Project Book

TECHNION
Israel Institute
of Technology

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

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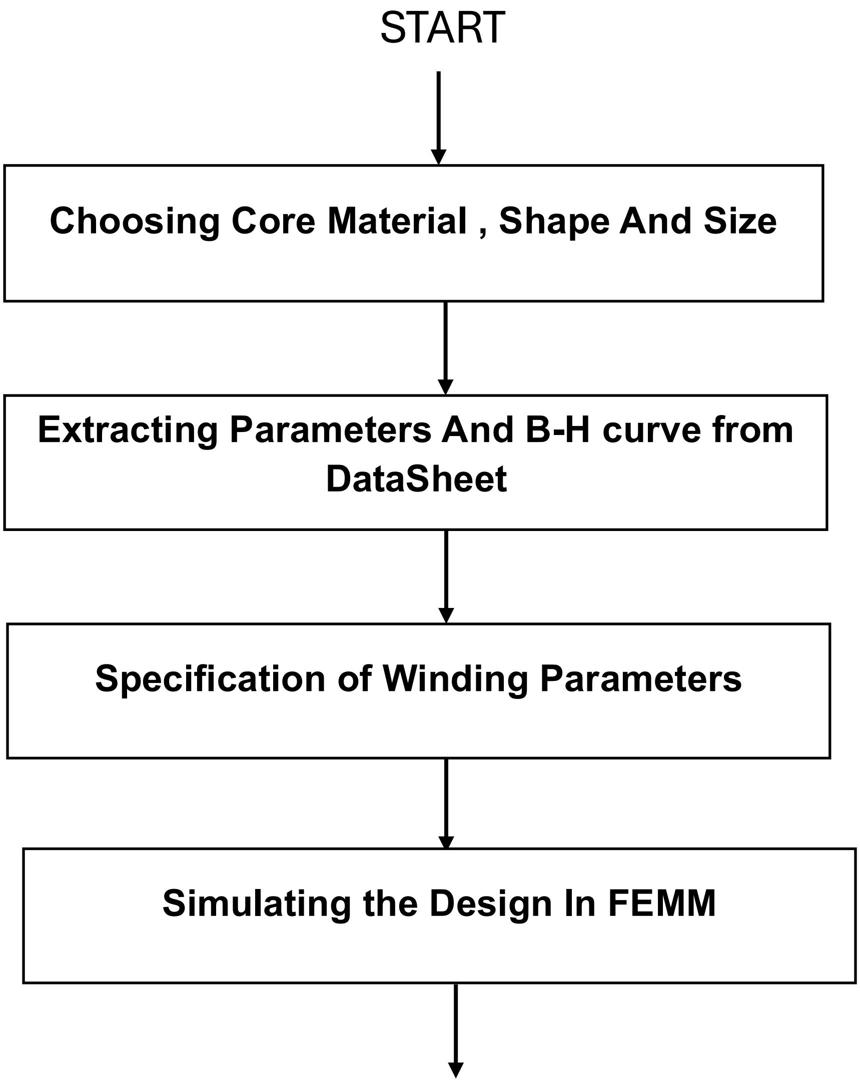
Abstract

This paper explores the design considerations and methodologies for developing an efficient inductor suitable for a boost converter operating at a frequency of 1 MHz. The converter is designed to handle an output current of 5 Amperes, with an input voltage of 48V and an output voltage of 60V. Key factors such as core material selection, winding techniques, and thermal management are discussed in detail to address the challenges associated with high-frequency operation. The study aims to optimize the inductor design to enhance the converter's efficiency and performance, ensuring stability and reliability. Through theoretical analysis and practical implementation, this research provides comprehensive guidelines and best practices for designing inductors in high-frequency power electronics applications.

Introduction

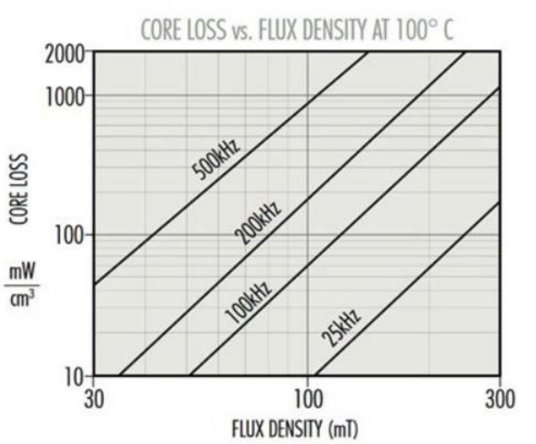
Designing an inductor for a boost converter operating at a frequency of 1 MHz with a specified output current of 5 Amperes, an input voltage of 48V, and an output voltage of 60V, presents a unique set of challenges and considerations. The inductor plays a critical role in the energy storage and transfer process, directly impacting the converter's efficiency, stability, and overall performance. High-frequency operation demands meticulous attention to core material selection, winding techniques, and thermal management to minimize losses and ensure reliable operation. This introduction will explore the key principles and design parameters essential for optimizing the inductor in such a high-frequency boost converter application, aiming to achieve maximum efficiency and performance while maintaining robustness under the specified electrical conditions.

Design Flow Chart

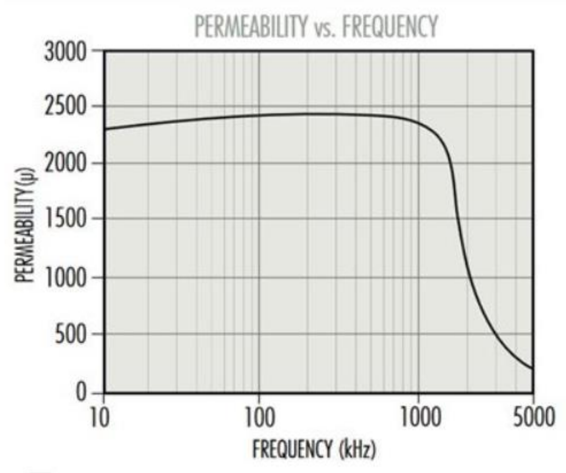


Choosing Core Material , Shape And Size

- **Core type: Ferrite core**



- **Core material: R – type***



When designing an inductor for high-frequency applications such as a 1 MHz boost converter, the choice of core material is crucial. Ferrite cores are commonly used in such applications due to their favorable properties.

Specifically, R-type ferrite core material is selected for the following reasons:

1 High-Frequency Performance**: Ferrite cores, especially those made from R-type material, exhibit excellent performance at high frequencies. They have low eddy current losses and can operate efficiently at frequencies in the MHz range. This makes them ideal for applications where minimizing losses and maintaining efficiency are critical.**

2 .Magnetic Properties**: R-type ferrite cores have high magnetic permeability, which allows for efficient energy storage and transfer. This characteristic is essential for the inductor to perform effectively in a boost converter, where it needs to handle rapid changes in current and voltage.**

3 .Temperature Stability**: Ferrite cores can maintain their magnetic properties over a wide temperature range. This thermal stability ensures consistent performance and reliability in varying operating conditions, which is crucial for power electronics applications that may experience significant temperature fluctuations.**

4 .Low Losses**: At high frequencies, core losses (hysteresis and eddy current losses) can significantly impact the overall efficiency of the converter. R-type ferrite**

materials are designed to minimize these losses, thus enhancing the efficiency of the boost converter.

5 .High Saturation Flux Density**: R-type ferrite cores have a high saturation flux density, which means they can handle higher levels of magnetic flux without saturating. This is important for maintaining inductance under varying load conditions and ensuring the converter can deliver consistent performance.**

By selecting an R-type ferrite core material, the inductor can effectively meet the demands of high-frequency operation, providing the necessary inductance, efficiency, and stability required for the boost converter to function optimally. This choice of core material is integral to achieving the desired performance characteristics and ensuring the reliability of the power converter in practical applications.

Refer https://www.mag-inc.com/Products/Ferrite-Cores/RMaterial#:~:text=R%20material%20is%20a%20medium,losses%20at%2095%C2%B0C

- **Selected core: 0_43825TC from magnetics manufacture**

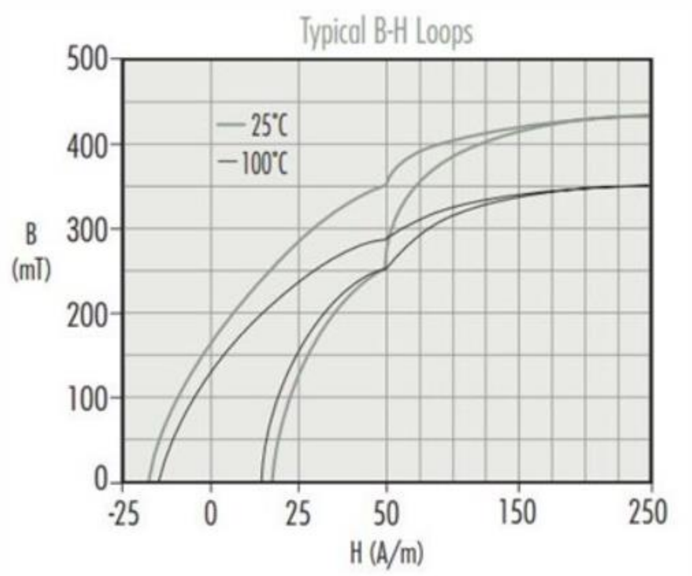
Current density (J) = 3 A/mm^2

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**

Extracting Parameters And B-H curve from DataSheet



- **Data from core datasheet:**

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

Specification of Winding Parameters

Wire Selection: 14 AWG

14 AWG Wire : The wire selected for the inductor is 14 AWG (American Wire Gauge), which is a standard wire size used in various electrical applications.

Inductance Calculation : In a Finite Element Method Magnetics (FEMM) simulation, using 3 turns of 14 AWG wire resulted in an inductance of approximately 35.6 microhenries (µH).

Practical Variability: While simulations provide a theoretical value, the actual inductance can vary during the practical assembly of the inductor due to factors such as winding tightness, spacing, and core material inconsistencies.

Current Carrying Capacity : Although the 14 AWG wire was used in the simulation, the required wire size based on current carrying capacity alone would be 10 AWG. However, using 10 AWG wire is impractical due to issues related to frequency and skin depth.

Skin Depth: At high frequencies, the effective current-carrying area of a conductor decreases due to the skin effect, which causes the current to flow primarily near the surface of the conductor. This effect is more pronounced at 1 MHz.

Wire Selection Trade-off: While 10 AWG wire would theoretically handle the current better, it is too thick for efficient high-frequency operation due to the skin depth

limitation. Thus, 14 AWG wire is chosen as a compromise, balancing current carrying capacity and high-frequency performance.

Number of Turns: 3

Inductor Turns: The number of turns of wire around the core is a critical factor in determining the inductance of the inductor.

Factors Influencing Turns:

Wire Selection: The choice of 14 AWG wire influences the number of turns needed to achieve the desired inductance.

Current Carrying Capacity: The wire must be capable of handling the specified current (5 Amperes) without overheating or excessive voltage drop.

Frequency: At 1 MHz, the inductor must maintain its performance without significant losses, which affects the choice of turns and wire size.

Core Type: The magnetic properties of the chosen R-type ferrite core also influence the number of turns required to achieve the target inductance.

Simulation Result: According to FEMM simulation, using 3 turns of 14 AWG wire results in an inductance of approximately 35.6 µH. This value is suitable for the intended application operating at 1 MHz.

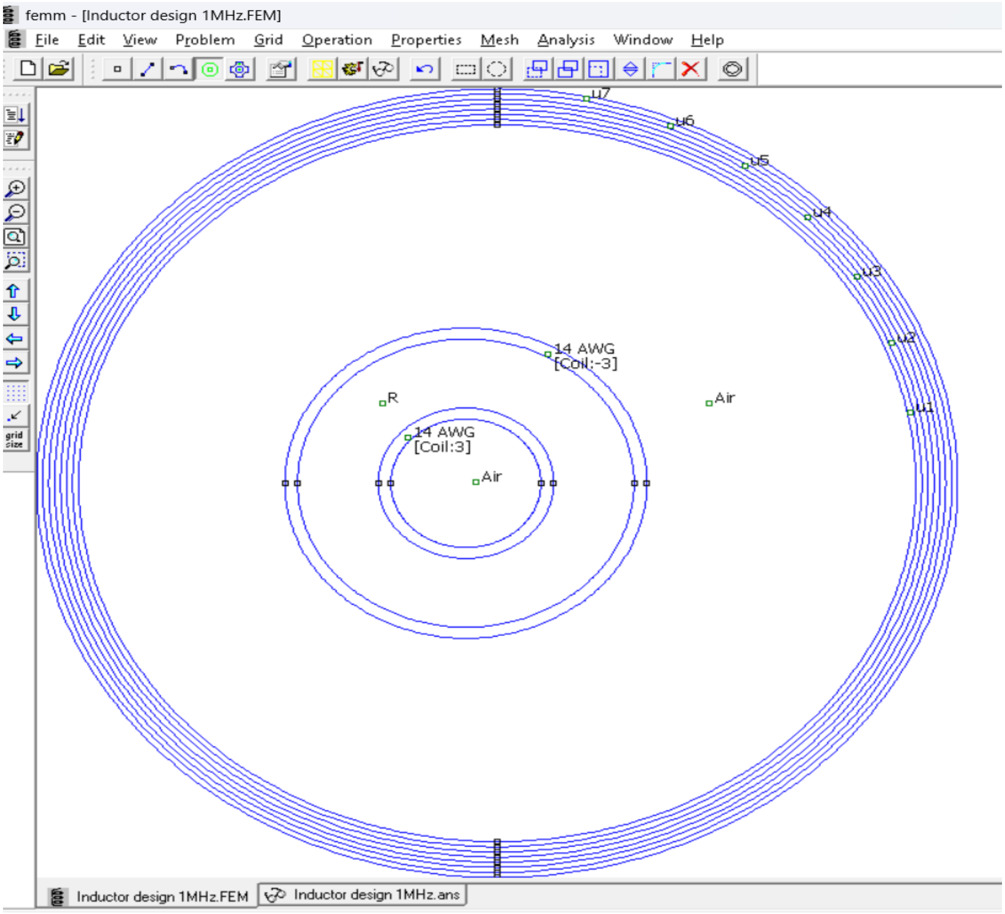
Practical Considerations: While the simulation provides a baseline, practical assembly factors such as

winding precision and core material variations can affect the actual inductance. Adjustments may be necessary during the prototyping and testing phases.

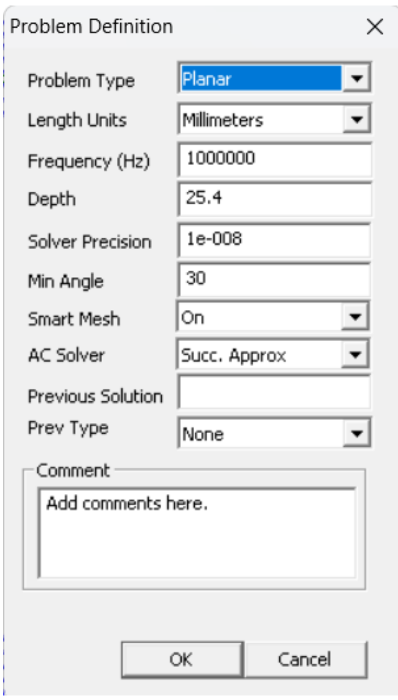
Summary:

-The selection of 14 AWG wire and 3 turns was based on achieving the necessary inductance (35.6 µH) for the high-frequency boost converter operating at 1 MHz. The wire size and number of turns were chosen to balance current carrying capacity and high-frequency efficiency, considering practical constraints such as skin depth and assembly variability.

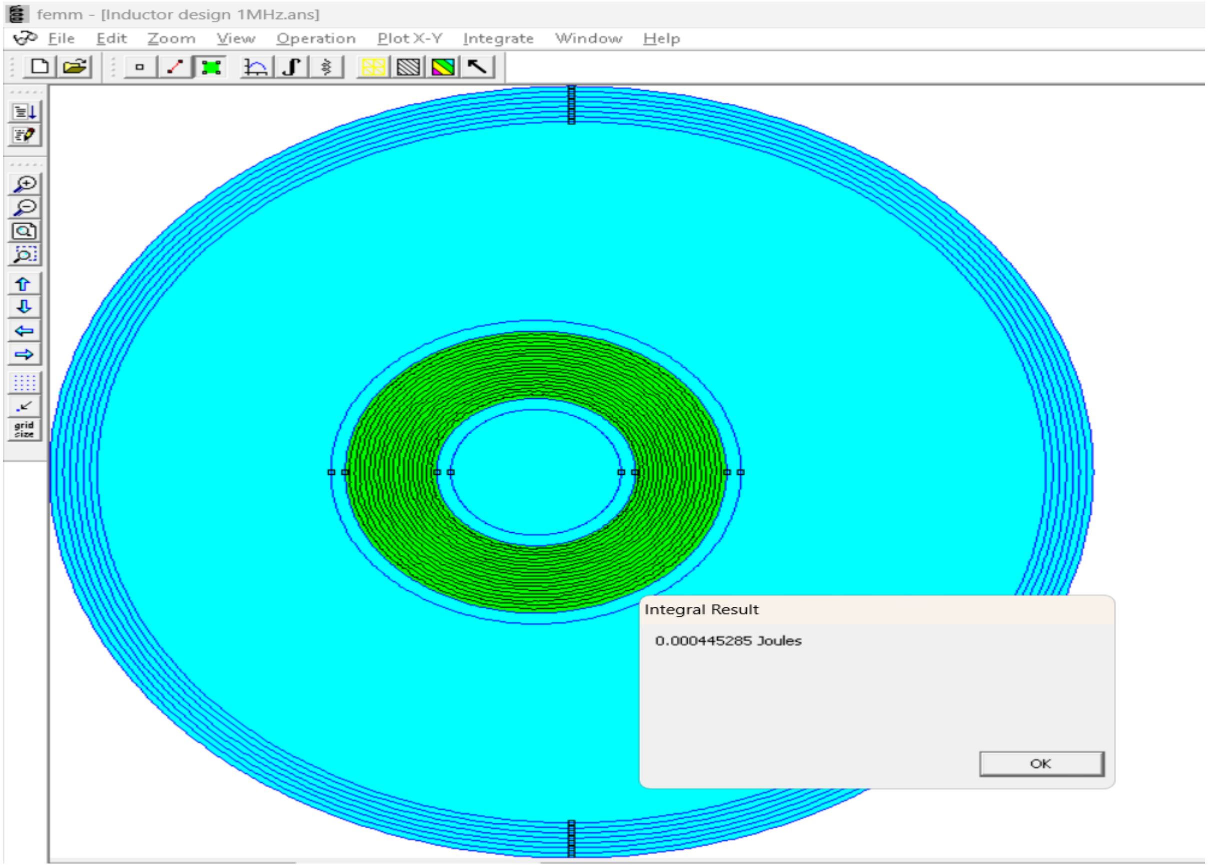
Simulating the Design In FEMM



- Entering Height and frequency parameter into FEMM software:



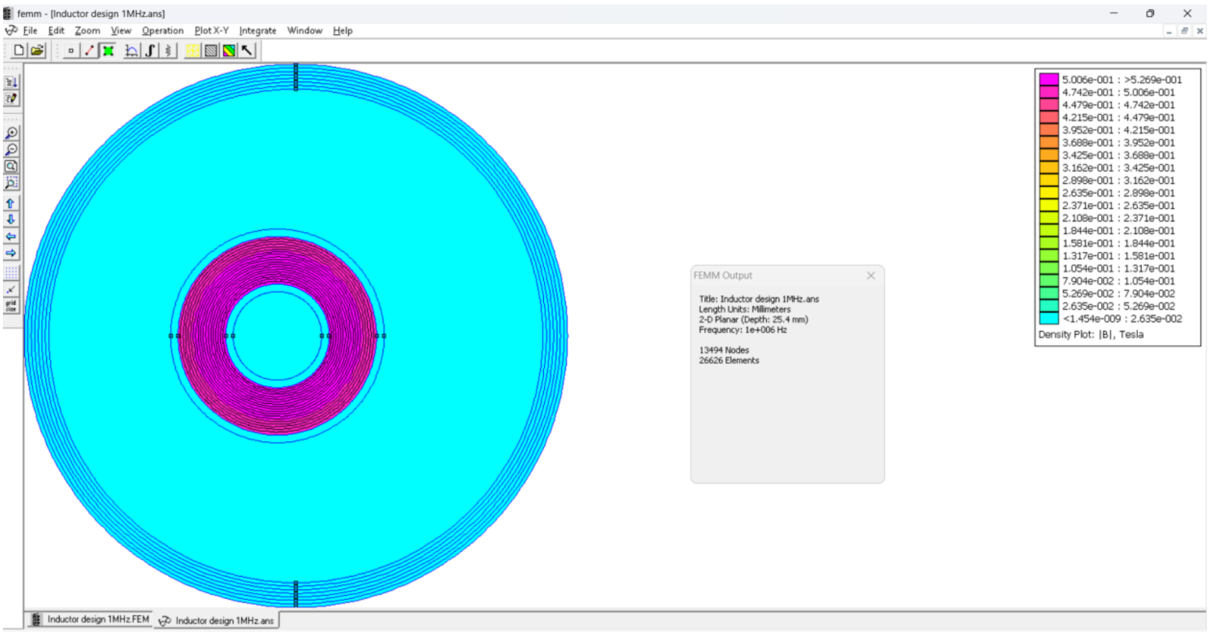
- Simulation into FEMM software:



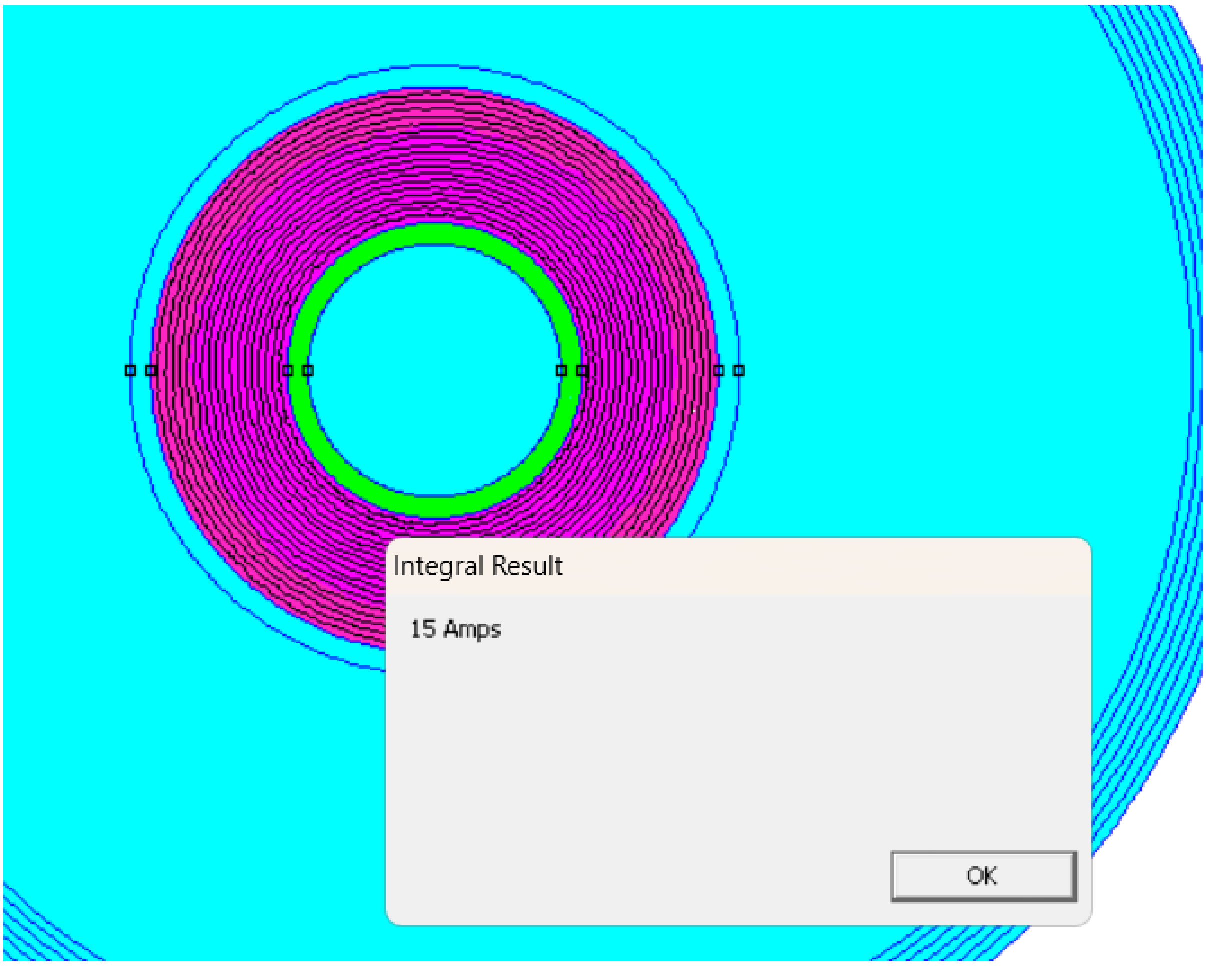
Energy = 0.000998897 Joules

I = 5 A

L = 35.6uH



Current in single winding = Total current/ No of turns = 15/3 = 5A



Python Code to Check Current Vs Inductance Graph

Python Code:

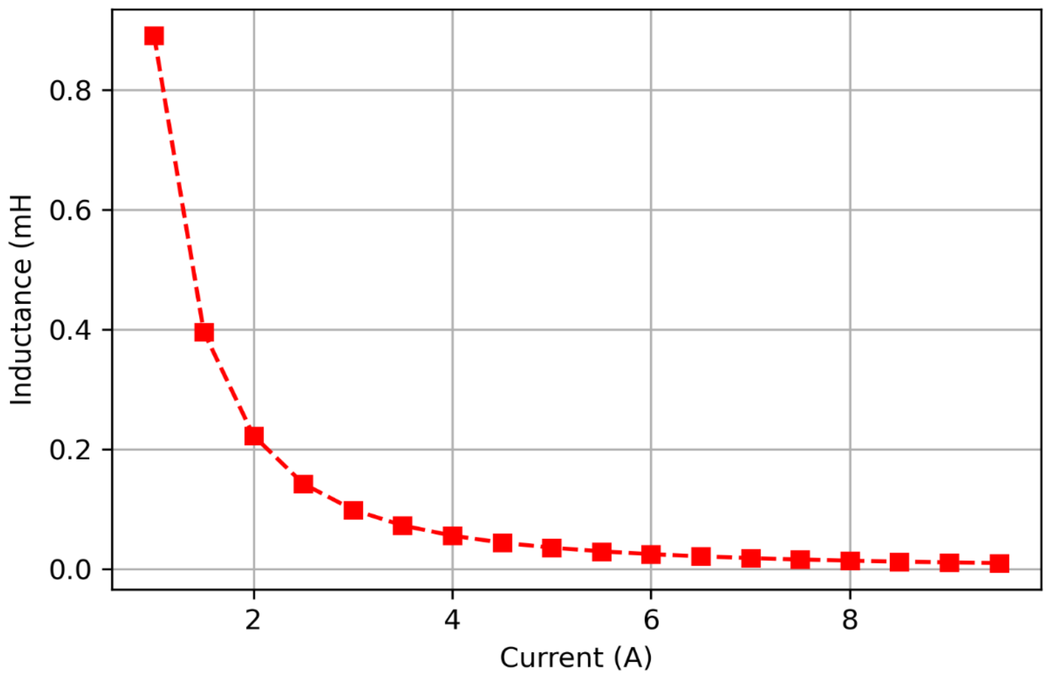
```
import femm
import numpy as np
import matplotlib.pyplot as plt

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

femm.closefemm()
```

```
#Plotting
#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)
```

FEMM Result:

Current	Inductance
1.0	0.00089109
1.5	0.00039604
2.0	0.00022277
2.5	0.00014257
3.0	9.90E-05
3.5	7.27E-05
4.0	5.57E-05
4.5	4.40E-05
5.0	3.56E-05
5.5	2.95E-05
6.0	2.48E-05
6.5	2.11E-05
7.0	1.82E-05
7.5	1.58E-05
8.0	1.39E-05
8.5	1.23E-05
9.0	1.10E-05
9.5	9.87E-06

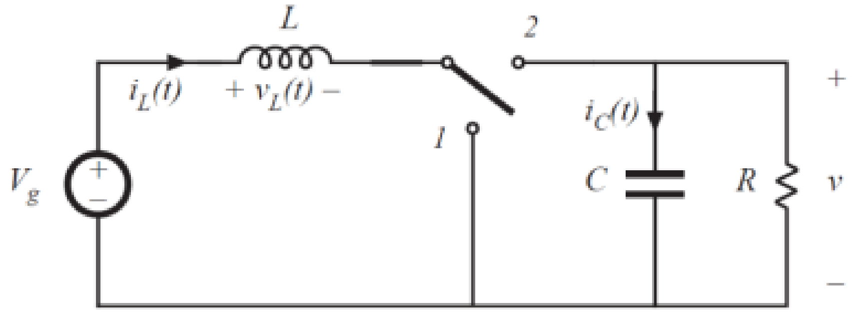
Graph:



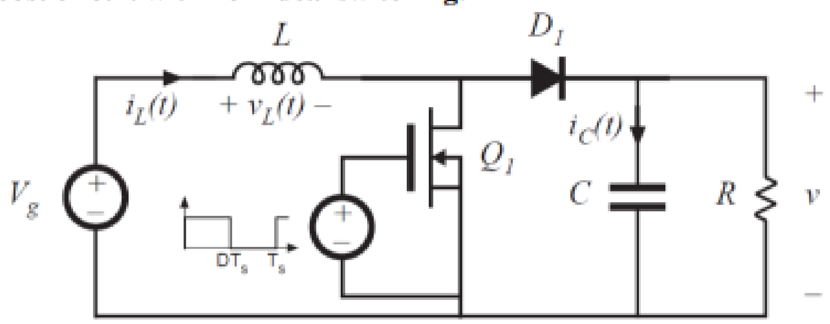
Boost Converter

Boost converter is a step-up voltage DC-DC converter, which increase the input voltage to a higher output voltage.

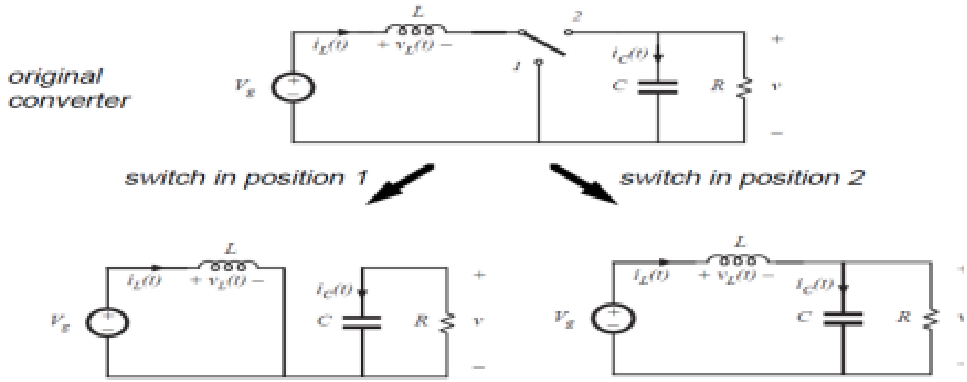
The boost circuit with ideal switching:



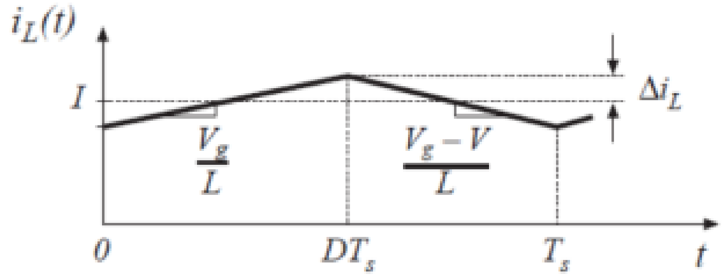
The boost circuit with non-ideal switching:



The switching is divided into two parts.
In the first part: Only the transistor is on (transmit).
In the second part: Only the Diode is on (transmit).



While the switching, the inductor current is:



$$\textit{Where D is DUTYCYCLE} = \frac{t_{transistor_{on}}}{T_{cycle}}$$

The voltage gain:
The average voltage on the inductor must be zero:

$$\int_0^{DT} V_g \, d\tau + \int_{DT}^{T} (V_g - V)\, d\tau = 0 \rightarrow DTV_g + D'T(V_g - V) = 0$$

$$\rightarrow DV_g + D'(V_g - V) = 0 \rightarrow V_g - D'V = 0$$

$$\boxed{\rightarrow V = \frac{1}{D'} V_g = \frac{1}{1-D} V_g}$$

Similarly, we do for the average capacitor current, it must be zero:

$$\int_0^{DT} -\frac{V}{R} d\tau + \int_{DT}^{T} \left(I_L - \frac{V}{R}\right) d\tau = 0 \rightarrow -\frac{DTV}{R} + D'T\left(I_L - \frac{V}{R}\right) = 0$$

$$\rightarrow -D\frac{V}{R} + D'I_L - D'\frac{V}{R} = 0 \rightarrow -\frac{V}{R} + D'I_L = 0$$

$$\rightarrow \frac{V}{R} = I_{out} = D'I_L$$

Ensuring the principle of power conservation:

$$V_g \cdot I_L = V_{out} D' \cdot \frac{I_{out}}{D'} = V_{out} \cdot I_{out}$$

DMT10H015LFG Transistor

The DMT10H015LFG is an N-channel MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) that is well-suited for high-efficiency power conversion applications. Below is a detailed explanation of its features and characteristics:

Key Features

1 Low On-Resistance (RDS(on)

- The DMT10H015LFG exhibits a very low on-resistance, typically around 1.5 milliohms (mΩ) at a V_{GS} (Gate-Source Voltage) of 10V. This low resistance minimizes conduction losses, thereby enhancing the efficiency of the power converter.

2 High Current Handling:

- This MOSFET is capable of handling high continuous drain currents, typically up to 100A. This feature makes it suitable for applications that demand significant current flow.

3. Fast Switching Speed:

- The DMT10H015LFG is designed for high-speed switching applications, featuring a low gate charge and

fast switching times. These characteristics are essential for high-frequency operations, such as those at 1 MHz, ensuring efficient and reliable performance.

4 Thermal Performance :

- The transistor offers excellent thermal performance, with a low thermal resistance from junction to case. This attribute is crucial for managing heat dissipation effectively, which is particularly important in high-power applications.

5. Robustness :

- The DMT10H015LFG has a high avalanche energy rating, indicating its capability to withstand high energy pulses. This contributes to the reliability and durability of the device under transient conditions.

Suitability for High-Frequency Boost Converters

1. Efficiency :

- The low on-resistance RDS(on1) of the DMT10H015LFG ensures minimal power loss during conduction, which is essential for maintaining high efficiency in boost converters. This is especially significant at high frequencies, such as 1 MHz, where switching losses can be considerable.

2. Current Capability:

- The high current handling capacity of the DMT10H015LFG supports applications requiring substantial current, ensuring the MOSFET operates within safe limits.

3. High-Frequency Operation:

- The fast switching characteristics of this MOSFET make it ideal for high-frequency applications. The low gate charge and rapid switching reduce switching losses, which are critical for maintaining efficiency at 1 MHz.

4. Thermal Management:

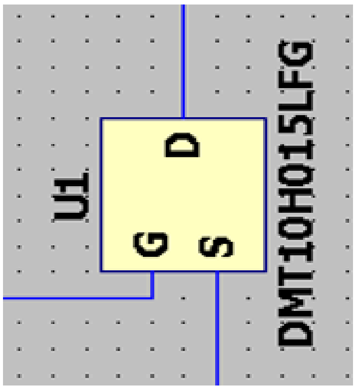
- Effective thermal management is vital in high-power applications to prevent overheating. The DMT10H015LFG's excellent thermal properties help maintain a safe operating temperature, thereby enhancing reliability and longevity.

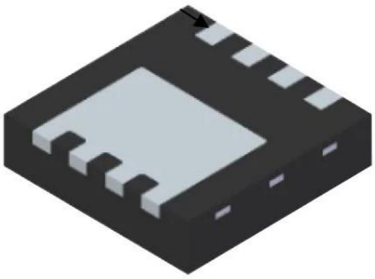
5. Reliability:

- The high avalanche energy rating and robust construction of the DMT10H015LFG ensure that the transistor can handle unexpected voltage spikes and transients without failure, contributing to the overall reliability of the power converter.

Conclusion

The DMT10H015LFG MOSFET, with its low on-resistance, high current handling capability, fast switching speed, excellent thermal performance, and robust design, is highly suitable for high-efficiency, high-frequency power conversion applications. These features collectively ensure optimal performance, reliability, and efficiency in demanding power converter designs.





https://eu.mouser.com/ProductDetail/Diodes-Incorporated/DMT10H015LCG-7?qs=EDJ299gKAZSAj6skAb1nsA%3D%3D&utm_id=6470900564&gad_source=1&gclid=CjwKCAjwzIK1BhAuEiwAHQmU3oaM-ejXStU2EKPbSaWW2_RY2zSzpy0g993CcsSN1BF2b5qBVfoqDRoCgtEQAvD_BwE

SR56F-AU Diode

The SR56F-AU is a Schottky barrier rectifier diode designed for use in high-efficiency power conversion applications. Below is a detailed explanation of its features and characteristics:

Key Features

1 Low Forward Voltage Drop:

- The SR56F-AU diode has a low forward voltage drop, typically around 0.55V at 5A. This low forward voltage drop reduces conduction losses, thereby improving the efficiency of the power converter.

2 High Current Capability:

- The SR56F-AU is capable of handling a continuous forward current of up to 5A, making it suitable for applications requiring substantial current flow. This ensures the diode can operate efficiently without being overstressed.

3 Fast Switching Speed:

- Schottky diodes are known for their fast switching capabilities. The SR56F-AU exhibits fast recovery times, which is essential for high-frequency applications such

as those operating at 1 MHz. This characteristic helps in minimizing switching losses and maintaining high efficiency.

4 Thermal Performance:

- The SR56F-AU diode offers good thermal performance, with a maximum junction temperature of 150°C. Efficient thermal management is crucial in high-power applications to prevent overheating and ensure reliable operation.

5 Low Leakage Current:

- This diode has a low reverse leakage current, which reduces power loss during the off-state and enhances the overall efficiency of the converter.

6 Compact Package:

- The SR56F-AU is available in a compact package, making it suitable for designs where space is limited. This allows for more flexible and compact circuit designs.

Suitability for High-Frequency Boost Converters

1Efficiency:

- The low forward voltage drop of the SR56F-AU ensures minimal power loss during conduction, which is crucial for maintaining high efficiency in boost converters. This is particularly important at high frequencies, such as 1 MHz, where both conduction and switching losses need to be minimized.

2 Current Capability:

- With its high current handling capacity, the SR56F-AU supports applications requiring substantial current, such as a boost converter with an output current of 5A. This ensures that the diode can handle the current demands without failure.

3 High-Frequency Operation:

- The fast switching characteristics of the SR56F-AU make it ideal for high-frequency applications. The diode's fast recovery time helps reduce switching losses, which are critical for maintaining efficiency at 1 MHz.

4 Thermal Management:

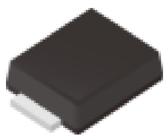
- Effective thermal management is vital in high-power applications to prevent overheating. The SR56F-AU's good thermal performance ensures that it can dissipate heat effectively, maintaining a safe operating temperature and enhancing reliability and longevity.

5 Reliability:

- **The low reverse leakage current and robust construction of the SR56F-AU ensure that the diode can operate reliably under various conditions. Its ability to handle high current and temperature stress adds to its reliability in power conversion applications.**

Conclusion

The SR56F-AU Schottky barrier rectifier diode, with its low forward voltage drop, high current handling capability, fast switching speed, good thermal performance, and low leakage current, is highly suitable for high-efficiency, high-frequency power conversion applications. These features collectively ensure optimal performance, reliability, and efficiency in demanding boost converter designs.



https://www.panjit.com.tw/upload/datasheet/SR56F-AU.pdf

Simulation in LtSpice

Designing a high-frequency inductor involves understanding and managing the nonlinear characteristics of the core material. The inductance of the core changes with respect to the current, which must be considered in the design process. Below is an explanation of how to derive the nonlinear inductance using data from the core datasheet.

Data from Core Datasheet

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)	3

Derivation of Flux and Inductance

Using the given parameters, we can derive the magnetic flux (Φ) and the inductance (L) considering the nonlinear properties of the core.

1) Magnetic Flux (Φ) Calculation:

- **The magnetic flux (Φ) is calculated by incorporating the nonlinear characteristics of the core.**
- **We use the hyperbolic tangent function (tanh) to represent the nonlinearity.**

The constants \(K_1 \) and \(K_2 \) are derived as follows:

$$K_1 = N \times Ae \times B \approx 3 \times 231 \times 0.02 \approx 13.86 \times 10^{-6} \approx 14.6 \times 10^{-6}$$

$$K_2 = \frac{N}{H \times Le} = \frac{3}{15 \times 82.8} \approx 0.0024154$$

Using these constants, the magnetic flux (Φ) as a function of the inductor current \(I(L) \) is given by:

$$\Phi = 14.6 \times 10^{-6} \times \tanh(2.4154 \times I(L))$$

2) Inductance (L) Calculation:

- **The inductance is derived from the magnetic flux by differentiating the flux with respect to the current.**

$$L = \frac{d\Phi}{dI}$$

Differentiating the above flux equation:

$$L = \frac{d}{dI}\left(14.6 \times 10^{-6} \times \tanh(2.4154 \times I(L))\right)$$

Using the chain rule for differentiation:

$$L = 35.2714 \times 10^{-6} \times \left(1 - \tanh^2(2.4154 \times I(L))\right) \text{ Henries}$$

This formula shows how the inductance (L) varies nonlinearly with the inductor current (I(L) .

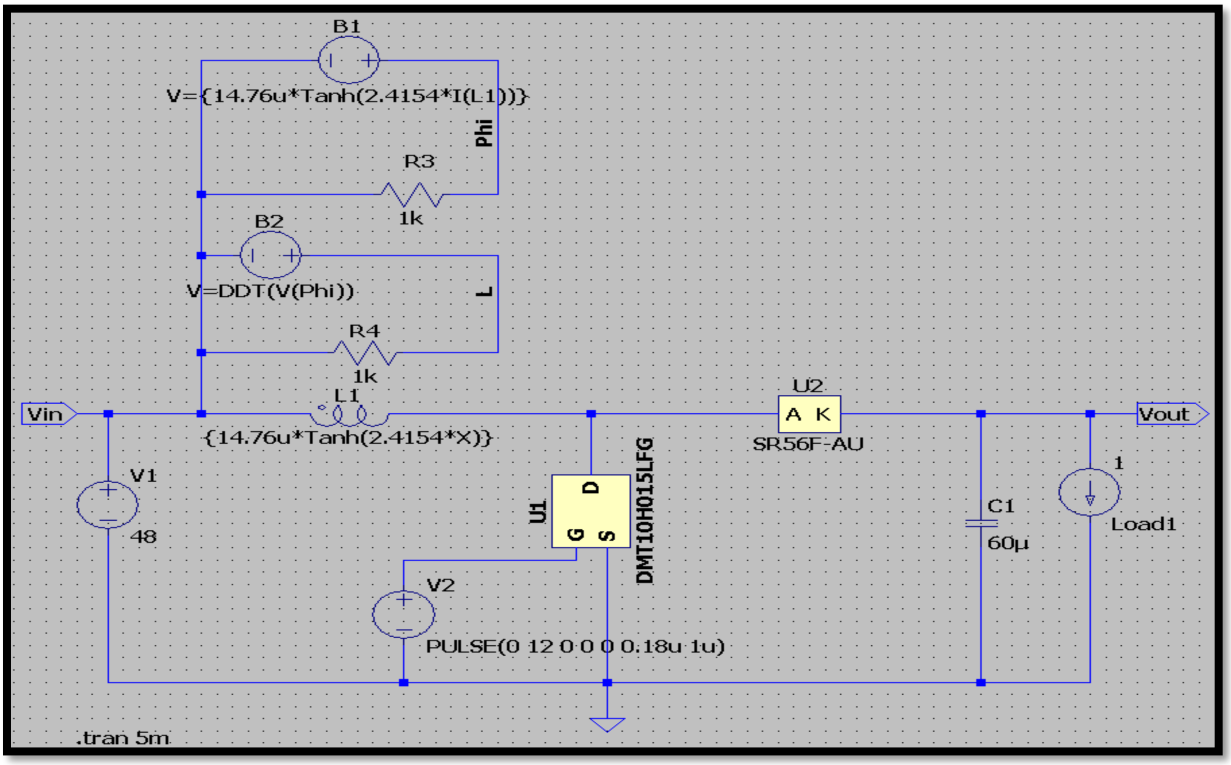
Practical Considerations in LTspice Simulation :

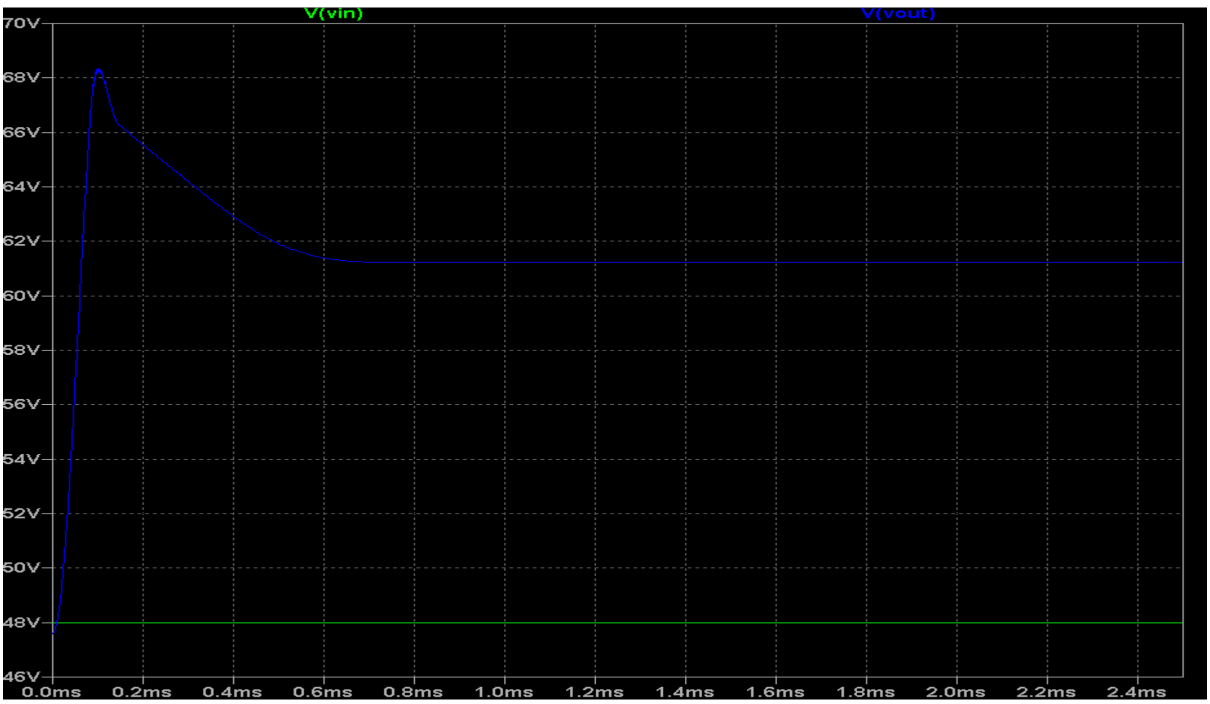
When implementing this design in LTspice, the nonlinear inductance model needs to be simulated accurately. The above derivations provide the basis for setting up the inductor parameters in LTspice to observe how the inductance changes with varying current demand. This simulation helps in understanding the inductor's performance under real operating conditions, ensuring that the design meets the required specifications.

Summary

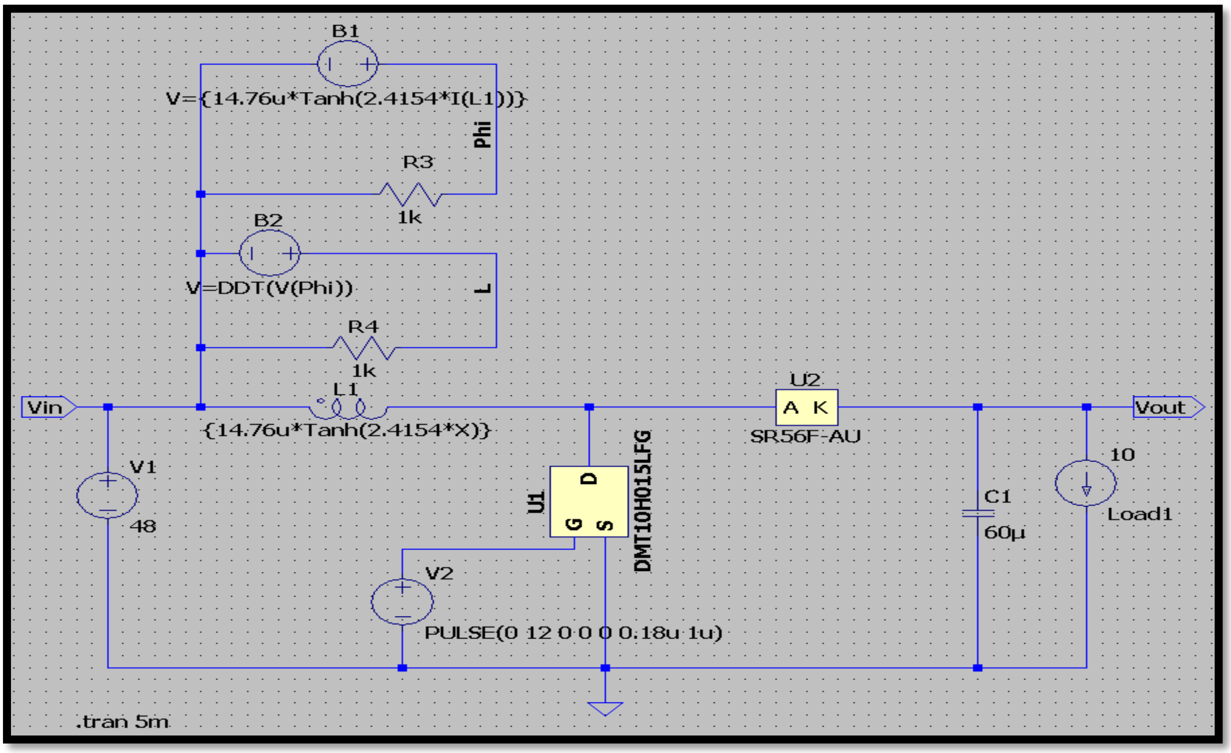
By considering the nonlinear characteristics of the core material, we can derive a more accurate model for the inductor's inductance. This approach ensures that the inductor will perform as expected in high-frequency applications, such as in a boost converter operating at 1 MHz. The derived formulas and simulation setup provide a robust framework for designing and verifying the inductor's performance.

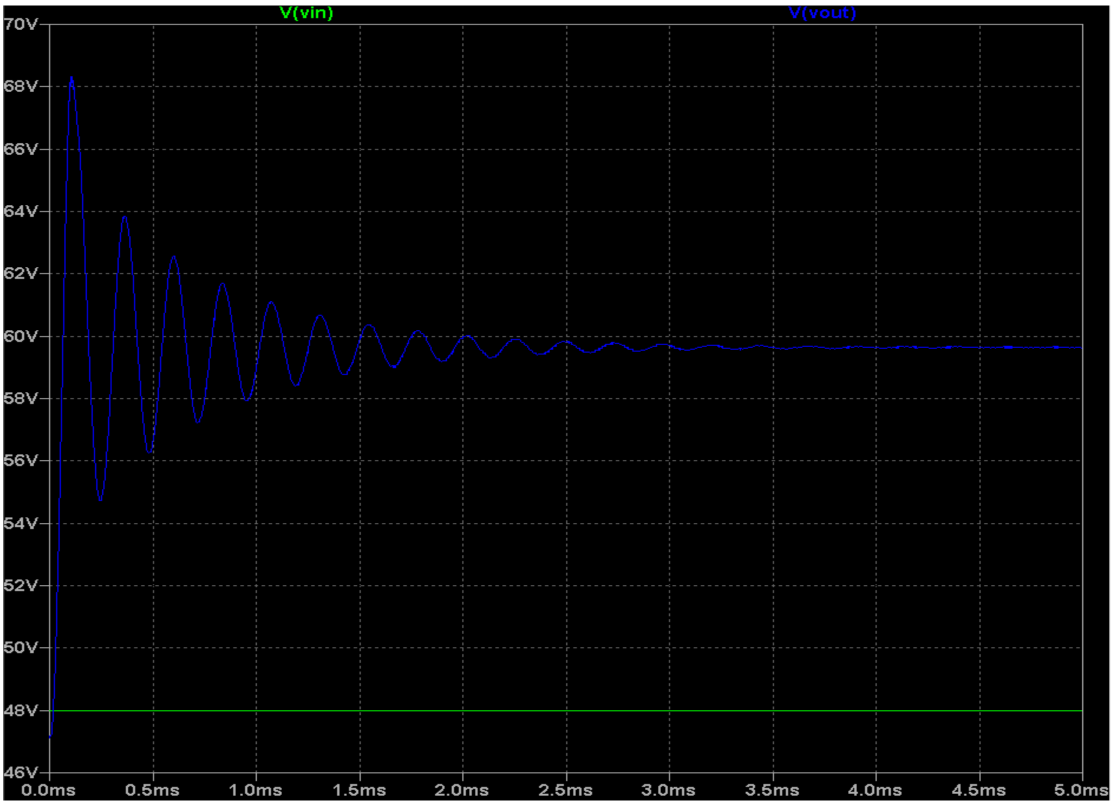
Case 1: Load demand is light load (1A). Boost converter deliver ~ 61V. Steady state condition achieve less than 6 msec.





Case 2: Load demand is high (10A). Boost converter deliver ~ 59.68V. Steady state condition achieve 3.5 msec i.e. longer time require to be in steady state condition for high load demand.





Summary

Case 1: Light Load Demand (1A)

In the scenario where the load demand is light, specifically 1 Ampere, the boost converter successfully delivers an output voltage of approximately 61V. The converter achieves steady-state conditions in less than 6 milliseconds. This rapid stabilization demonstrates the converter's efficiency and responsiveness under light load conditions.

Case 2: High Load Demand (10A)

In contrast, under high load demand conditions, with a current requirement of 10 Amperes, the boost converter delivers an output voltage of approximately 59.68V. Achieving steady-state conditions in this scenario takes longer, with the system stabilizing in 3.5 milliseconds. The increased time to reach steady-state under high load demand indicates the additional effort required by the converter to handle the substantial current, reflecting the dynamic response and performance characteristics of the system under varying load conditions.

Conclusion

These observations highlight the boost converter's capability to maintain near-target voltage levels under both light and high load demands, with a notable difference in the time required to reach steady-state conditions. The converter's efficiency in quickly stabilizing under light loads and its ability to manage higher loads, albeit with a slightly longer stabilization period, underscore its reliability and robustness in diverse operating scenarios.

Resources :

1) **BOOK : DC/DC BOOK OF KNOWLEDGE By Steve Roberts**

2) **BOOK : POWER ELECTRONICS Converters, Applications, and Design THIRD EDITION**

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