

= 0.00126 [w-s]

Calculate the electrical conditions, K_e.

$$K_e = 0.145 P_o B_m^2 \text{x} 10^{-4}$$

=0.000108

Calculate the core geometry, K_e. See the design specification, window utilization factor, K_u.

$$K_g = \frac{(\text{Energy})^2}{K_e \alpha} \quad [\text{cm}^5]$$

=0.0146 cm^5

Core number	EFD-20
Manufacturer	Philips
Material	3C85
Magnetic path length, MPL	= 4.7 cm
Core weight, W_{tfe}	= 7.0 grams
Copper weight, W_{tcu}	= 6.8 grams
Mean length turn, MLT	= 3.80 cm
Iron area, A_c	= 0.31 cm^2
Window Area, W_a	= 0.501 cm^2
Area Product, A_p	= 0.155 cm^4
Core geometry, K_g	= 0.00506 cm^5
Surface area, A_t	= 13.3 cm^2
Core Permeability	= 2500
Winding Length, G	= 1.54 cm

Calculate the current density, J, using a window utilization, Ku = 0.3.(Ku defined before)

$$J = \frac{2(\text{Energy})(10^4)}{B_m A_p K_u}, \quad [\text{amps/cm}^2]$$

=2167

Calculate the primary wire area, $A_{pw(B)}$.

$$A_{pw(B)} = \frac{I_{prms}}{J} \quad [\text{cm}^2]$$

=0.000244

Calculate the required number of primary strands, S_{np}. I planned awg #26 wire bare area is equal to 0.0013 cm^2. As seen from table:

Table 1. Cable Information Table

A.W.G.	C.M.A.	Diameter (mm)	mm^2	Size	
#32	63	0.20	0.03		0.3A
#30	101	0.26	0.05		0.5A
#28	160	0.32	0.08		0.7A
#26	254	0.41	0.13		1.0A
#24	404	0.51	0.20		2.0A
#22	643	0.64	0.33		3.0A
#20	1,020	0.81	0.52		5.0A
#18	1,624	1.02	0.82		7.0A
#16	2,583	1.29	1.31		10.0A

$$S_{np} = \frac{A_{wp(B)}}{\#26\ (\text{bare area})}$$

=0.18

Calculate the number of primary turns, Np. Half of the available window is primary, W_{ap} /2. Using the number of strands, S_{np}, and the area for awg #26.

$$W_{ap} = \frac{W_a}{2}$$

=0.25 cm^2

$$N_p = \frac{K_u W_{ap}}{S(\#26(\text{Bare Area}))}, \quad [\text{turns}]$$

=321 turn

Calculate the required gap, l_g.

$$l_g = \frac{0.4\pi N^2 A_c \left(10^{-8}\right)}{L} - \left(\frac{\text{MPL}}{\mu_m}\right), \quad \text{[cm]}$$

=0.27 cm

=106 mils

Calculate the fringing flux factor, F

$$F = 1 + \frac{l_g}{\sqrt{A_c}} \ln\left(\frac{2G}{l_g}\right)$$

=2.18

Calculate the new number of turns, N_{np}, by inserting the fringing flux, F

$$N_{np} = \sqrt{\frac{l_g L}{0.4\pi A_c F\left(10^{-8}\right)}}, \quad \text{[turns]}$$

=217 turn

Calculate the peak flux density, B_{pk}

$$B_{pk} = \frac{0.4\pi N_{np} F\left(I_{p(pk)}\right)\left(10^{-4}\right)}{l_g + \left(\frac{\text{MPL}}{\mu_m}\right)}, \quad \text{[tesla]}$$

=0.286 tesla

Calculate the primary, the new for µohm /cm. AWG 26 old value is 1345.

$$(\text{new})\mu\Omega / cm = \frac{\mu\Omega / cm}{S_{np}}$$

=7472

Calculate the primary winding resistance, R_p

$$R_p = MLT\left(N_{np}\right)\left(\frac{\mu\Omega}{cm}\right) \text{x} 10^{-6} \quad \text{[ohms]}$$

=6.16 ohm

Calculate the primary copper loss, P_p

$$P_p = I_p^2 R_p \quad \text{[watts]}$$

=1.73 W

Calculate the secondary turns, N_{s1}

$$N_{s1} = \frac{N_{np}(V_{o1} + V_d)(1 - D_{max} - D_w)}{(V_p D_{max})} \quad \text{[turns]}$$

=5.6 use 6 turn

Calculate the secondary peak current, I $_{s1(pk)}$

$$I_{s1(pk)} = \frac{2 I_{o1}}{(1 - D_{max} - D_w)} \quad \text{[amps]}$$

=41.5 A

Calculate the secondary rms current, I $_{s(rms)}$

$$I_{s1(rms)} = I_{s1(pk)} \sqrt{\frac{(1 - D_{max} - D_w)}{3}} \quad \text{[amps]}$$

=15.13A

Calculate the secondary wire area, A $_{swl(B)}$

$$A_{swl(B)} = \frac{I_{s1(rms)}}{J} \quad [\text{cm}^2]$$

=0.00699 cm^2

Calculate the required number of secondary strands, S_{nsi}.

$$S_{ns1} = \frac{A_{swl(B)}}{\text{wire}_A}$$

=5.37 use 6

Calculate the, S_1 secondary

$$(S_1)\mu\Omega / cm = \frac{\mu\Omega / cm}{S_{ns1}}$$

=250

Calculate the winding resistance, R_{s1}.

$$R_{s1} = MLT(N_{s1})\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$

=0.0057 ohm

Calculate the secondary copper loss, P_{sl}.

$$P_{s1} = I_{s1}^2 R_{s1} \quad \text{[watts]}$$

=1.3 W

Calculate the secondary turns, N_{s2}.

$$N_{s2} = \frac{N_{np}(V_{o2}+V_d)(1-D_{\max}-D_w)}{(V_p D_{\max})} \quad \text{[turns]}$$

=2.6 turn use 3 turn

Calculate the secondary peak current, I $_{S2(pk)}$

$$I_{s2(pk)} = \frac{2I_{o2}}{(1-D_{\max}-D_w)} \quad \text{[amps]}$$

=10A

Calculate the secondary rms current, I $_{s2(rms)}$.

$$I_{s2(rms)} = I_{s2(pk)}\sqrt{\frac{(1-D_{\max}-D_w)}{3}} \quad \text{[amps]}$$

=3.65A

Calculate the secondary wire area, A $_{sw2(B)}$.

$$A_{sw2(B)} = \frac{I_{s2(rms)}}{J} \quad [\text{cm}^2]$$

=0.00168 cm^2

Calculate the required number of secondary strands, S_{ns2}.

$$S_{ns2} = \frac{A_{sw2(B)}}{wire_A}$$

=1.29 use 2

Calculate the, S_2 secondary,

$$(S_2)\mu\Omega/cm = \frac{\mu\Omega/cm}{S_{ns2}}$$

=672

Calculate the winding resistance, R_{s2}.

$$R_{s2} = MLT(N_{s2})\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$

=0.0076 ohm

Calculate the secondary copper loss, P_{s2}.

$$P_{s2} = I_{s2}^2 R_{s2} \quad \text{[watts]}$$

=0.1 W

Calculate the window utilization, K_u

$$\left(N_p S_{np}\right) \quad \text{[primary]}$$

=39

$$\left(N_{s1} S_{ns1}\right) \quad \text{[secondary]}$$

=36

$$\left(N_{s2} S_{ns2}\right) \quad \text{[secondary]}$$

=6

N_t =81 turn AWG #26

$$K_u = \frac{N_t A_w}{W_a}$$

=0.210

Calculate the total copper loss, P_{cu}.

$$P_{cu} = P_p + P_{s1} + P_{s2} \quad \text{[watts]}$$

=3.1 W

Calculate the regulation, a, for this design.

$$\alpha = \frac{P_{cu}}{P_o} \text{x} 100 \quad [\%]$$

=2%

Calculate the ac flux density, B_{ac}.

$$B_{ac} = \frac{0.4\pi N_{np} F\left(\frac{I_{p(pk)}}{2}\right)\left(10^{-4}\right)}{l_g + \left(\frac{\text{MPL}}{\mu_m}\right)}, \quad [\text{tesla}]$$

=0.143 tesla

Calculate the watts per kilogram, WK

$$WK = 4.855\left(10^{-5}\right)(f)^{(1.63)}\left(B_{ac}\right)^{(2.62)} \quad [\text{watts/kilogram}]$$

=41.9[watts/kilogram]

Calculate the core loss, Pfe.

$$P_{fe} = \left(\frac{\text{milliwatts}}{\text{gram}}\right) W_{tfe} \text{x} 10^{-3} \quad [\text{watts}]$$

=0.293 W

Calculate the total loss

$$P_{\Sigma} = P_{fe} + P_{cu} \quad [\text{watts}]$$

=3.4 W

Calculate the watt density

$$\psi = \frac{P_{\Sigma}}{A_t} \quad [\text{watts/cm}^2]$$

=0.255

Calculate the temperature rise

$$T_r = 450(\psi)^{(0.826)} \quad [^{\circ}\text{C}]$$

=145 ^{0}C

We have use very big heatsink for our system because of temperature high power output side.

Output Capacitor:

Capacitor voltage have to be bigger than 12V and also as low as possible resistance in capacitance.

Diodes:

Low forward voltage can be 1V. Since, most of the diodes forward voltage around 1V.

Element Selection

PFC Element Selections:

Rectifier Diode Selection:

When selecting diode most important things for my system are as follows:

- Break Voltage
- Forward Voltage
- Maximum Frequency

I used two **GSIB2580** diode packets for my system because of high break voltage range.

Forward voltage is around 1V.

Inductor selection:

When choosing inductor, we consider;

- Inductance
- Resistance
- Maximum energy capacity.
- Max current.

Inductance is around 1.7 mH for my system. Therefore, I used **three "Kool Mμ" 77083A7** toroid's cores from Magnetics Inc. has 0.07 ohm for 0.68 mH inductor.

MOSFET selection:

Important things for selecting MOSFET are

- Voltage capacity
- Max freq
- Rds

According to these parameter. I chose proper MOSFET for my system. The MOSFET called **"IPW65R045C7"** with 0.045 ohm Rds.

Boost Diode Selection:

I chose "**IDH16G65C5"** diode. Since, as seen from calculation diode breakdown voltage must be bigger than 400V. Also, Max current on diode must be bigger than 0.35 A. Selected diode supplies these two conditions.

Capacitor selection:

"CBB60" run capacitor 450V 130 μF with 0.1 DF is used on my system. Since output max value is equal to 410 V and output capacitance must be bigger than 103 μF.

Controller Selection:

I used LT1509 PFC controller as a controller. Because, its efficiency and PFC is very high as %98.

Fly-back Component Selection:

Capacitor at snubber:

Manufacturer: United Chemi-Con

Manufacturer Part Number: ESMH401VEN661QR55T

Capacitance: 660 uF

Voltage Rated: 400V

Capacitor at output:

Manufacturer: Nichicon

Manufacturer Part Number: UPW1H471MHD

Capacitance: 1000 uF

Voltage Rated: 50 V

MOSFET:

Manufacturer: STMicroelectronics

Manufacturer Part Number: IRF630

Voltage Rated: 600V

Current Rated: 9A

Diode:

Manufacturer: SMC Diode Solutions

Manufacturer Part Number: MBRF10200

Voltage Rated: 200V

Current Rated: 10A

Controller Selection:

I used LT8316 Fly-back controller as a controller. Because, its efficiency is very high and it is in DCM mode.

Simulation Results

PFC without fly-back part simulation result with different voltage:

There are 90V and 260 V-rms input PFC Simulations and Circuits. Simulation results shows input and output voltage, input voltage and current and input and output power.

The circuit is as follows:

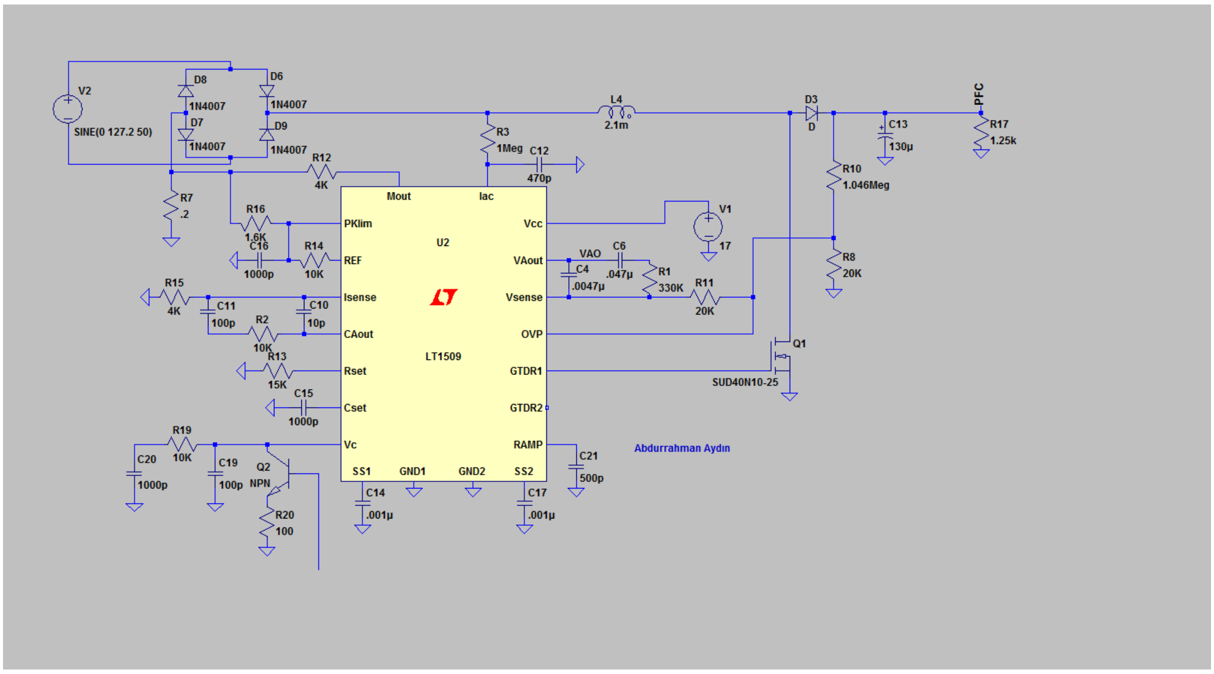


Figure 8. PFC side Circuit (only PFC)

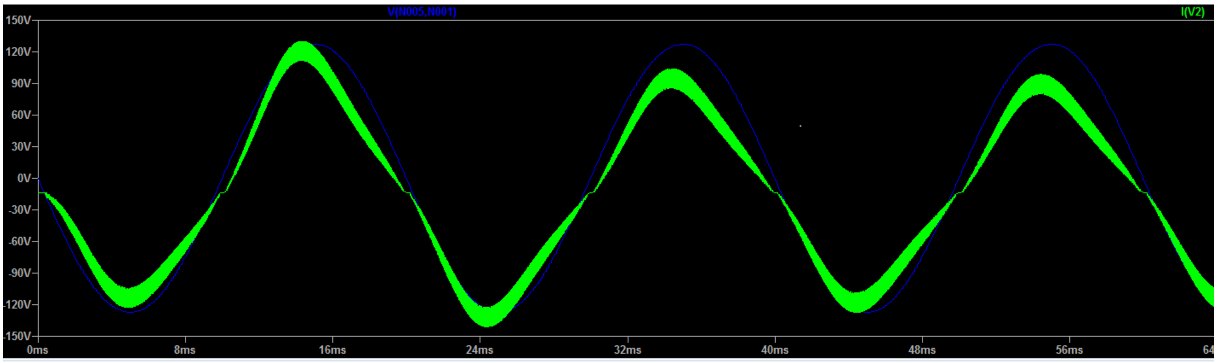


Figure 9. 90 V-rms Input Voltage and Current PFC Simulation

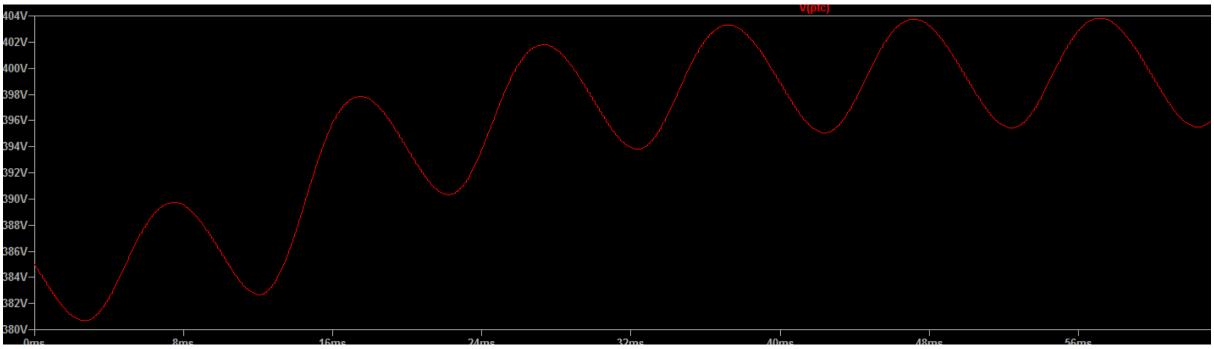


Figure 10.90 V-rms Input Output Voltage Simulation

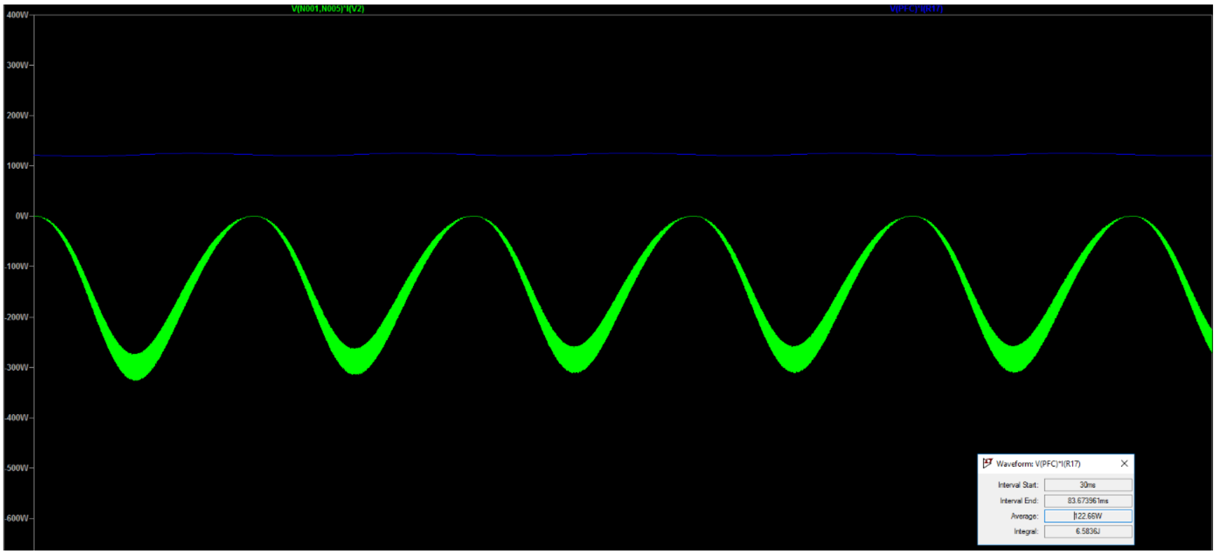


Figure 11. 90 V-rms Input Average Output Power Simulation

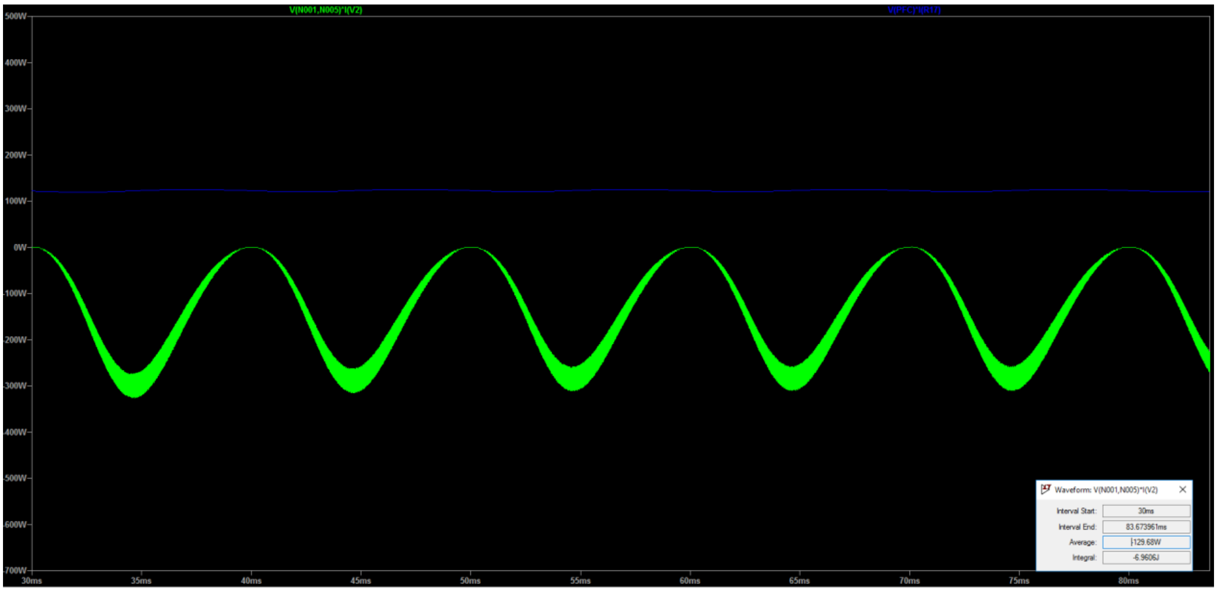


Figure 12. 90 V-rms Input PFC Average Input Power Simulation

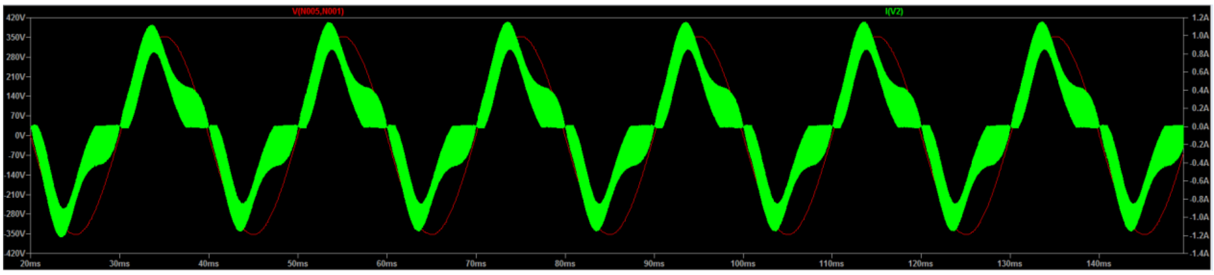


Figure 13. 260 V-rms Input PFC Input Voltage and Current Simulation

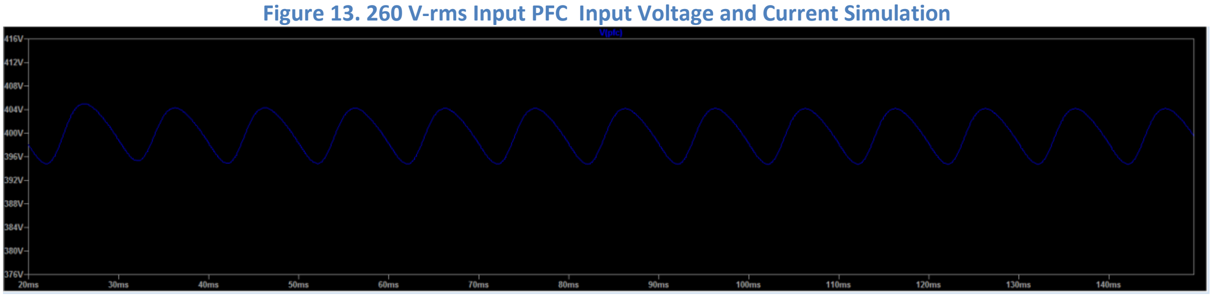


Figure 14. 260 V-rms Input PFC Output Voltage Simulation

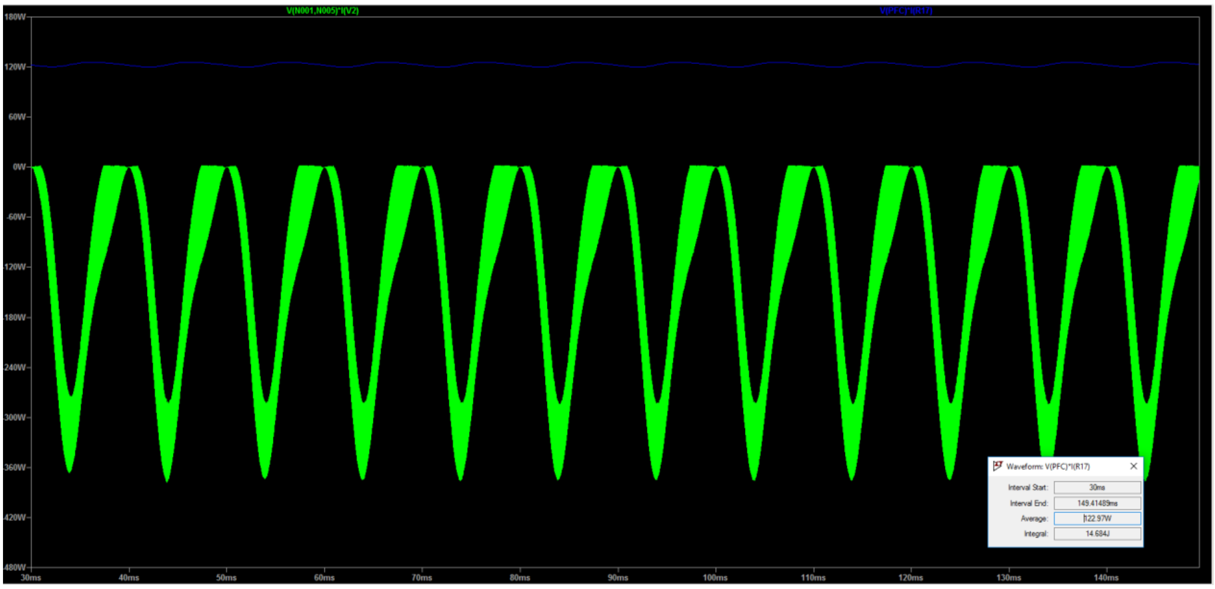


Figure 15. 260 V-rms Input PFC Average Input Power Simulation

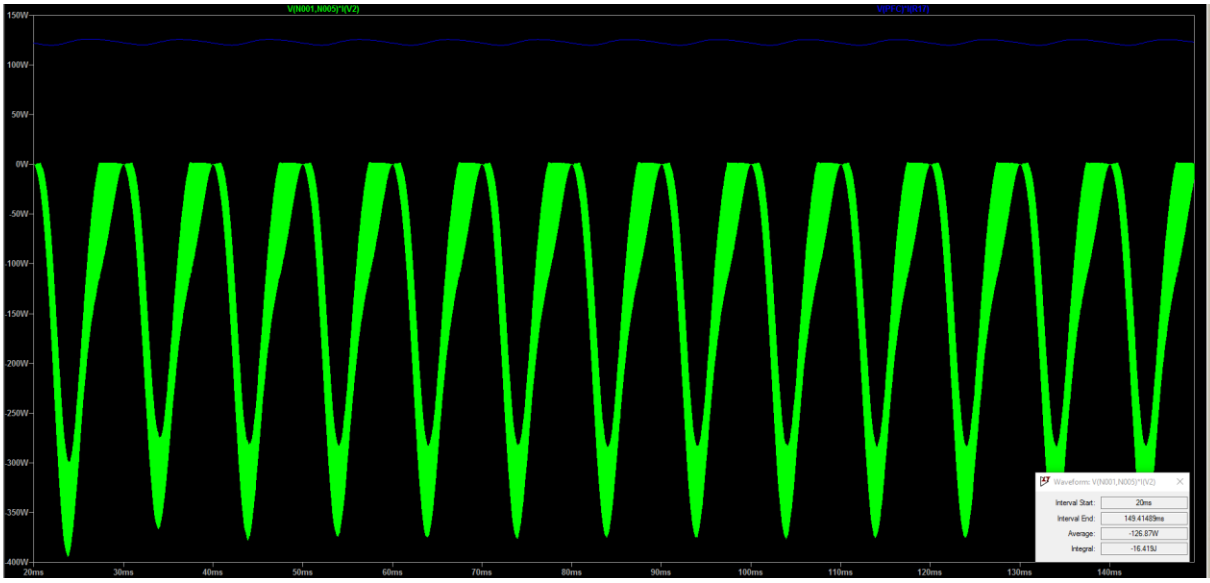


Figure 16. 260 V-rms Input PFC Average Output Power Simulation

Lets continue with overall design:

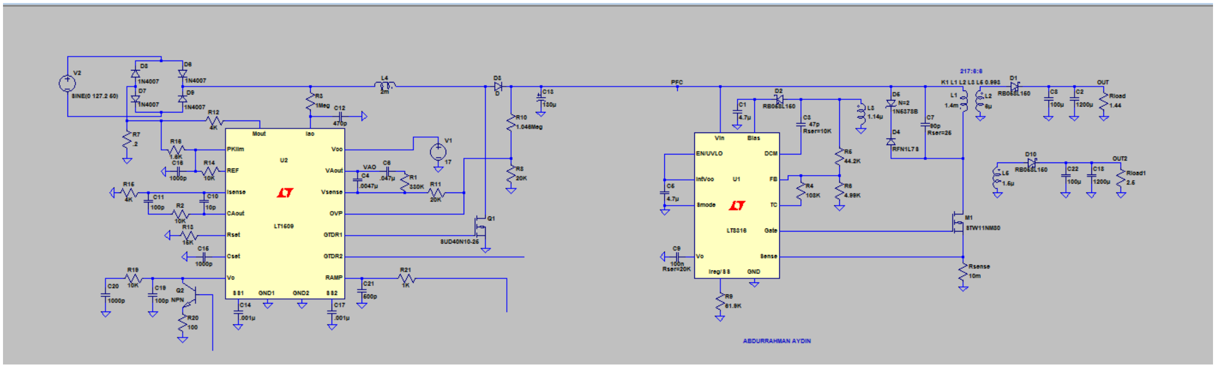


Figure 17. Overall Design Of Fly-back Converter Circuit

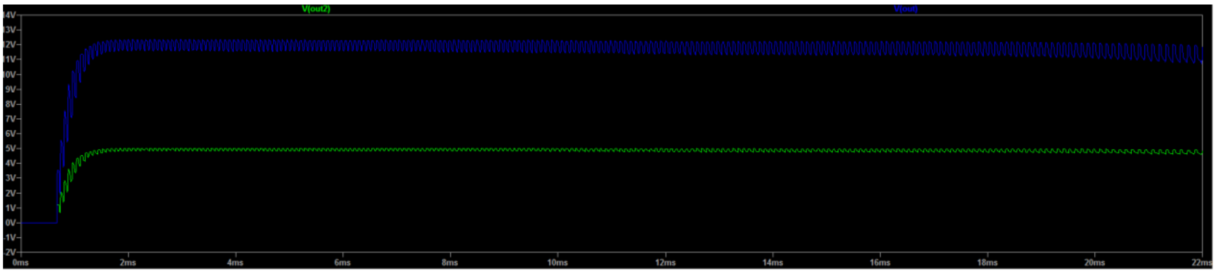


Figure 18.Output Voltages of Both Sides Simulation

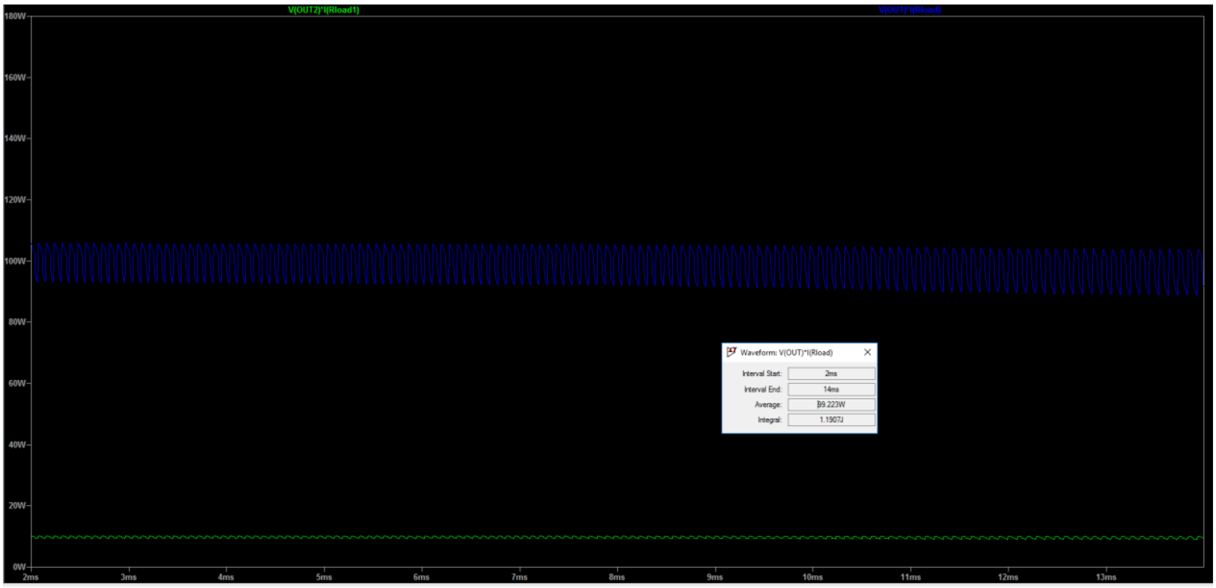


Figure 19. 12V 100 Watt Output Average Power Simulation

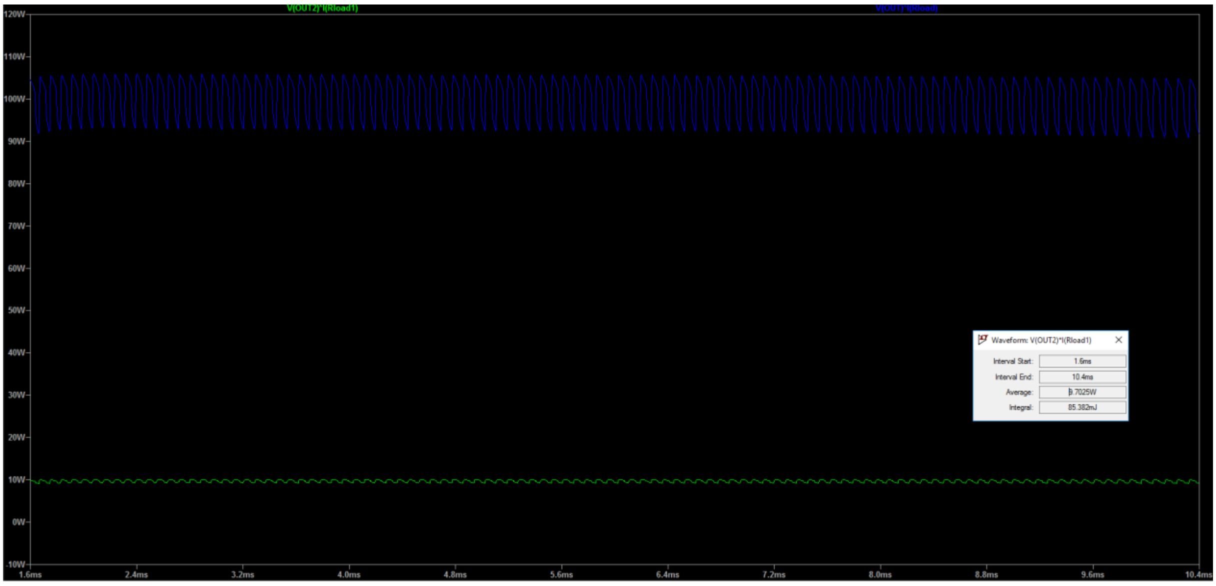


Figure 20. 5V 10 Watt Output Average Power Simulation

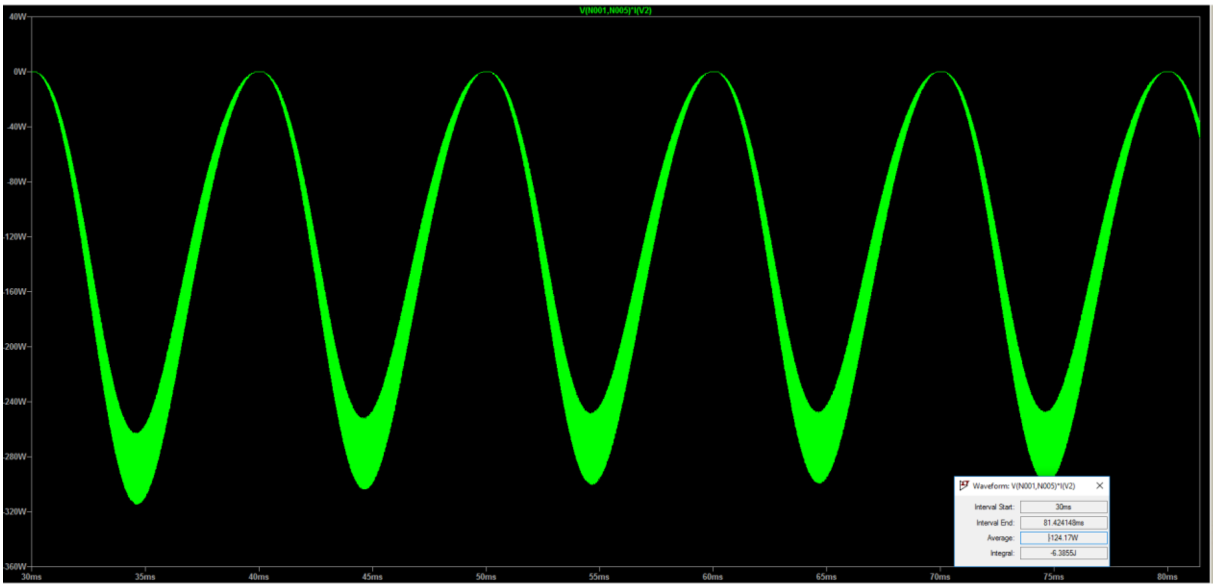


Figure 21. 165 V Input Average Power Simulation

Simulation and Calculation Comparison

PFC Side:

We did our calculation according to 2mH inductor and 130 microfarad capacitor but our output ripple less than expected because of controller mechanism. Also, I observed that total losses of calculated and simulation are almost equal. Also, I observed that switching loss is neglected by simulation program. Therefore, simulation result efficiency value is better than calculated side. As seen from simulation results, 129.3-122.83=6.47 W loss and calculation result is 7.3 W. Also, I observed that we can use smaller capacitor and inductor for our system results of simulations. Also, I observed that controller is very important for high "Power Correction" as %98 for my system. Different voltage input changes our output power. When our input voltage increases, our efficiency increases also.

Overall Design:

Simulation result efficiency is worse than calculated as expected. Since, I combined PFC and Fly-back side. I used two different controller so these two component could not match totally. Also, two controller and its components consume energy too. Simulation results are worse than calculated values but our system can provides requires. We can take better result changing transformer values. Efficiency of calculated side is around %92. However, simulation results show efficiency as %88.

Conclusion

In this hardware project, we observed AC to DC fly-back converter with controller. The output voltage is adjusted according to feedbacks taking from output sides. We observed simulation results and calculation results are similar but not same. Also, we learned that using material is very important for project. Moreover, we learned that we can not trust calculations totally. For example, we did not observe any problem theoretically. However, we can encounter some problems on simulation works. Therefore, I have to test our simulation again and again for taking better results and understanding the behavior of the components. Also, we observed switching loss is big problem for our system. Since, switching loss cause to increase temperature of our components. Therefore, control part is very important especially high frequency switching. Also, DCM mode increases our efficiency. To protect components, we have to use snubbers because of high voltage on MOSFETs. To conclude, we got idea about making AC to DC converter with PFC. Making this setup is very difficult and it takes very long time, I think that the project is very beneficial for us. Thanks to our instructor for this project.

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[5] Infineon," PFC boost converter design guide"[Revised Jan.2016]