KAZAKH BRITISH TECHNICAL UNIVERSITY

School of Information Technology and Engineering

Fee 2 laboratory work 6, High frequency transformer operation

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Almaty 2024

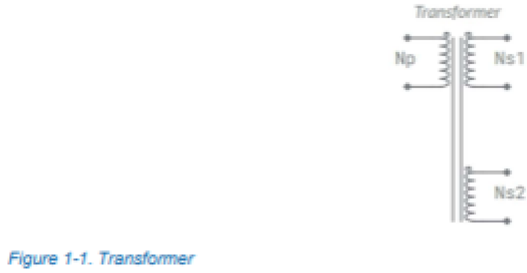


Figure 1: Transformer

Lab 5: Project Lab – High frequency transformer operation
Section 1: Amplifiers

1 Real-World Scenario

The goal of this lab is to investigate the behavior of a high-frequency power transformer, which is widely used in isolated switching power supplies to step-up and step down the voltage and to achieve galvanic isolation between the source and the load. First, we review the principle of operation and the main equations and waveforms of a transformer. Next, we simulate the transformer to analyze the effects of its parameters on voltage and current waveforms. Finally, we perfom lab experiments to observe the voltages and currents of a real high-frequency transformer under square-wave voltage operation.

2 Theory and background

Introduction In this section, we review the fundamental concepts relevant to the operation of a transformer. First, we analyze the principle of operation and the resulting voltage and current waveforms. Next, we discuss the effect of magnetizing and leakage inductance on the transformer operation. Finally, we analyze the effect of windings resistance.

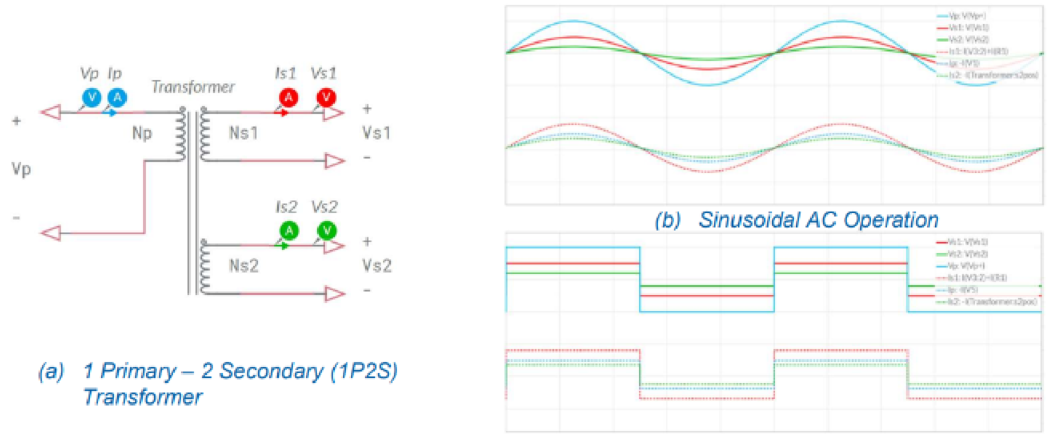
3 Ideal Transformer

A transformer is comprised of a primary coil with No turns and N secondary coils with Ns...,NSN turns, wounded around a core of magnetic material. The transformer converts the AC primary voltage Vp(t), applied to the primary coil, into the AC secondary voltages Vs (t), ..., VsN(t) of secondary coils, according to Equations 1-1:

$\mathrm{V}_s 2 = Ns1/Np2 * Vp(t)$
$Vsn(t) = Ns1/Np2 * Vp(t)$ (1)

Equation 1-2 $$I_p(t) = \frac{N_{s1}}{N_p} I_{s1}(t) + \ldots + \frac{N_{sN}}{N_p} I_{sN}(t)$$

Figure 1-2(a) shows a transformer with two secondary coils. Figures 1-2(b) and 1-2(c) show the primary and secondary voltage and current waveforms of the transformer with N_p =10, N_{s1} = 5, N_{s2} = 2, R_{o1} = R_{o2} = 50Ω, subjected to a 100kHz/20Vpp sinusoidal and square-wave primary voltage.



(a) 1 Primary – 2 Secondary (1P2S) Transformer

(b) Sinusoidal AC Operation

(c) Square-Wave AC Operation

Figure 1-2. Ideal Transformer Input and Output Waveforms in AC Operation.

Figure 2: Ideal transformer Input and Output Waveforms in AC operation

$$Llm.pk = \frac{1}{Lm} \int_0^{Ts/4} Vp(t)dt = \frac{Vlm}{4FsLm}$$

$$\lambda = \int_0^{Ts/4} Vp(t)dt = \frac{Vlm}{4fs} < Ilm * Lm = \lambda$$

$$CopperLoss(IRLoss):$$

$\mathrm{P}_{\mathrm{Cu}} = I^2R$

Core Loss (Eddy Current and Hysteresis Loss): $P_{\text{core}} = P_{\text{eddy}} + P_{\text{hysteresis}}$

Total Loss (Copper Loss + Core Loss): $P_{\text{total}} = P_{\text{Cu}} + P_{\text{core}}$

Efficiency (%): Efficiency$(\%) = \frac{P_{\text{output}}}{P_{\text{input}}} \times 100$ (4)

Parallel Connection:

$$I_{\text{total}} = I_1 + I_2 + \ldots + I_n$$

Series Connection:

$$V_{\text{total}} = V_1 + V_2 + \ldots + V_n$$

1-5 Single, Parallel and Series Connections of Secondary Coils

Connecting a single secondary coil to a load resistor R_o, while the other one is open, results in Equations 1-12:

Equation 1-12 $$V_{Lm} = \frac{V_p}{1+\frac{N_{sx}^2}{N_p^2}\frac{R_p}{R_{sx}+R_o}},\ I_{sp} = \frac{V_{Lm}}{N_p^2}\frac{N_{sx}^2}{R_{sx}+R_o},\ P_{Rsx} = \frac{R_{sx}V_{Lm}^2}{(R_{sx}+R_o)^2}\frac{N_{sx}^2}{N_p^2},\ P_{Ro} = \frac{R_o V_{Lm}^2}{(R_{sx}+R_o)^2}\frac{N_{sx}^2}{N_p^2}$$

where the subscript *sx* can be *s1* or *s2*. The two secondary coils can be connected in parallel only if $N_{s1} = N_{s2}$. This connection is adopted if a higher output current rating is required. The two coils in parallel are equivalent to a single secondary coil with resistance $R_{seq} = R_{s1}R_{s2}/(R_{s1}+R_{s2})$ and turns number $N_{seq} = N_{s1} = N_{s2}$. The two secondary coils can be connected in series. This connection is adopted if a higher output voltage rating is required. The two coils in series are equivalent to a single secondary coil with resistance $R_{seq} = R_{s1}+R_{s2}$ and turns number $N_{seq} = N_{s1}+N_{s2}$. Connecting the parallel or series secondary coils to a load resistor R_o results in the Equations 1-13:

Equation 1-12 $$V_{Lm} = \frac{V_p}{1+\frac{N_{seq}^2}{N_p^2}\frac{R_p}{R_{seq}+R_o}},\ I_{sp} = \frac{V_{Lm}}{N_p^2}\frac{N_{seq}^2}{R_{seq}+R_o},\ P_{Rseq} = \frac{R_{seq}V_{Lm}^2}{(R_{seq}+R_o)^2}\frac{N_{seq}^2}{N_p^2},\ P_{Ro} = \frac{R_o V_{Lm}^2}{(R_{seq}+R_o)^2}\frac{N_{seq}^2}{N_p^2}$$

where R_{seq} and N_{seq} are determined according to the selected connection. Given the connection of secondary coils, the primary coil rms current and ohmic loss and transformer efficiency are given by Equations 1-13:

Figure 3: Parallel and series connections of secondary coils

Check Your Understanding

Note: The following questions are meant to help you self-assess your understanding so far. You can view the answer key for all "Check your Understanding" questions at the end of the lab.

1-1 What is the function of a transformer?

A. to convert a square-wave source voltage into a sinusoidal load voltage
B. to convert a primary voltage into proportional secondary voltages
C. to transform a voltage source into a current source

1-2 What are the factors determining the ratio between primary voltage and secondary voltages?

A. the cross section and length of coils
B. the cross section and magnetic path length of magnetic core
C. the primary and secondary coils turn numbers and secondary coils connection

1-3 How is the primary coil current related to the secondary coils currents?

A. it is the sum of secondary coils currents, each one multiplied by the relevant secondary-to-primary turns ratio
B. it is the sum of secondary coils currents
C. it is the inverted sum of secondary coils currents

1-4 What is the effect of transformer magnetizing inductance?

A. the primary coil current is affected by a triangular ripple component
B. the secondary coils currents are affected by a triangular ripple component
C. the secondary coils voltages are affected by a triangular ripple component

1-5 How can the peak amplitude of magnetizing current be reduced?

A. by increasing the primary coil voltage or the secondary coils turns numbers
B. by increasing the magnetizing inductance or the operation frequency
C. by decreasing the magnetizing inductance or the primary coil turns number

1-6 Why do we need to limit the magnetizing current?

A. to reduce the size of the transformer
B. to prevent secondary coils overvoltage
C. to prevent the magnetic core saturation

Figure 4: Test

2 Exercise

The transformer of the DC-AC Inverter Section of the TI Power Electronics Board for NI ELVIS III is characterized by the following nominal parameters:

- $N_{s1}/N_p = N_{s2}/N_p = 0.585$
- $R_p = 50\text{m}\Omega$, $R_{s1} = 30\text{m}\Omega$, $R_{s2} = 35\text{m}\Omega$
- $L_m = 100\mu\text{H}$, $L_p = 0.5\mu\text{H}$, $\lambda_{max} = 105\mu\text{Vs}$
- $P_{core} \approx 0\text{W}$

Two connection options are available for secondary coils #1 and #2:

option (a): the secondary coil #1 is open and the secondary coil #2 is connected to a 100Ω load resistor R_o

option (b): the secondary coils #1 and #2 are connected in series with a 100Ω load resistor R_o

2-1 Assuming the voltage applied to primary coil is a 100kHz-20Vpp square-wave, use the equations provided in the **Theory and Background** section to calculate:

- the peak value of magnetizing current, in milli Ampère with one decimal digit of accuracy:

option (a): $I_{Lm,pk}$ [mA] = _____ **option (b):** $I_{Lm,pk}$ [mA] = _____

- the value of the Volt-second integral applied to the primary coil, in micro Volt-second with one decimal digit of accuracy:

option (a): λ [μVs] = _______ **option (b):** λ [μVs] = _______

- the amplitude of the square-wave voltage applied to load resistor R_o, in Volts with two decimal digits of accuracy:

option (a): V_{Ro} [V] = _________ **option (b):** V_{Ro} [V] = _________

- the amplitude of the square-wave primary coil current, in milli Ampère with one decimal of accuracy:

option (a): I_{sp} [mA] = _______ **option (b):** I_{sp} [mA] = _______

- the transformer efficiency, with three decimal digits of accuracy:

option (a): η = ____________ **option (b):** η = _____________

2-2 Assuming the voltage applied to primary coil is a 20Vpp square-wave, use the equations provided in the **Theory and Background** section to calculate the minimum operating frequency allowing to prevent the core saturation, in kilo Hertz with three decimal digits of accuracy:

option (a): $f_{s,min}$ [kHz] = __________
option (b): $f_{s,max}$ [kHz] = __________

Figure 5: Caption

1-1. B
1-2. C
1-3. A
1-4. A
1-5. B
1-6. C

2-1

a) $I_{Lm,pk}\,[mA] = \dfrac{V_{Lm}}{4 f_s L_m} = 2{,}06$

b) $I_{Lm} = \dfrac{1}{100 \cdot 10^{-5}} \cdot \int_0^{2{,}5 \cdot 10^{-6}} 20\,(t)\,dt$

$T = \dfrac{1}{f} = \dfrac{1}{100 \cdot 10^{3}} = 1 \cdot 10^{-5}$

$U_{Lm} = \dfrac{U_p}{1 + \dfrac{N_{Sx}^2}{N_p^2} \cdot \dfrac{R_p}{R_{Sx} + R_o}} = \dfrac{10V}{1 + (0{,}585)^2 \cdot \dfrac{50}{35+100}} = 9{,}99V$

$U_p = \dfrac{V_{pp}}{2} = \dfrac{20}{2} = 10V$

$R_p = 50 m\Omega$.

$R_{S2} = 35 m\Omega$.

$R_o = 100\,\Omega$

$$\boxed{\begin{aligned} N_{seq} &= N_1 + N_2 \\ R_{seq} &= R_{S1} + R_{S2} \end{aligned}}$$

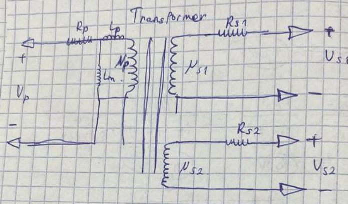
$I_{Lm,peak} = \dfrac{V_{Lm}}{4 \cdot f_s \cdot L_m} = \dfrac{10}{4 \cdot 10^5 \cdot 100 \cdot 10^{-6}} = 250\,mA$

a) $\lambda\,[\mu Vs] = \dfrac{U_{Lm}}{4 f_s} = \dfrac{9{,}99V}{4 \cdot 10^5} = 2{,}49 \cdot 10^{-5} = 2{,}5 \cdot 10^{-5}$

b) $\lambda_{series} = 25\,\mu Vs$.

option (a)

$U_{R_o}\,[V] = \dfrac{R_{o1} V_{Lm}}{R_{S1} + R_{o1}} \cdot \dfrac{N_{S1}}{N_p} = 0{,}585 \cdot \dfrac{9{,}99V \cdot 100}{30 \cdot 10^{-4} + 100} = \dfrac{5}{135} = 4{,}49$



b) $U_{Ro}\,[V] = 0{,}585 \cdot \dfrac{9{,}99V \cdot 100}{100 + 85} = 3{,}159$

4) option (a)

$I_{sp}\,[mA] = V_{Lm}\left((0{,}585)^2 \cdot \dfrac{1}{100+50} + (0{,}585)^2 \dfrac{1}{100+35}\right)$

$= 9{,}99 \cdot (0{,}00263 + 0{,}00253) = 0{,}05$ $\quad \dfrac{V_{Lm}}{N_p^2} \dfrac{N_{Sx}^2}{R_{Sx} + R_o}$

b) same $= 0{,}0253 = (0{,}585)^2 \cdot 9{,}99 \cdot \dfrac{1}{135}$

5) $\eta = \dfrac{P_{load}}{P_{load} + P_{loss}}$

$P = I \cdot U$

$P_{loss} = P_{RSx} + P_{core} = 0W +$

$P_{loss} = P_{core} + P_{RSx} = 0W + 0{,}0655 = 0{,}6655$

$P_{RSx} = \dfrac{N_{Sx}^2}{N_p^2} \cdot V_{Lm}^2 \cdot \dfrac{R_{Sx}}{(R_{Sx} + R_o)^2} = (9{,}99V)^2 \cdot (0{,}585)^2 \cdot \dfrac{35}{(35+100)^2} =$

$= 34{,}15 \cdot 0{,}0019 = \boxed{0{,}0655}$

$P_{load} = P_{Ro_1} + P_{Ro_2}$

$P_{Ro} = \dfrac{N_{Sx}^2}{N_p^2} \cdot V_{Lm}^2 \cdot \dfrac{R_o}{(R_{Sx} + R_o)^2} = \dfrac{100}{(135)^2} (0{,}585)^2 \cdot (9{,}99)$

$= 0{,}1873$

$\eta = \dfrac{P_{load}}{P_{load} + P_{loss}} = \dfrac{0{,}1873}{0{,}252} = 0{,}743$

Simulation high frequency transformer operation zero DC component in Primary Coil Voltage

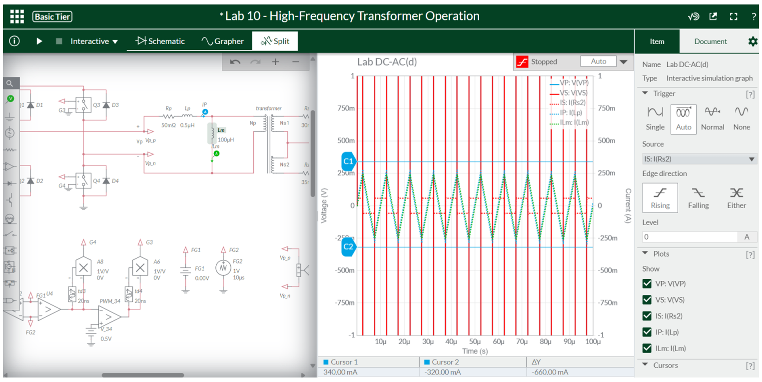


Figure 7: Simulation of High frequency transformer operation

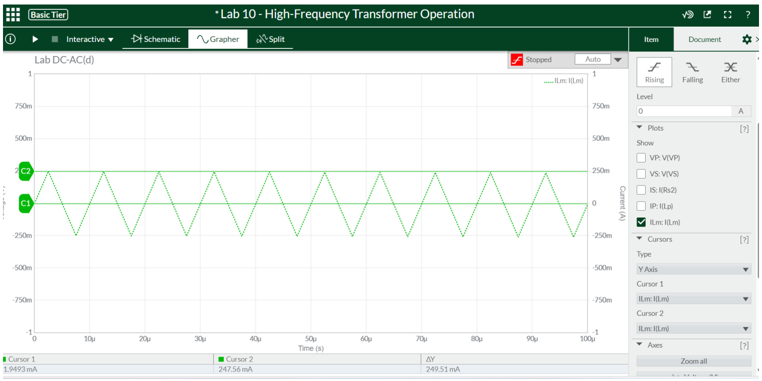


Figure 8: Simulation Ilm(peak,peak)

Determine Ilm(peak)

$$Ilm = \frac{249.51}{2} \tag{7}$$

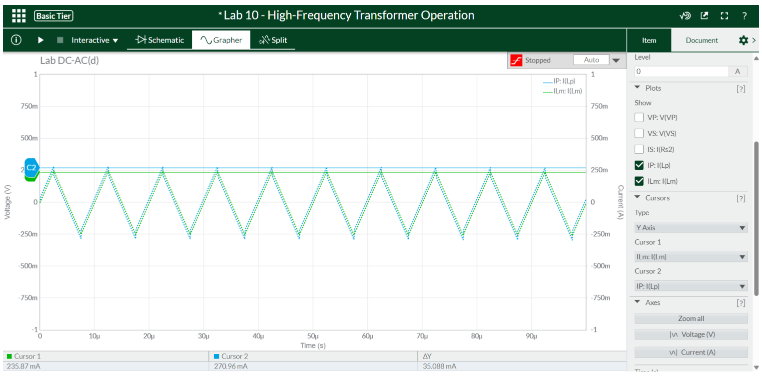


Figure 9: Isp= Ip,peak- Ilm,pk

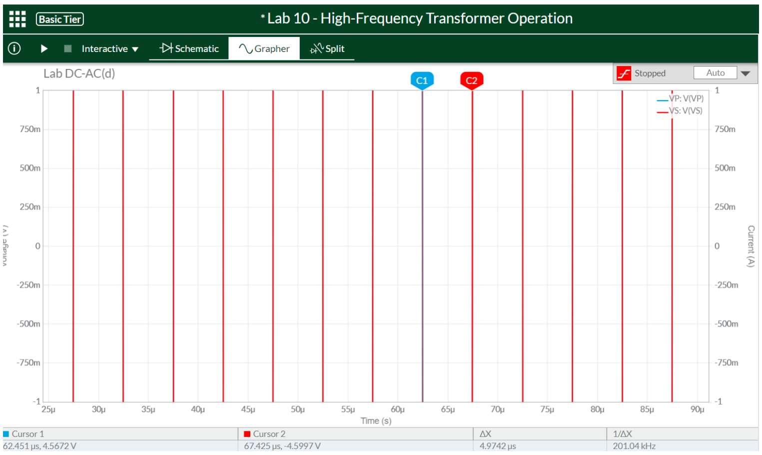


Figure 10: Amplitude of Vr0

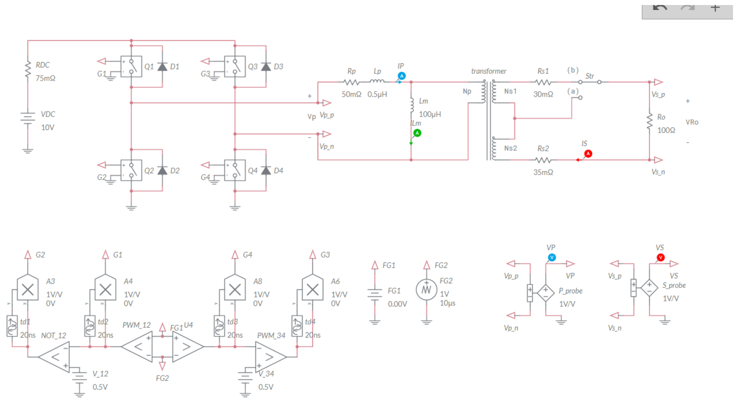


Figure 11: b) part of Simulation

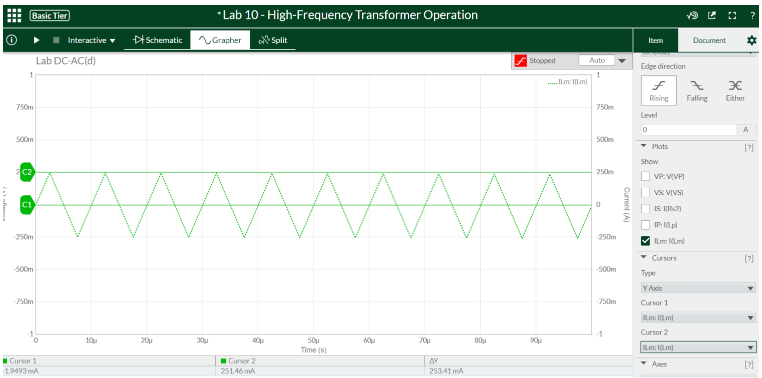


Figure 12: b) part of Simulation

Second Simulation part with non- zero DC component in Primary Coil Voltage

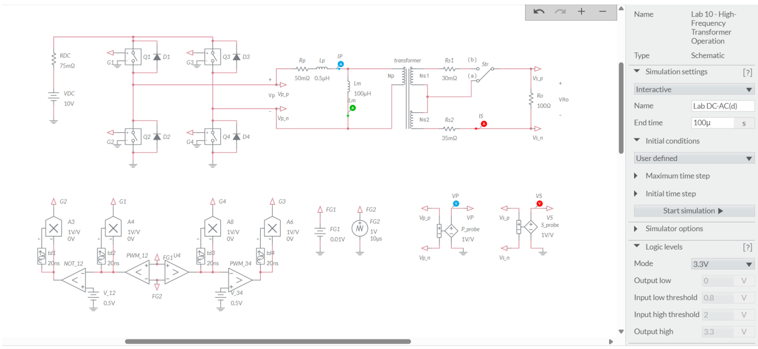


Figure 13: non- Zero Simulation

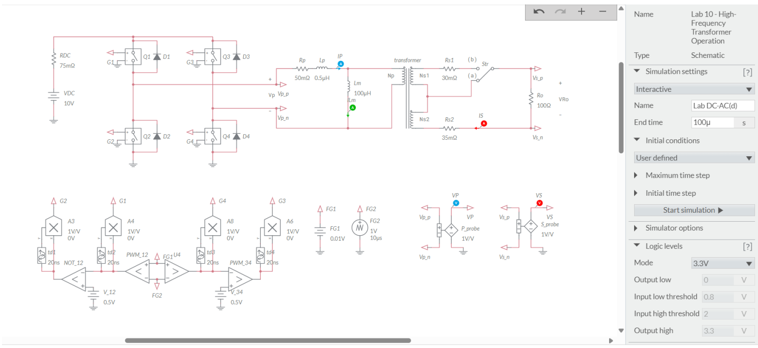


Figure 14: non- Zero Simulation

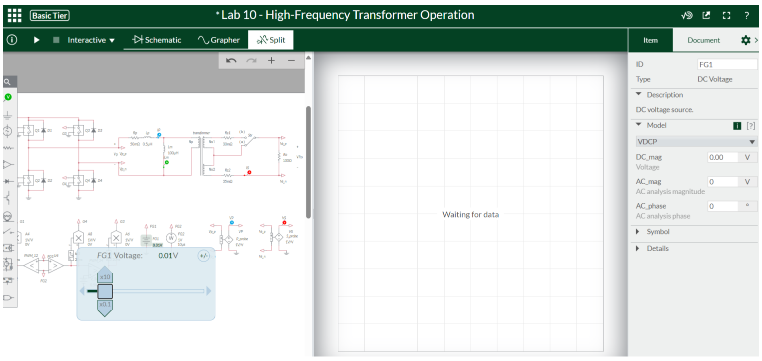


Figure 15: Setting parameters for non- Zero Simulation

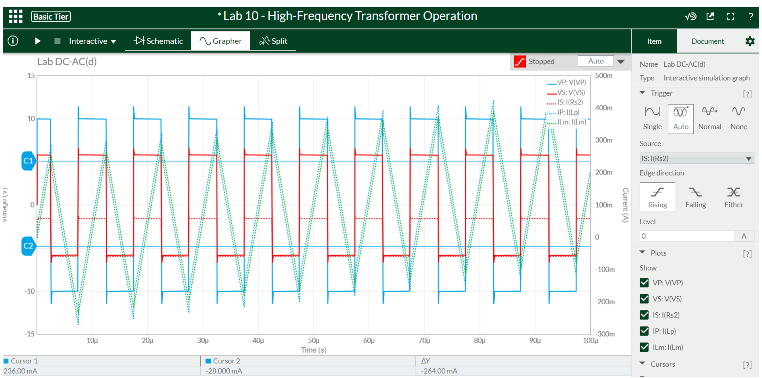


Figure 16: Setting parameters for non- Zero Simulation

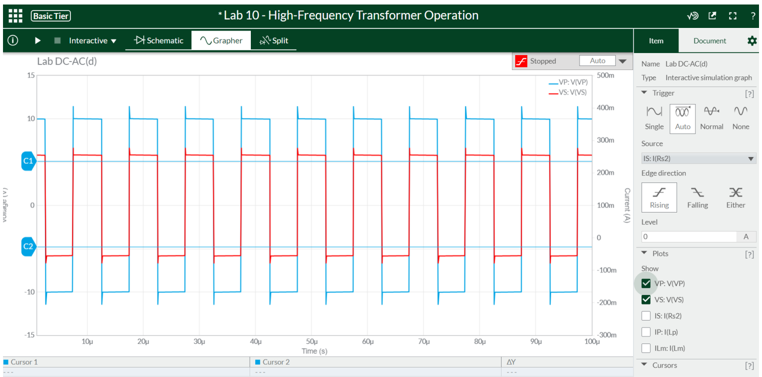


Figure 17: Setting parameters for non- Zero Simulation

4 Conclusion

In conclusion, the operation of high-frequency transformers is a critical aspect of modern power electronics and electrical engineering. These transformers operate at frequencies significantly higher than traditional transformers, typically in the kHz to MHz range, offering several advantages such as smaller size, reduced weight, and higher efficiency. One of the key principles governing their operation is the behavior of magnetic materials at high frequencies, where core losses and skin effect become significant factors influencing transformer performance. Design considerations for high-frequency transformers include careful selection of core materials, winding configurations, insulation techniques, and cooling methods to optimize efficiency and minimize losses. High-frequency transformers find wide applications in various fields such as power supplies, inverters, converters, radio frequency (RF) circuits, telecommunications, and renewable energy systems. Their compact size, fast response, and high power density make them indispensable components in modern electronic devices and systems.