INDUCTOR DESIGN 1MHZ/5A AND SIMULATION IN BOOST CONVERTER

TECHNION
Israel Institute of Technology

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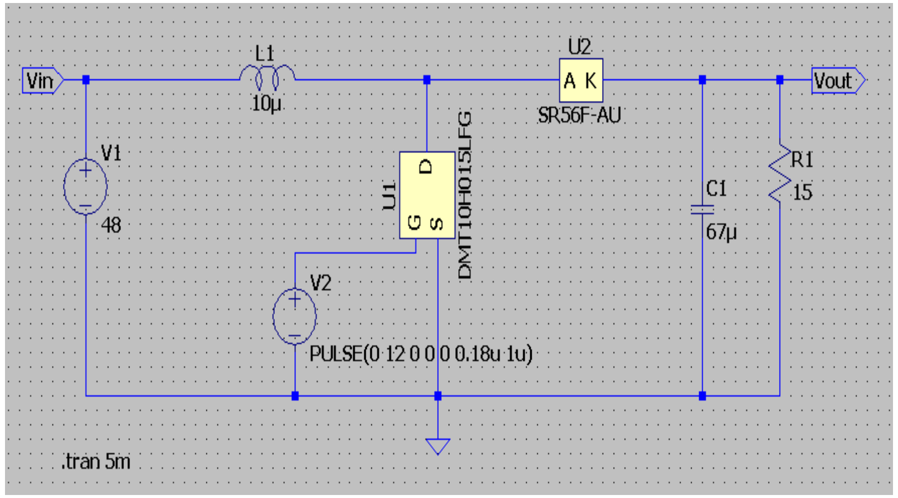
Introduction:

Designing Inductor to work in 1mhz/5A in FEMM software

Simulating the inductor in boost converter using Ltspice tool

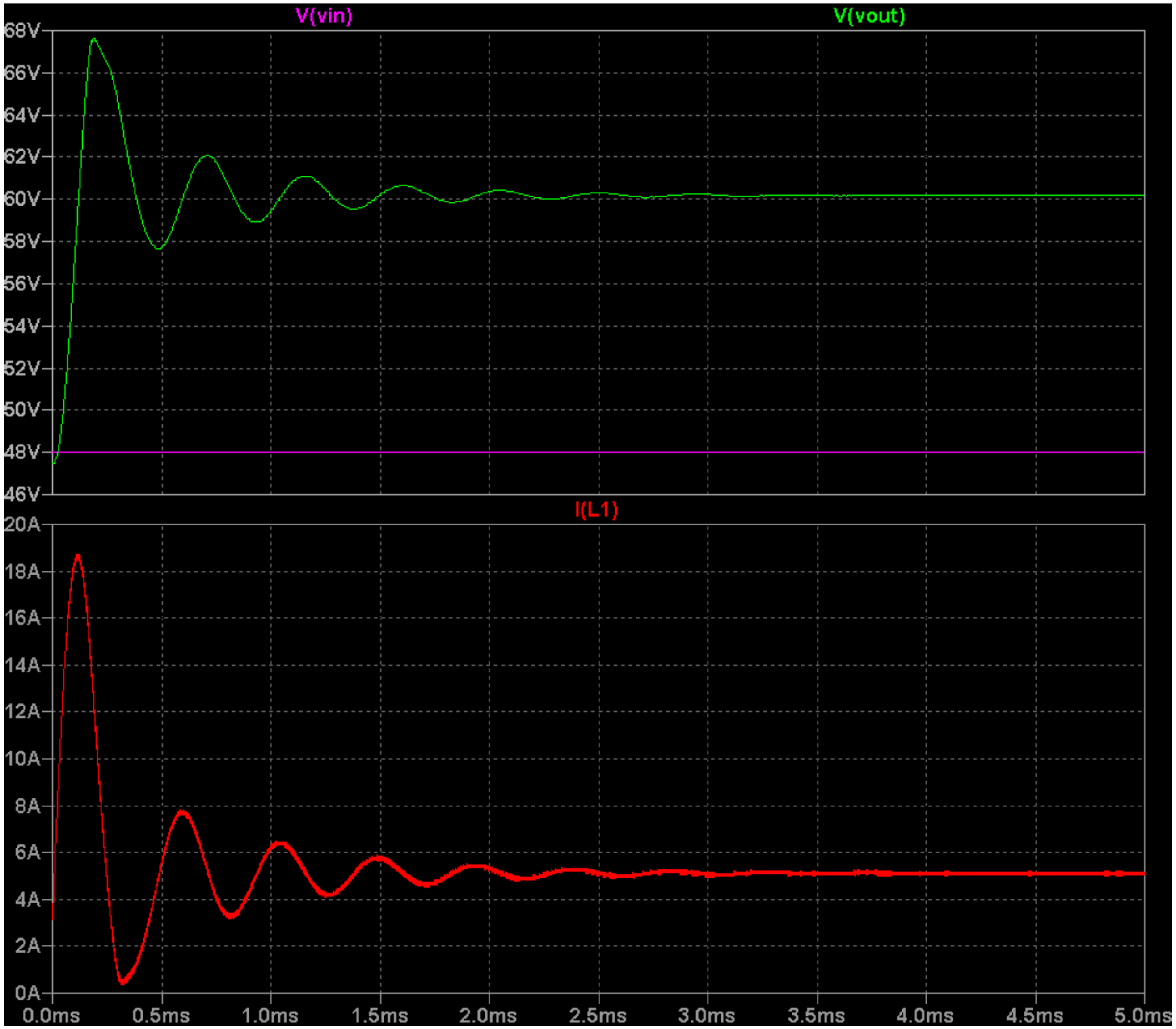
An ideal inductor

- Vin = 48V
- Vout = 60V
- Frequency = 1 MHz
- Idc (continuous) = 5A
- Ipeak = 10A



INDUCTOR SELECTION

Case 1: Inductance selected 48uH

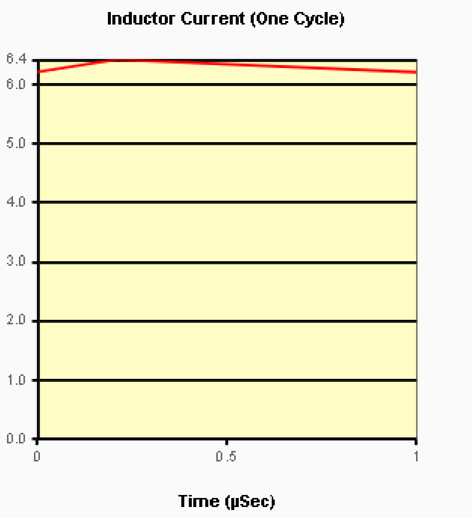


INDUCTOR SELECTION

IHLP-6767GZ-8A - 47 boost µH Ind. Loss Calculator

Ratings		
Inductance	47	µH
25° C DC Res	0.0527	Ohms
Isat	7	Amps
I(Heat)	7.25	Amps

Inputs: Enter data into yellow fields					Outputs		
Frequency =	1000000	Hz			ET_{ckt}	9.90	V-usec
Output Current =	5	Amps			F(eff)	964981.5	Hertz
Ambient Temp =	25	°C			Res	0.060823	Ohms
Volts In =	48	Volts			I_{max}	6.42	Amps
Volts Out =	60	Volts			I_{min}	6.21	Amps
V_{SW} =	0.5	Volts			I_{ripple}	0.21	Amps
V_D =	0.5	Volts			Duty	0.21	
I_{ind} =	6.3	Amps			P_{core}	0.032	Watts
ET_{100} =	23.01	V-usec			P_{dc}	2.426	Watts
B_{pk} =	43.0	G			P_{ac}	0.021	Watts
A	0.696	Inch	17.65	mm	P_{tot}	2.479	Watts
B	0.675	Inch	17.15	mm	Temp. Coeff.	12.5	°C/W
C	0.276	Inch	7.0	mm	Temp Rise	31.0	°C
					Comp Temp	56.0	°C
Reference Cost	5.5						



INDUCTOR SELECTION

- **Case 1: Inductance selected 48uH**

Pros:

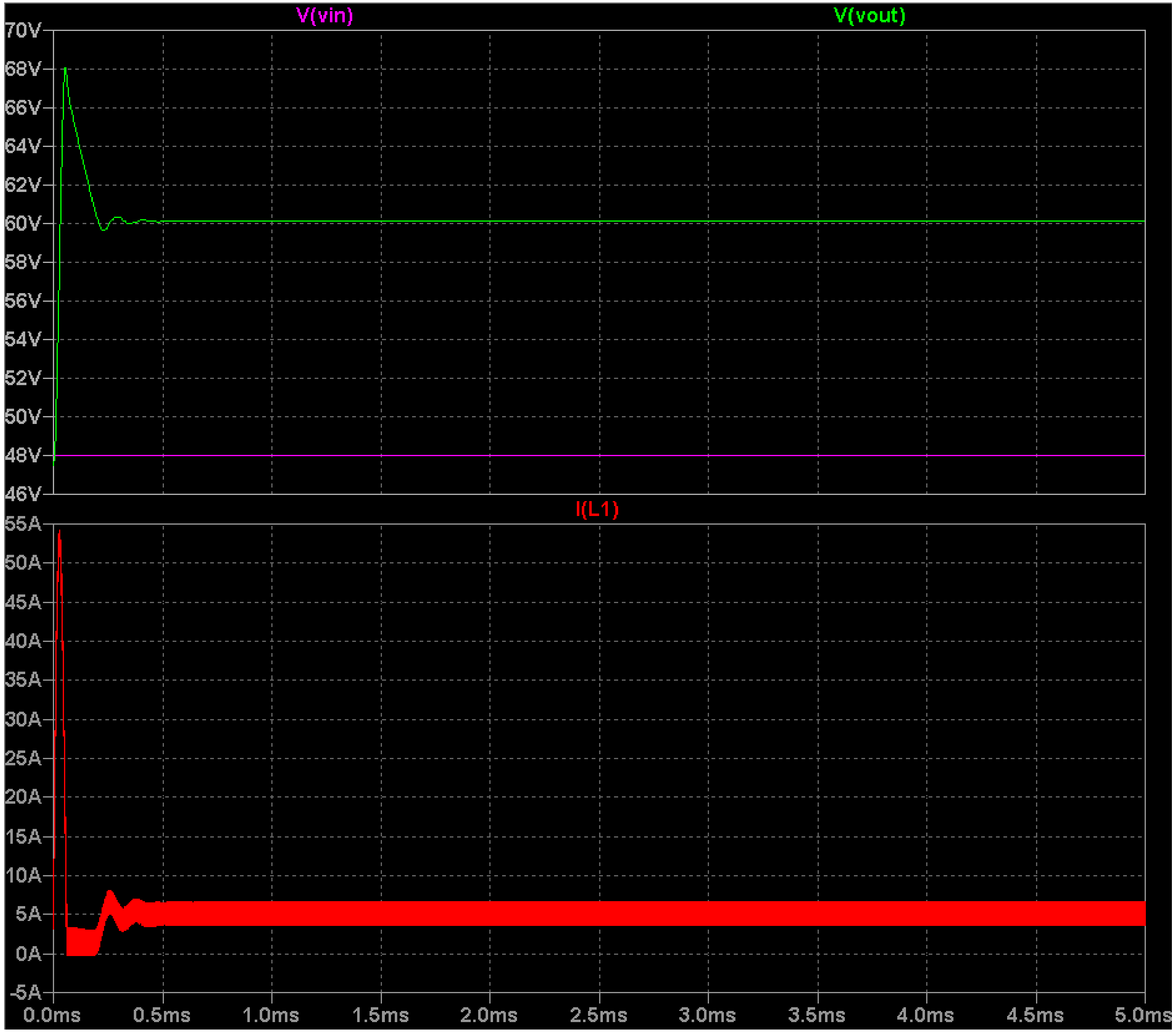
- Ripple in inductor less
- Peak current requirement less

Cons:

- More time to take for reaching at steady state level
- More noise
- More transient time
- More Power loss in inductor
- Efficiency affected

Case 2: Inductance selected 3.3uH

INDUCTOR SELECTION

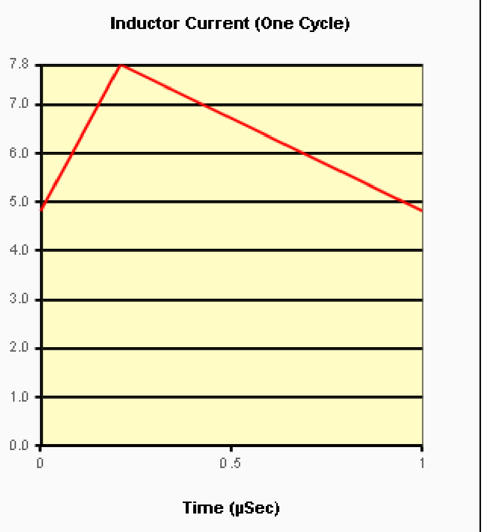


INDUCTOR SELECTION

IHLP-6767GZ-8A - 3.3 boost µH Ind. Loss Calculator		
Inputs: Enter data into yellow fields		**Outputs**

Ratings		
Inductance	3.3	µH
25° C DC Res	0.00306	Ohms
Isat	32	Amps
I(Heat)	32.2	Amps

Input	Value	Unit			Output	Value	Unit
Frequency =	1000000	Hz			ET_{ckt}	9.90	V-usec
Output Current =	5	Amps			F(eff)	964981.5	Hertz
Ambient Temp =	25	°C			Res	0.003532	Ohms
Volts In =	48	Volts			I_{max}	7.82	Amps
Volts Out =	60	Volts			I_{min}	4.82	Amps
V_{SW} =	0.5	Volts			I_{ripple}	3.00	Amps
V_D =	0.5	Volts			Duty	0.21	
I_{ind} =	6.3	Amps			P_{core}	0.699	Watts
ET_{100} =	7.67	V-usec			P_{dc}	0.141	Watts
B_{pk} =	129.0	G			P_{ac}	0.110	Watts
A	0.696	Inch	17.65	mm	P_{tot}	0.949	Watts
B	0.675	Inch	17.15	mm	Temp. Coeff.	10.9	°C/W
C	0.276	Inch	7.0	mm	Temp Rise	10.4	°C
					Comp Temp	35.4	°C
Reference Cost	5.5						



INDUCTOR SELECTION

Case 2: Inductance selected 3.3uH

- By selecting lower value of inductance, loss in inductor becomes 0.949 watts.

Pros:

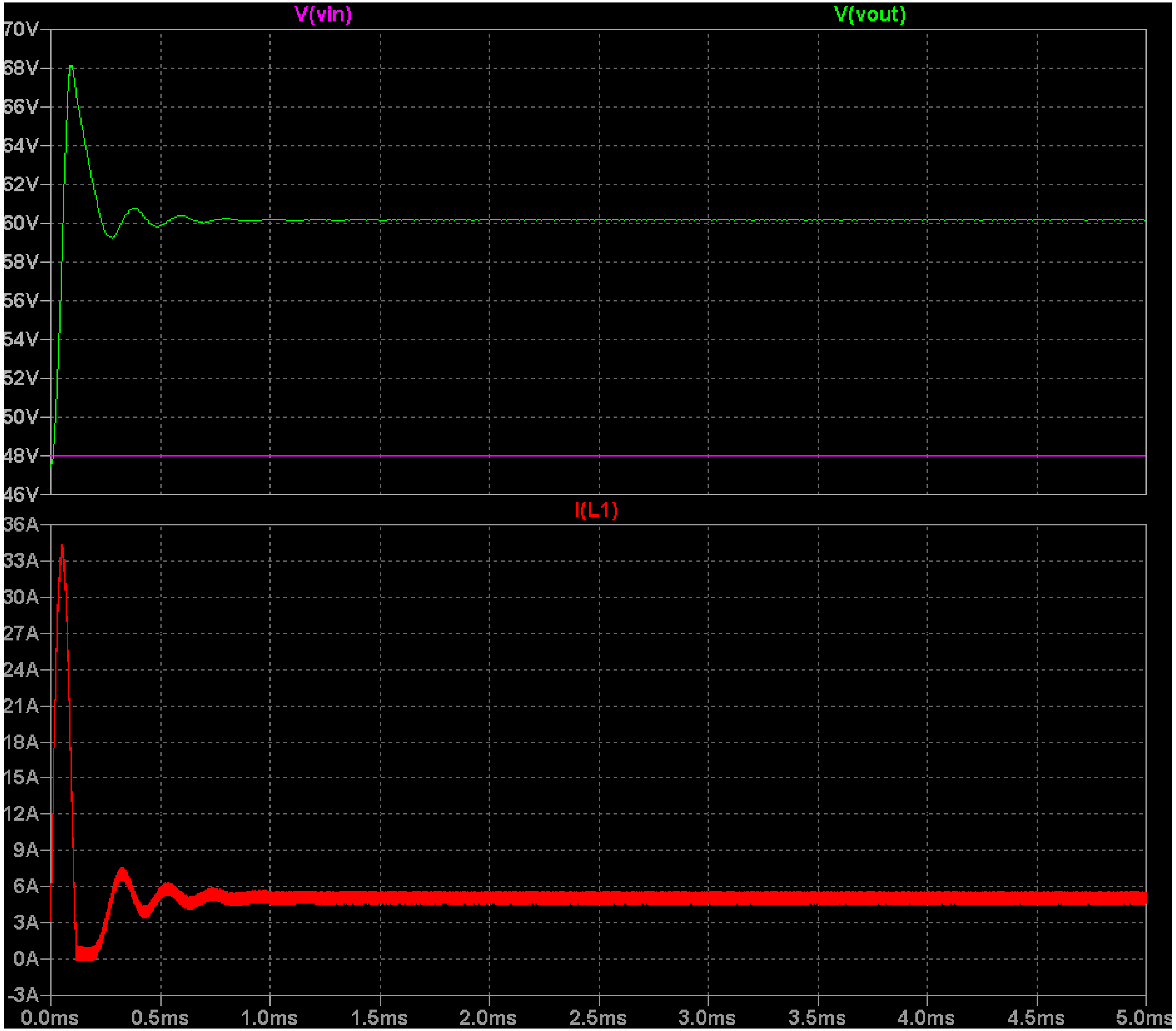
- Reach faster at steady state level than 47uH
- Less power loss than 47uH

Cons:

- Ripple in inductor more
- More noise at transient time
- High Peak current

Case 3: Inductance selected 10uH

INDUCTOR SELECTION

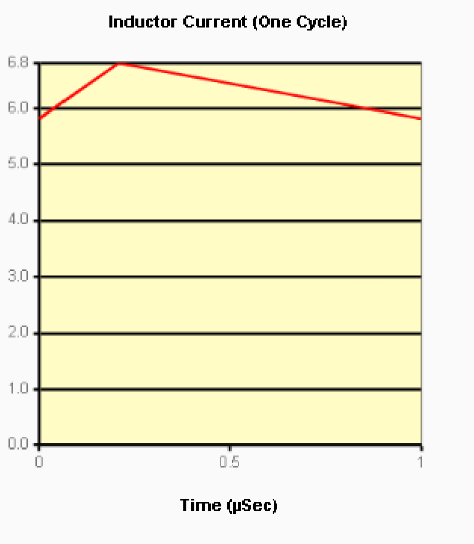


INDUCTOR SELECTION

IHLP-6767GZ-8A - 10 boost µH Ind. Loss Calculator

Ratings		
Inductance	10	µH
25° C DC Res	0.0102	Ohms
Isat	13	Amps
I(Heat)	16	Amps

Inputs: Enter data into yellow fields					**Outputs**		
Frequency =	1000000	Hz			ET_{ckt}	9.90	V-usec
Output Current =	5	Amps			F(eff)	964981.5	Hertz
Ambient Temp =	25	°C			Res	0.011772	Ohms
Volts In =	48	Volts			I_{max}	6.81	Amps
Volts Out =	60	Volts			I_{min}	5.82	Amps
V_{SW} =	0.5	Volts			I_{ripple}	0.99	Amps
V_D =	0.5	Volts			Duty	0.21	
I_{ind} =	6.3	Amps			P_{core}	0.229	Watts
ET_{100} =	9.15	V-usec			P_{dc}	0.470	Watts
B_{pk} =	108.2	G			P_{ac}	0.140	Watts
A	0.696	Inch	17.65	mm	P_{tot}	0.839	Watts
B	0.675	Inch	17.15	mm	Temp. Coeff.	13.3	°C/W
C	0.276	Inch	7.0	mm	Temp Rise	11.1	°C
					Comp Temp	36.1	°C
Reference Cost	5.5						



INDUCTOR SELECTION

Case 3: Inductance selected 10uH

- By selecting calculated value of inductance, loss in inductor becomes 0.843 watts.

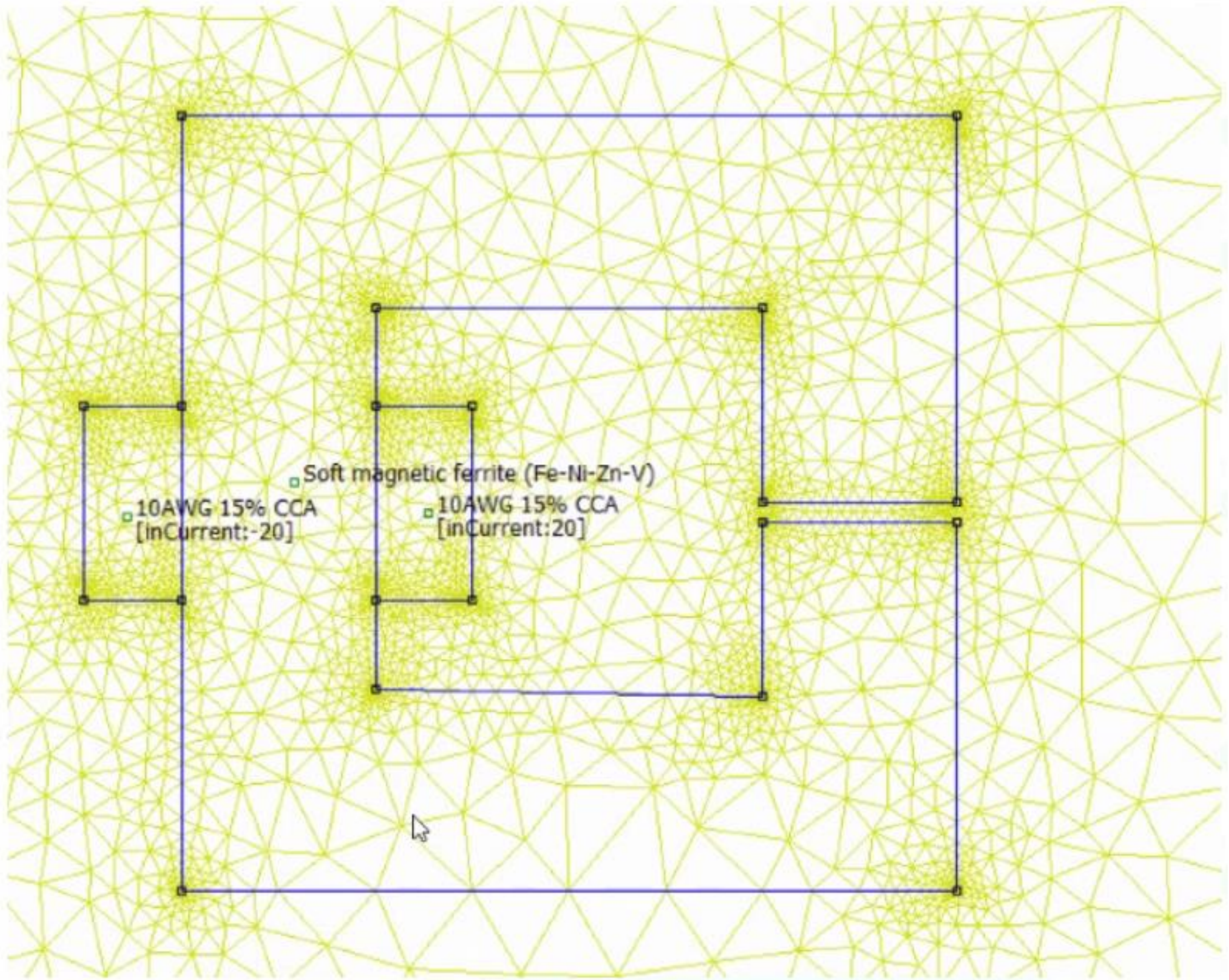
Pros:

- Reach faster at steady state level than 47uH
- Ripple is less than 3.3uH inductor
- Less power loss among all
- Highest efficiency of good among all

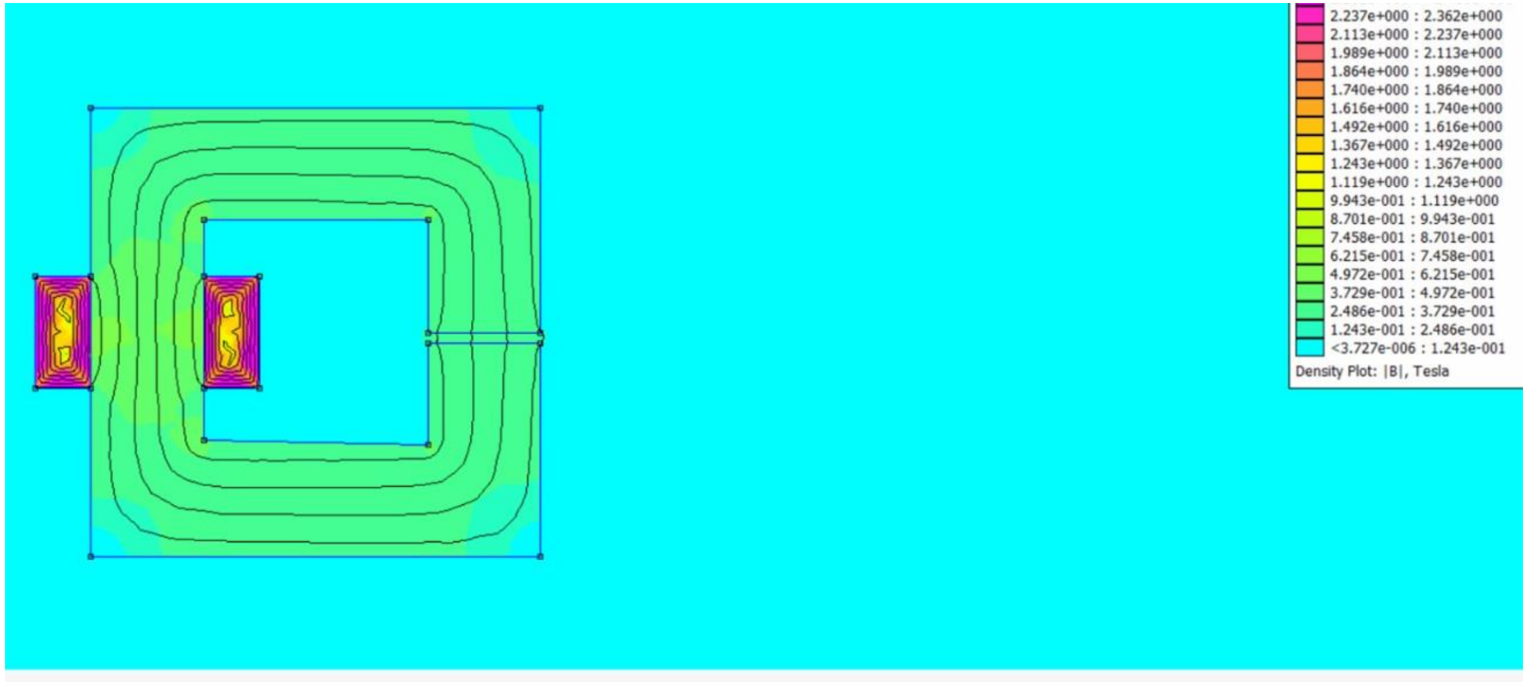
Cons:

- Ripple in inductor more than 47uH
- High Peak current than 47uH but maximum peak current is satisfied

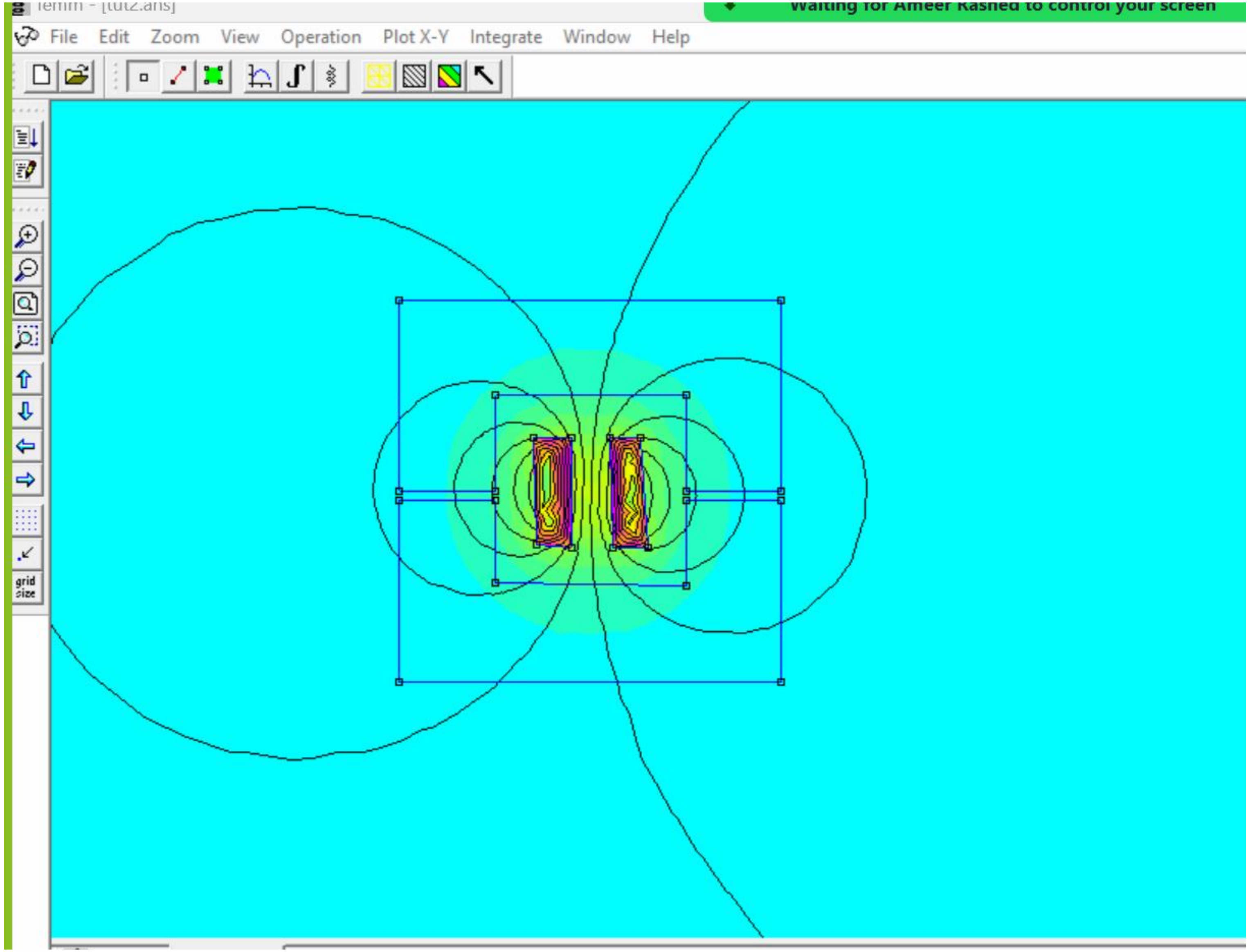
BASIC INDUCTOR:1



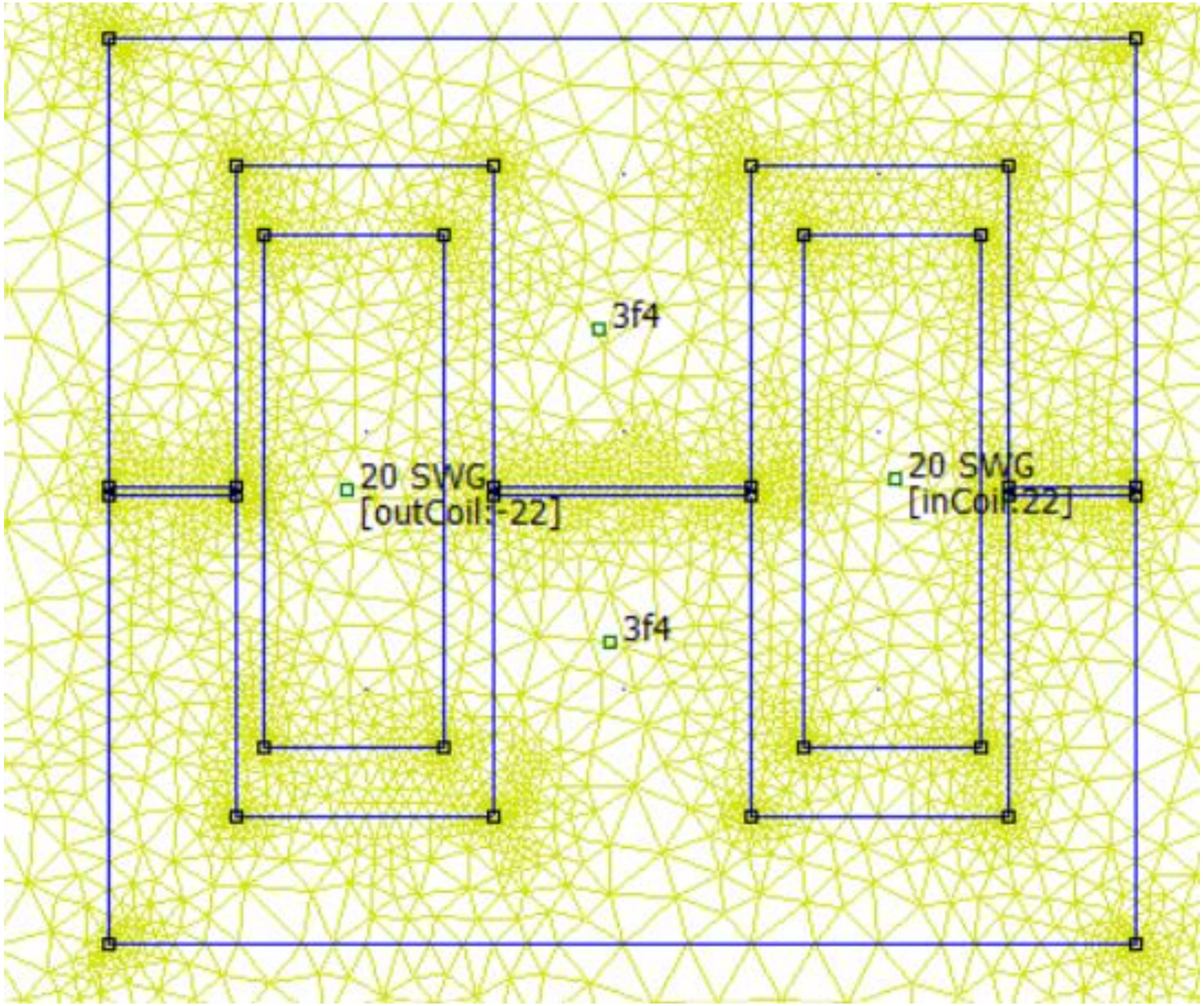
BASIC INDUCTOR:1 (FEMM)



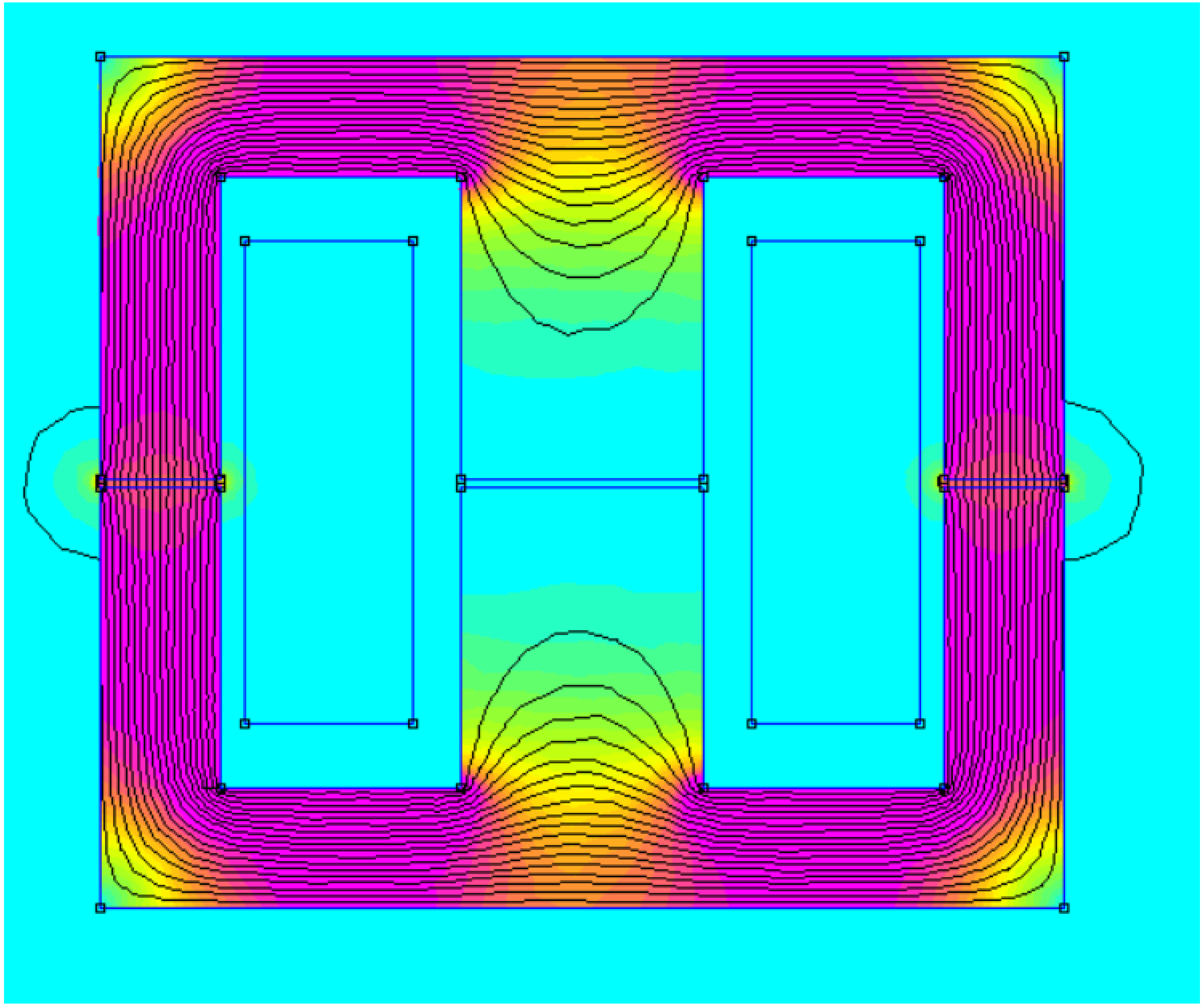
BASIC INDUCTOR: 2



DOUBLE E INDUCTOR (FEMM)



DOUBLE E INDUCTOR (simulation results)



DOUBLE E RESULTS (FEMM)

Winding results

Circuit Properties

Circuit Name

inCoil

Results

Total current = 0.25 Amps
Voltage Drop = 0.116093+I*265.678 Volts
Flux Linkage = 4.22839e-005-I*1.70387e-008 Webers
Flux/Current = 0.000169136-I*6.81549e-008 Henries
Voltage/Current = 0.464372+I*1062.71 Ohms
Real Power = 0.0145116 Watts
Reactive Power = 33.2097 VAr
Apparent Power = 33.2097 VA

OK

Total current

ntegral Result

5.5 Amps

OK

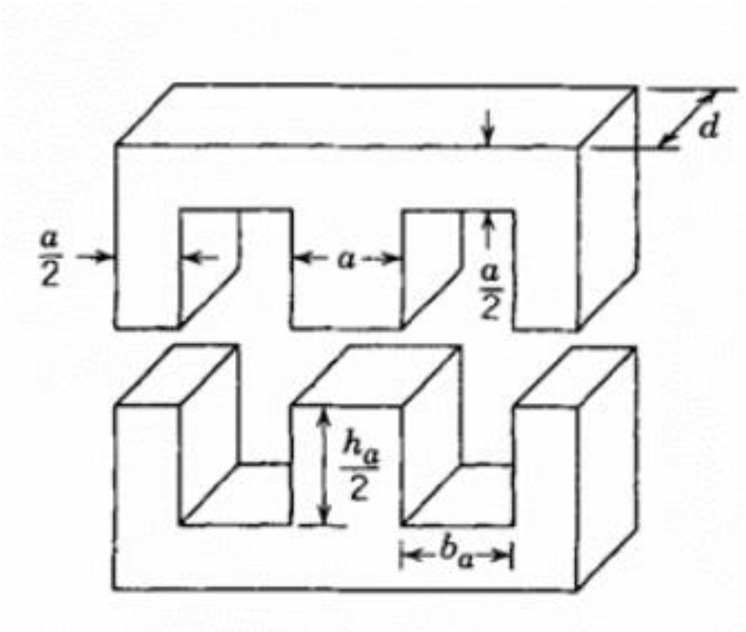
Total loss

Integral Result

0.0290303 Watts

OK

CHOOSING INDUCTOR PROPERTIES: SIZING

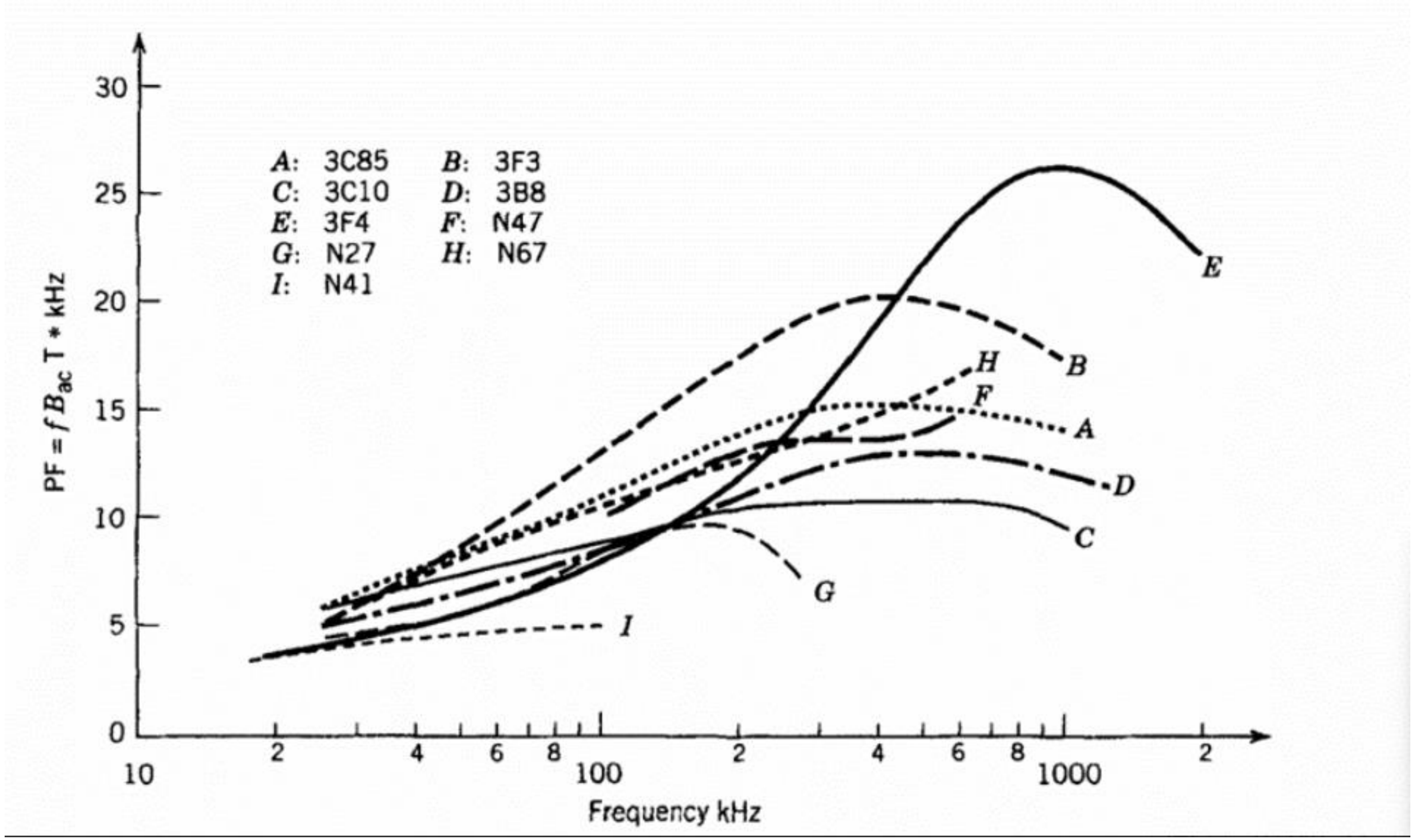


Characteristic	*Relative Size*	*Absolute Size for a = 1 cm*
Core area A_{core}	$1.5a^2$	$1.5\ cm^2$
Winding area A_w	$1.4a^2$	$1.4\ cm^2$
Area product AP $= A_w A_c$	$2.1a^4$	$2.1\ cm^4$
Core volume V_{core}	$13.5a^3$	$13.5\ cm^3$
Winding volume $V_w{}^a$	$12.3a^3$	$12.3\ cm^3$
Total surface area of assembled inductor/transformer[b]	$59.6a^2$	$59.6\ cm^2$

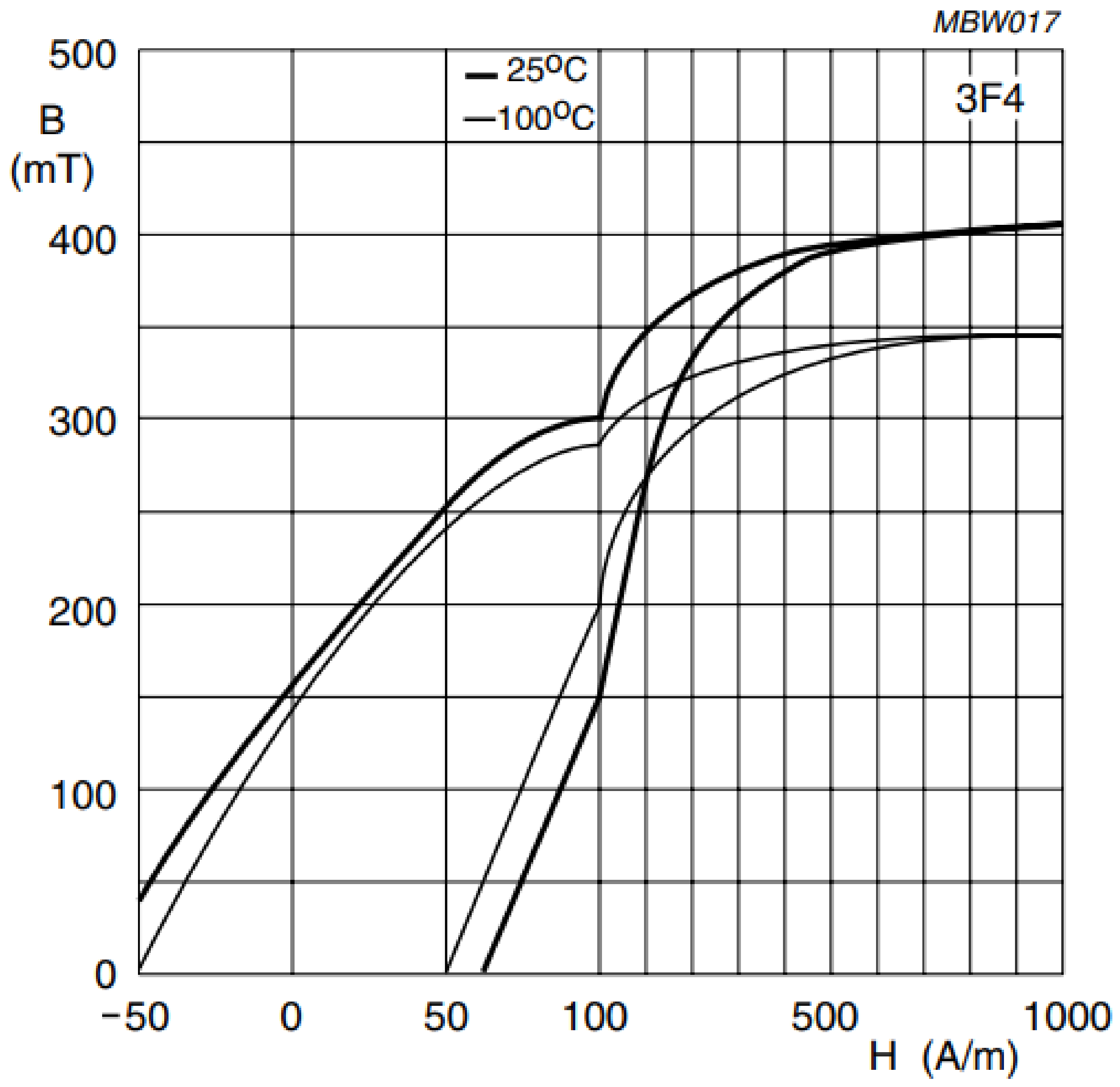
d =1.5a , h = 2.5a, b, = 0.7a and h = 2a.

REFRENCE: POWER ELECTRONICS 3rd EDITION , NED MOHAN , TORE

CHOOSING INDUCTOR PROPERTIES: CORE MATERIAL



CHOOSING INDUCTOR PROPERTIES: CORE MATERIAL



CHOOSING INDUCTOR PROPERTIES: WINDING MATERIAL

Copper was chosen as the winding material due to its high conductivity. Additionally, the flexibility of copper makes winding easier, which reduces the volume of copper needed. This results in a coil with a lower weight. For the thickness of the copper wire, we will choose the thickest possible to minimize wasted power.

$$P_{w,sp} = k_{Cu}\,\rho_{Cu}\,(J_{rms})^2$$

$$J_{rms} = I_{rms}/A_{cu}$$

DOUBLE E CONS

Cons:

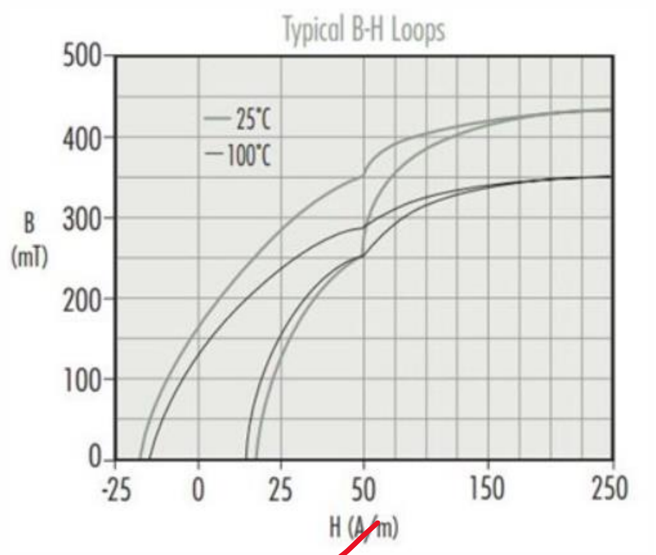
Complex Manufacturing: The double E core design can be more complex and costly to manufacture compared to simpler core shapes.

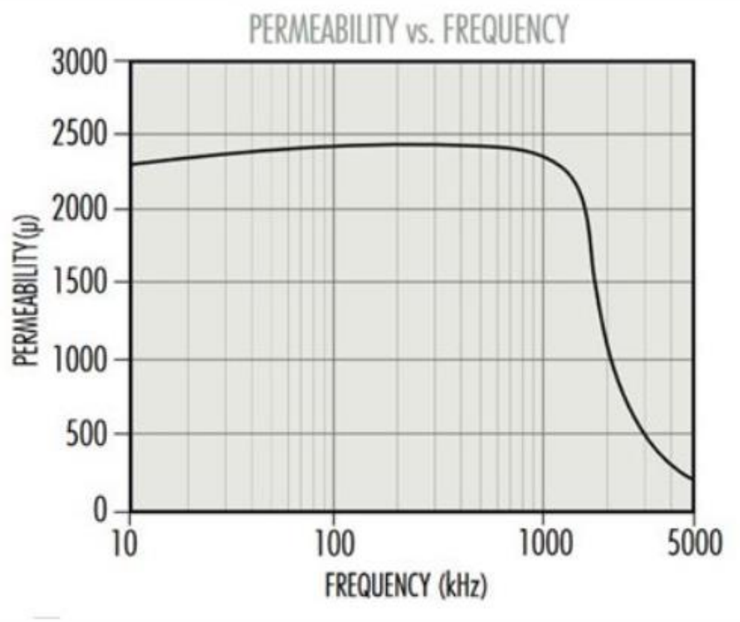
Higher Cost: Due to the complexity and materials used, double E inductors can be more expensive.

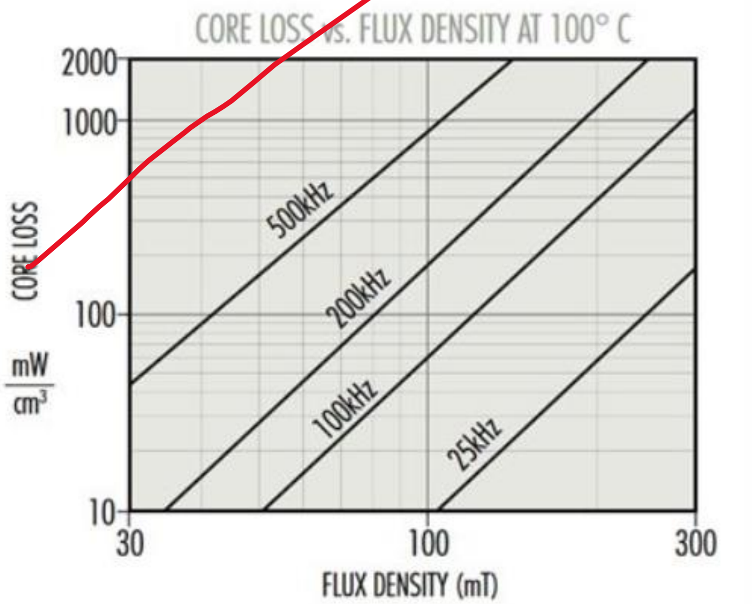
Limited Availability: They might not be as readily available as other types of inductors, which can be a limitation for some applications.

TOROID INDUCTOR: CORE TYPE

- Core type: Ferrite core- R type material.





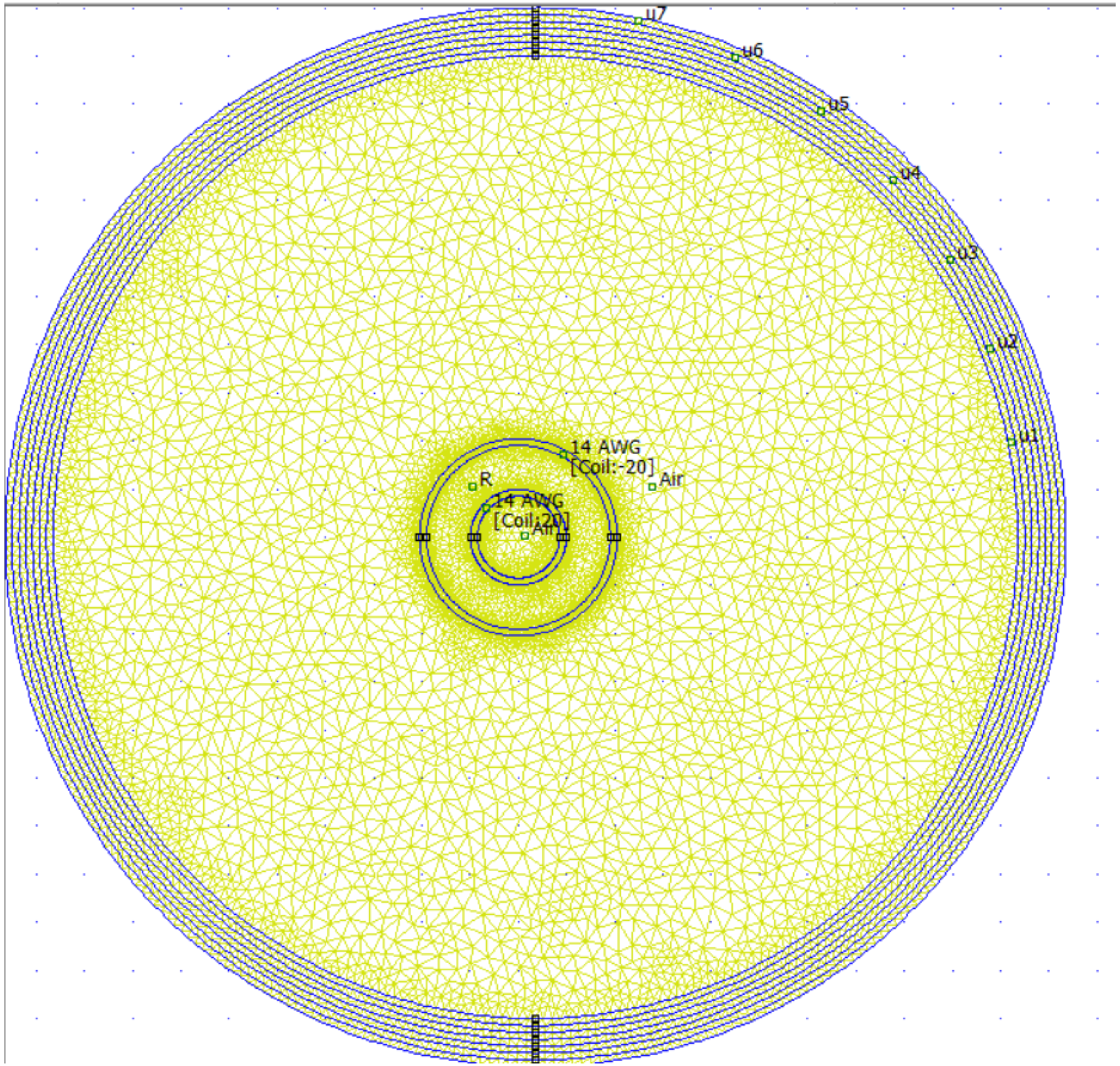


TOROID INDUCTOR: CORE TYPE

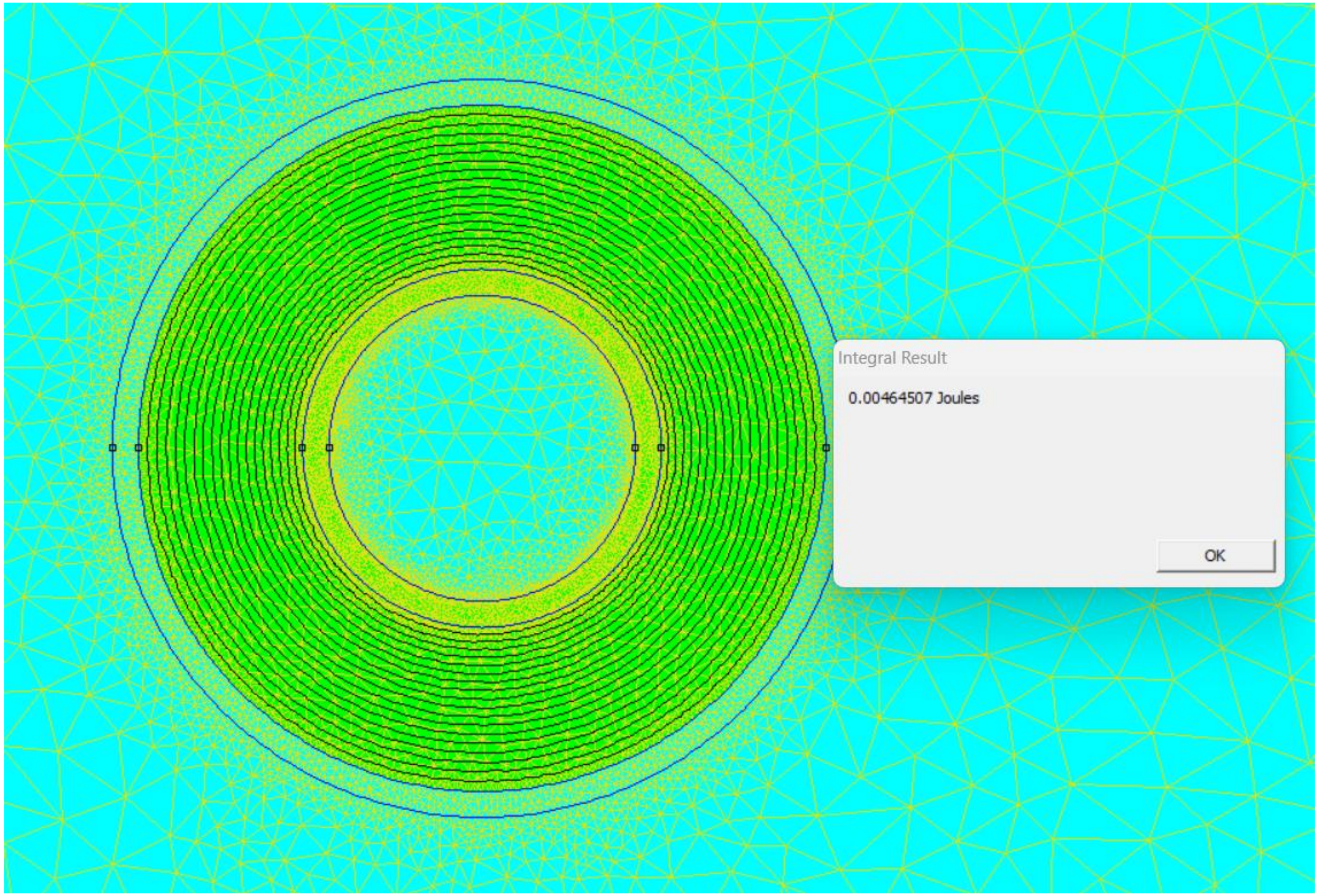
- Selected core: **0_43825TC** from magnetics manufacture
  - Current density (J) = 3 A/mm^2
  - Current (I) = 10 A
- Area product: (L*I^2)/(B*Kw*Kc*J) = (35.6u*10*10)/(0.02*0.6*1*3*10^6)

  = 9.88* 10^-7 cm^4
- Inductance: ~35.6uH
- Wire Selection: 14 AWG

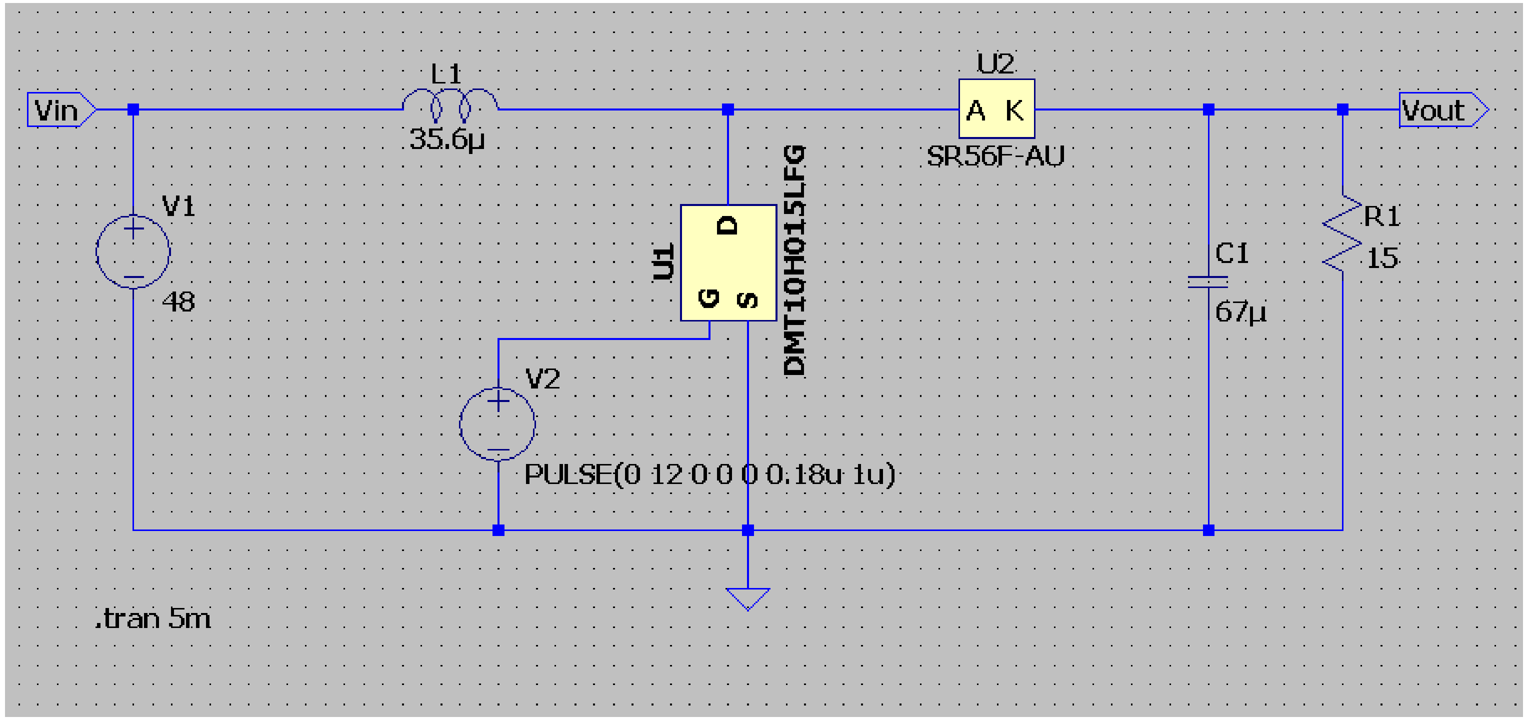
TOROID INDUCTOR: DESING



TOROID INDUCTOR: FEMM RESULTS



Ideal toroid



Simulating nonlinearity OF toroid

No.	Parameters	Values
1	AL (inductance)	8.06 uH/N^2
2	Le (path length)	82.8 mm
3	Ae (cross section)	231 mm^2
4	B (flux density)	0.02 Tesla
5	H (flux intensity)	15 A/m
6	Outer length	38.1 mm
7	Inner length	19 mm
8	Height	25.4 mm
9	N (number of turns)	20

Python Code to Check Current Vs Inductance Graph

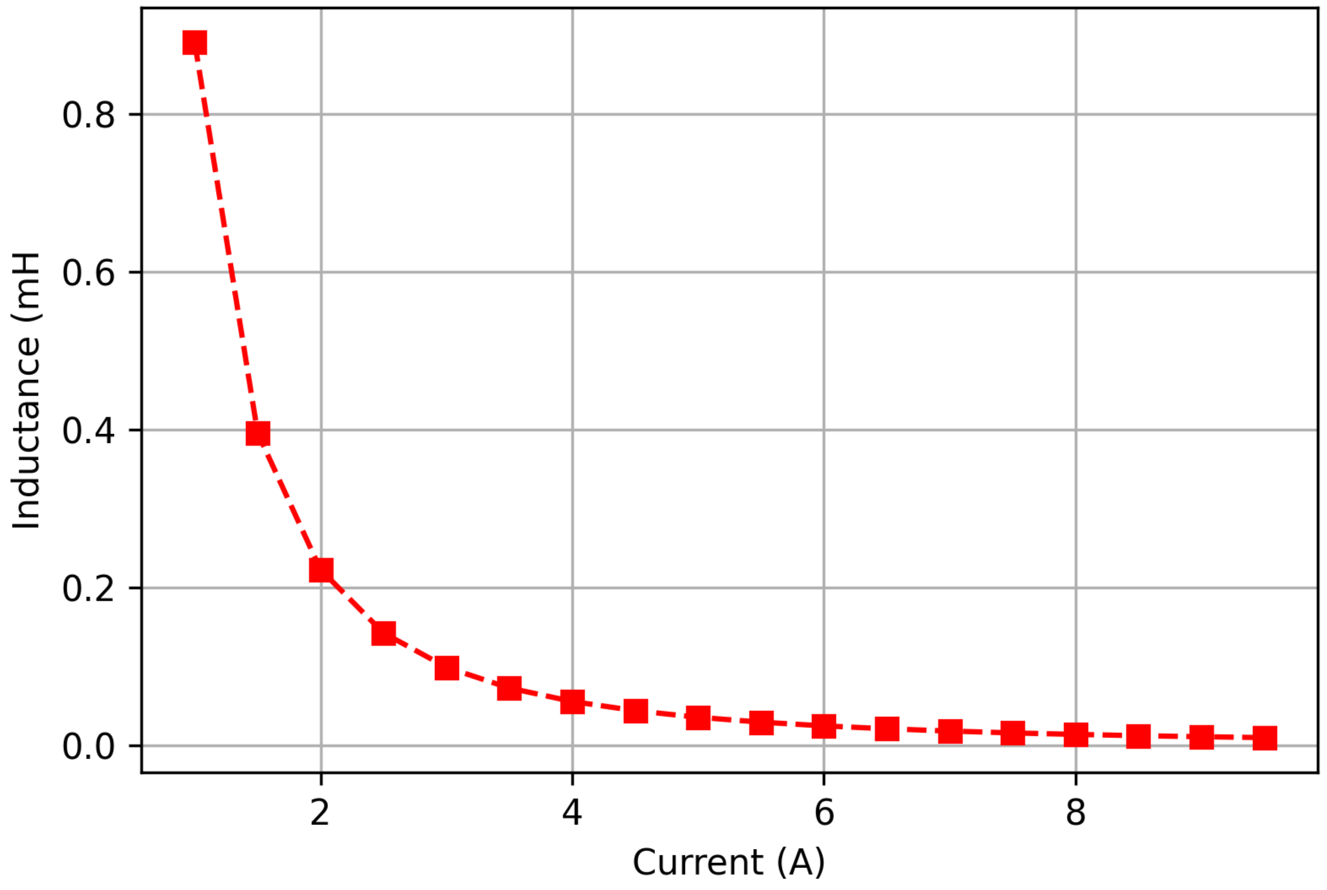
```
import femm
import numpy as np
import matplotlib.pyplot as plt

femm.openfemm()
femm.opendocument("Inductor design 1MHz.FEM"); #save FEMM file where Python install
femm.mi_saveas("tem.fem") #save into Temporary file

min=1; max=10; step=0.5
Npoints = int((max-min)/step)
I=np.arange (min, max, step, dtype=np.float64)
W=np.arange (min, max, step, dtype=np.float64)
L=np.arange (min, max, step, dtype=np.float64)
print("FEMM Result:")
for k in range (0, Npoints):
    femm.mi_modifycircprop("Coil",5,I[k])
    femm.mi_analyze()
    femm.mi_loadsolution()
    femm.mo_selectblock(6.5,6.2)  #Select inner winding
    femm.mo_selectblock(9.5,17.5) #Select Outer winding
    femm.mo_selectblock(9.5,10.5) #Select Core

    W[k]=femm.mo_blockintegral(2) #Field Energy
    L[k]=2*W[k]/I[k]**2        #Inductance
    print(I[k],L[k])          #Print result Current Vs Inductance graph
#Plot Current Vs Inductance graph
plt.figure(1)
plt.plot(I,L*1e3, 'rs--')
plt.grid(True)
plt.ylabel("Inductance (mH("
plt.xlabel("Current (A)")
plt.savefig("L_vs_Current.png",dpi=300)
```

From FEMM to lTspice

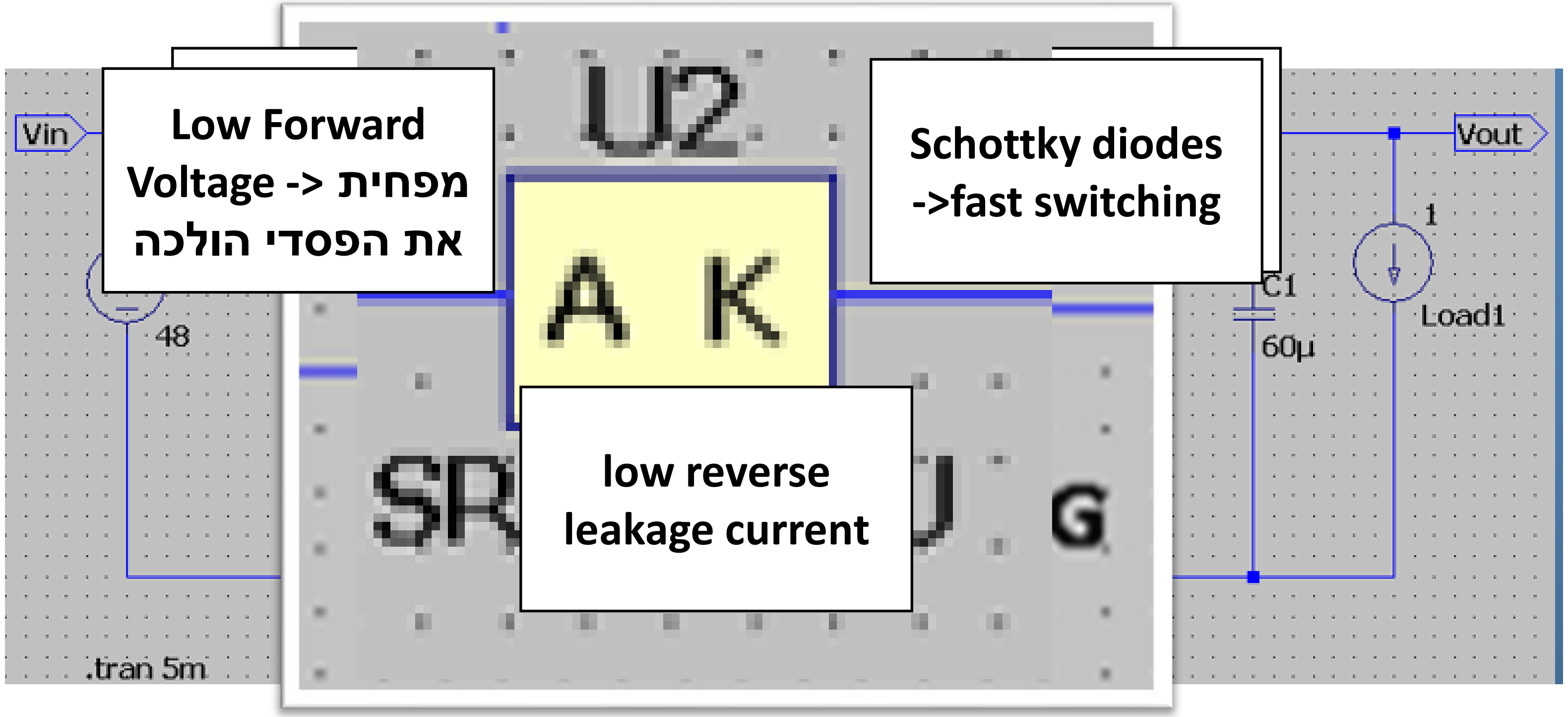


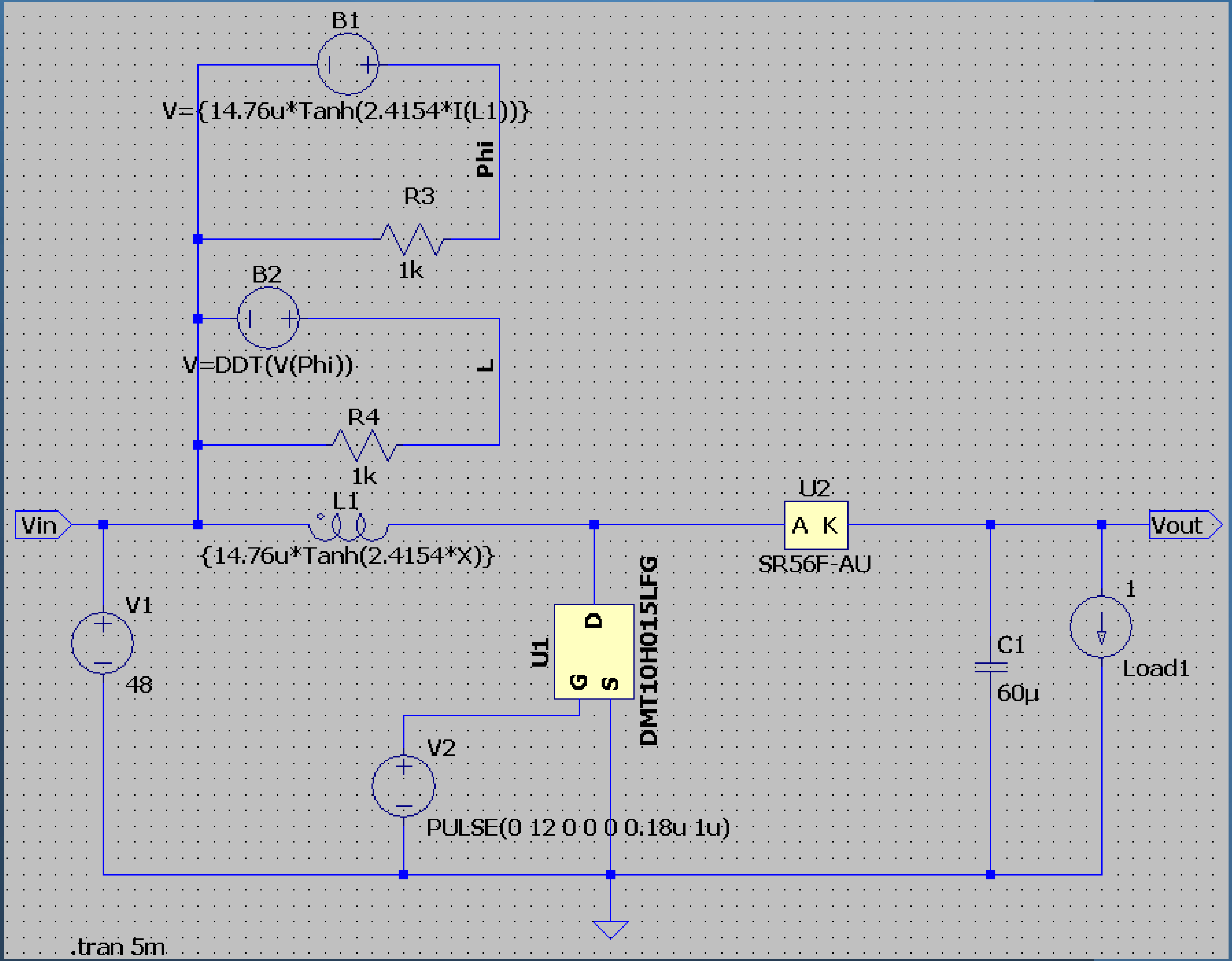
From FEMM to Ltspice

$$\Phi = N \cdot A_e \cdot B \cdot \tanh\left(\frac{N}{H \cdot L_e} \cdot I(L)\right)$$

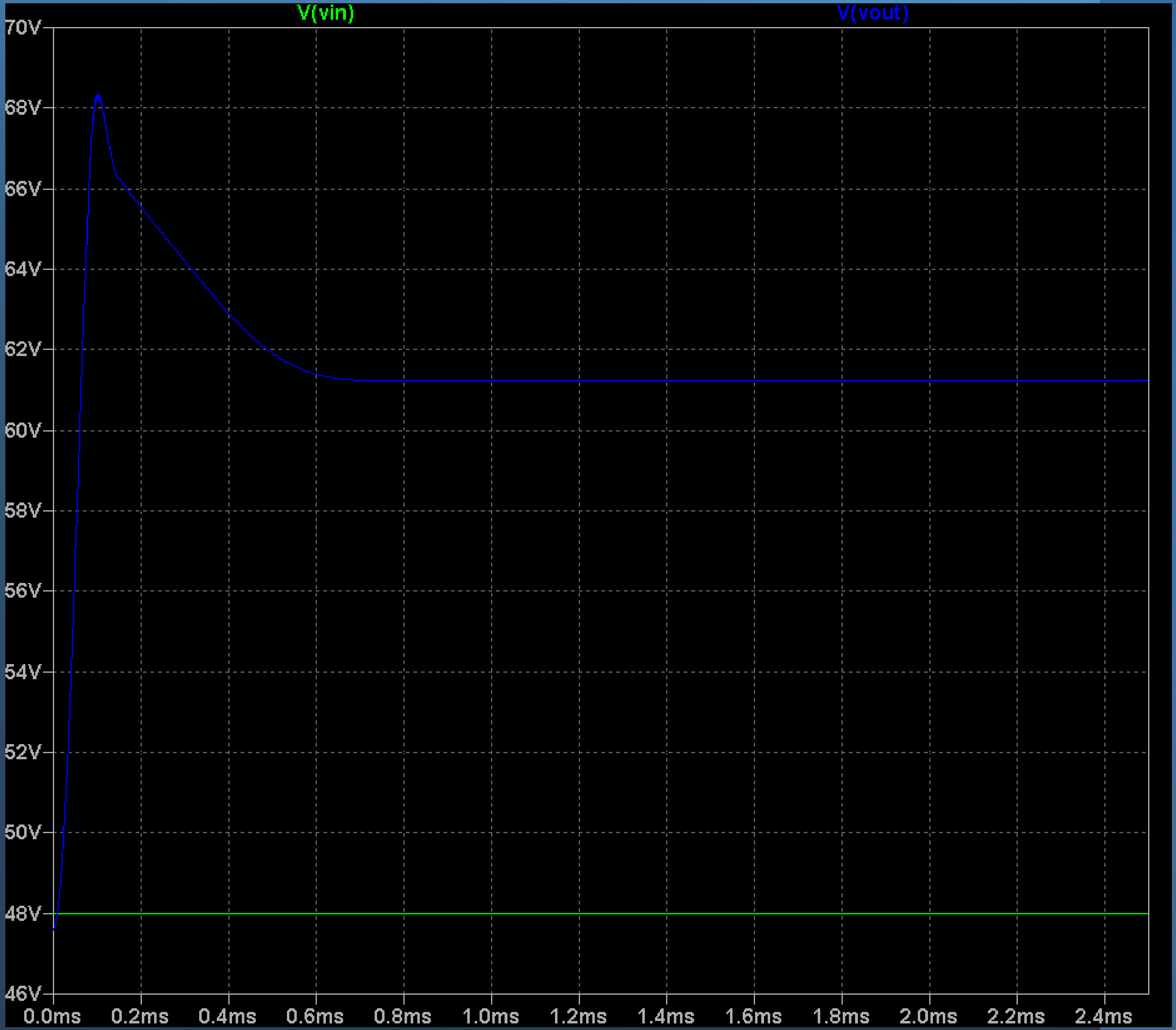
- K1 = N*Ae*B ~= 14.6 * 10^-6
- K2 = N/(H*Le) = 2.4154
- Flux (ϕ)= 14.6 * 10^-6 * tanh (2.4154*I(L))
- L = dϕ/dI

$$L = N \cdot A_e \cdot B \cdot \left(\frac{N}{H \cdot L_e}\right) \cdot \left(1 - \tanh^2\left(\frac{N}{H \cdot L_e} \cdot I(L)\right)\right)$$

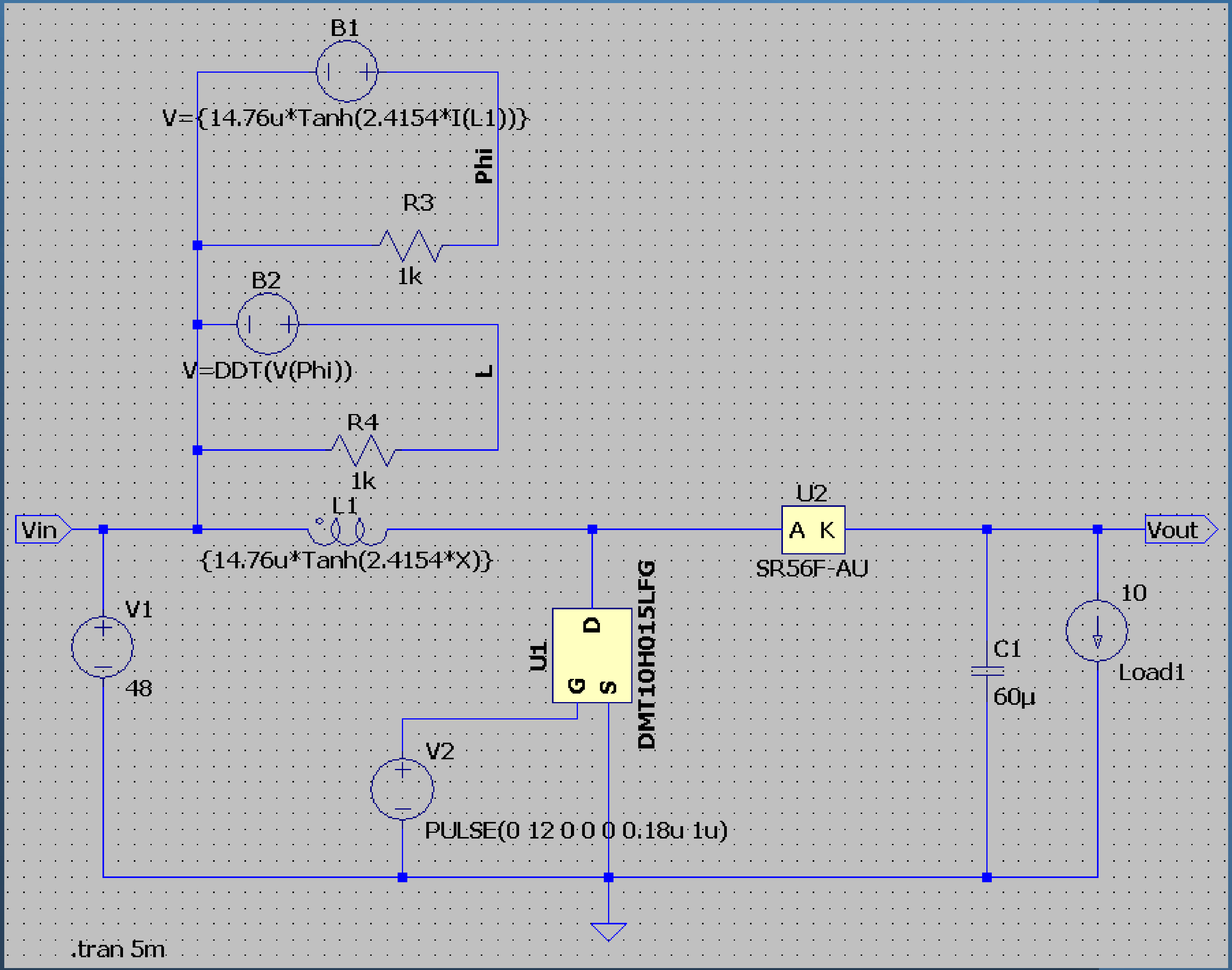

Low Forward
Voltage -> מפחית
את הפסדי הולכה
Schottky diodes
->fast switching
low reverse
leakage current
Vin
48
.tran 5m
U2
A K
Vout
1
C1
60µ
Load1

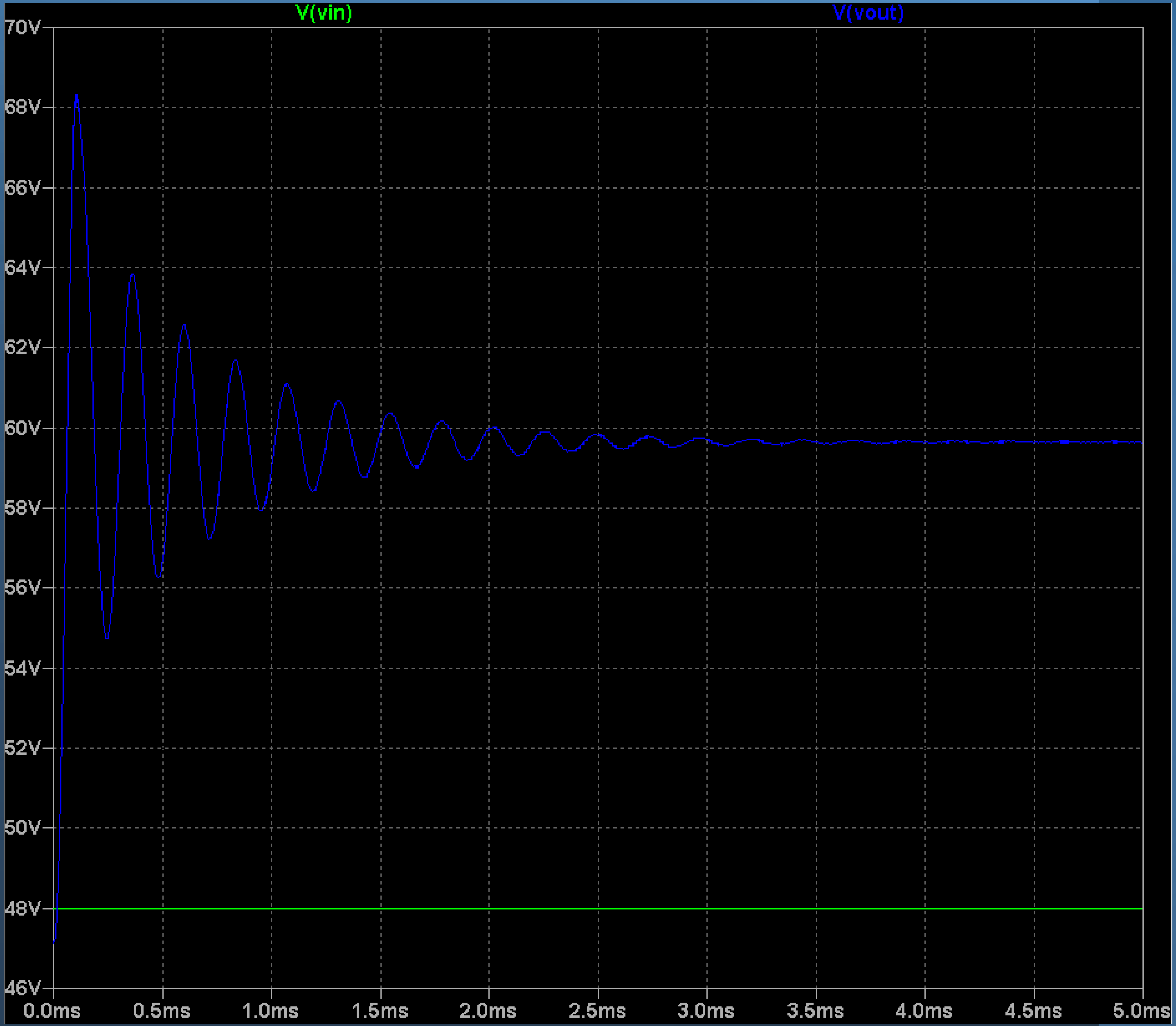


B1
V={14.76u*Tanh(2.4154*I(L1))}
Phi
R3
1k
B2
V=DDT(V(Phi))
L
R4
1k
L1
Vin
{14.76u*Tanh(2.4154*X)}
U2
A K
SR56F-AU
Vout
V1
48
U1
D
G S
DMT10H015LFG
C1
60µ
1
Load1
V2
PULSE(0 12 0 0 0 0.18u 1u)
.tran 5m



V(vin)
V(vout)
70V
68V
66V
64V
62V
60V
58V
56V
54V
52V
50V
48V
46V
0.0ms
0.2ms
0.4ms
0.6ms
0.8ms
1.0ms
1.2ms
1.4ms
1.6ms
1.8ms
2.0ms
2.2ms
2.4ms


B1
V={14.76u*Tanh(2.4154*I(L1))}
Phi
R3
1k
B2
V=DDT(V(Phi))
L
R4
1k
L1
Vin
{14.76u*Tanh(2.4154*X)}
U2
A K
SR56F-AU
Vout
V1
48
U1
D
G S
DMT10H015LFG
C1
60µ
10
Load1
V2
PULSE(0 12 0 0 0 0.18u 1u)
.tran 5m


V(vin)
V(vout)
70V
68V
66V
64V
62V
60V
58V
56V
54V
52V
50V
48V
46V
0.0ms
0.5ms
1.0ms
1.5ms
2.0ms
2.5ms
3.0ms
3.5ms
4.0ms
4.5ms
5.0ms

Thank you!