A

Report

of

Assignments

in

Power Electronics Laboratory

Prepared

by

Shivraj Vishwakarma

(M. Tech., PE, Roll No. – 224102112)

Submitted

To

Dr. A. Ravindranath

(*Asst. Professor*)

Department of Electronics & Electrical Engg.

Indian Institute of Technology, Guwahati

Experiment - 08

To Study the Operation of Single-Phase and Three Phase Voltage Source Inverters (VSI) Using MATLAB/Simulink.

NAME: SHIVRAJ VISHWAKARMA ROLL. NO. 224102112

1. DESIGN PARAMETERS:

PARAMETERS	Single-phase VSI	Three-phase VSI
Output voltage	230 V, 50 Hz	400 V, 50 Hz
Output Power	1 kW	10 kW
Switching Frequency	10 kHz	10 kHz
Load type	Resistive	Resistive, Y-connected
Modulation index	0.4 and 0.8	0.4 and 0.8

2. PROCEDURE:

1. Consider a single-phase full-bridge VSI with LC filter and resistive load. The switching signals are generated using sine-triangle PWM with bipolar voltage switching. Calculate the input voltage, load resistance and LC filter parameters for the modulation index values given in the table.
2. Simulate the single-phase VSI using the parameters calculated in step 1. Take the snapshots of input voltage, output voltage of full-bridge (i.e., PWM voltage before filter), load voltage, and inductor current. Check whether load voltage is 230 V, 50 Hz, sine-wave.
3. Repeat steps 1 and 2 when the switching signals generated using sine-triangle PWM with unipolar voltage switching.
4. Now consider a three-phase, three-leg VSI supplying a three-phase Y-connected resistive load through an LC filter. The switching signals are generated using sine-triangle PWM. Calculate the input voltage, load resistance and LC filter parameters for the modulation index values given in the table.
5. Simulate the three-phase VSI using the parameters calculated in step 4. Take the snapshots of input voltage, output voltage of full-bridge (i.e., PWM voltage before filter), load voltage, and inductor current. Check whether load voltage is three-phase, 400 V, 50 Hz, balanced and sinusoidal.

1. Single Phase Full-Bridge VSI with LC filter and resistive load

➢ CIRCUIT DIAGRAM:

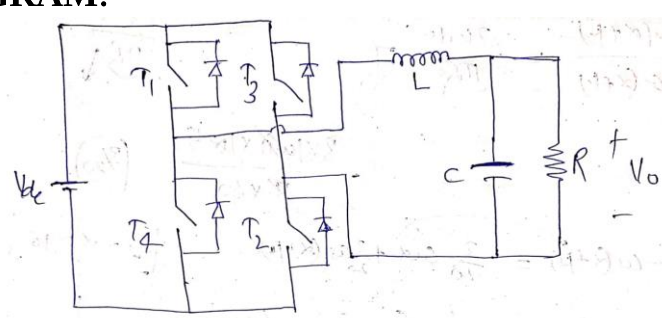


Fig 1: Single Phase full bridge VSI

➢ DESIGN PARAMETERS CALCULATION:

1). INPUT VOLTAGE:

We know that for single phase full bridge invereter the fundamental component of output voltage can be given as

$$\widehat{V_{01}} = m_a V_{dC} \Rightarrow V_{01_{RMS}} = \frac{m_a V_{dC}}{\sqrt{2}} \Rightarrow V_{dC} = \frac{\sqrt{2}\, V_{01_{RMS}}}{m_a} \qquad (1)$$

Using the given values as $V_{01_{RMS}} = 230\ V$, at $m_a = 0.4$

$$V_{dC} = \frac{\sqrt{2}*230}{0.4} = \mathbf{813.17\ V} \qquad (2)$$

And at $m_a = 0.8$, $\quad V_{dC} = \frac{\sqrt{2}*230}{0.8} = \mathbf{406.58\ V} \qquad (3)$

2). LOAD RESISTANCE:

Since the output power is given as P = 1 kW, so by using power expression,

$$P = \frac{{V_o}^2}{R} \Rightarrow R = \frac{{V_o}^2}{P} = \frac{230^2}{1000} = \mathbf{52.9\ \Omega} \qquad (3)$$

3). FILTER INDUCTOR & CAPACITOR:

Assuming **L = 2 mH**, and since frequency is 10 kHz, so by using,

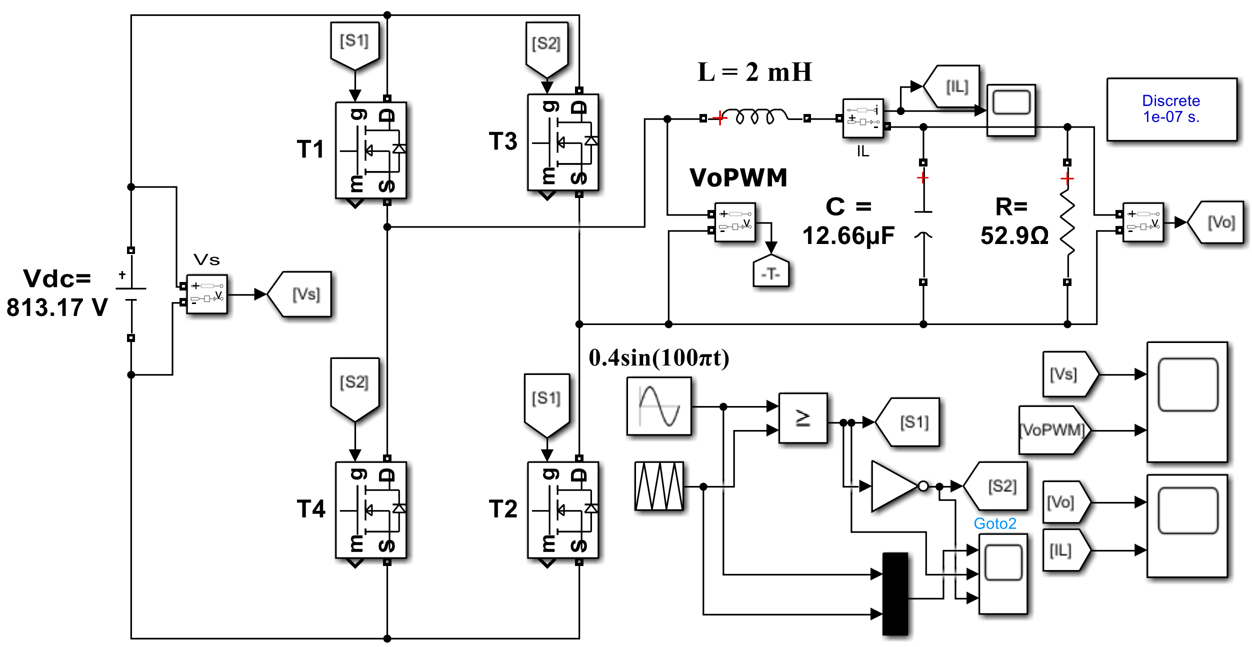
$$\omega = \frac{1}{\sqrt{LC}} \quad \Rightarrow C = \frac{1}{4\pi^2 f^2 L} \quad \Rightarrow C = \mathbf{12.66\ \mu F} \qquad (3)$$

2. Simulation of Single Phase Full-Bridge VSI

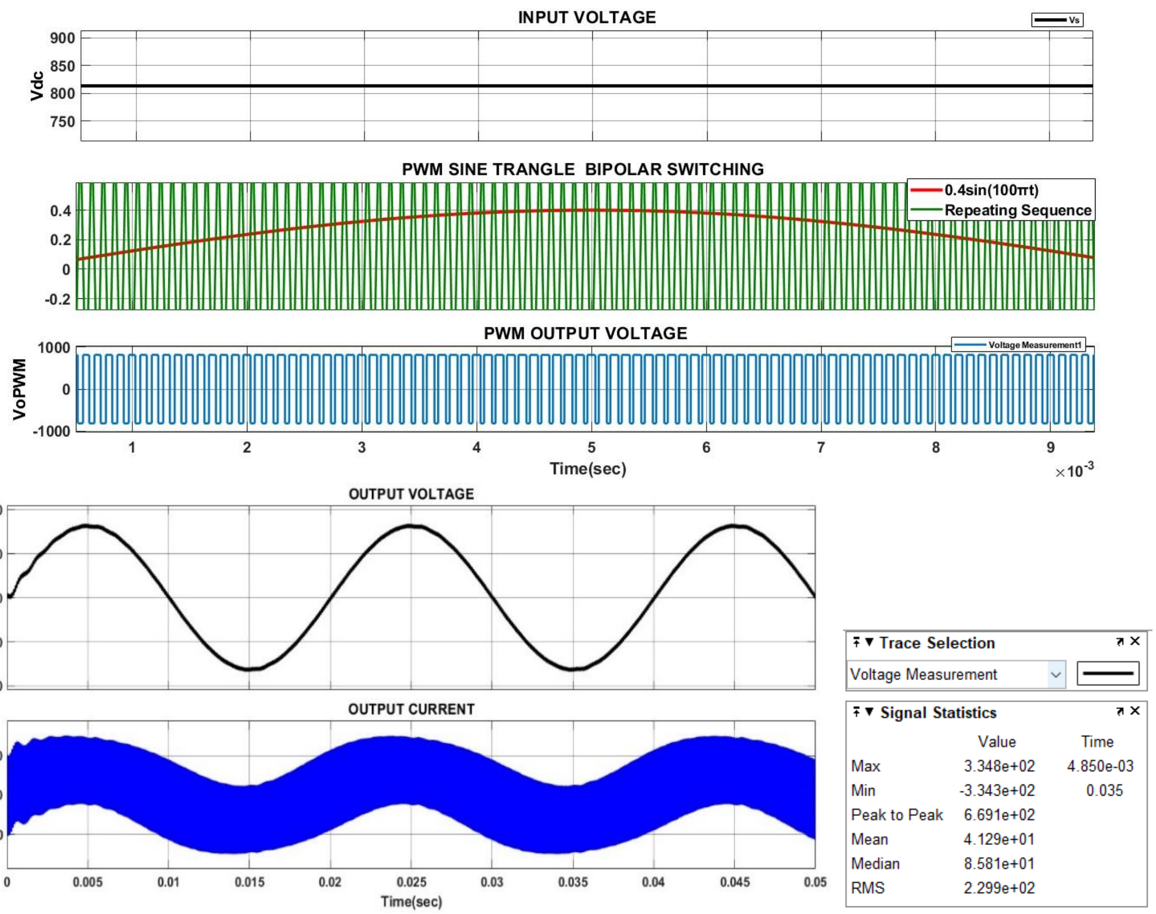
➢ SIMULATION CONFIGRATION:

❖ At m =0.4

➢ SIMULATED CIRCUIT:



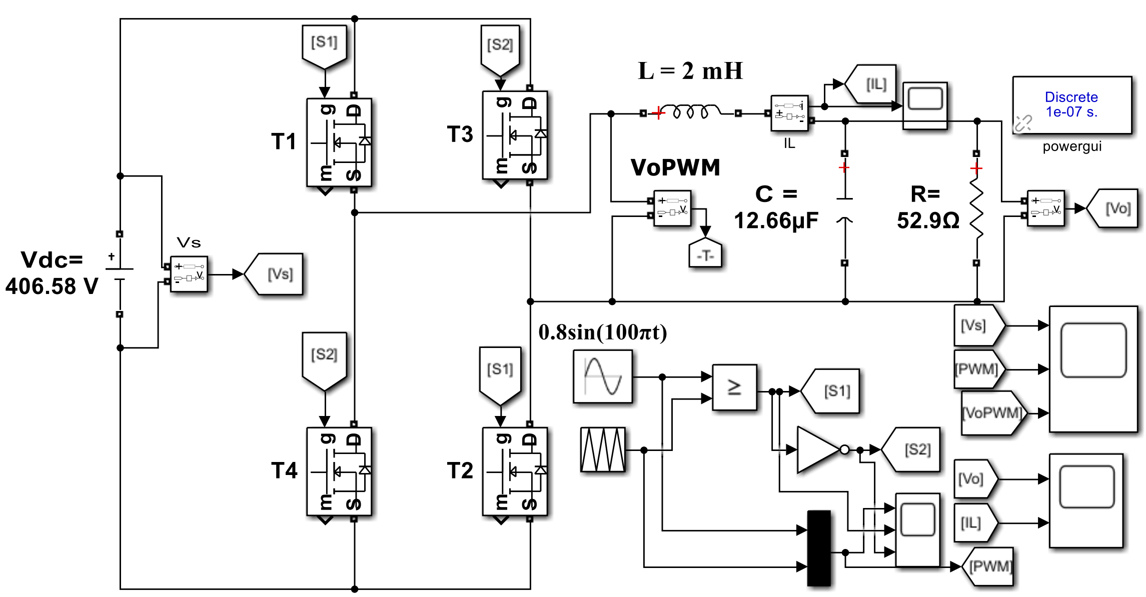
➢ WAVEFORMS OBTAINED:



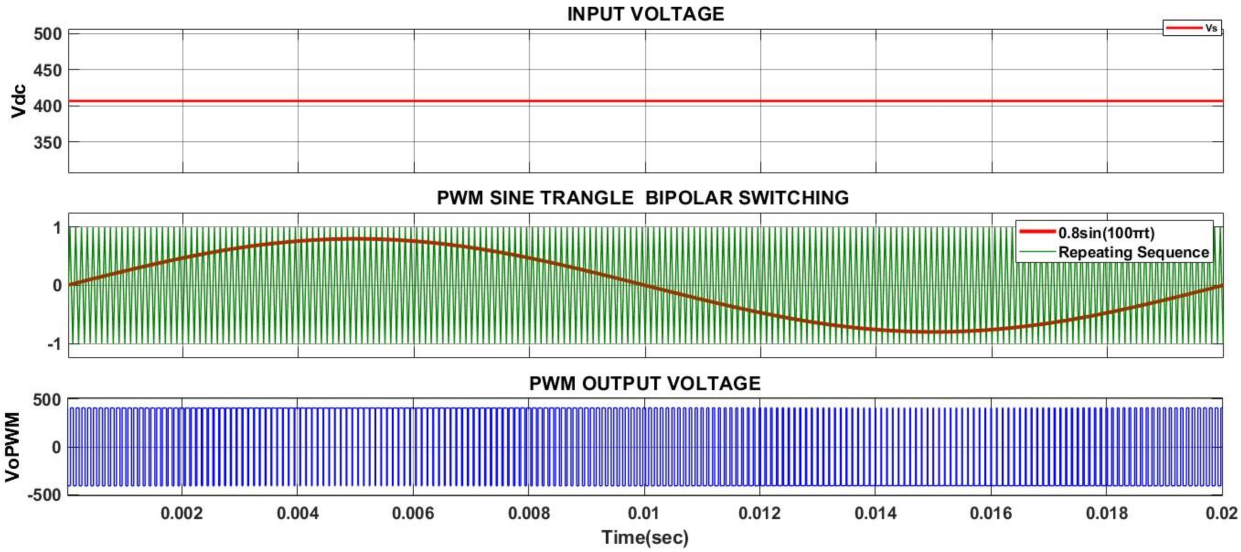
- **OBSERVATION**: RMS value of Vo = **299.9 V**

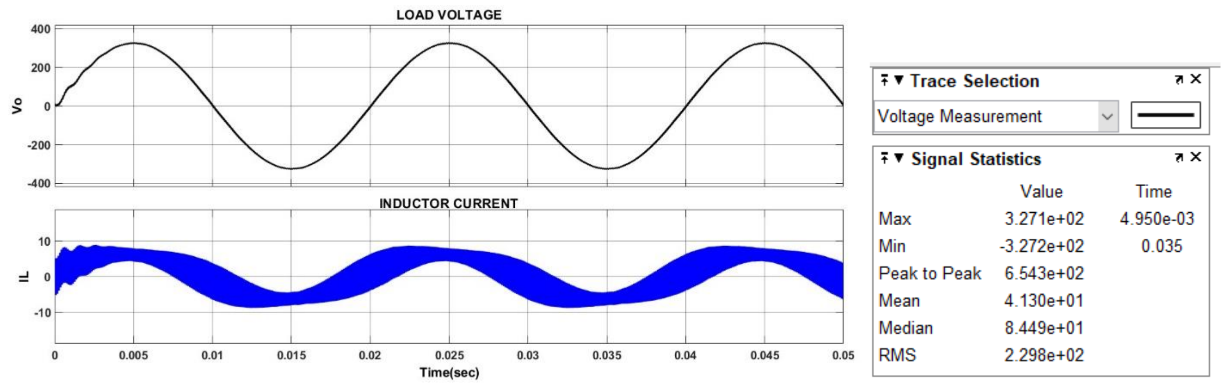
❖ At m =0.8

- **SIMULATED CIRCUIT:**



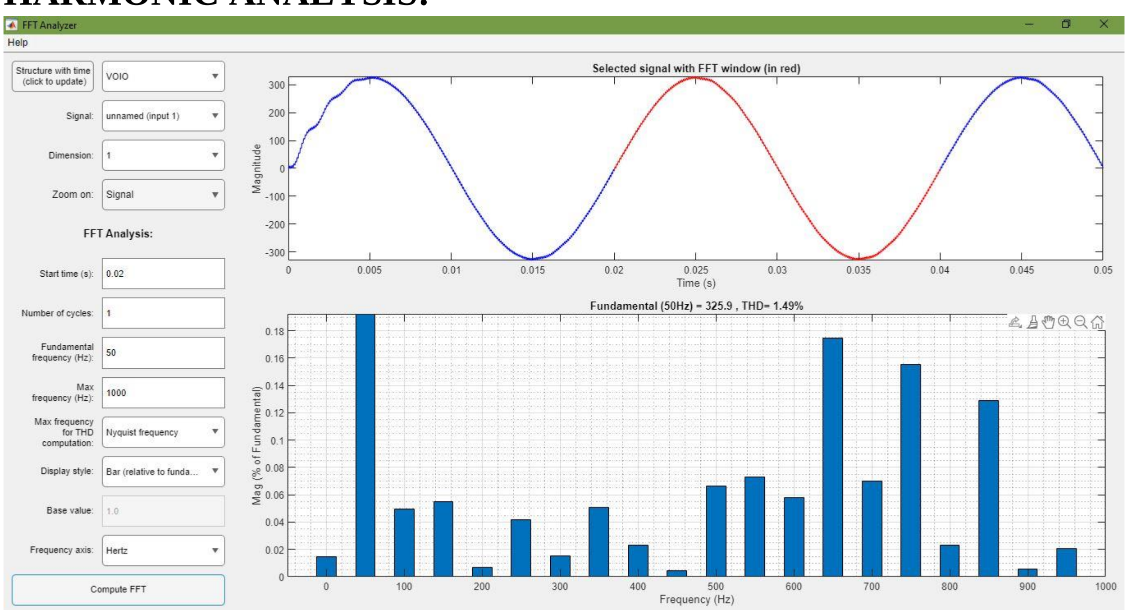
➢ WAVEFORMS OBTAINED:





➢ OBSERVATION: RMS value of Vo = **299.9 V**

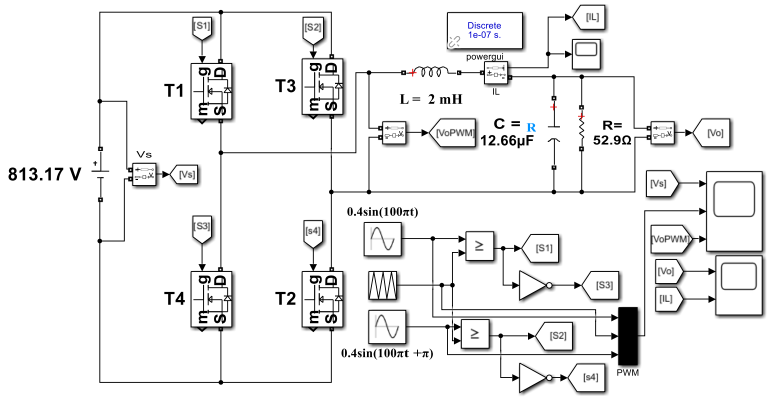
➢ HARMONIC ANALYSIS:



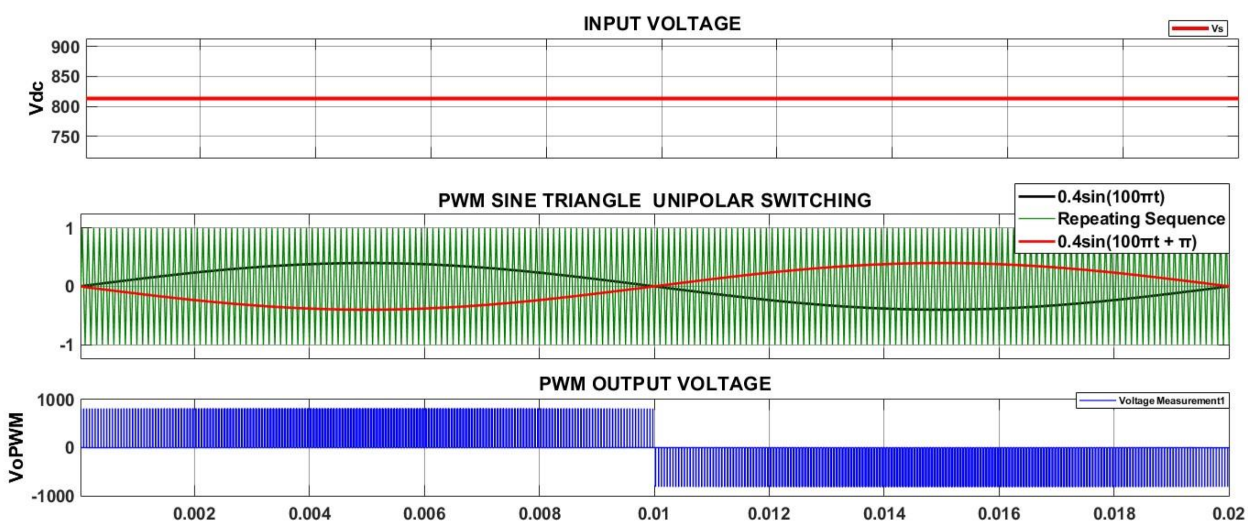
3. Single Phase Full-Bridge VSI with Unipolar PWM Switching

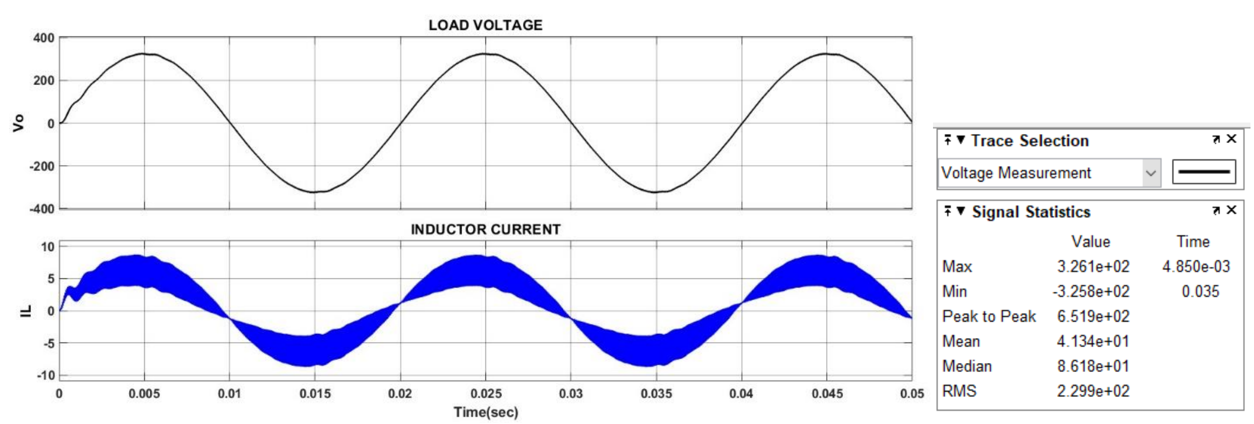
❖ At m =0.4

- **SIMULATED CIRCUIT:**



- **WAVEFORMS OBTAINED:**

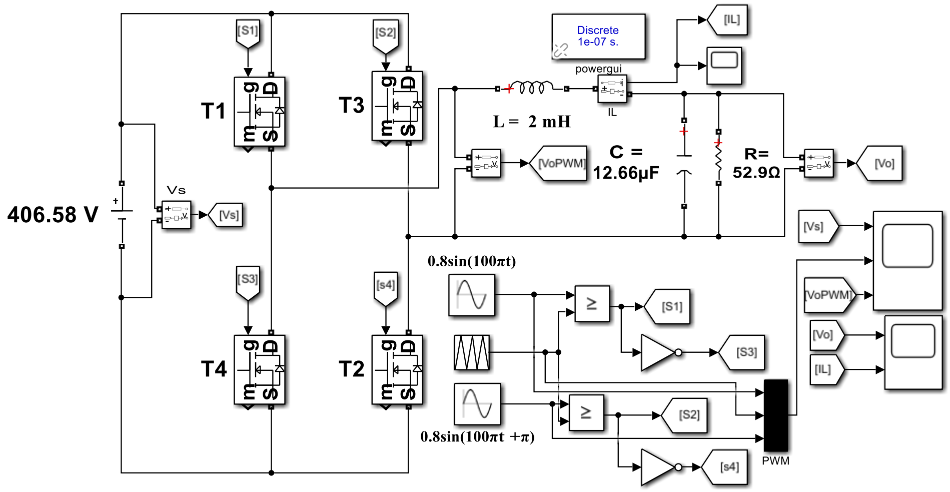




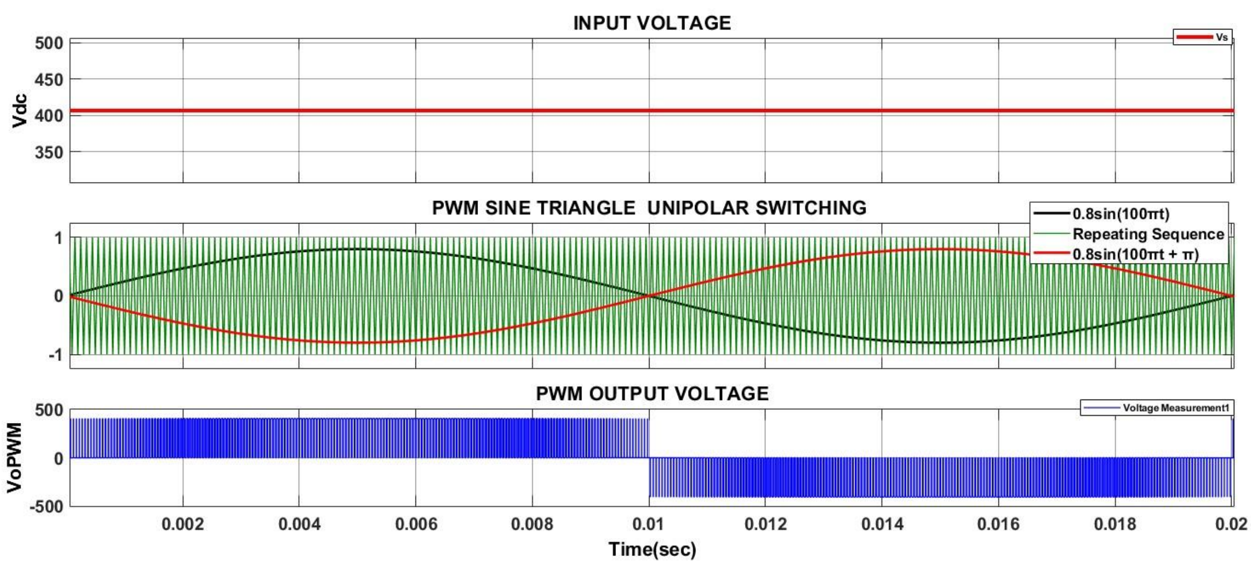
- **OBSERVATION**: RMS value of Vo = **299.9 V**

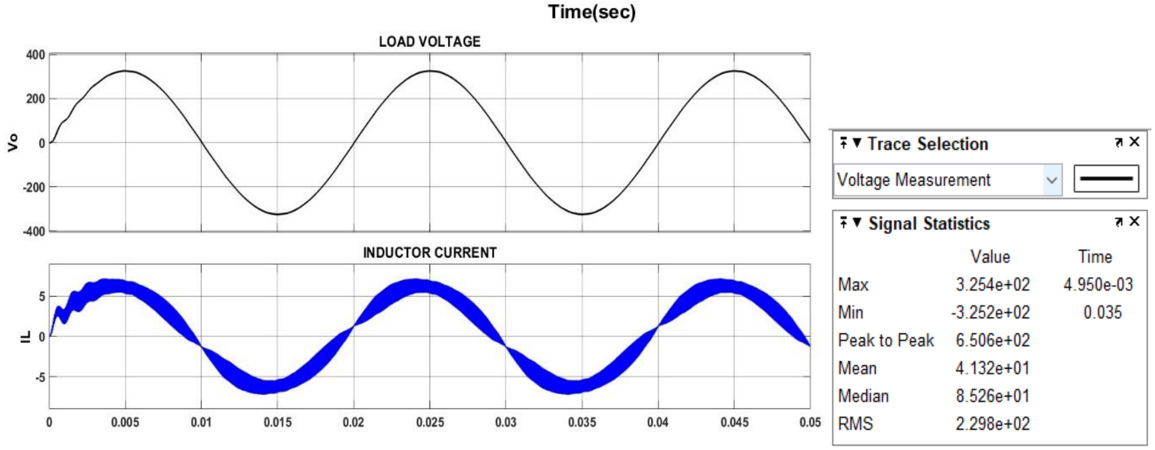
❖ At m =0.8

➢ SIMULATED CIRCUIT:



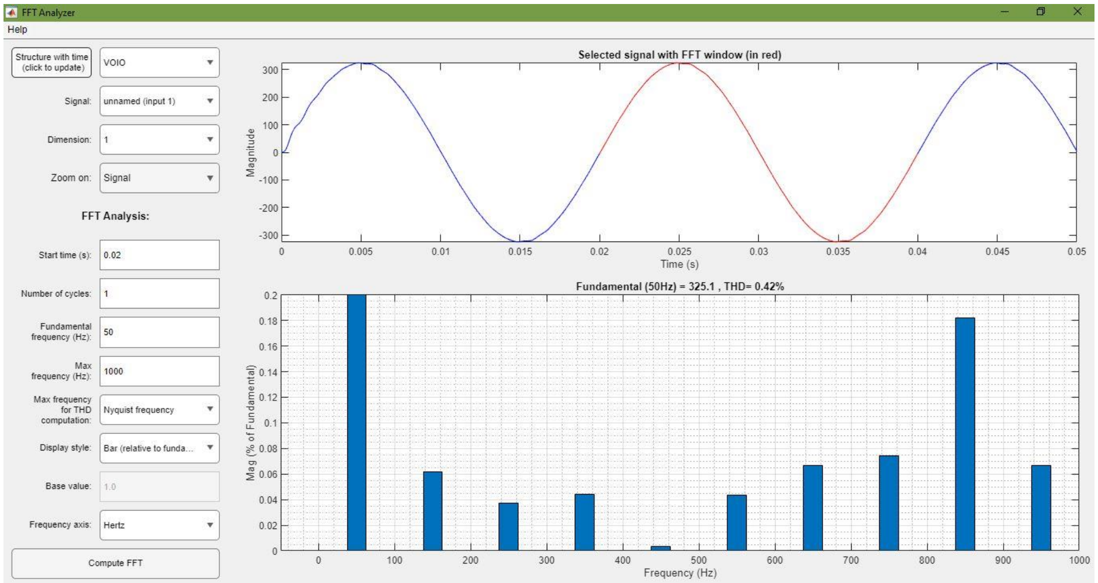
➢ WAVEFORMS OBTAINED:





➢ **OBSERVATION**: RMS value of Vo = **299.8 V**

➢ HARMONIC ANALYSIS:



4. Three Phase Full-Bridge VSI

➢ CIRCUIT DIAGRAM:

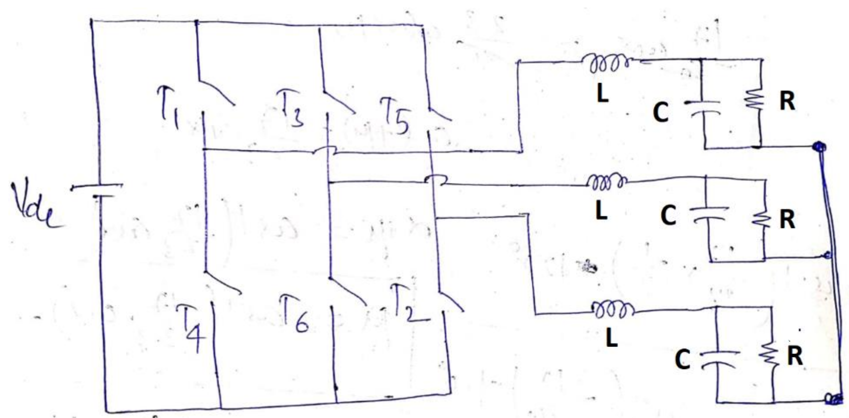


Fig 2: Three Phase full bridge VSI

➢ DESIGN PARAMETERS CALCULATION:

1). INPUT VOLTAGE:

We know that for three phase full bridge invereter the line to line RMS voltage of fundamental component of output voltage can be given as

$$V_{LL_1} = \frac{\sqrt{3}m_a V_{dC}}{2\sqrt{2}} \Rightarrow \quad V_{dC} = \frac{2\sqrt{2}\,V_{LL_1}}{\sqrt{3}m_a} \tag{5}$$

Using the given RMS values as $V_{LL_1} = 400\ V$,

$$\text{And at } m_a = 0.4, \quad V_{dc} = \frac{2\sqrt{2}*400}{\sqrt{3}*0.4} = \mathbf{1632.993\ V} \tag{6}$$

$$\text{And at } m_a = 0.8, \quad V_{dc} = \frac{2\sqrt{2}*400}{\sqrt{3}*0.8} = \mathbf{816.4966\ V} \tag{7}$$

2). LOAD RESISTANCE:

Since the output power is given as P = 10 kW, so by using power expression,

$$P = \frac{{V_o}^2}{R} \Rightarrow R = \frac{{V_o}^2}{P} = \frac{400^2}{10000} = \boldsymbol{16\ \Omega} \tag{8}$$

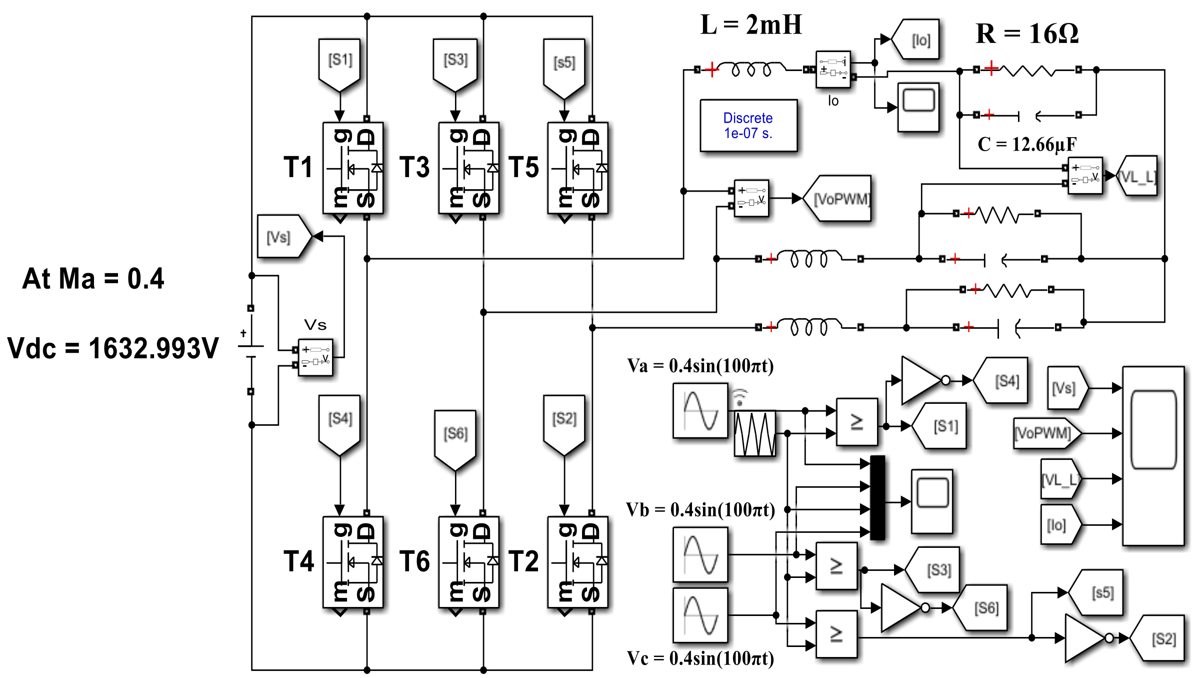
3). FILTER INDUCTOR & CAPACITOR:

Assuming **L = 2 mH**, and since frequency is 10 kHz, so by using,

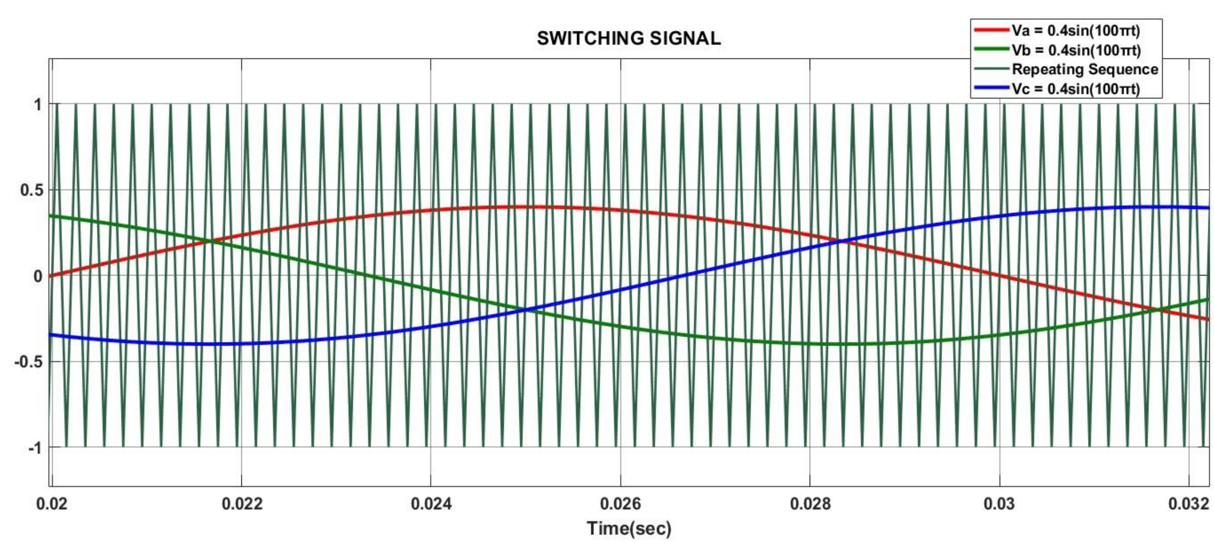
$$\omega = \frac{1}{\sqrt{LC}} \quad \Rightarrow C = \frac{1}{4\pi^2 f^2 L} \quad \Rightarrow C = \mathbf{12.66}\ \mu\boldsymbol{F} \tag{9}$$

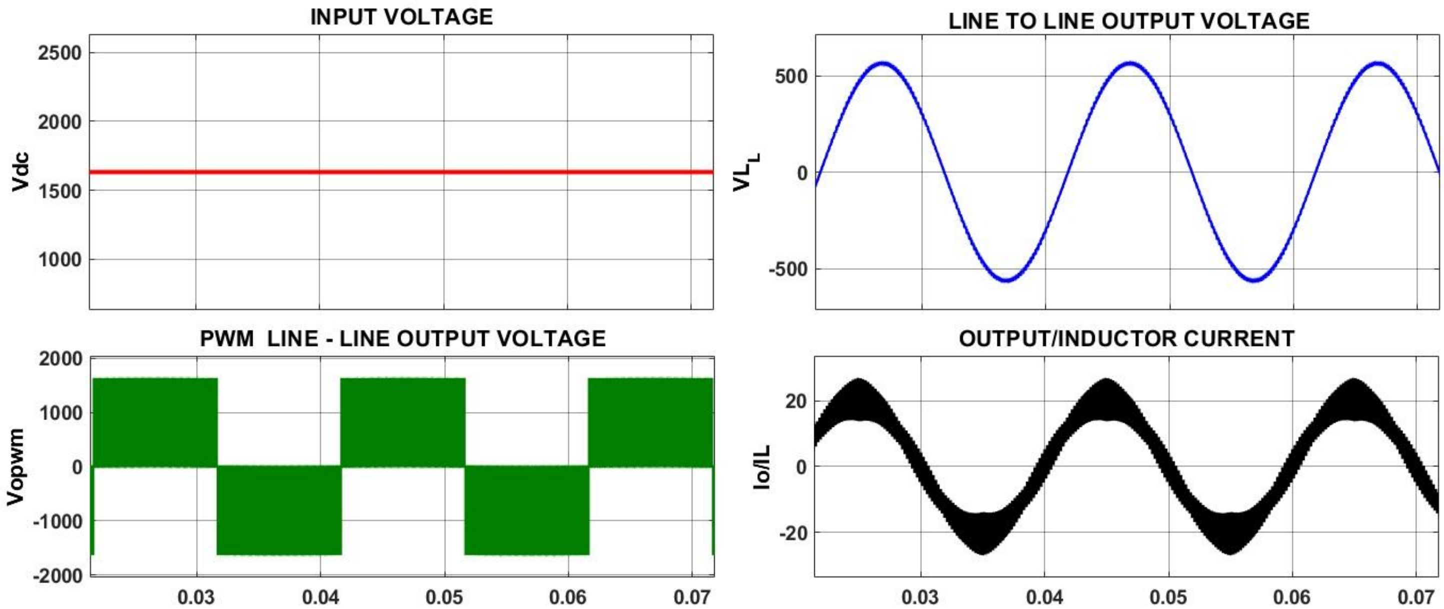
5. Simulation of Three Phase Full-Bridge VSI

➢ SIMULATED CIRCUIT:

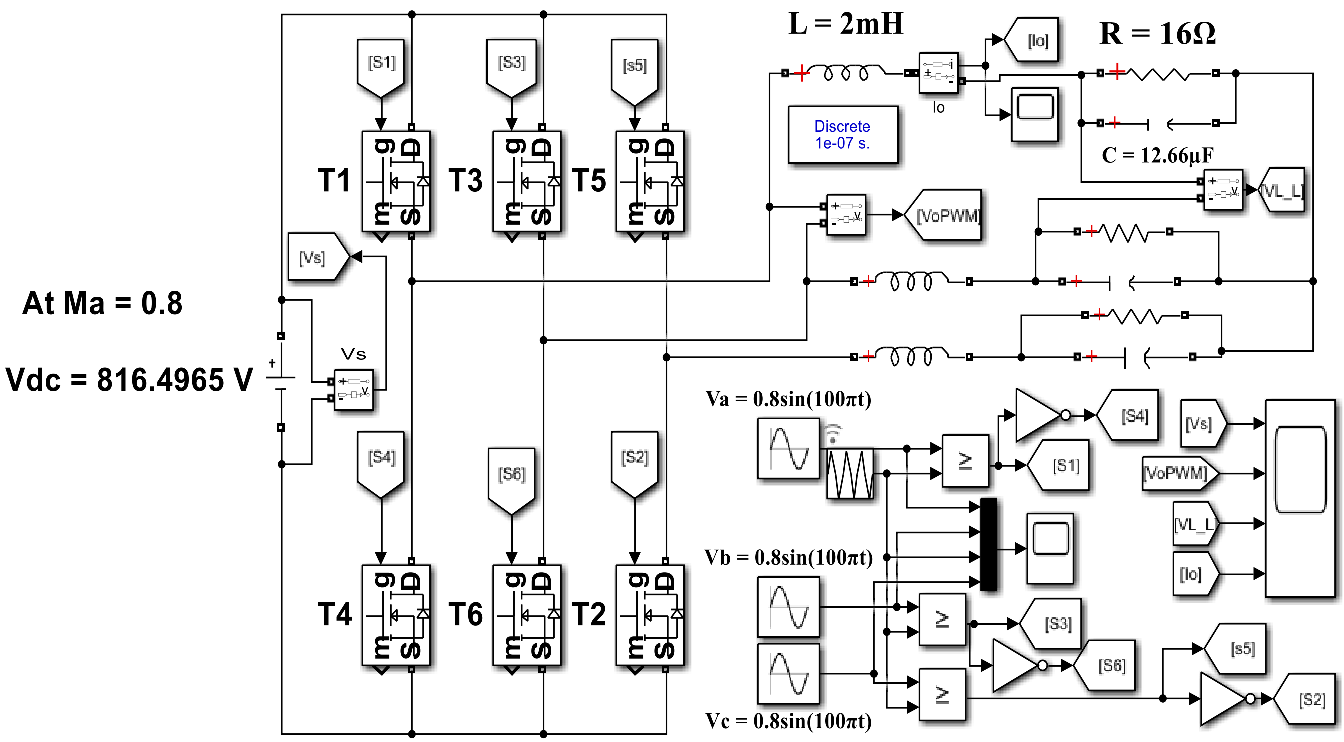


➢ WAVEFORMS OBTAINED:

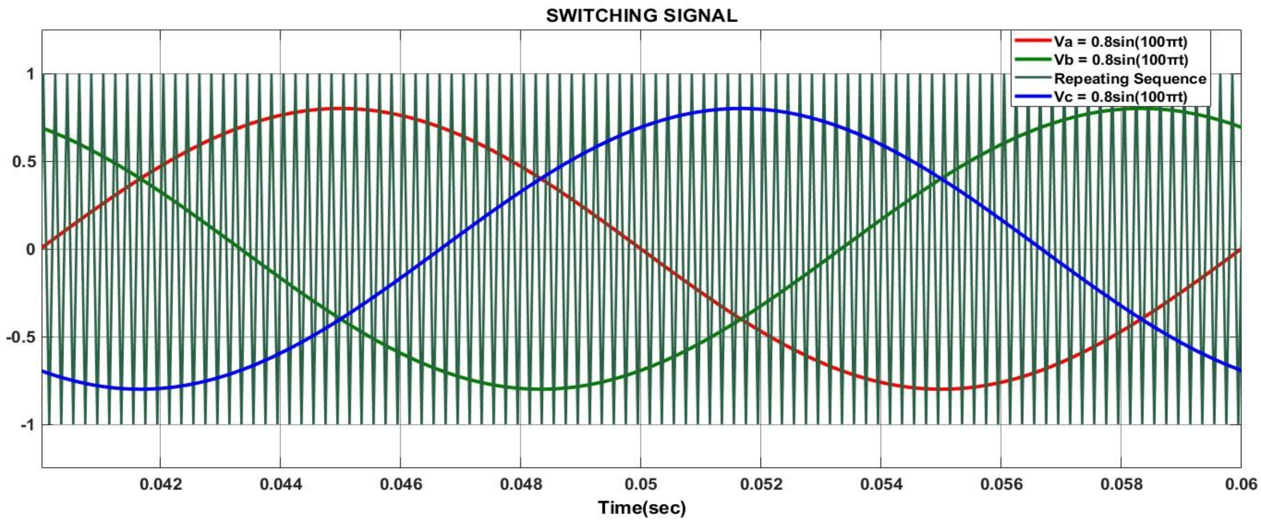


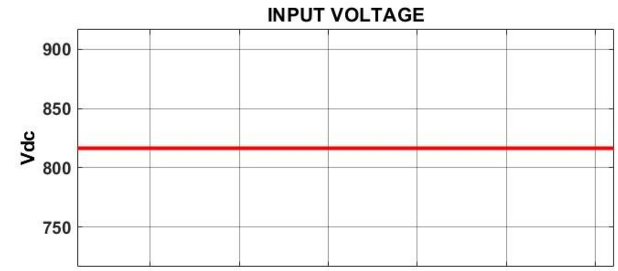


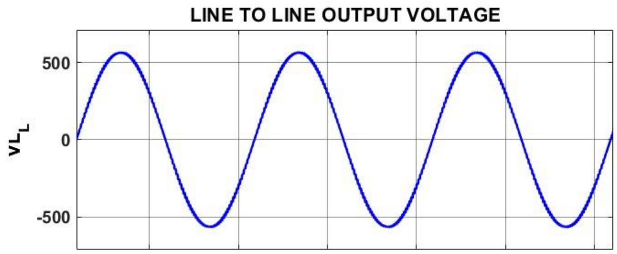
➢ SIMULATED CIRCUIT:

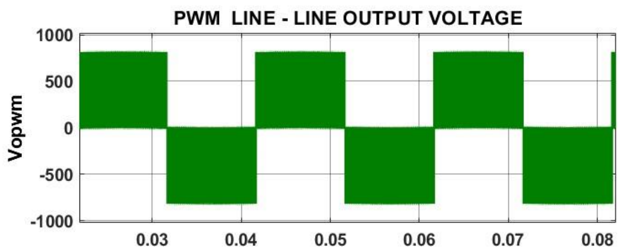


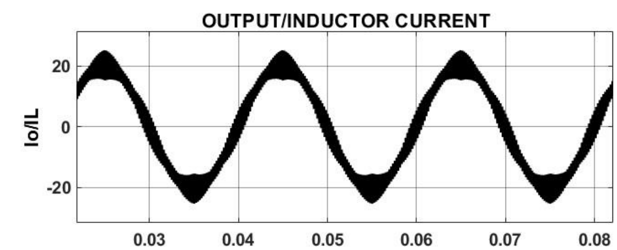
➢ WAVEFORMS OBTAINED:











➢ OBSERVATION:

Trace Selection: Vo

Signal Statistics

	Value	Time
Max	5.725e+02	0.047
Min	-5.723e+02	0.017
Peak to Peak	1.145e+03	
Mean	2.251e-01	
Median	-3.385e-01	
RMS	3.989e+02	

Fig 3: Vo at m_a= 0.4

Trace Selection: Vo

Signal Statistics

	Value	Time
Max	5.694e+02	0.067
Min	-5.702e+02	0.017
Peak to Peak	1.140e+03	
Mean	2.216e-01	
Median	-5.843e-01	
RMS	3.986e+02	

Fig 4: Vo atm_a= 0.8

- RMS value of Vo at m = 0.4: **398.9 V**
- RMS value of Vo at m = 0.8: **398.6 V**

Experiment - 07

To study the operation of Three phase Uncontrolled & Controlled Rectifiers using MATLAB/SIMULINK

.NAME: SHIVRAJ VISHWAKARMA ROLL. NO. 224102112

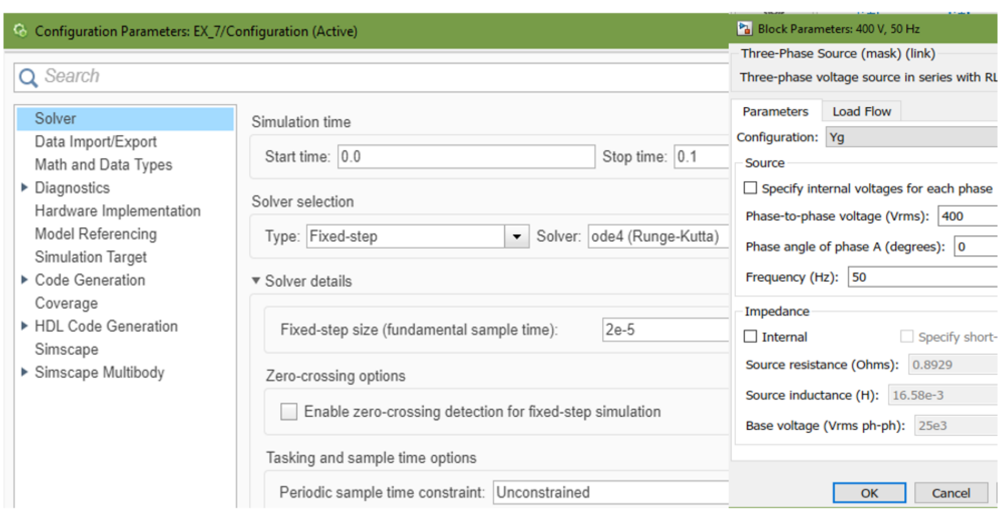
1. —DESIGN PARAMETERS:

Parameter	Value
Input voltage	400 V, 50 Hz, Three-phase
Source Inductance	10 mH
Load Parameters	20 Ω in series with 20 mH Inductance

2. PROCEDURE:

1. Simulate a Three-phase uncontrolled rectifier (with six diodes) with no source inductance. Take the snapshots for source voltages, source currents, load voltage, and load current. Note down the average value, peak-peak ripple in load voltage and load current.
2. Repeat step 2 with source inductance. Observe the change in load voltage and source current waveforms. Note down the commutation angle ‘u’ and match with the theoretical value.
3. Simulate a Three-phase controlled rectifier (with six Thyristors) with no source inductance. Consider four values of Firing angles: α = 30 deg, α = 60 deg, α = 120 deg, and α = 150 deg. Take the snapshots for source voltages, source currents, load voltage, and load current. Note down the average value, peak-peak ripple in load voltage and load current.
4. Repeat step 2 with source inductance. Observe the change in load voltage and source current waveforms. Note down the commutation angle ‘u’ and match with the theoretical value.

3. SIMULATION CONFIGRATION:



1. Full-Bridge Uncontrolled Rectifier without Ls

➢ CIRCUIT DIAGRAM:

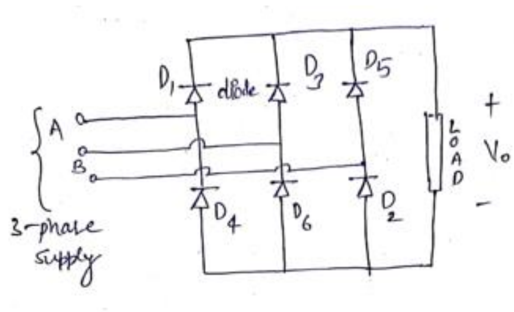
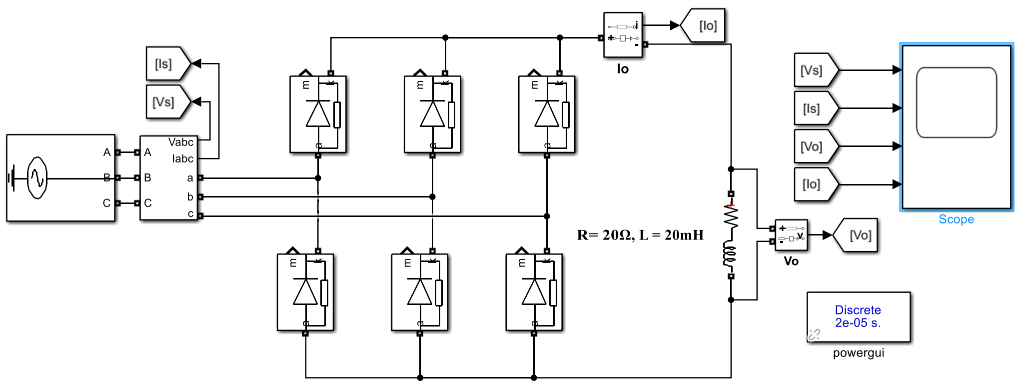
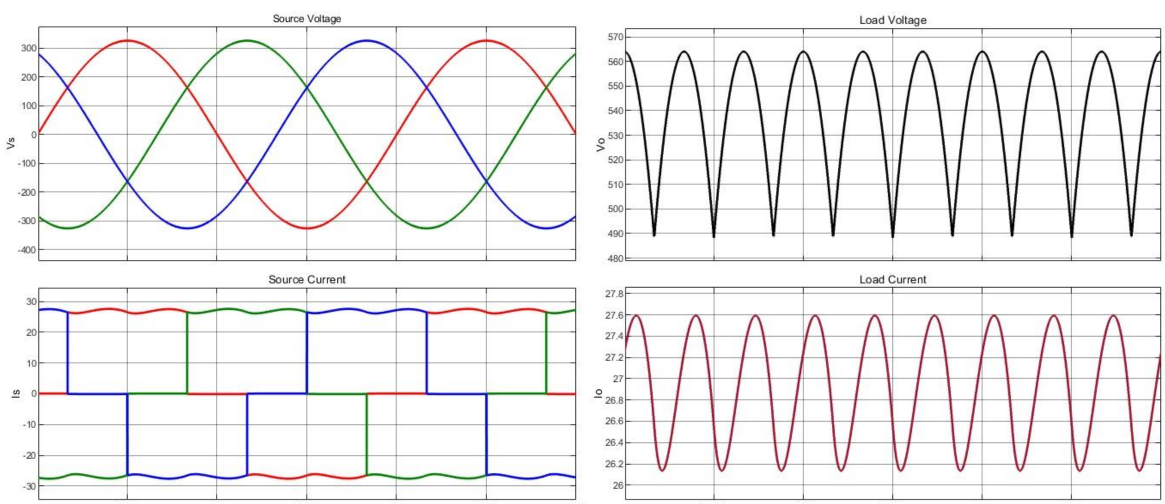


Fig 1: Three phase full wave Uncontrolled Rectifier

➢ SIMULATED CIRCUIT:



➢ WAVEFORMS OBTAINED:



Trace Selection: Vo		
Signal Statistics	Value	Time
Max	5.640e+02	0.030
Min	4.883e+02	0.045
Peak to Peak	7.577e+01	
Mean	5.385e+02	
Median	5.448e+02	
RMS	5.390e+02	

Trace Selection: Io		
Signal Statistics	Value	Time
Max	2.759e+01	0.041
Min	2.613e+01	0.025
Peak to Peak	1.459e+00	
Mean	2.693e+01	
Median	2.699e+01	
RMS	2.693e+01	

➤ OBSERVATION:

LOAD	Peak – Peak Ripple in Io
R= 20 Ω Case 1	16.16 A
R= 20 Ω, L = 20 mH Case 2	12.22 A
R= 20 Ω, L = 200 mH Case 3	2.154 A

2. Full-Bridge Uncontrolled Rectifier with Ls = 10 mH

➤ CIRCUIT DIAGRAM:

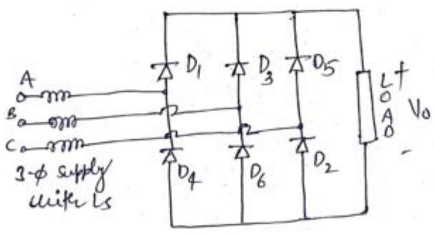
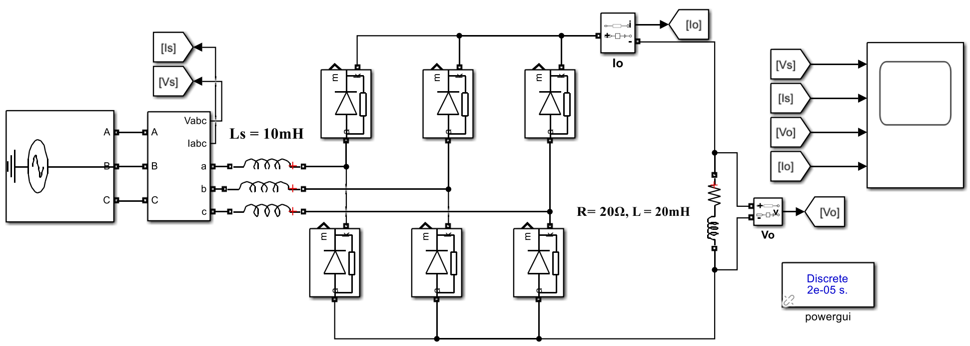
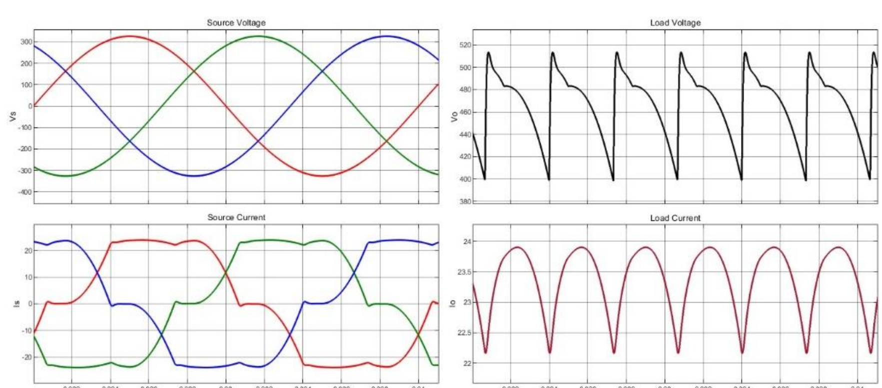


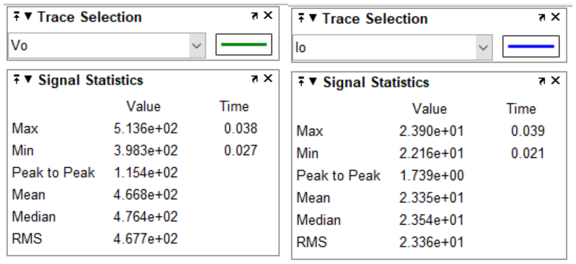
Fig 2: Three phase full wave Uncontrolled Rectifier with source inductance

SIMULATED CIRCUIT:



➤ WAVEFORMS OBTAINED:





- **OBSERVATION:**

Average value of Vo	466.8 V
Peak – Peak value of Vo	115.4 V
Average value of Io	23.35 A
Peak – Peak value of Io	1.739 A

- **Calculation of Commutation Angle:**

We can use the equation (5) derived in section 4 (controlled rectifier case) to find the value of commutation angle μ by taking α = 0 ⇒ $cos(\alpha+\mu) = cos\alpha - \frac{2\omega Ls}{V_{max}} I_o$

$$\Rightarrow \ \mu = \cos^{-1}\{1 - \frac{2\omega Ls}{V_{ml}} I_o\}$$

Where I_o is average load current; $L_s = 10\ mH$ is source inductance; $\omega = 100\pi$ is source voltage frequency, V_{ml}= $400\sqrt{2}$,

- **Obtained Result:** using $I_{o_{avg}} = 23.35\ A$, $\mu = \cos^{-1}(0.74065) \Rightarrow \boldsymbol{\mu = 42.21°}$
- **Theoretical value:**

By equation (7), taking α = 0 for Diode Rectifire we get,

$$\mu = 2\tan^{-1}\{\sqrt{\frac{3\omega L_S}{\pi R}}\} \quad \Rightarrow \mu = 2\ \tan^{-1}(\sqrt{\frac{3}{20}}) \quad \Rightarrow \boldsymbol{\mu = 42.34°}$$

3. Full-Bridge Controlled Rectifier without Ls

- **CIRCUIT DIAGRAM:**

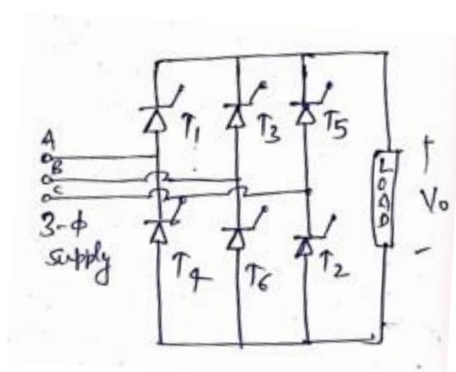
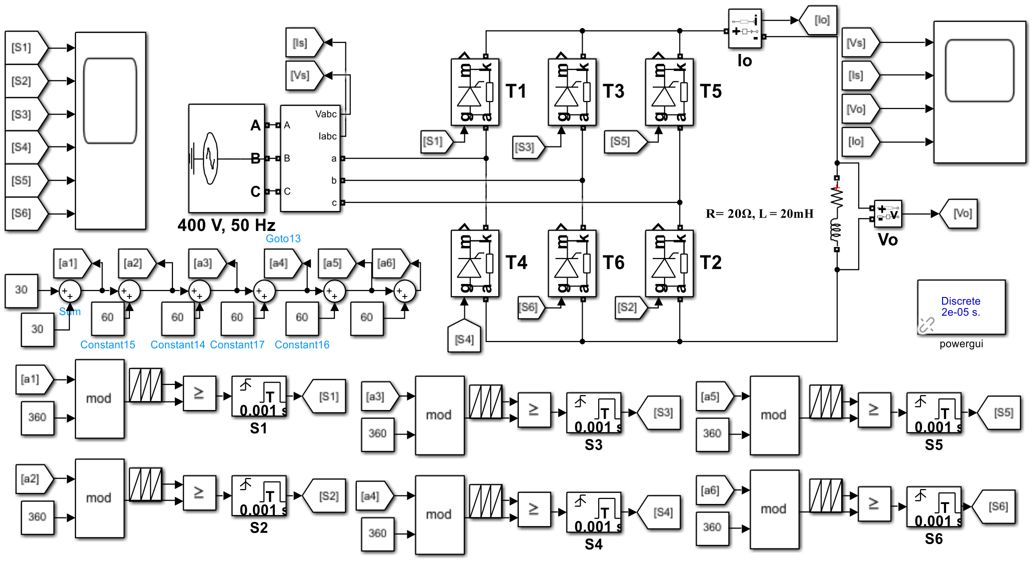


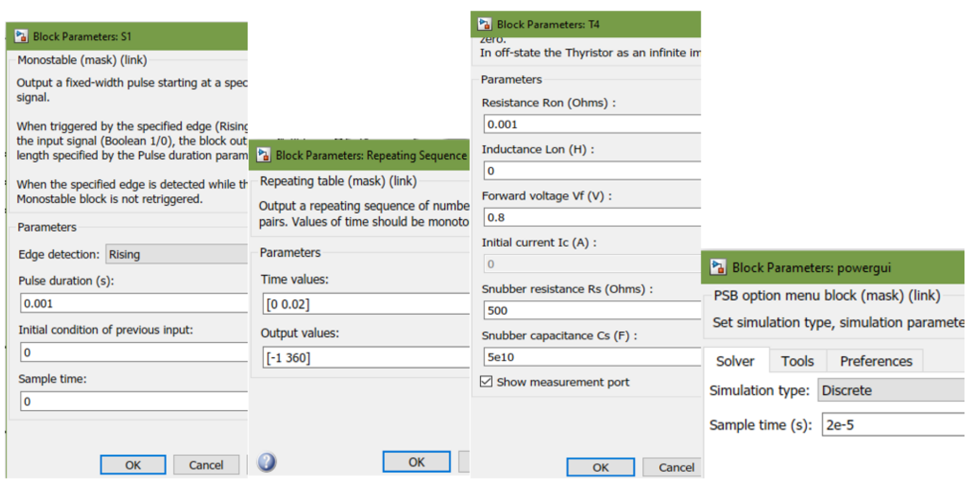
Fig 3: Three phase full wave Controlled Rectifier

1. At α = 30°,

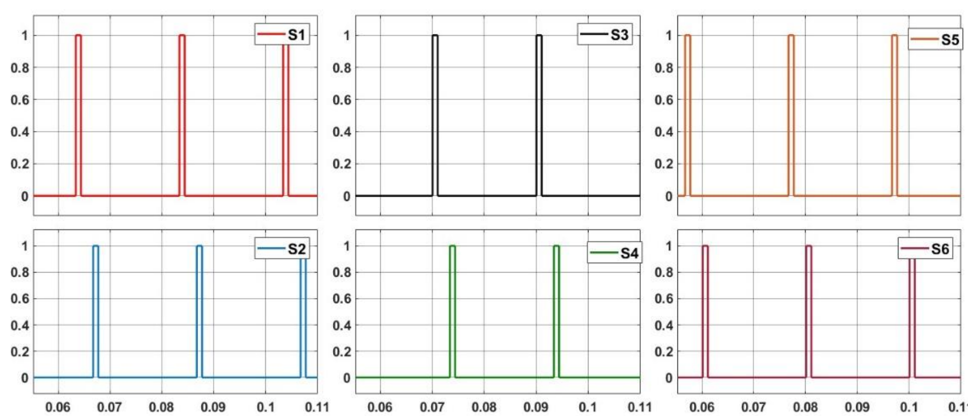
➢ SIMULATED CIRCUIT:



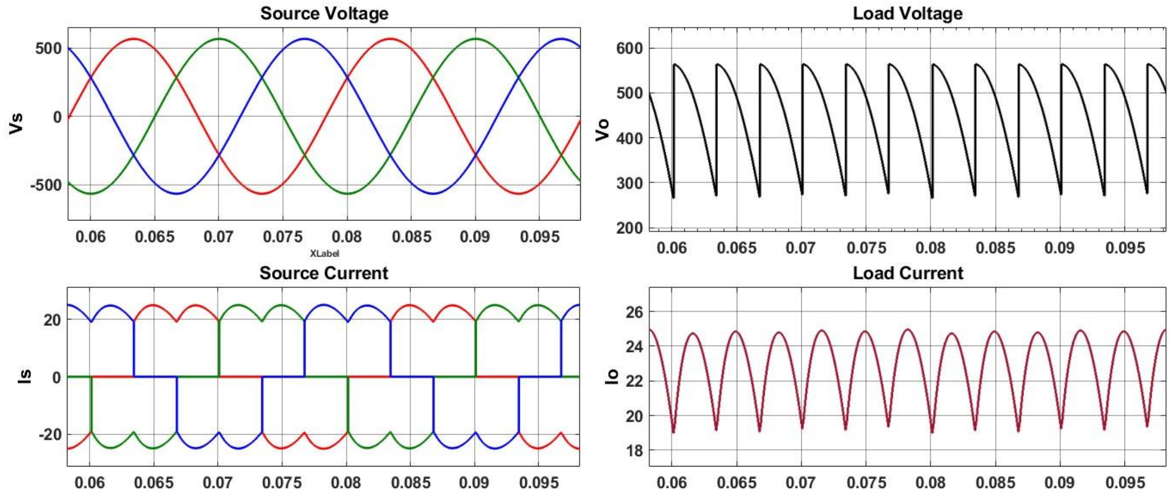
➢ SIMULATION CONFIGRATION:

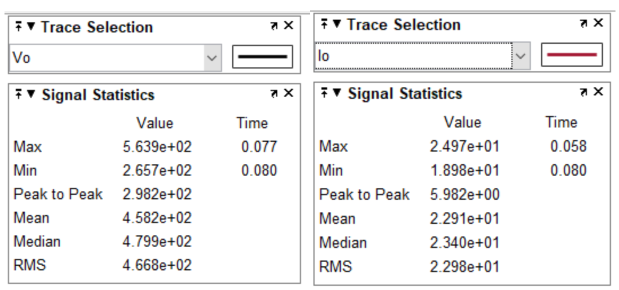


➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:



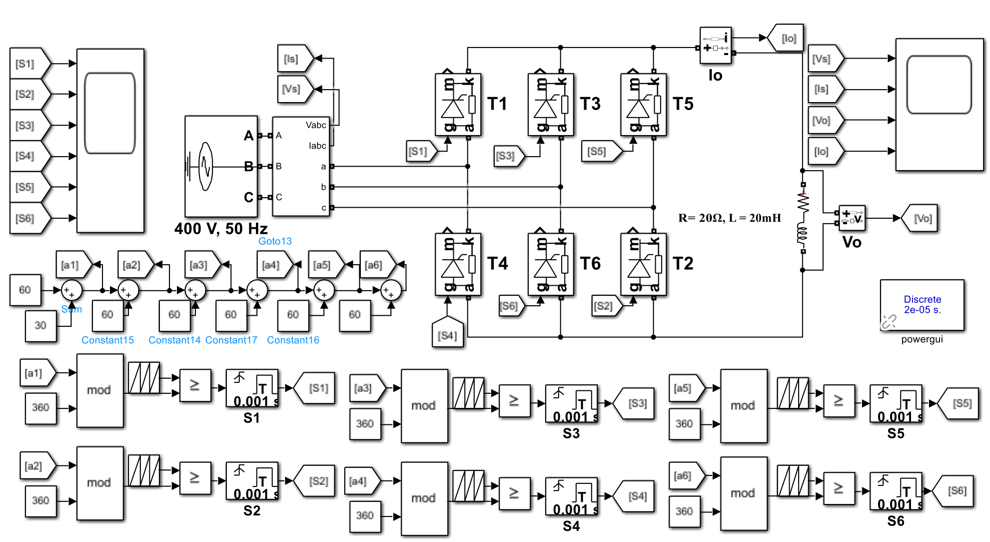


➢ OBSERVATION:

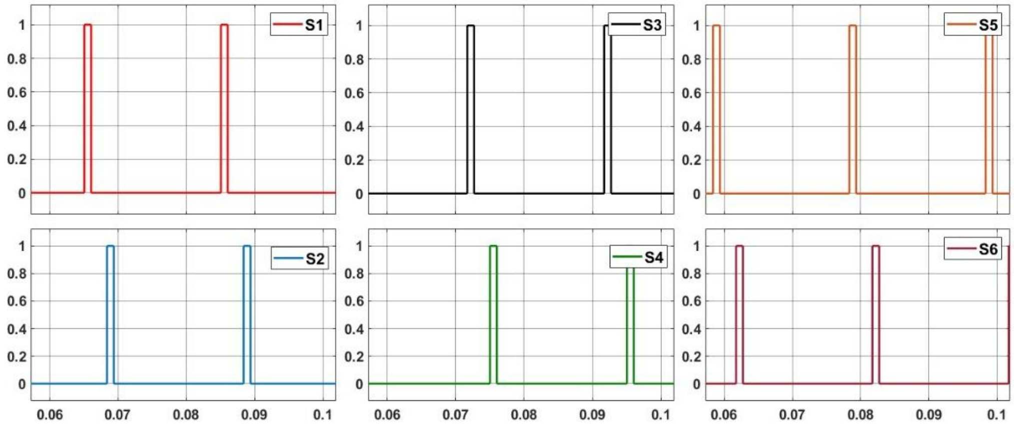
Average value of Vo	458.2 V
Peak – Peak value of Vo	298.2 V
Average value of Io	22.91 A
Peak – Peak value of Io	5.982 A

2. At α = 60°,

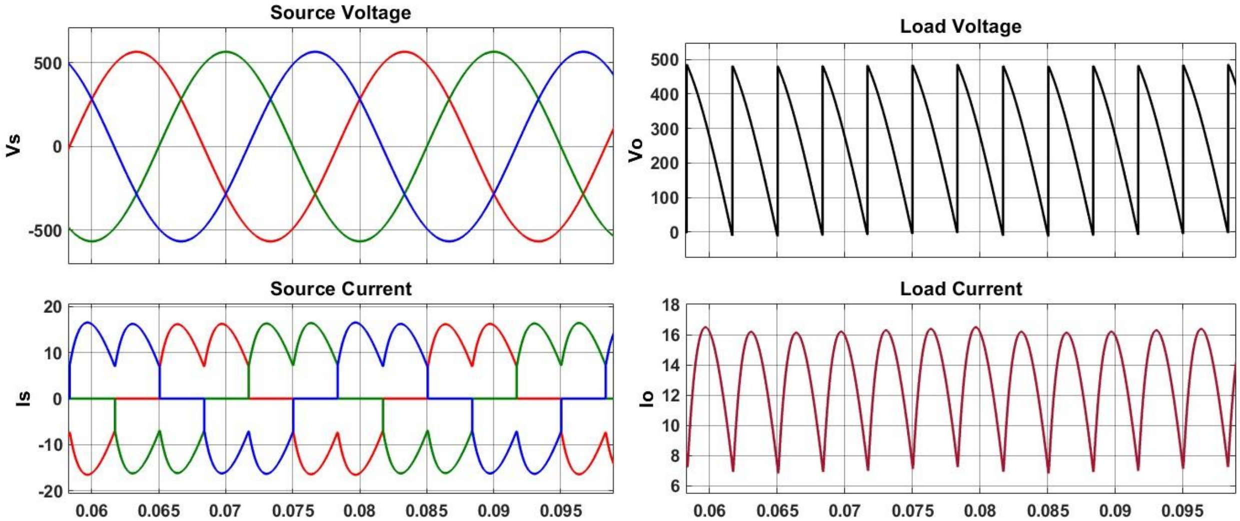
➢ SIMULATED CIRCUIT:

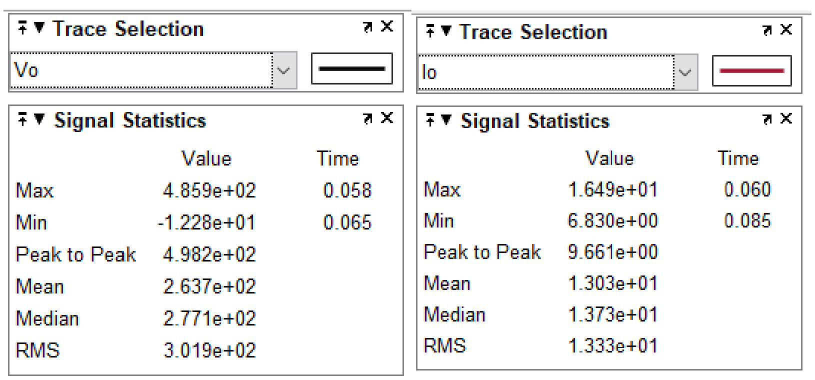


➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:



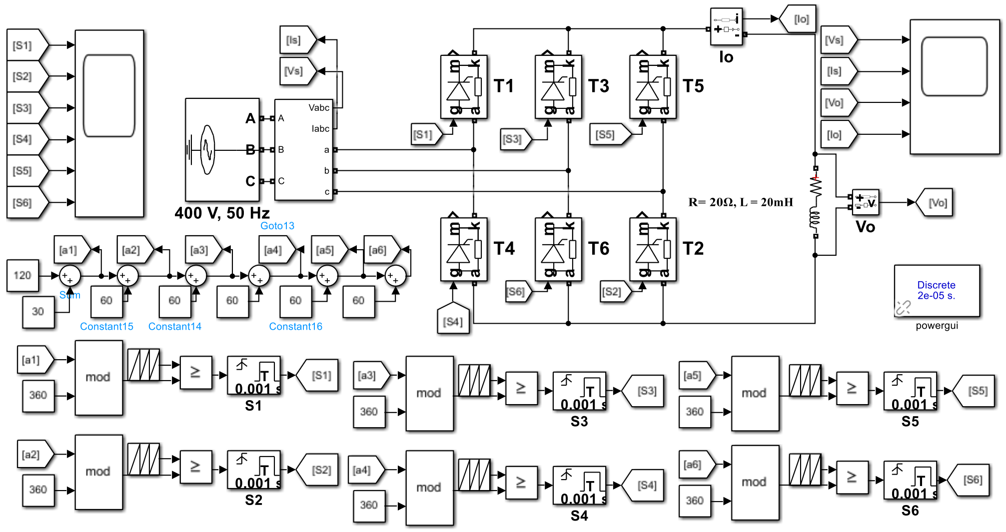


➢ OBSERVATION:

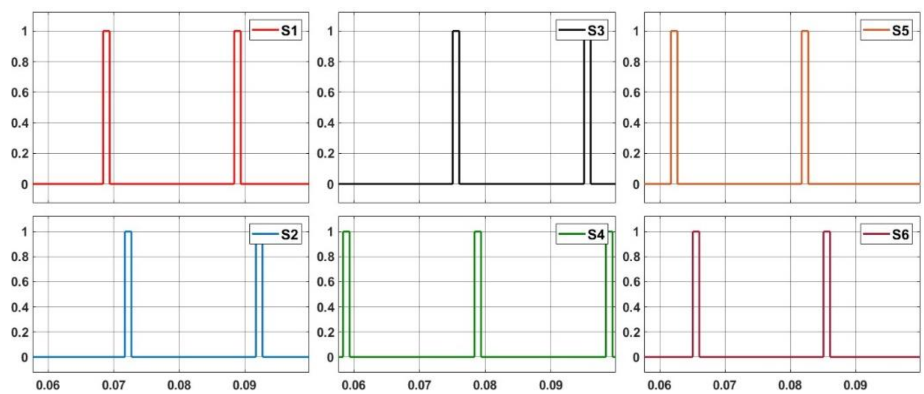
Average value of Vo	263.7 V
Peak – Peak value of Vo	498.2 V
Average value of Io	13.03 A
Peak – Peak value of Io	9.661 A

3. At α = 120°,

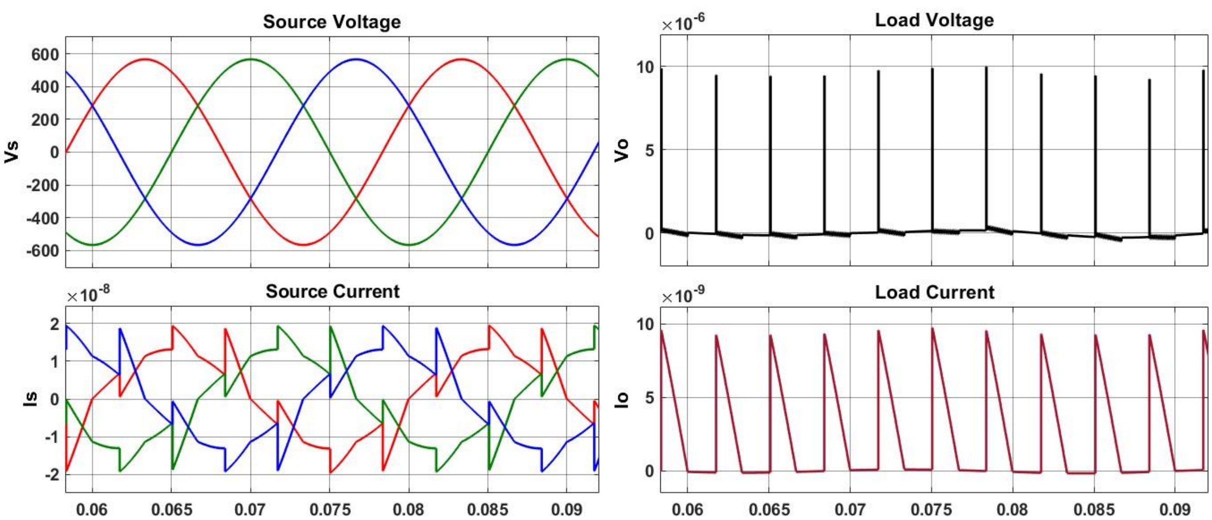
➢ SIMULATED CIRCUIT:

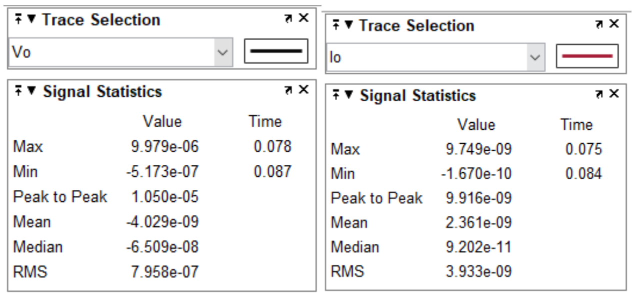


➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:




Trace Selection: Vo

Signal Statistics

	Value	Time
Max	9.979e-06	0.078
Min	-5.173e-07	0.087
Peak to Peak	1.050e-05	
Mean	-4.029e-09	
Median	-6.509e-08	
RMS	7.958e-07	

Trace Selection: Io

Signal Statistics

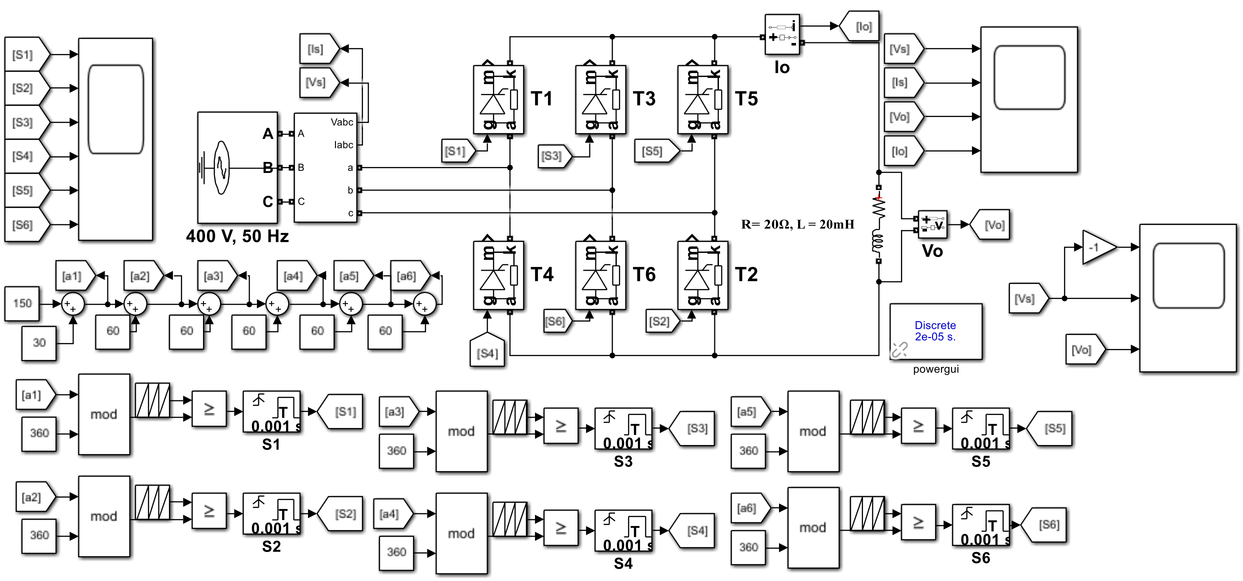
	Value	Time
Max	9.749e-09	0.075
Min	-1.670e-10	0.084
Peak to Peak	9.916e-09	
Mean	2.361e-09	
Median	9.202e-11	
RMS	3.933e-09	

➢ OBSERVATION:

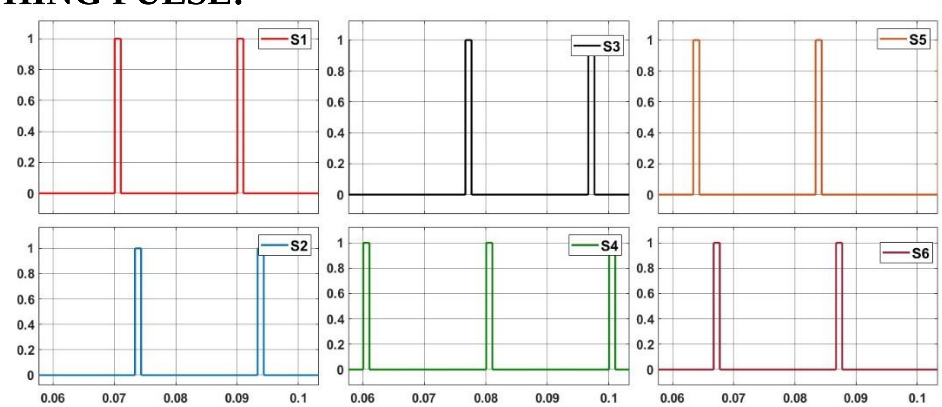
Average value of Vo	-4.029×10^{-9} V $\approx$ 0 V
Peak – Peak value of Vo	1.05×10^{-5} V $\approx$ 0 V
Average value of Io	2.361×10^{-9} A $\approx$ 0 A
Peak – Peak value of Io	9.916×10^{-9} A $\approx$ 0 A

4. At α = 150°,

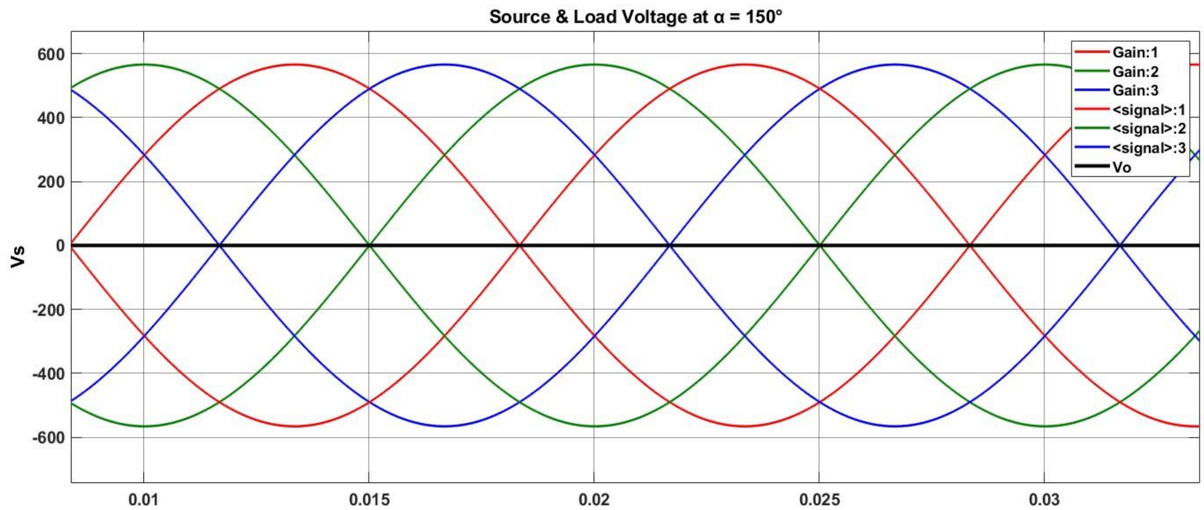
➢ SIMULATED CIRCUIT:

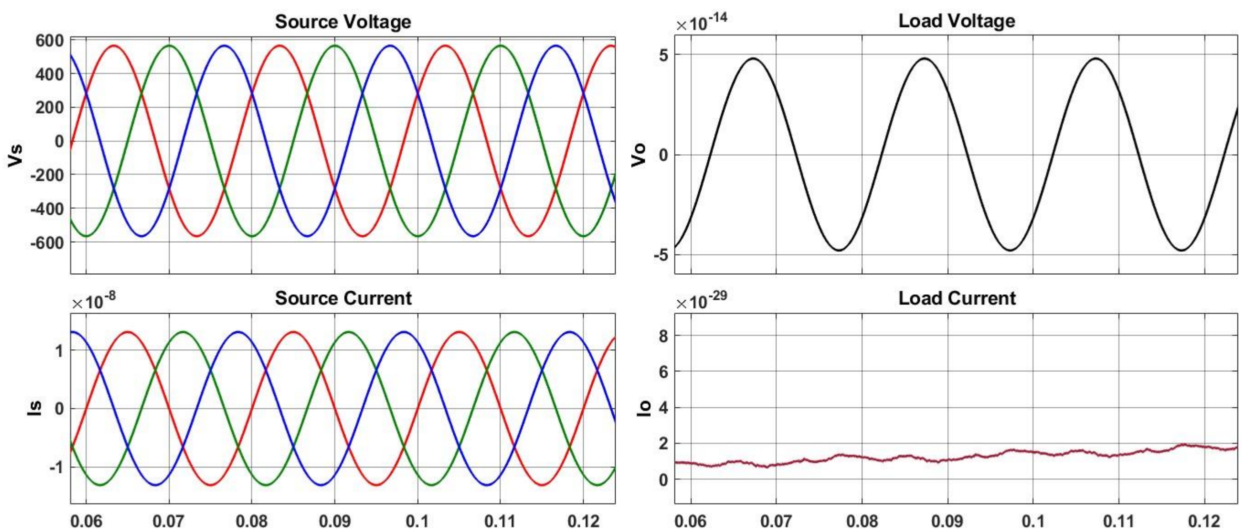


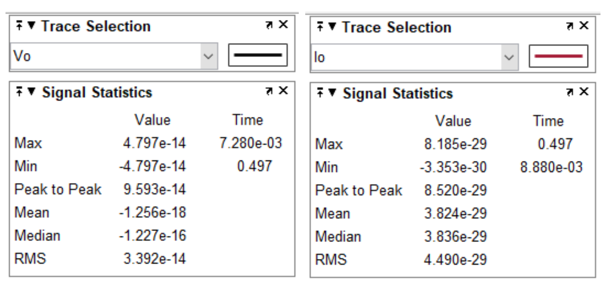
➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:







➢ OBSERVATION:

Average value of Vo	$-1.256*10^{-18}$ V ≈ 0 V
Peak – Peak value of Vo	$9.593*10^{-14}$ V ≈ 0 V
Average value of Io	$3.824*10^{-29}$ A ≈ 0 A
Peak – Peak value of Io	$8.520*10^{-29}$ A ≈ 0 A

➢ Clarification for the waveform of output at α = 120° & 150°:

- For the given load the output voltage and current is coming approximately 0 beacuase this load is not an ideal load the inductance is very low.
- If we appy an ideal load here or a constant current load then we will be getting some output waveform according to the firing angle & it will be comparable with our source waveform.

4. Full-Bridge Controlled Rectifier with Ls = 10 mH

➢ CIRCUIT DIAGRAM:

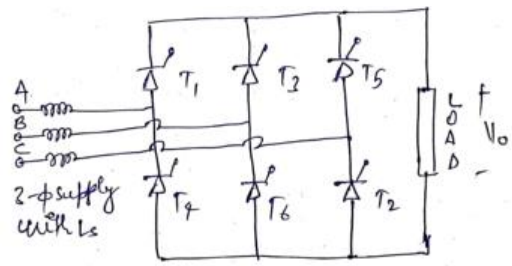


Fig 4: Three phase full wave Controlled Rectifier with source inductance

➢ Calculation of Commutation Angle:-

Until now, the current commutation between thyristors has been considered to be instantaneous. This condition is not valid in real cases due to the presence of the source/Line inductance *L*. During the commutation, the current through the thyristors cannot change instantaneously, and for this reason, during the commutation angle $\boldsymbol{\mu}$**,** all thyristors are conducting simultaneously.

Therefore, during the commutation, the following relationship for the load voltage holds

$$v_o = 0 \qquad \forall \qquad \alpha \le \boldsymbol{\omega t} \le \alpha + \mu \qquad (1)$$

The effect of the commutation on the supply current, the voltage waveforms, and the thyristor current waveforms can be observed in below Fig.

During the commutation, the following expression holds

$$L\frac{di_s}{dt} = v_s = V_{max}sin(\omega t) \quad \alpha \le \omega t \le \alpha + \mu \qquad (2)$$

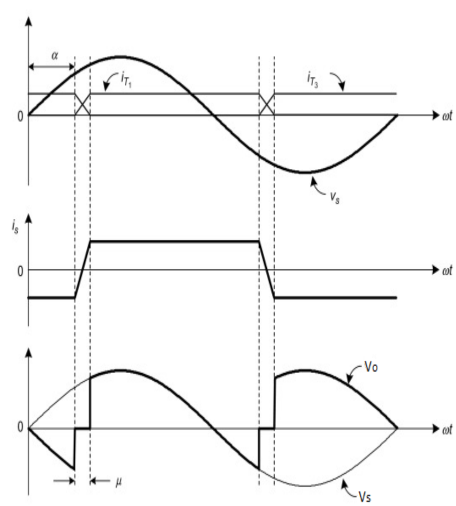
Integrating above Eq. over the commutation interval yields

$$\int_{-I_o}^{I_o} di_s = \frac{V_{max}}{L}\int_{\alpha/\omega}^{\alpha+\mu/\omega} sin(\omega t)\, dt \qquad (3)$$

$$I_{o_{avg}} = \frac{V_m}{2\omega L_S}\{Cos\ \alpha - \cos(\ \alpha +\ \mu)\} \qquad (4)$$

From above Eq., the following relationship for the commutation angle $\boldsymbol{\mu}$ is obtained:

$$cos(\alpha+\mu) = cos\alpha - \frac{2\omega Ls}{V_{max}}I_o \qquad (5)$$



For three Phase full wave-controlled rectifier the expression for the average load voltage is given by

$$V_{o(avg)} = \frac{1}{\frac{\pi}{3}}\left\{\int_{60+\alpha}^{60+\alpha+\mu} -\frac{3}{2}V_{BO}d(\omega t) \ + \ \int_{60+\alpha+\mu}^{120+\alpha} V_{AB}\, d(\omega t)\right\}$$

$$= \frac{3V_{ml}}{2\pi}[cos(\alpha+\mu) + cos\alpha] \qquad (6)$$

Since $I_{O_{avg}} = \frac{V_{O_{avg}}}{R}$ therefore using equation (4) and (6) we get

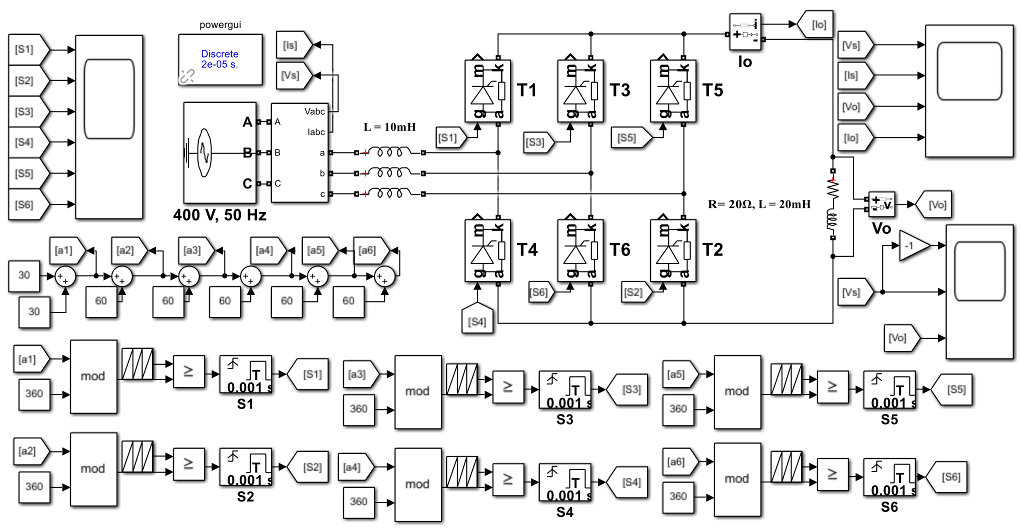
$$\frac{\cos\alpha - \cos(\alpha+\mu)}{\cos\alpha + \cos(\alpha+\mu)} = \frac{3\omega L_S}{\pi R} \qquad (7)$$

Using given parameter as source inductance $L_s = 10\ mH$; $\omega = 100\pi$, & R = 20 Ω, & equation 7

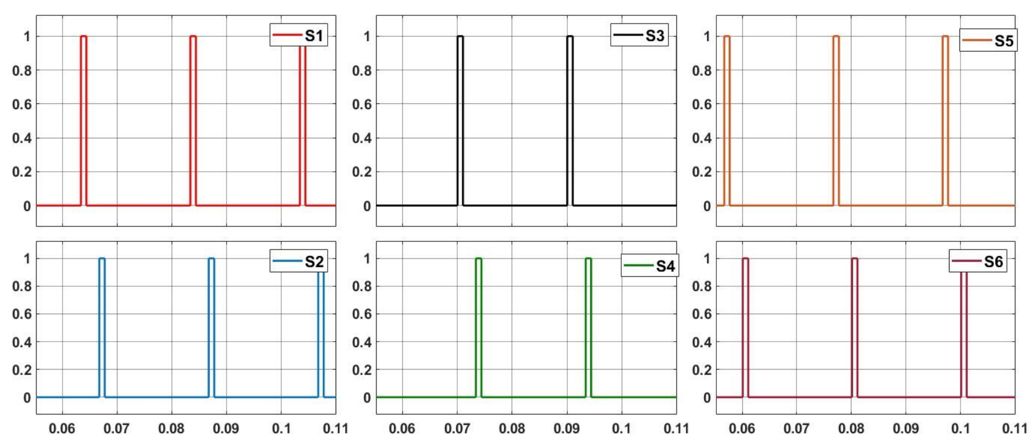
$$\mu = \{\cos^{-1}\left(\frac{17}{23}\cos\alpha\right) - \alpha\}^{\circ} \qquad (8)$$

1. At α = 30°,

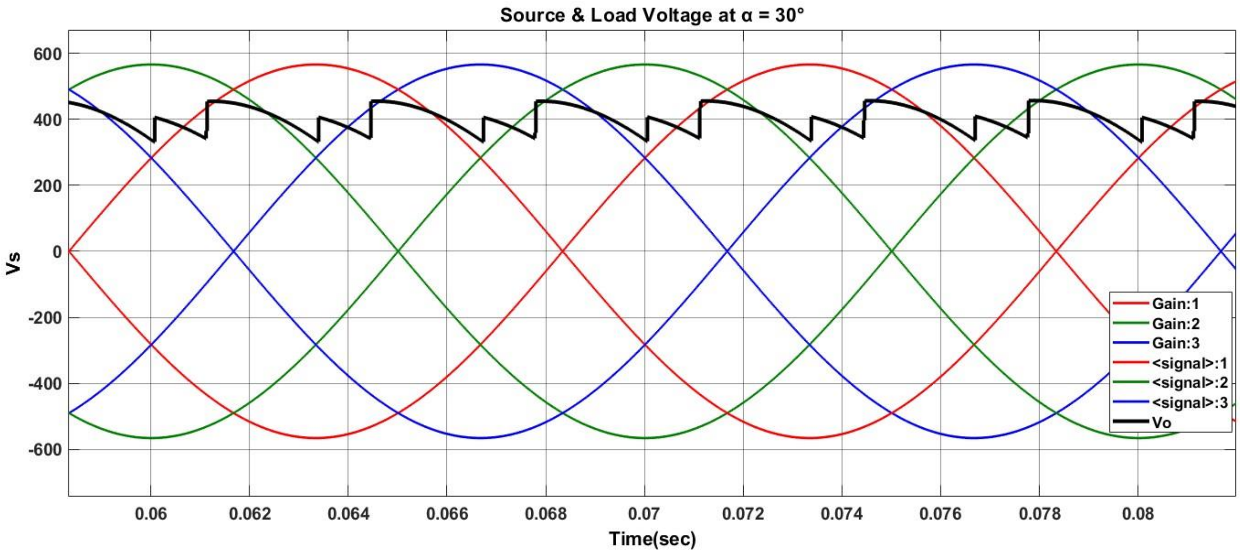
➢ SIMULATED CIRCUIT:

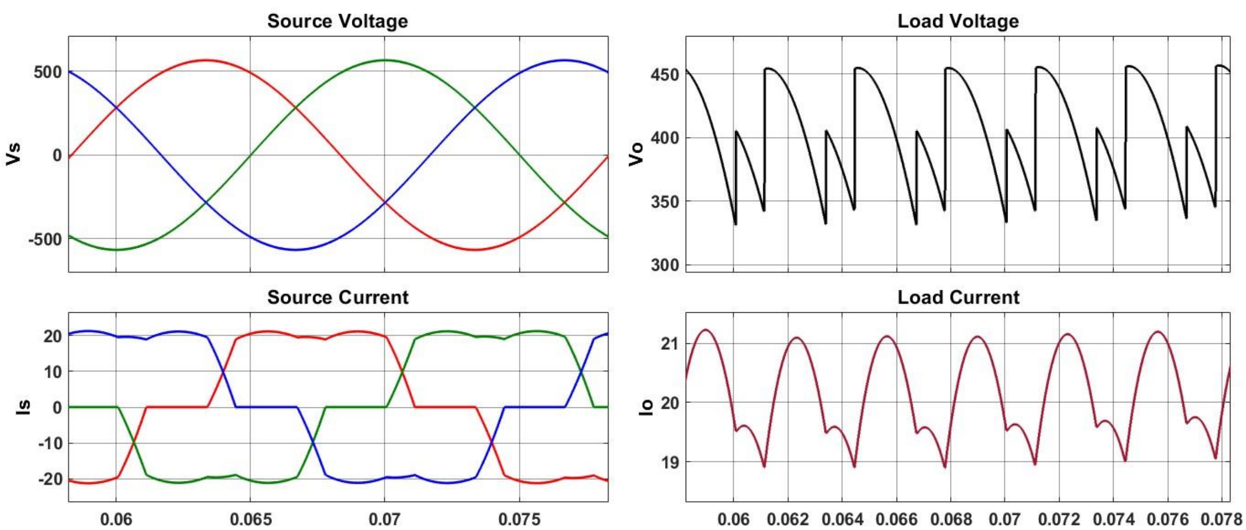


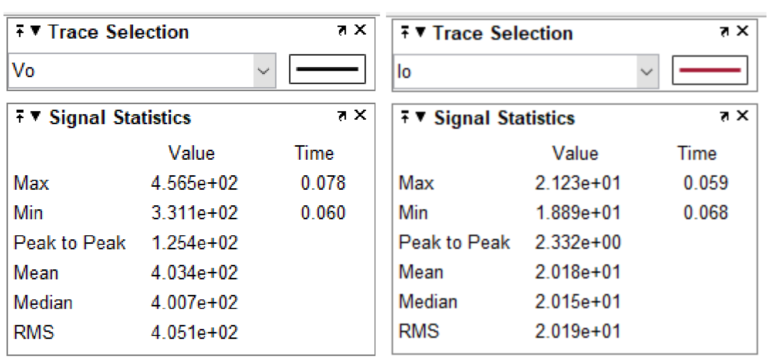
➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:







Trace Selection: Vo

Signal Statistics

	Value	Time
Max	4.565e+02	0.078
Min	3.311e+02	0.060
Peak to Peak	1.254e+02	
Mean	4.034e+02	
Median	4.007e+02	
RMS	4.051e+02	

Trace Selection: Io

Signal Statistics

	Value	Time
Max	2.123e+01	0.059
Min	1.889e+01	0.068
Peak to Peak	2.332e+00	
Mean	2.018e+01	
Median	2.015e+01	
RMS	2.019e+01	

➢ Calculation of Commutation Angle:-

➢ Obtained Result:

Using equaton (5) & given parameter as

source inductance $L_s = 10\ mH$; $\omega = 100\pi$, V_{max}= $400\sqrt{2}$, & R = 20 Ω, $\alpha = 30°$, I_o = 20.18 A we get,

$$\cos(30° + \mu) = \{\frac{\sqrt{3}}{2} - \frac{20.18\pi}{200\sqrt{2}}\} \Rightarrow \mu = \cos^{-1}(0.641882) - 30° \Rightarrow \boldsymbol{\mu = 20.068°}$$

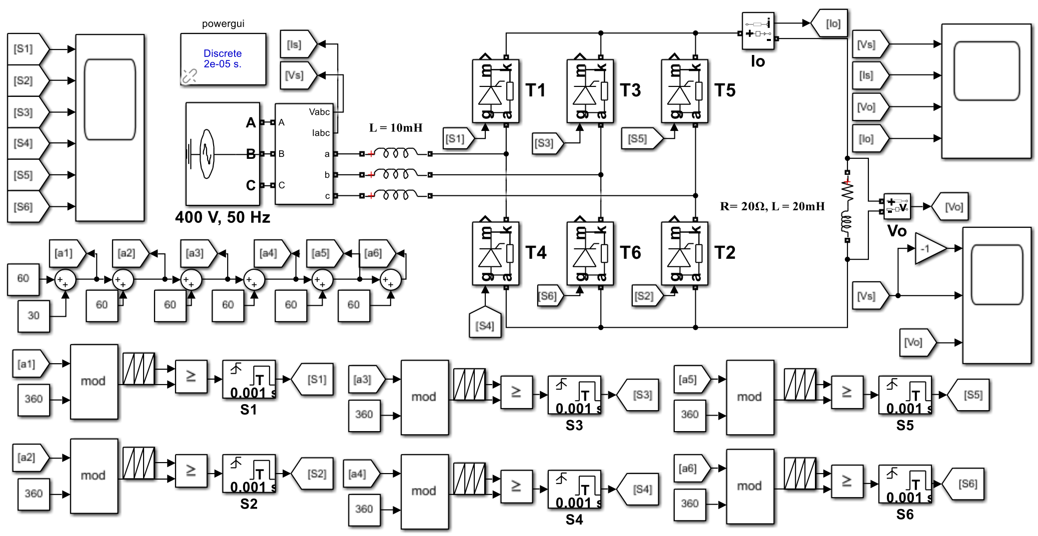
➢ Theoretical value:

By using equation (8) with the value of α = 30° we get,

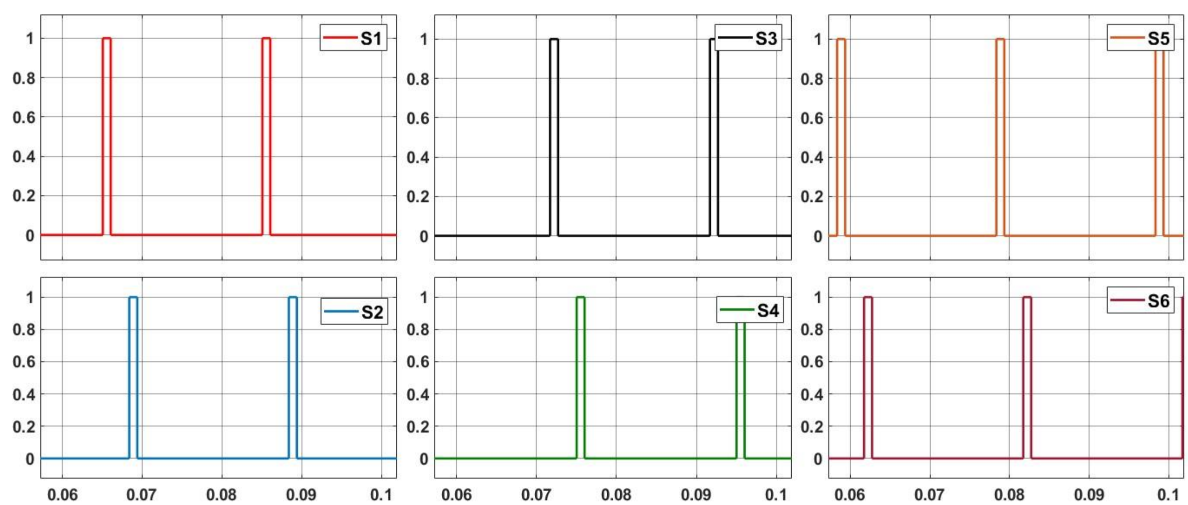
$$\mu = \{\cos^{-1}\left(\frac{17}{23}\cos\alpha\right) - \alpha\}° \Rightarrow \boldsymbol{\mu = 20.20°}$$

➢ α = 60°

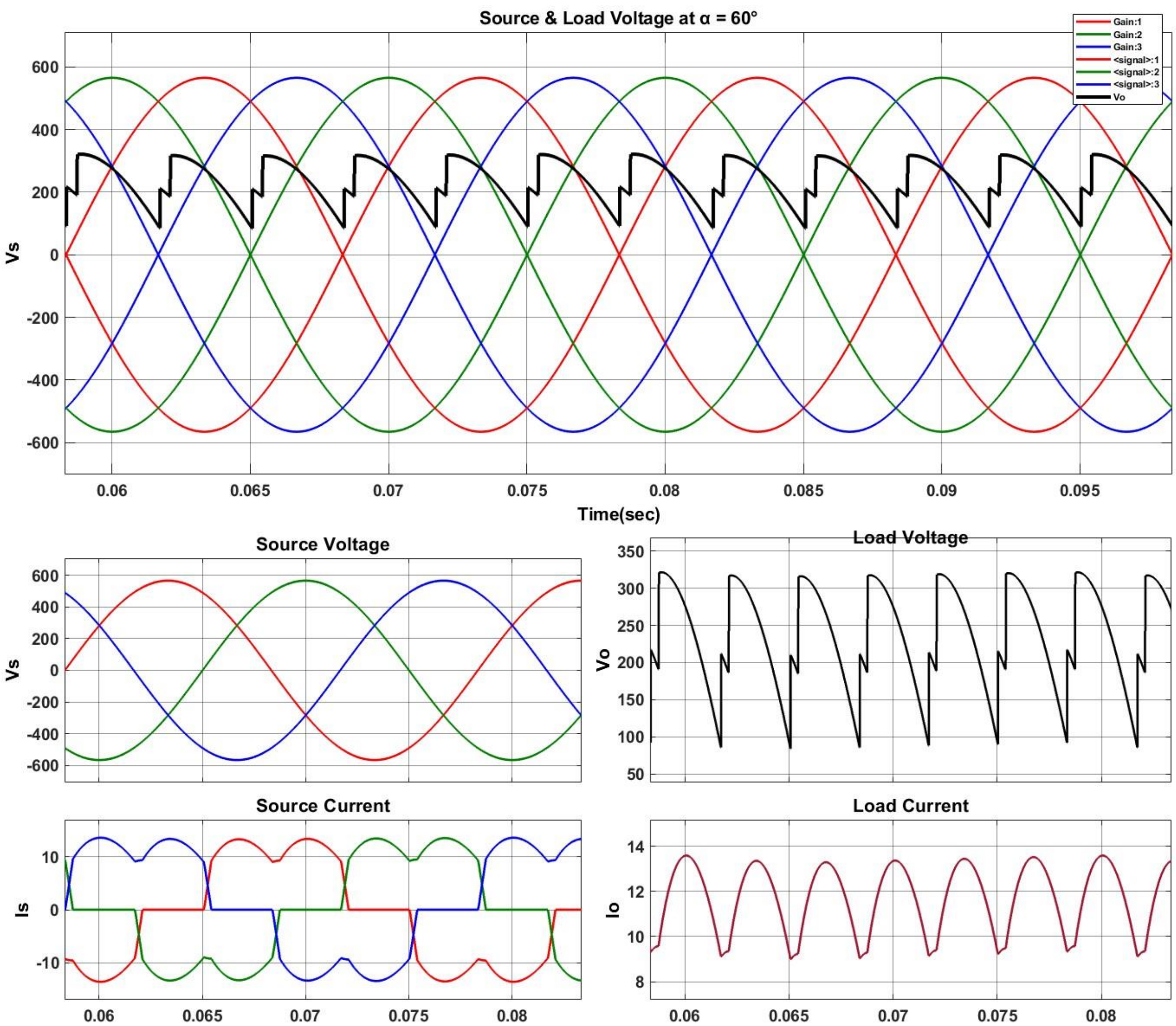
➢ SIMULATED CIRCUIT:



➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:



Trace Selection: Vo

Signal Statistics

	Value	Time
Max	3.215e+02	0.059
Min	8.394e+01	0.065
Peak to Peak	2.376e+02	
Mean	2.370e+02	
Median	2.451e+02	
RMS	2.466e+02	

Trace Selection: Io

Signal Statistics

	Value	Time
Max	1.359e+01	0.080
Min	9.004e+00	0.065
Peak to Peak	4.589e+00	
Mean	1.171e+01	
Median	1.209e+01	
RMS	1.181e+01	

- **Calculation of Commutation Angle:-**

- **Obtained Result:**

Using equaton (5) & given parameter as
source inductance $L_s = 10\,mH$; $\omega = 100\pi$, V_{max}= $400\sqrt{2}$, & R = 20 Ω, $\alpha = 60°$, I_o = 11.71 A
we get,

$$\cos(\,60° + \,\mu\,) = \{\frac{1}{2} - \frac{11.71\pi}{200\sqrt{2}}\} \Rightarrow \mu = \,\cos^{-1}(0.3699) - 60° \Rightarrow \boldsymbol{\mu = 8.288}°$$

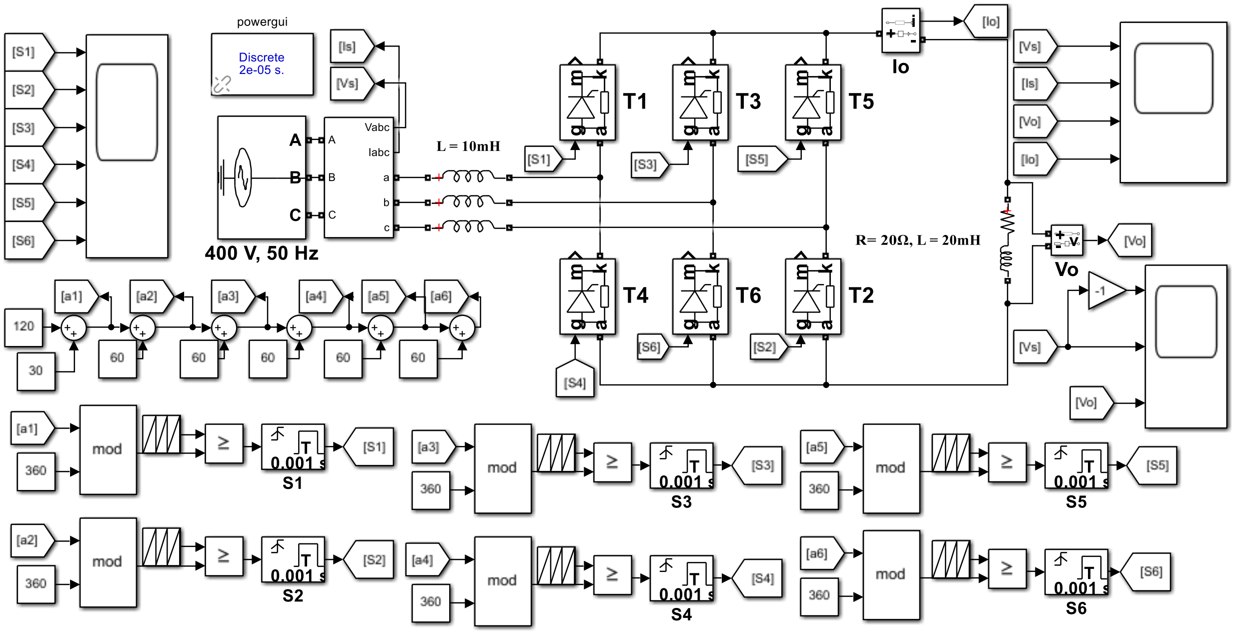
➢ Theoretical value:

By using equation (8) with the value of α = 30° we get,

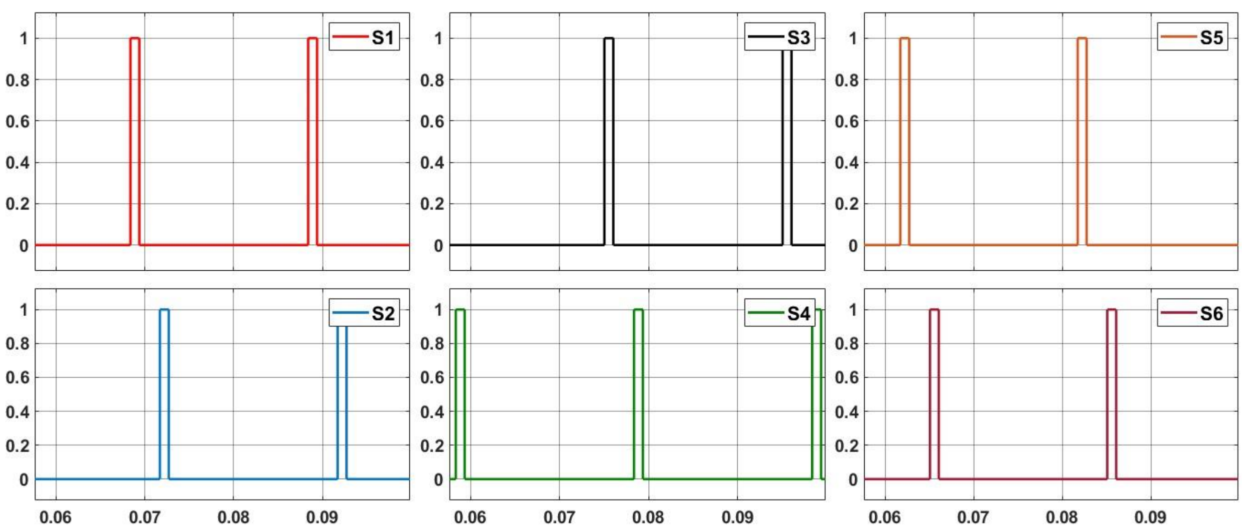
$$\mu = \{\cos^{-1}\left(\frac{17}{23}\cos\alpha\right) - \alpha\}^{\circ} \Rightarrow \boldsymbol{\mu = 8.31^{\circ}}$$

➢ α = 120°

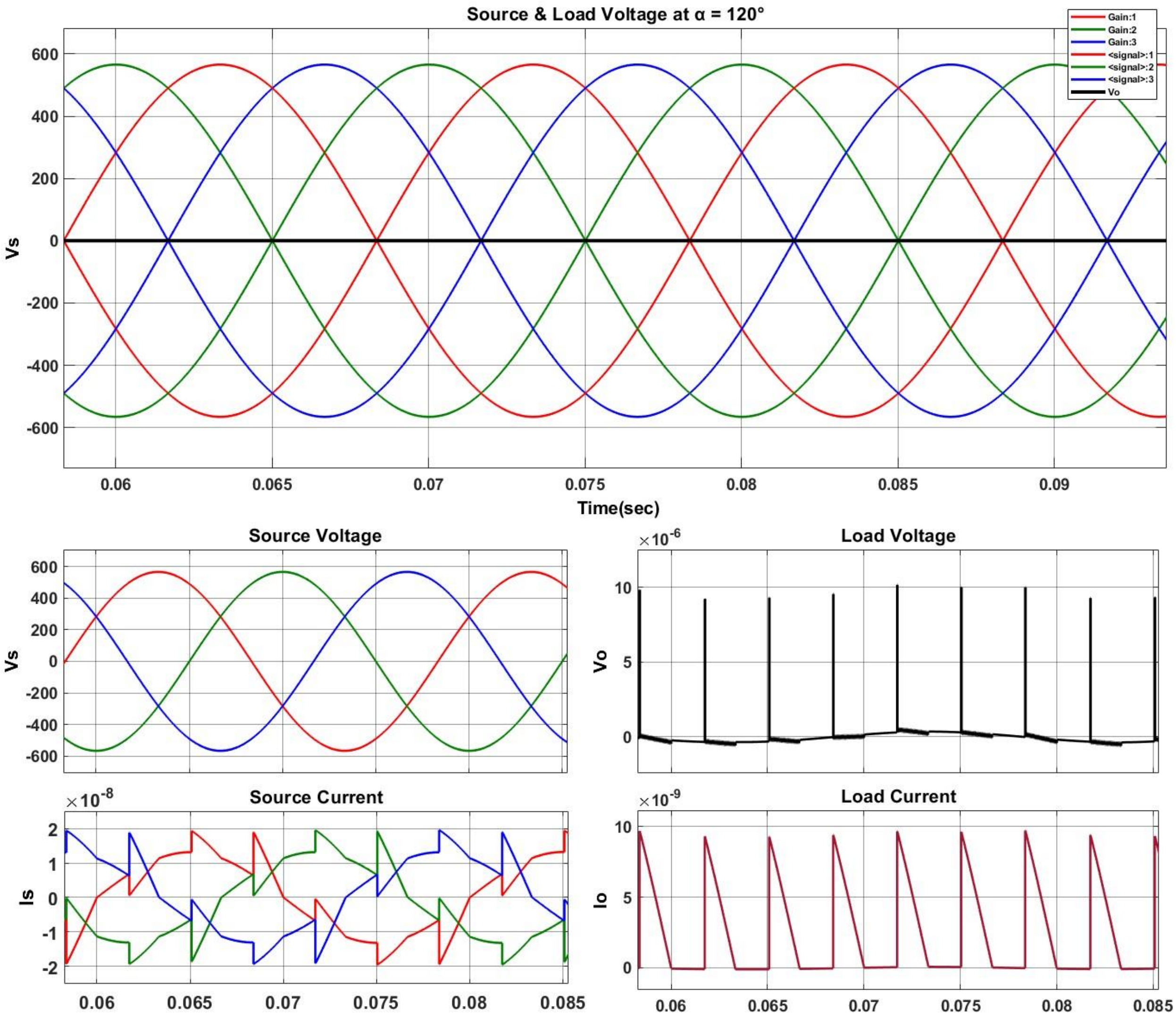
➢ SIMULATED CIRCUIT:



➢ SWITCHING PULSE:



➢ WAVEFORMS OBTAINED:



Trace Selection: Vo

Signal Statistics

	Value	Time
Max	1.016e-05	0.072
Min	-6.044e-07	0.083
Peak to Peak	1.077e-05	
Mean	-3.050e-08	
Median	-1.390e-07	
RMS	8.361e-07	

Trace Selection: Io

Signal Statistics

	Value	Time
Max	9.721e-09	0.078
Min	-1.141e-10	0.064
Peak to Peak	9.835e-09	
Mean	2.373e-09	
Median	5.979e-11	
RMS	3.956e-09	

- **Calculation of Commutation Angle:-**

- **Obtained Result:**

Using equaton (5) & given parameter as
source inductance $L_s = 10\, mH$; $\omega = 100\pi$, V_{max}= $400\sqrt{2}$, & R = 20 Ω, $\alpha = 120°$, I_o = $2.373*10^{-9}$ $\approx 0\ A$ A we get,

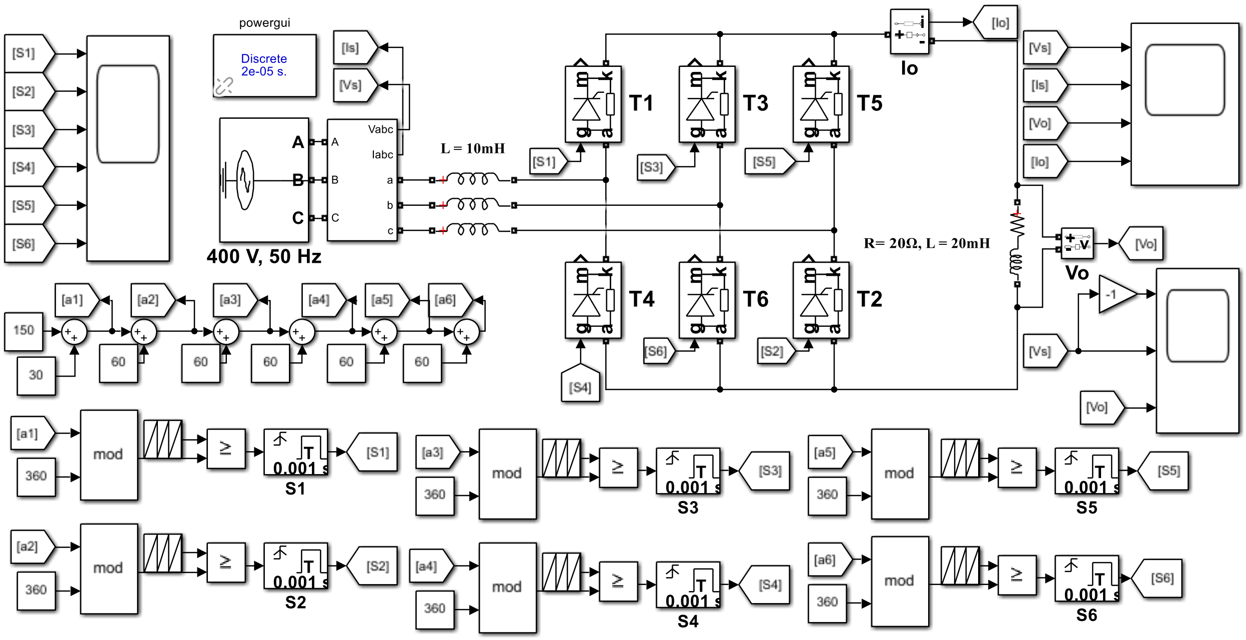
$$\cos(\,\alpha + \,\mu\,) = \{\, \cos\alpha \,\} \Rightarrow \mu = \,0°$$

- ## **Theoretical value:**

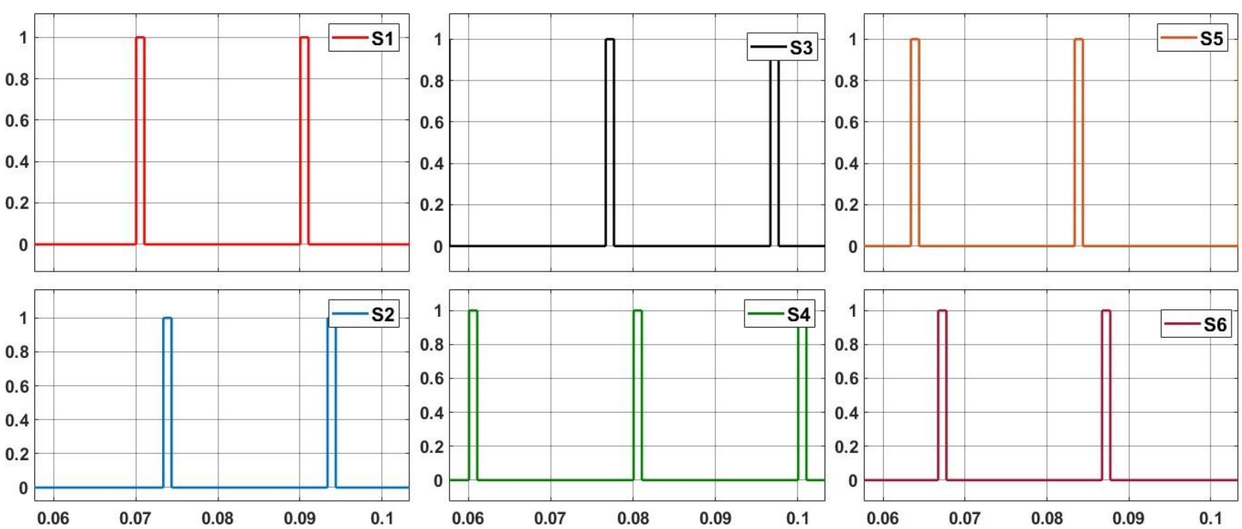
By using equation (8) with the value of α = 30° we get,

$$\mu = \{\cos^{-1}\left(\frac{17}{23}\cos\alpha\right) - \alpha\}^{\circ} \Rightarrow \boldsymbol{\mu = -8.31^{\circ}} \textbf{ which is not possible hence } \boldsymbol{\mu = 0^{\circ}}$$

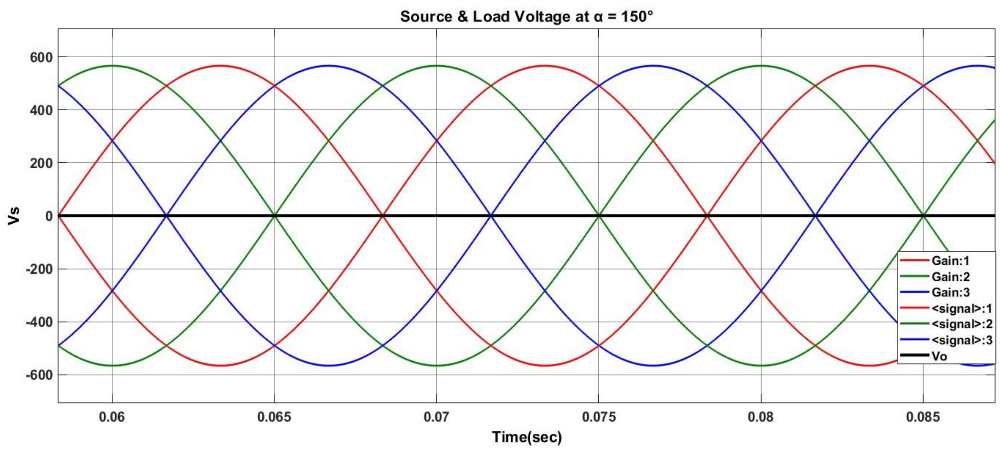
- ## **α = 150°**
- ## **SIMULATED CIRCUIT:**

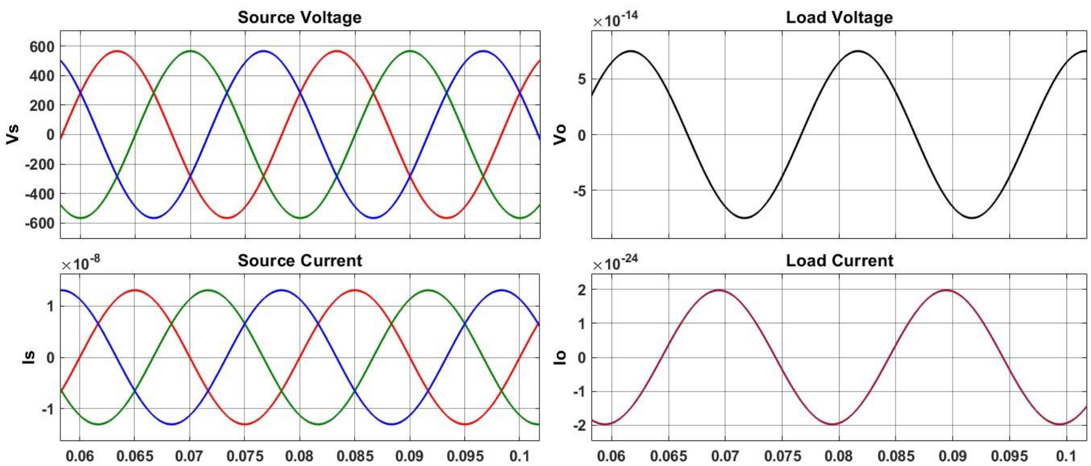


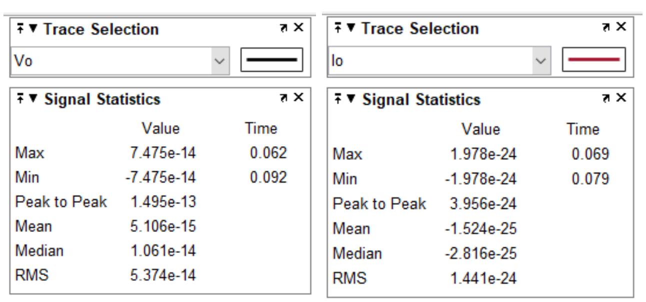
- ## **SWITCHING PULSE:**



- ## **WAVEFORMS OBTAINED:**







Trace Selection: Vo

Signal Statistics

	Value	Time
Max	7.475e-14	0.062
Min	-7.475e-14	0.092
Peak to Peak	1.495e-13	
Mean	5.106e-15	
Median	1.061e-14	
RMS	5.374e-14	

Trace Selection: Io

Signal Statistics

	Value	Time
Max	1.978e-24	0.069
Min	-1.978e-24	0.079
Peak to Peak	3.956e-24	
Mean	-1.524e-25	
Median	-2.816e-25	
RMS	1.441e-24	

➢ Obtained Result:

Using equaton (5) & given parameter as
source inductance $L_s = 10\ mH$; $\omega = 100\pi$, V_{max}= $400\sqrt{2}$, & R = 20 Ω, $\alpha = 150°$,
I_o = -1.524*10^{-25} $\approx 0\ A$ A we get,

$$\cos(\alpha + \mu) = \{\cos\alpha\} \Rightarrow \mu = 0°$$

➢ Theoretical value:

By using equation (8) with the value of α = 150° we get,

$$\mu = \{\cos^{-1}\left(\frac{17}{23}\cos\alpha\right) - \alpha\}° \Rightarrow \boldsymbol{\mu = -20.2°} \text{ which is not possible hence } \boldsymbol{\mu = 0°}$$

Experiment - 06

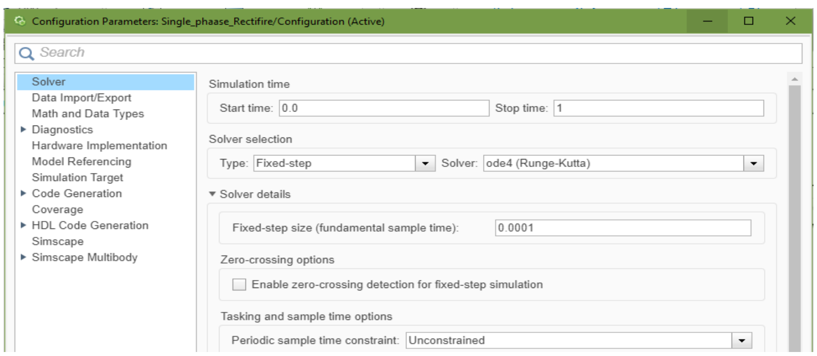
To study the operation of single phase Uncontrolled & Controlled Rectifiers using MATLAB/SIMULINK

.NAME: SHIVRAJ VISHWAKARMA ROLL. NO. 224102112

1. DESIGN PARAMETERS

Parameter		Value
Input voltage		230 V, 50 Hz
Source Inductance		10 mH
Load Parameters	R Load Case (1)	20 Ω
	RL Load Case (2)	20 Ω in series with 20 mH Inductance
	RL Load Case (3)	20 Ω in series with 200 mH Inductance

2. SIMULATION CONFIGRATION



1. Full-Bridge Uncontrolled Rectifier without Ls

3. CIRCUIT DIAGRAM

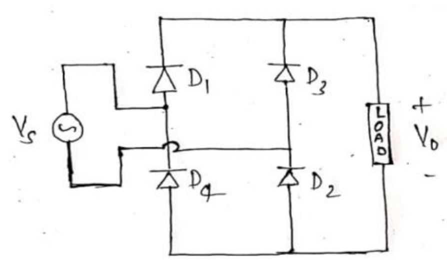
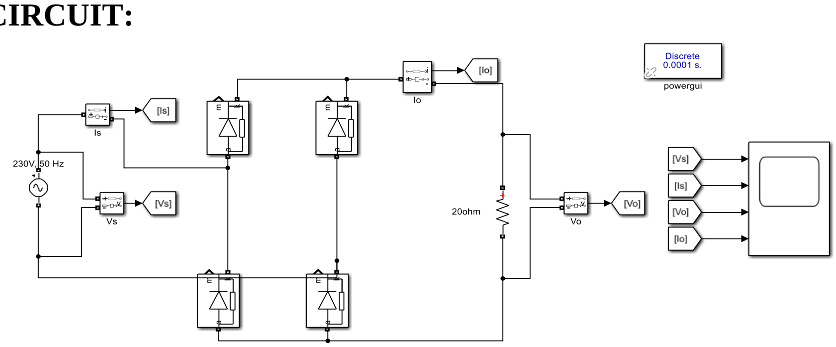


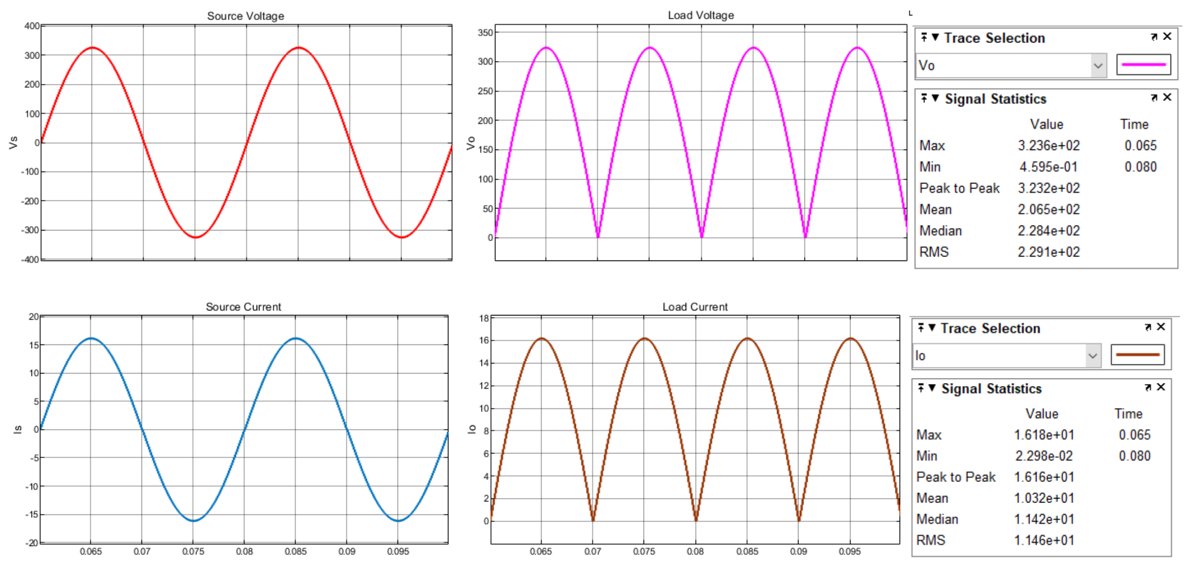
Fig 1: Circuit diagram of Uncontrolled full wave Rectifier

CASE-1, Load R= 20Ω,

SIMULATED CIRCUIT:

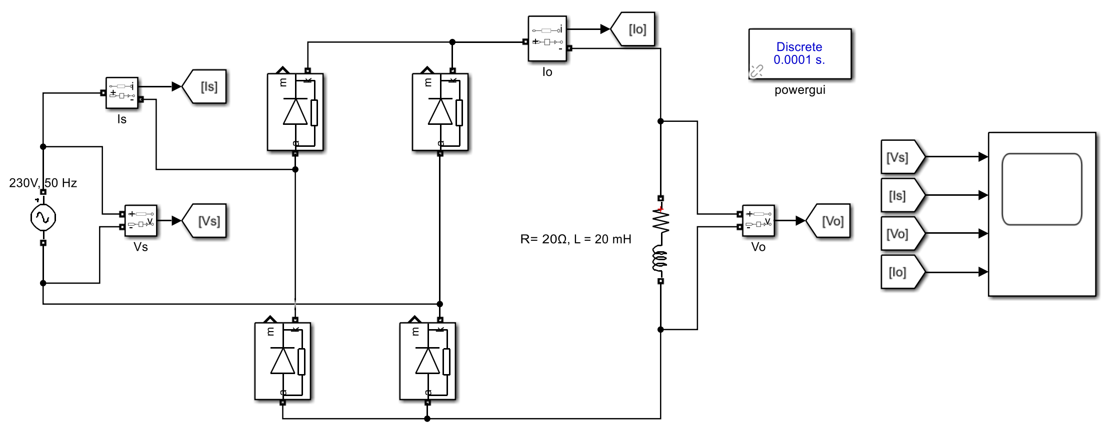


➢ WAVEFORMS OBTAINED:

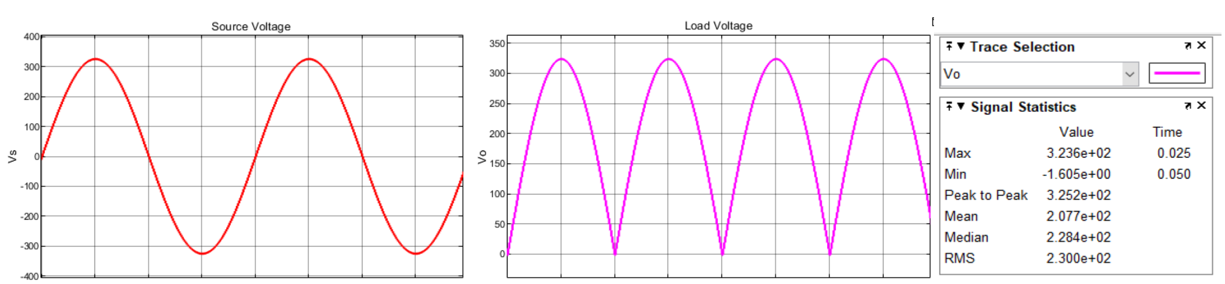


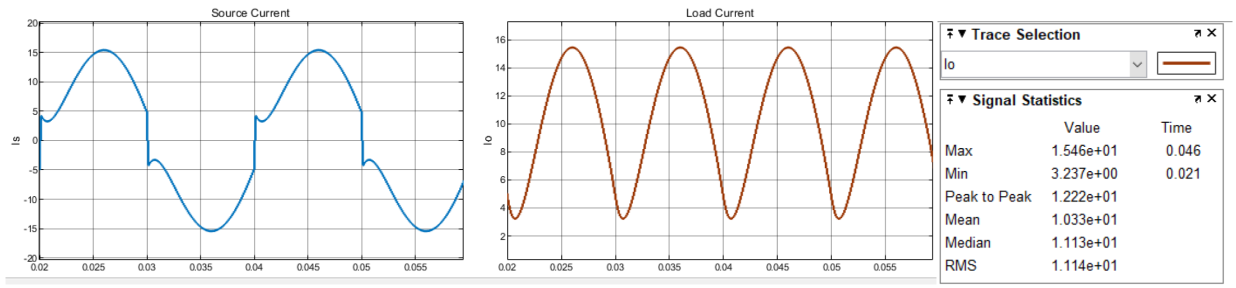
CASE-2, Load R= 20Ω, L = 20 mH

SIMULATED CIRCUIT:



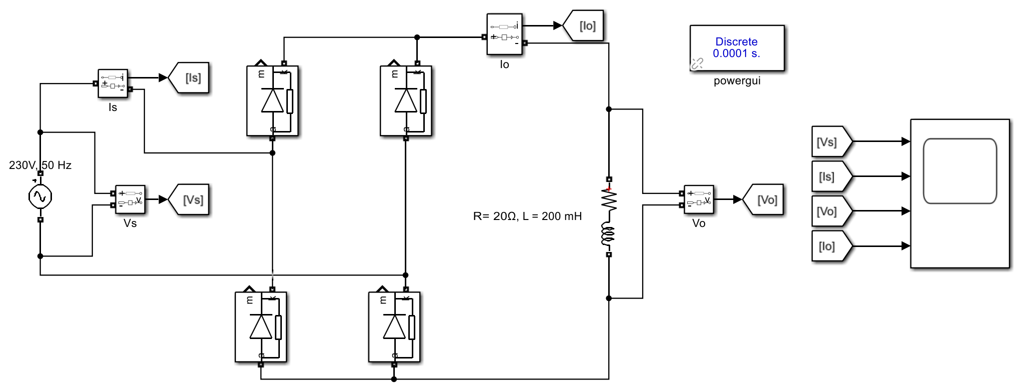
➢ WAVEFORMS OBTAINED:



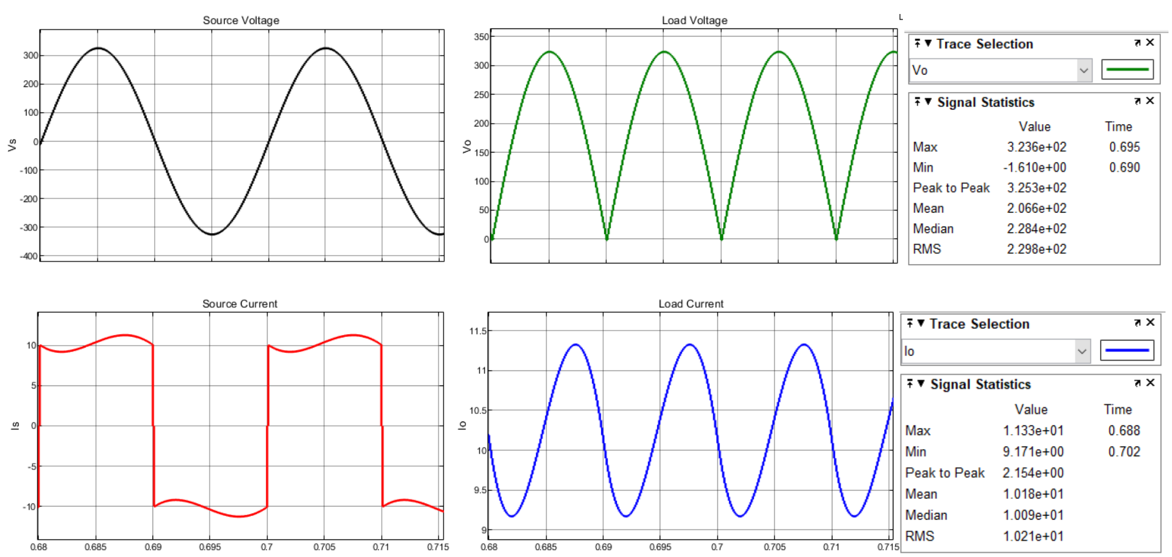


CASE-3, Load R= 20Ω, L = 200 mH

SIMULATED CIRCUIT:



➢ WAVEFORMS OBTAINED:



➢ OBSERVATION:

LOAD	Peak – Peak Ripple in Io
R= 20 Ω Case 1	16.16 A
R= 20 Ω, L = 20 mH Case 2	12.22 A
R= 20 Ω, L = 200 mH Case 3	2.154 A

2. Full-Bridge Uncontrolled Rectifier with Ls = 10 mH

4. CIRCUIT DIAGRAM

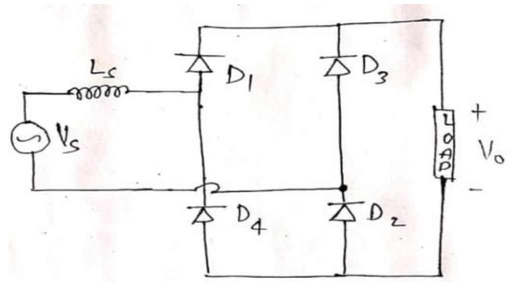
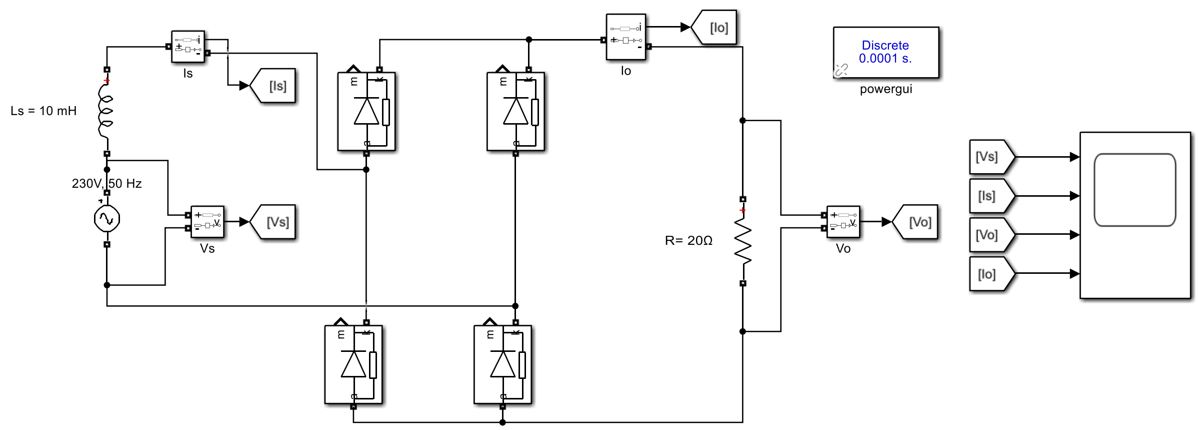


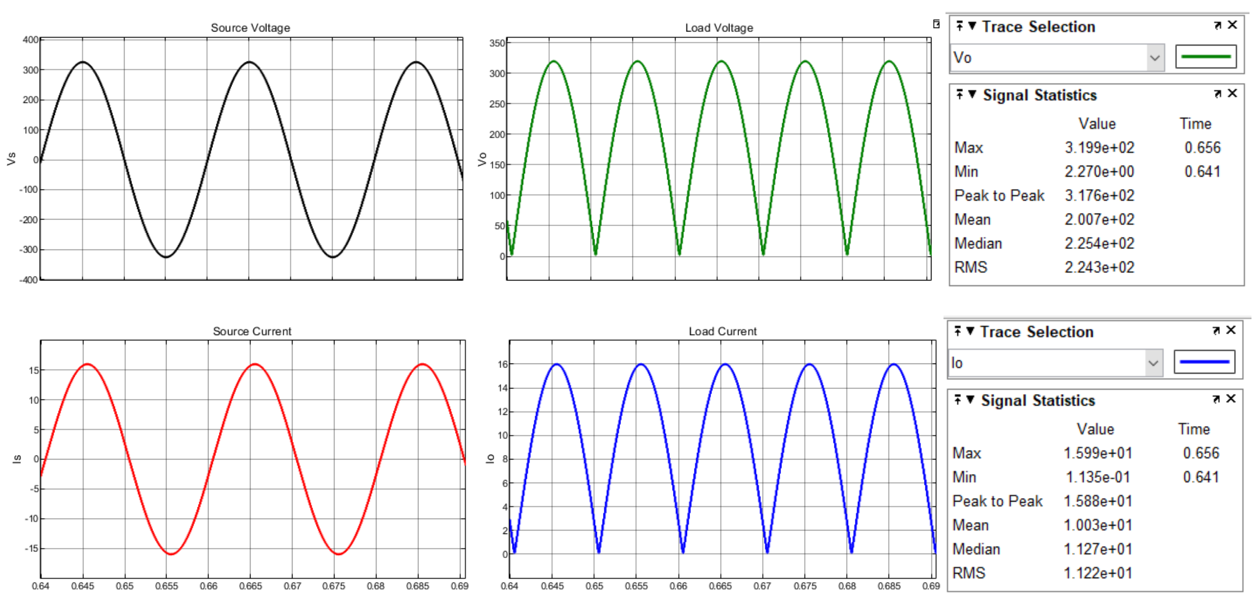
Fig 2: Circuit diagram of Uncontrolled full wave Rectifier with source inductance

CASE-1, Load R= 20Ω,

➢ SIMULATED CIRCUIT:

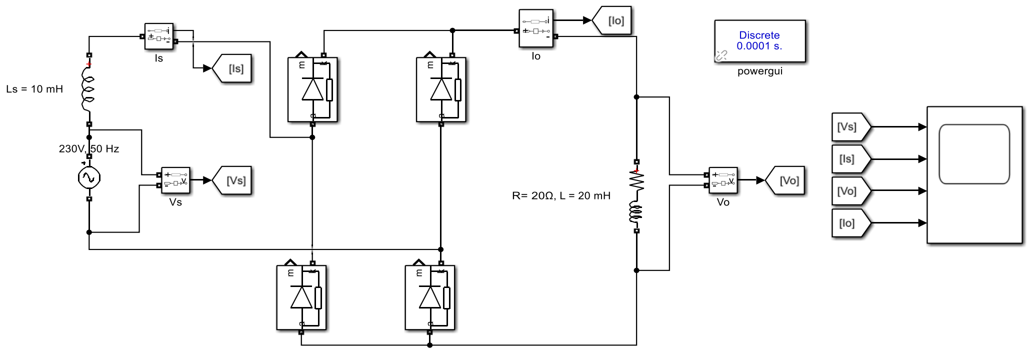


➢ WAVEFORMS OBTAINED:

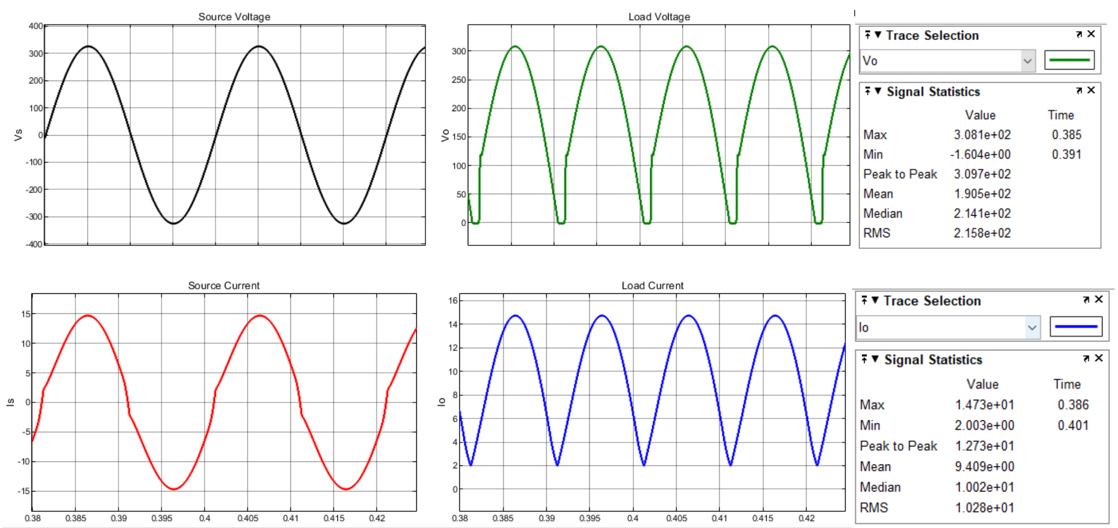


CASE-2, Load R= 20Ω, L = 20 mH

➢ SIMULATED CIRCUIT:

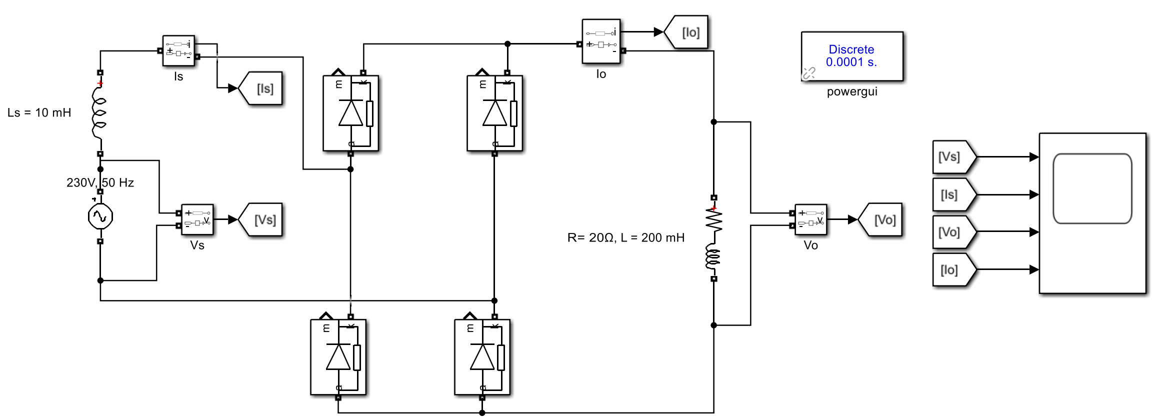


➢ WAVEFORMS OBTAINED:

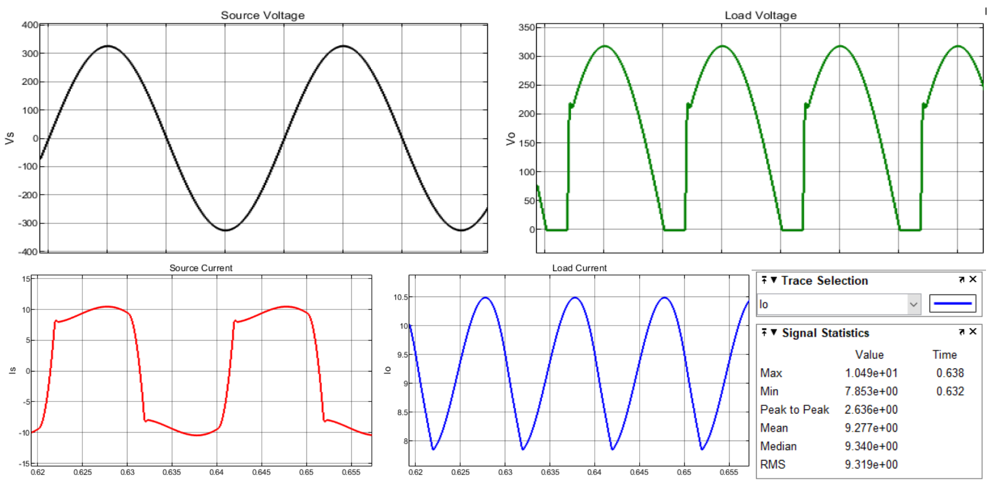


CASE-3, Load R= 20Ω, L = 200 mH

➢ SIMULATED CIRCUIT:



➢ WAVEFORMS OBTAINED:



➢ Calculation of Commutation Angle:

We can use the equation (5) derived in section 4 to find the value of commutation angle μ by taking α = 0

$$\Rightarrow \quad cos(\alpha + \mu) = cos\alpha - \frac{2\omega Ls}{V_{max}} I_o$$

$$\Rightarrow \quad \mu = \cos^{-1}\{1 - \frac{2\omega Ls}{V_{max}} I_o\}$$

Where I_o is average load current; $L_s = 10\ mH$ is source inductance; $\omega = 100\pi$ is source voltage frequency, V_{max}= $230\sqrt{2}$,

➢ Obtained Result:

using $I_{o_{avg}} = 9.277\ A$, $\mu = \cos^{-1}(.8207) \Rightarrow \boldsymbol{\mu = 34.835°}$

➢ Theoretical value:

By equation (7), taking α = 0 for Diode Rectifire we get,

$$\mu = 2\tan^{-1}\{\sqrt{\frac{2\omega L_S}{\pi R}}\} \quad \Rightarrow \mu = 2\ \tan^{-1}(\sqrt{\frac{1}{10}}) \quad \Rightarrow \boldsymbol{\mu = 35.097°}$$

3. Full-Bridge Controlled Rectifier without Ls

➢ CIRCUIT DIAGRAM:

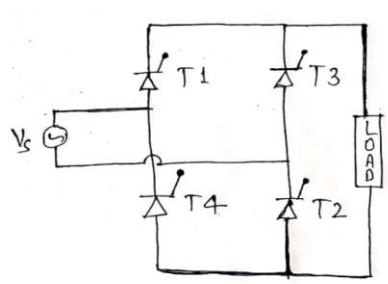


Fig 4: Circuit diagram of Controlled full wave Rectifier

➢ FIRING CIRCUIT DESIGHN:

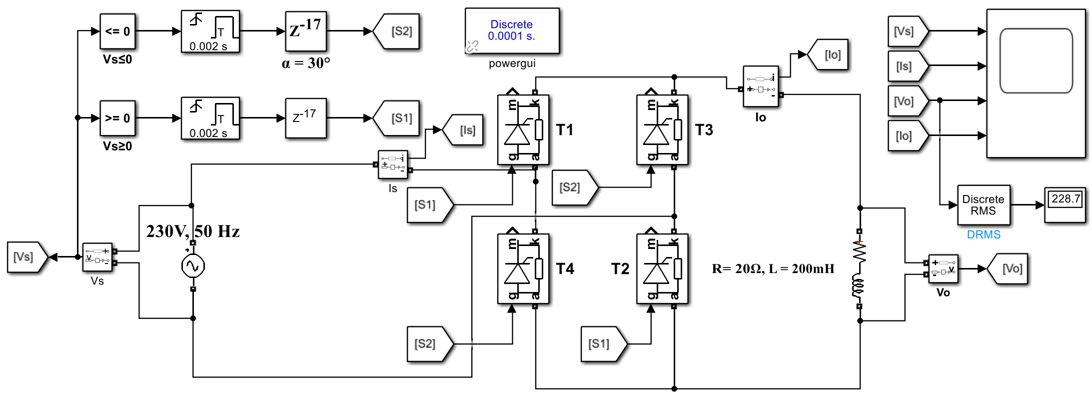
Delay corresponding to $\boldsymbol{\alpha = \frac{\alpha T_s}{360° * t_{sample}}}$

For α = 30°, delay = 16.66 ≈ 17

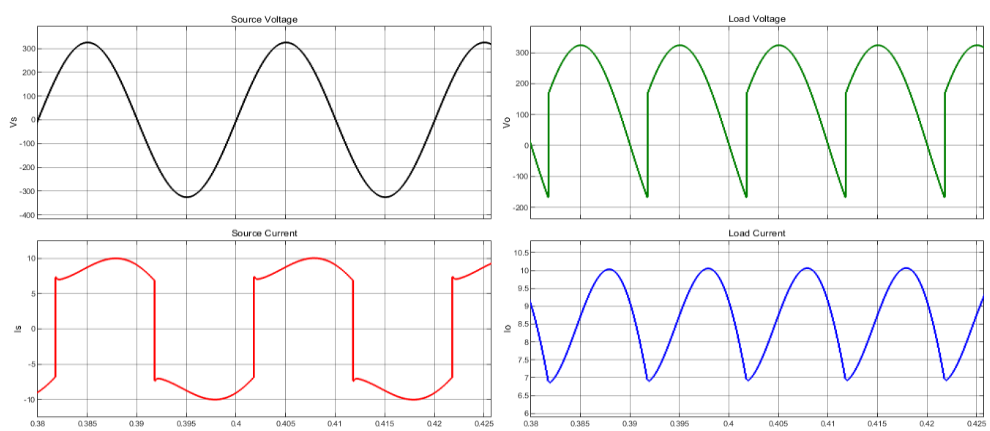
For α = 90°, delay = 50

1. At α = 30°,

➢ SIMULATED CIRCUIT:

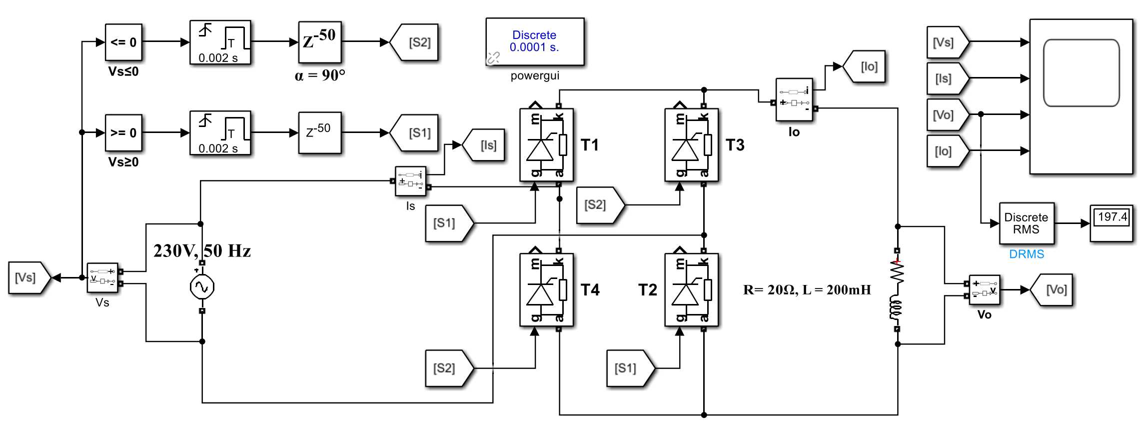


➢ WAVEFORMS OBTAINED:

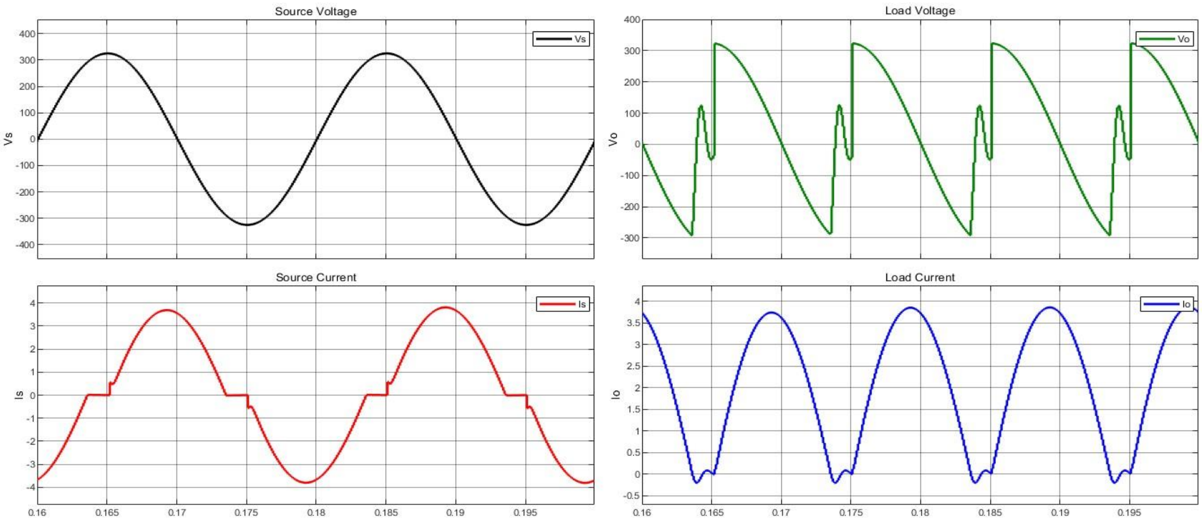


2. At α = 90°,

➢ SIMULATED CIRCUIT:



➢ WAVEFORMS OBTAINED:



➢ OBSERVATION:

With the change in α from 30° to 90° waveform of V_o and I_o both gets change as –

- For α = 30°, wave form of V_o have a large positive area and a very small negative area, but at α = 90° the positive area(charging) gets reduced and negative area(discharging) gets increased.
- For α = 30°, wave form of I_o is continuous & smooth but at α = 90° waveform also crosses zero and becomes negative for a very small duration.

Overall average value of both Vo and Io gets reduced at α = 90°.

4. Full-Bridge Controlled Rectifier with Ls = 10 mH

➢ CIRCUIT DIAGRAM:

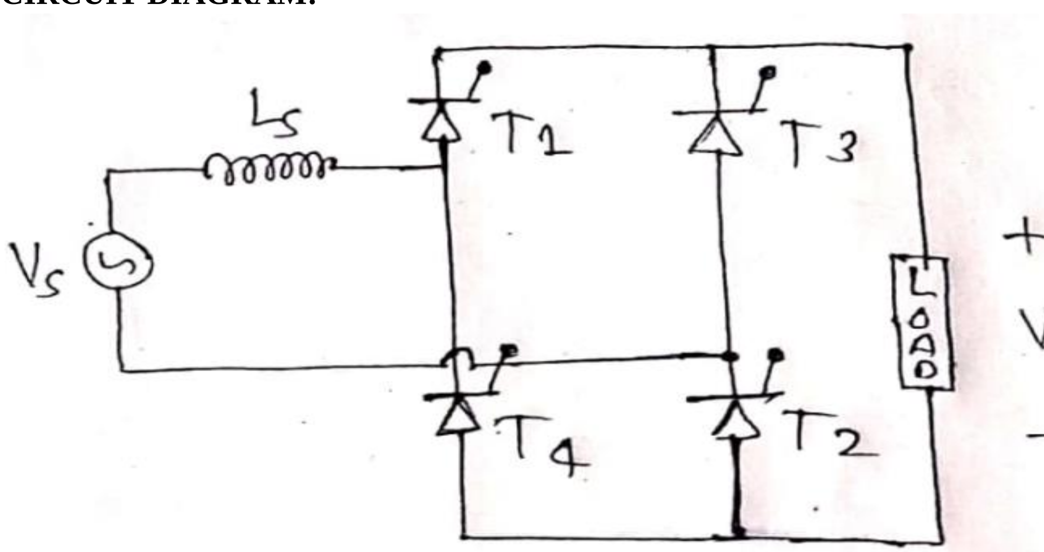
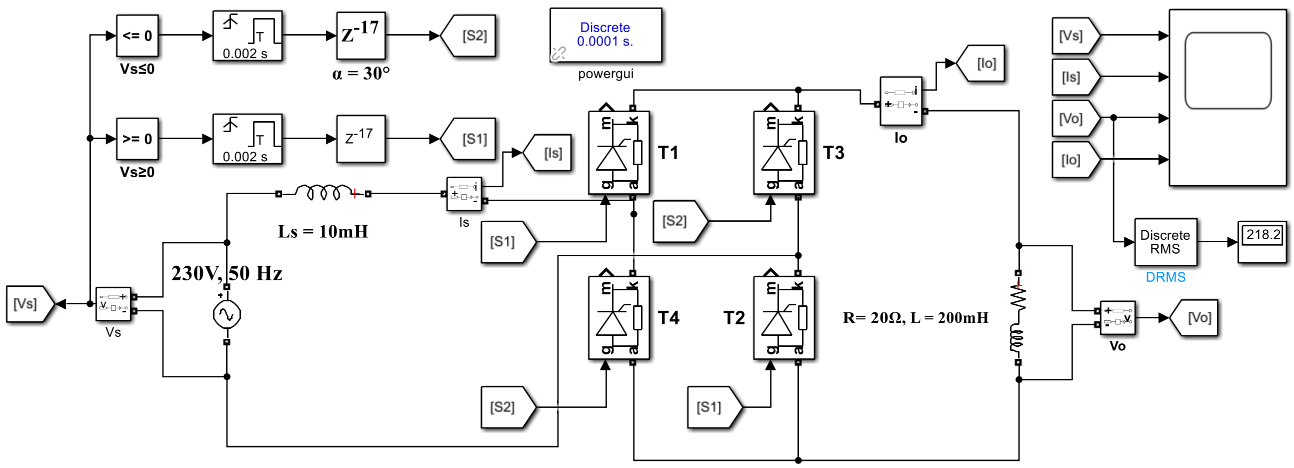


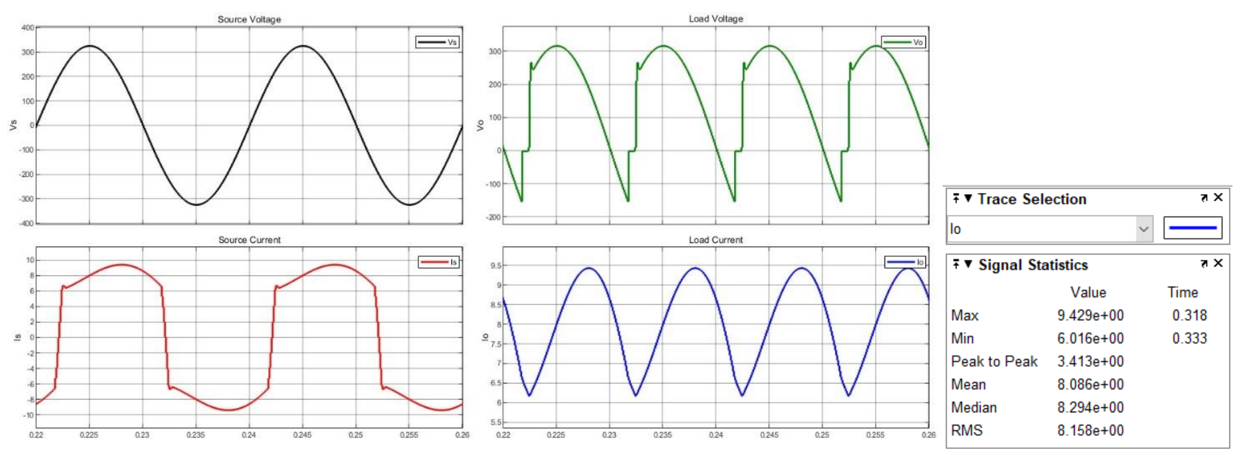
Fig 2: Circuit diagram of Uncontrolled full wave Rectifier with source inductance

1. At α = 30°,

➢ SIMULATED CIRCUIT:



WAVEFORMS OBTAINED:



➢ Calculation of Commutation Angle:-

Until now, the current commutation between thyristors has been considered to be instantaneous. This condition is not valid in real cases due to the presence of the source/Line inductance L. During the commutation, the current through the thyristors cannot change instantaneously, and for this reason, during the commutation angle $\boldsymbol{\mu}$**,** all four thyristors are conducting simultaneously.

Therefore, during the commutation, the following relationship for the load voltage holds

$$v_o = 0 \qquad \forall \qquad \alpha \leq \boldsymbol{\omega t} \leq \alpha + \mu \tag{1}$$

The effect of the commutation on the supply current, the voltage waveforms, and the thyristor current waveforms can be observed in below Fig.

During the commutation, the following expression holds

$$L\frac{di_s}{dt} = v_s = V_{max} sin(\omega t) \quad \alpha \le \omega t \le \alpha + \mu \qquad (2)$$

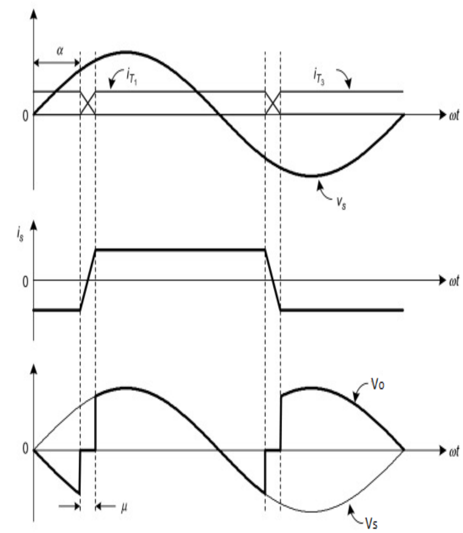
Integrating above Eq. over the commutation interval yields

$$\int_{-I_o}^{I_o} di_s = \frac{V_{max}}{L}\int_{\alpha/\omega}^{\alpha+\mu/\omega} sin(\omega t)\, dt \qquad (3)$$

$$I_{O_{avg}} = \frac{V_m}{2\omega L_S}\{Cos\ \alpha - \cos(\alpha + \mu)\} \qquad (4)$$

From above Eq., the following relationship for the commutation angle $\boldsymbol{\mu}$ is obtained:

$$cos(\alpha + \mu) = cos\alpha - \frac{2\omega Ls}{V_{max}} I_o \qquad (5)$$



the expression for the average load voltage is given by

$$V_{o(avg)} = \frac{1}{\pi}\int_{\alpha+\mu}^{\pi+\alpha} V_m sin(\omega t)\, d(\omega t) = \frac{V_{max}}{\pi}[cos(\alpha + \mu) + cos\alpha] \qquad (6)$$

Since $I_{O_{avg}} = \frac{V_{O_{avg}}}{R}$ therefore using equation (4) and (6) we get

$$\frac{\cos\alpha - \cos(\alpha + \mu)}{\cos\alpha + \cos(\alpha + \mu)} = \frac{2\omega L_S}{\pi R} \qquad (7)$$

- ## Obtained Result:

Using equaton (5) & given parameter as source inductance $L_s = 10\ mH$; $\omega = 100\pi$, V_{max}= $230\sqrt{2}$, & R = 20 Ω, $\alpha = 30°$, I_o = 8.086 A we get,

$$\cos(30° + \mu) = \{\frac{\sqrt{3}}{2} - \frac{8.086\pi\sqrt{2}}{230}\} \Rightarrow \mu = \cos^{-1}(0.709829) - 30° \Rightarrow \boldsymbol{\mu = 14.78°}$$

- ## Theoretical value:

By using equation (7) with all the values we get,

$$\mu = \cos^{-1}\left(\frac{9\sqrt{3}}{22}\right) - 30° \Rightarrow \boldsymbol{\mu = 14.88°}$$

EE561: Power Electronics Laboratory

Experiment - 05

Output Voltage Regulation of Buck Converter using Type-II Compensator

.NAME: SHIVRAJ VISHWAKARMA ROLL. NO. 224102112

- **Objective:** The objective of this experiment is to design a Type-II compensator for a buck converter to regulate its output voltage.
- **Parameters:**

Parameter	Value
Input voltage	24 V
Inductor	50 μH
Capacitor	100 μF
Load Resistance	2 Ω
Switching frequency	100 kHz
Desired Gain cross-over frequency of compensated system	100 Hz
Desired Phase Margin	120°

- **Procedure:**
  - Simulate the buck converter in open-loop
  - Find out the output voltage to duty ratio transfer function of the converter and find the dc gain and location of poles, zeros.
  - Draw the bode plot of open loop system using MATLAB and note down the find the dc gain, gain cross-over frequency, phase cross-over frequency, gain-margin and phase margin.
  - Design a Type-II compensator using K-factor method and write the transfer function of compensator. Draw the bode plot of compensator, and Loop-transfer function. note down the values & find the dc gain, gain cross-over frequency, phase cross-over frequency, gain-margin and phase-margin of the compensated system.
  - Simulate the converter with the Type-II compensator and verify the working with step change in reference voltage from 10 V to 15 V.
  - Take the snapshots of simulation results and prepare the report
- **Uncompensated Buck Converter (Open Loop):**

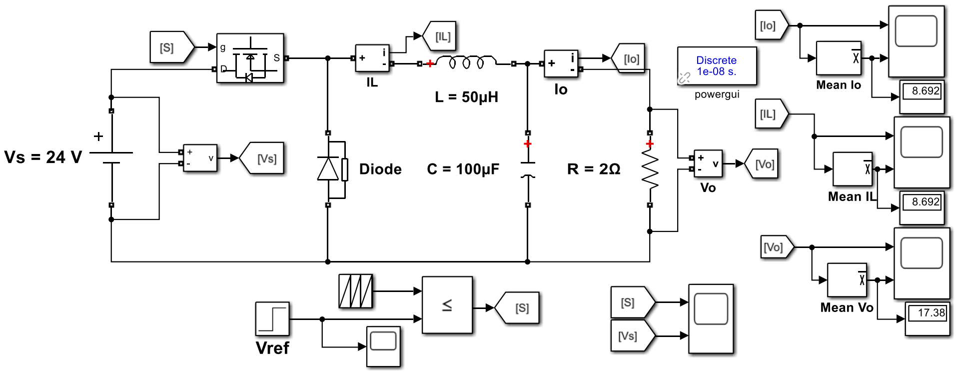


Fig. 1: Open loop Buck Converter simulation circuit

➢ WAVEFORMS:

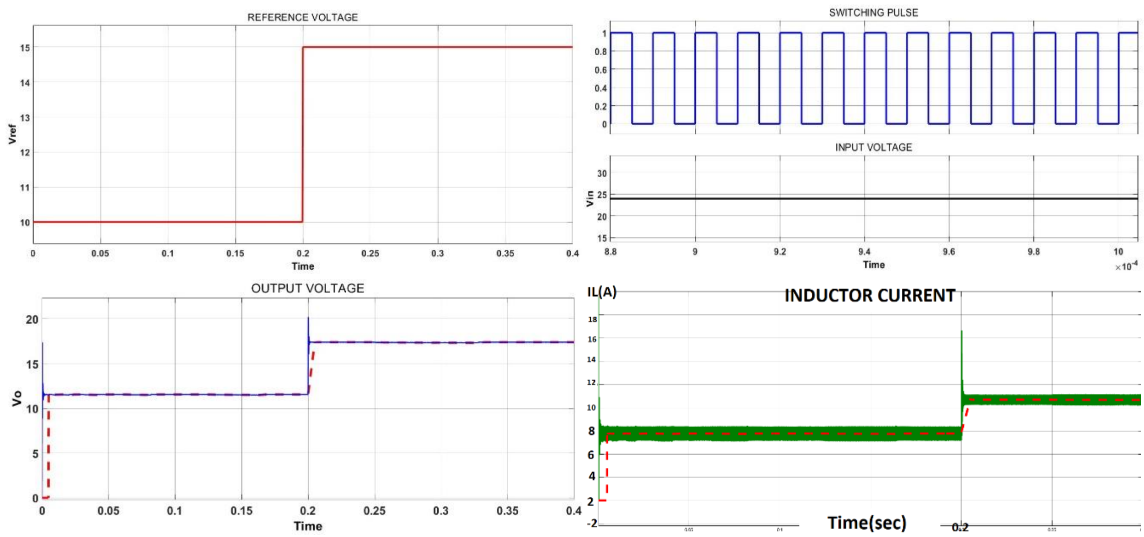


Fig. 2: Waveforms of Vo, I_L, Input & reference Voltage and switching pulse

➢ Uncompensated Buck Converter Design:

❖ Derivation of Transfer function using small signal analysis:

The transfer function is derived using small signal analysis comes as:

$$G_{vd}(s) = \frac{V_o(s)}{D(s)} = \frac{V_{in}}{s^2LC + \frac{sL}{R} + 1} \Rightarrow G_{vd}(s) = \frac{V_{in}}{\{\frac{s}{\omega_o}\}^2 + \frac{s}{Q\omega_O} + 1} \quad (1)$$

$$\text{Were, } \omega = \frac{1}{\sqrt{LC}};\, Q = R\sqrt{\frac{L}{C}}$$

By substituting the values of V_{in}, f_0, Wo and Q the in equation (1) we get the open loop transfer function of Buck Converter as (ω_0 = 14142.13rad/sec, f_o = 2251.93, Q = 2.828, Q(dB) = 9.029)

$$G_P = G_{vd}(s) = \frac{24}{5*10^{-9}s^2 + 2.5*10^{-5}s + 1} \quad (2)$$

➢ MATLAB CODE:

```
1)   v = 24;
2)   L = 50e-6;
3)   C = 100e-6;
4)   R = 2;
5)   F = 100e3;
6)   num = [v];
7)   den = [L*C L/R 1];
8)   y= tf (num, den);
9)   bode(y)
```

➢ BODE PLOT: –

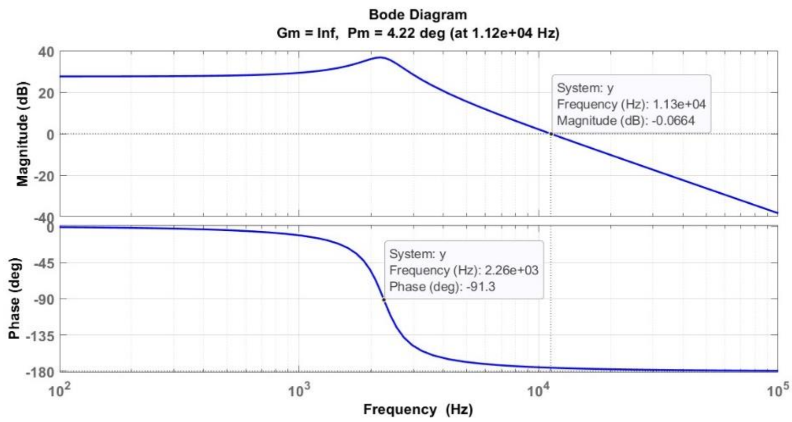


Fig. 3: Bode Plot of Uncompensated Buck Converter

✓ For the uncompensated buck converter, the DC gain K with the help of Bode plot is **27.6 DB** & the value of phase margin (PM) at ω_{gc} is **4.22°** & GM is ∞, cross-over frequency is $1.12*10^4$ Hz.

Design of TYPE- II Compensator:

- Desired the gain cross-over frequency 100 Hz.
- Phase Margin (P.M.) $\{\phi_m\}$ is given 120° & the phase Angle of uncompensated Buck converter (G_p) at ω_{gc} *is* 0.907° by the help of this we can easily find the phase boost for that given system

$$\phi_b = \phi_m - \phi_p - 90° \Rightarrow \phi_b = 120° + 0.907° - 90° \Rightarrow \boldsymbol{\phi_b = 30.907°}$$

- Now the value of K will be calculated using the formula for type II compensator as

$$K = \tan\{45° + \frac{\phi_b}{2}\} \Rightarrow \boldsymbol{K = 1.76415} \tag{3}$$

- Transfer Function of TYPE -II compensator is given by

$$a(s) = \frac{G_{MB}\left(1+\frac{\omega_Z}{s}\right)}{\left(1+\frac{s}{\omega_p}\right)} \tag{4}$$

Where,

$$\boldsymbol{G_{MB}} = \frac{\mathbf{1}}{|\,\boldsymbol{G_p(j\omega_c)}\,|} = 0.04168,\ \boldsymbol{\omega_Z} = \frac{\boldsymbol{\omega_c}}{\boldsymbol{K}} = 356.1594\ rad/sec\ \&\ \boldsymbol{\omega_p} = \boldsymbol{K} * \boldsymbol{\omega_C} = 1108.45\ rad/sec$$

Now the Transfer Function of TYPE- II Compensater will be

$$a(s) = \frac{46.2s+16454.6}{s^2+1108.45s} \tag{5}$$

MATLAB CODE:

```
10)    Gmb= (0.04168);
11)     n = [1108.45 394784.88];
12)     d = [1 1108.45 0];
13)     a=tf(gmb*(n), d);
14)     bode(a)
```

BODE PLOT:

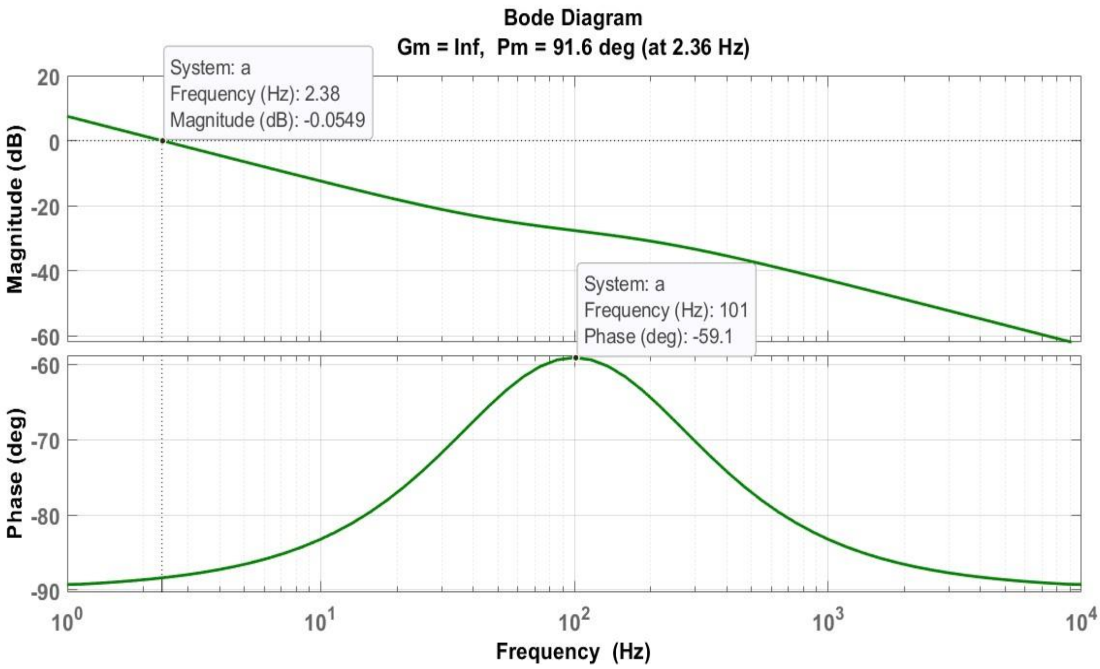


Fig. 4: Bode Plot of TYPE-II Compensator

➢ Buck Converter with TYPE-II Compensater:

$$a(s).G_{vd}(s) = \frac{24G_{MB}\left(1+\frac{\omega_Z}{s}\right)}{(5{*}10^{-9}s^2 + 2.5{*}10^{-5}s+1)\left(1+\frac{s}{\omega_p}\right)} \tag{6}$$

By substituting the values in equation, the loop transfer function is obtained as:

$$a(s).G_{vd}(s) = \frac{1108.8s + 3.9491{*}10^5}{(5{*}10^{-9}\ s^4 + 3.054{*}10^{-5}s^3{+}1.028s^2 + 1108.45s)} \tag{7}$$

➢ MATLAB CODE:

```
b= tf(y*a);
bode(b)
margin(b)
```

➢ BODE PLOT:

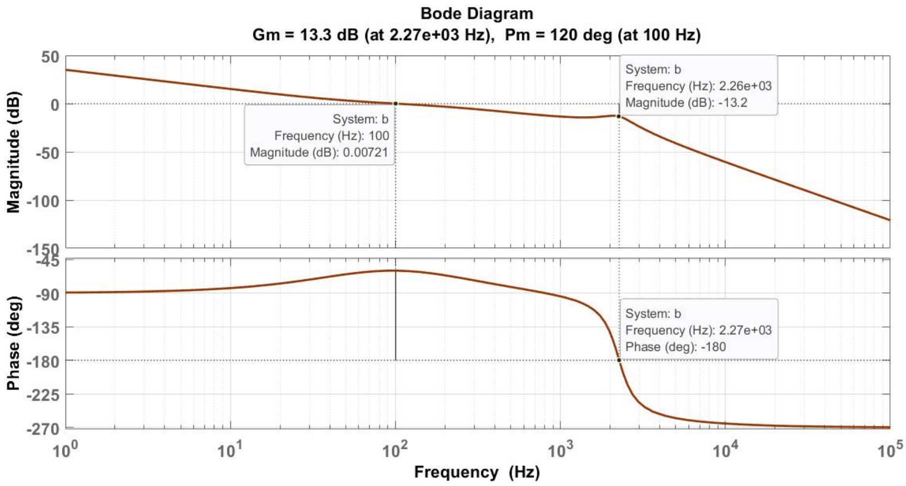


Fig. 5: Bode Plot of Compensated Buck Converter

➢ COMBINED BODE PLOT:

```
v = 24;
L = 50e-6;
C = 100e-6;
R = 2;
F = 100e3;
num = [v];
den = [L*C L/R 1];
y=tf (num, den);
bode(y)
margin(y)
hold on;
gmb= (0.04168);
n = [1108.45 394784.88];
d = [1 1108.45 0];
a=tf(gmb*(n), d);
bode(a)
margin(a)
hold on;
b= tf(y*a);
bode(b)
margin(b)
```

MATLAB Code

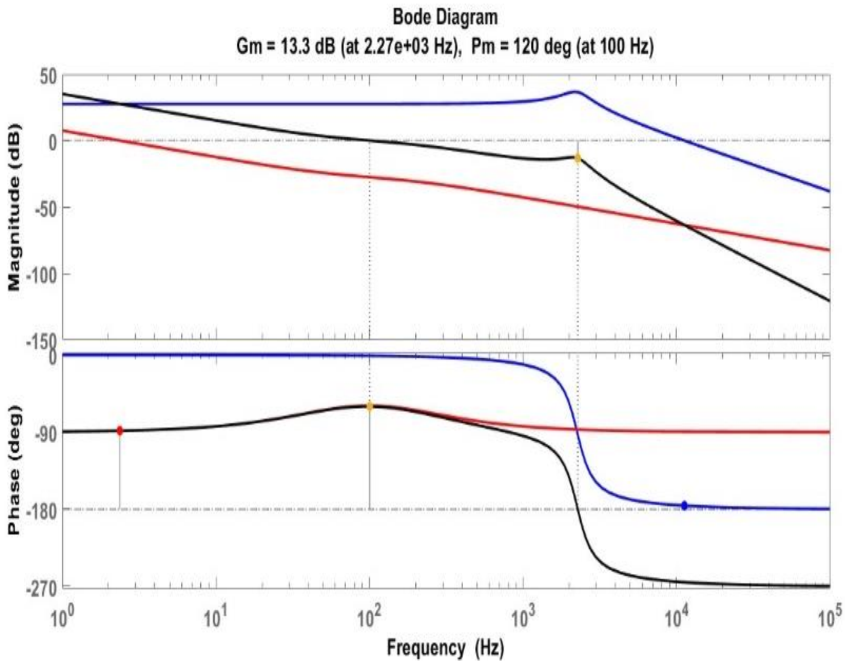


Fig. 6: Combined Bode Plot of whole system

➢ SIMULATEDCIRCUIT:

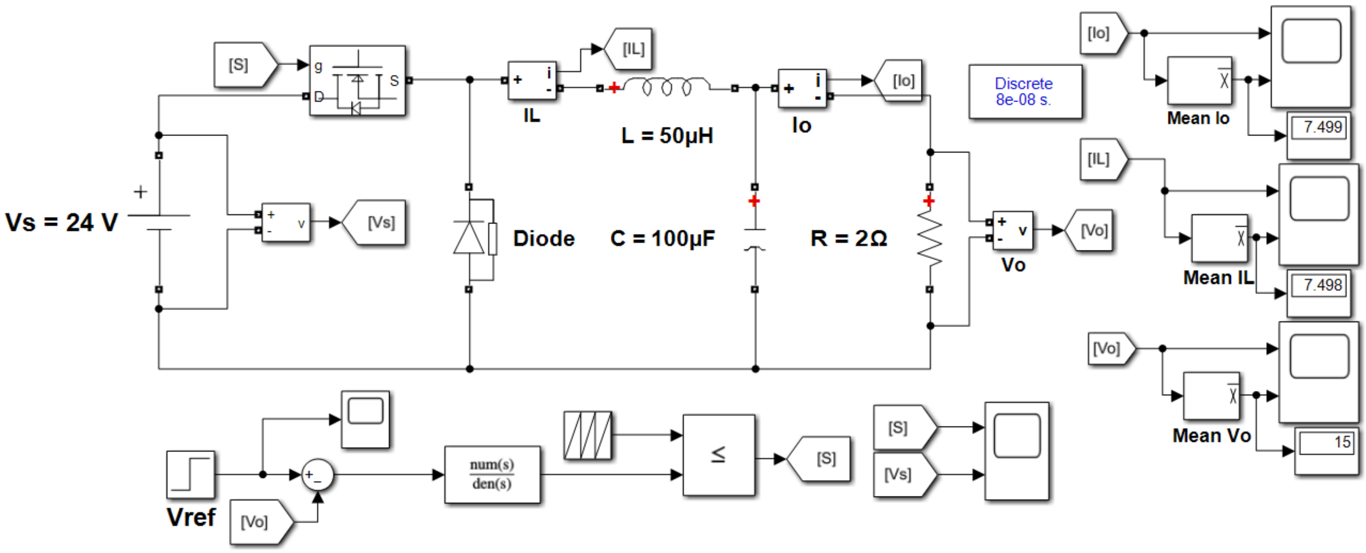


Fig. 7: Simulated Diagram of Compensated Buck Converter

➢ SIMULATION CONFIGRATION & PARAMETERS:

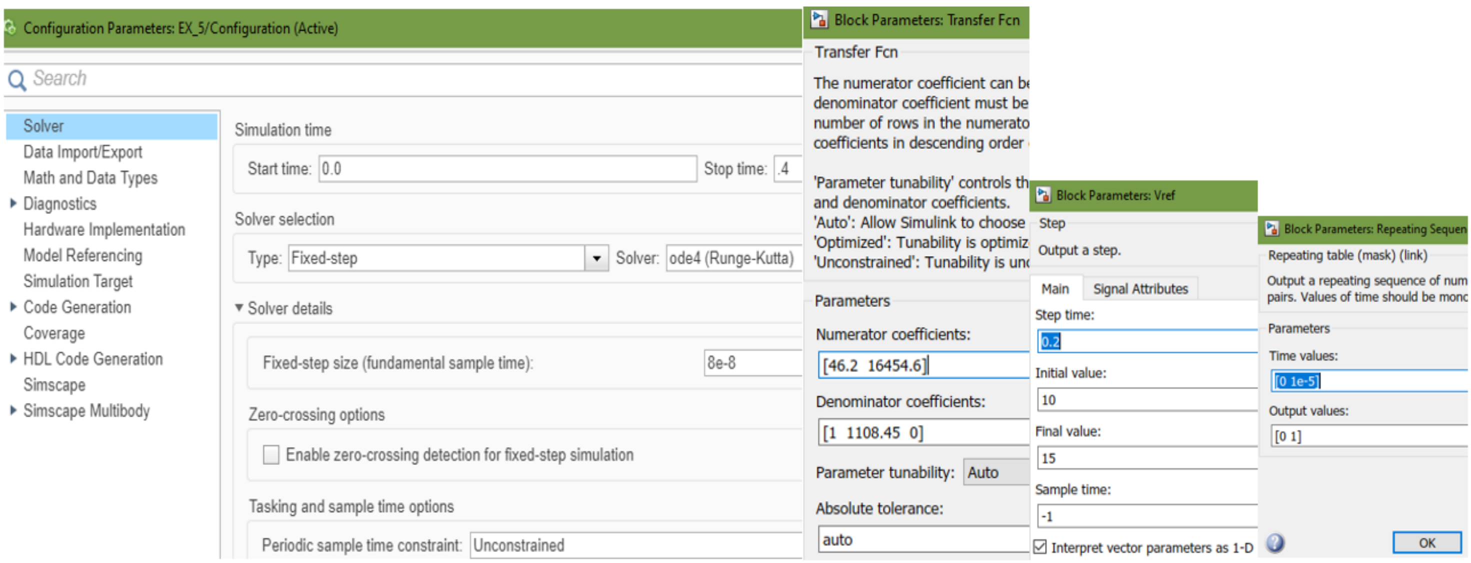


Fig. 8: Step Voltage, simulation configuration

➢ WAVEFORMS:

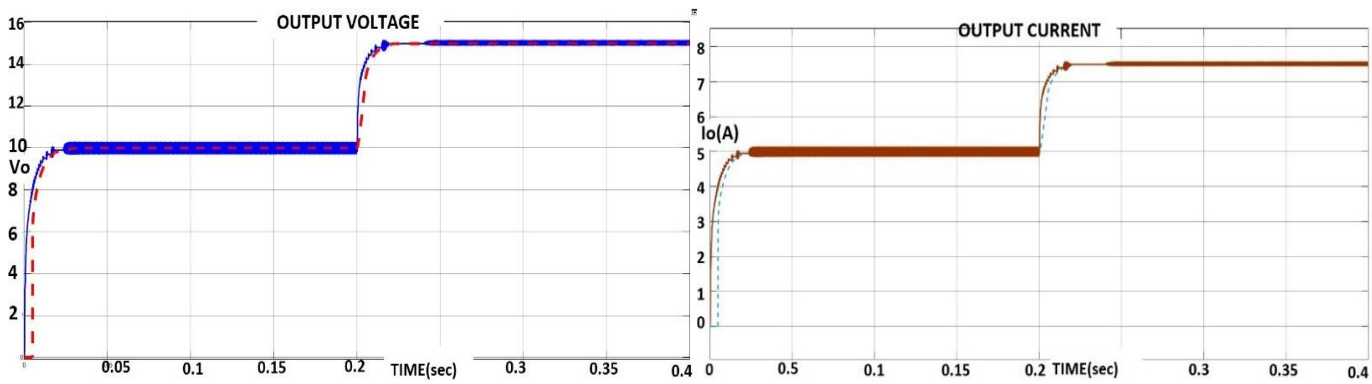


Fig. 9: Output Voltage, Output Current

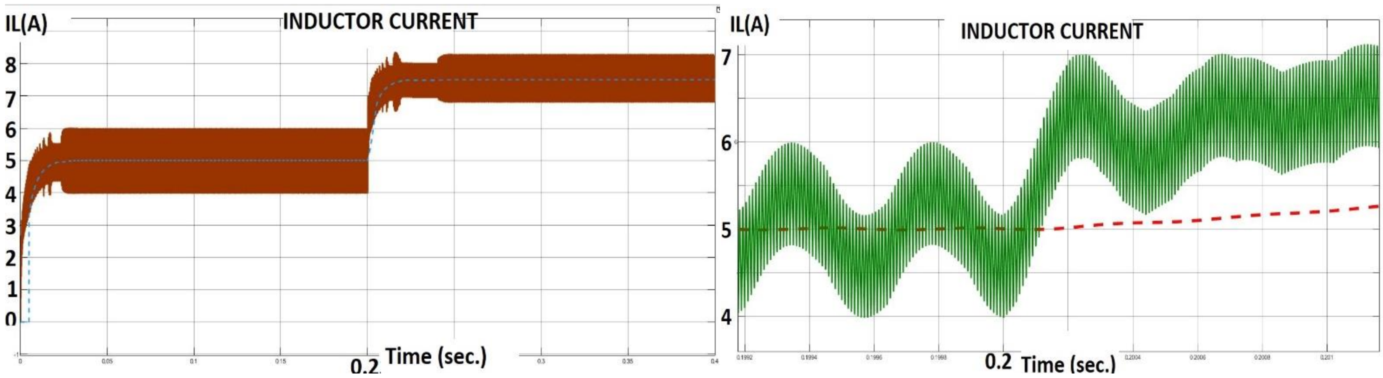


Fig. 8: Inductor Current & its Ripple

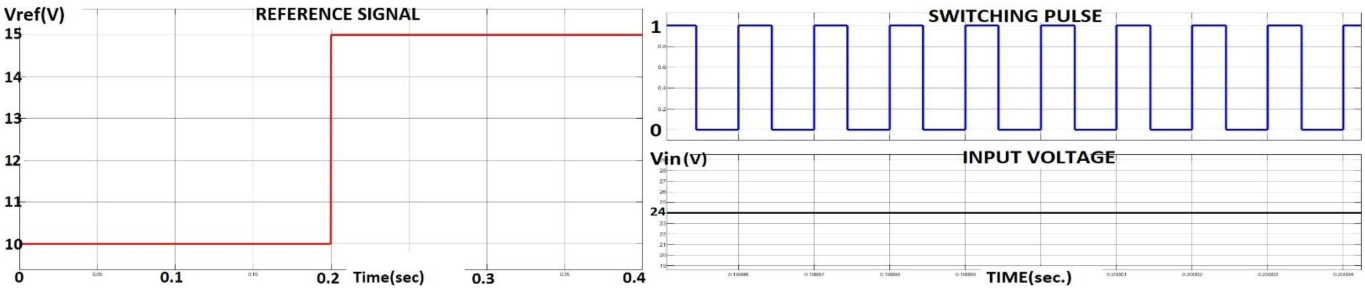


Fig. 9: Reference Voltage, Switching pulse & Input Voltage

Experiment 4

Design & Simulation of FLYBACK and SEPIC converter using MATLAB/SIMULINK

1. FLYBACK CONVERTER

1. **PARAMETERS:** Input voltage = 24 V, switching frequency = 20 kHz, Duty ratio =1/3, Resistance = 5 Ω, Capacitance =200 µF, Ripple inductor current 20% of the average inductor current, Turn ratio N1:N2 =1:5

2. **CIRCUIT DIAGRAM:**

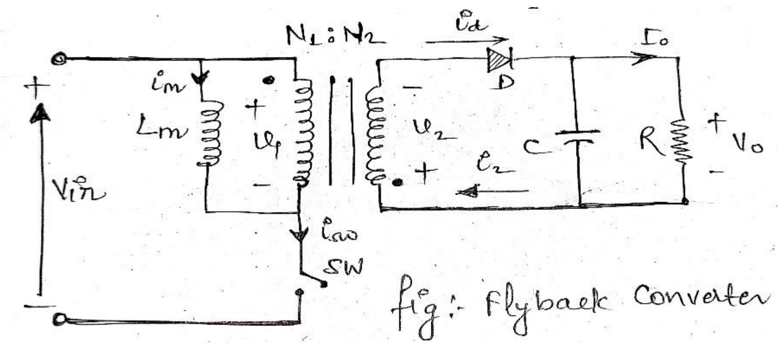


Fig:1 Circuit diagram of flyback converter

3. **THEORETICAL WAVEFORMS OF FLYBACK CONVERTER:**

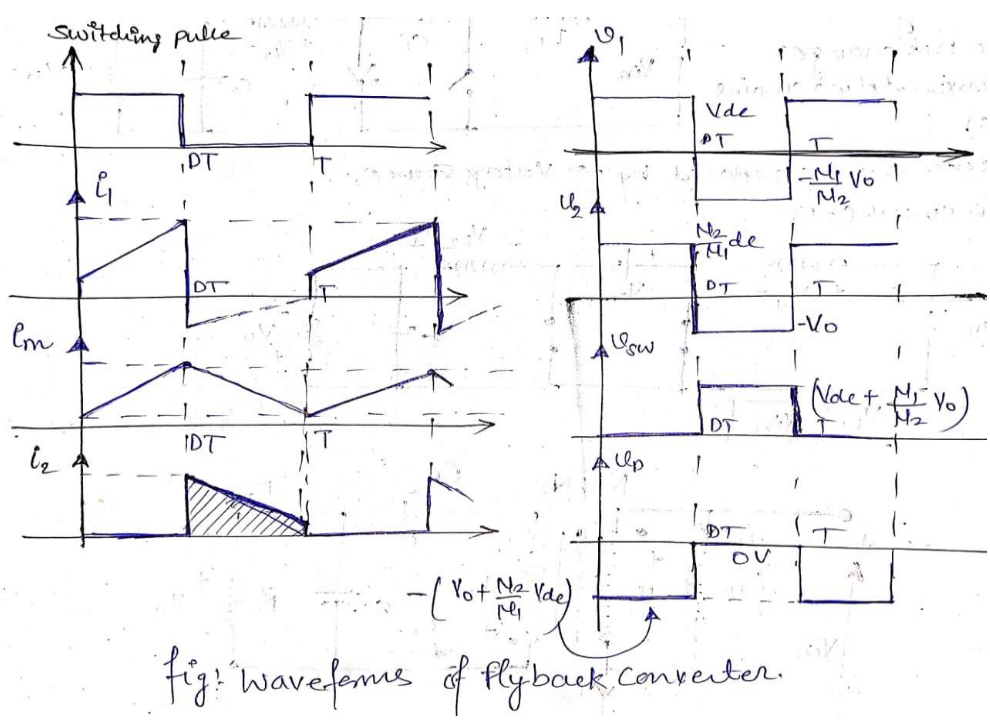


Fig 2: theoretical waveforms of flyback converter

4. **DESIGN PARAMETERS:**

   a. The value of output voltage =

$$\boldsymbol{V_0 = \frac{N_2}{N_1} V_I \frac{D}{1-D} = 60V}$$

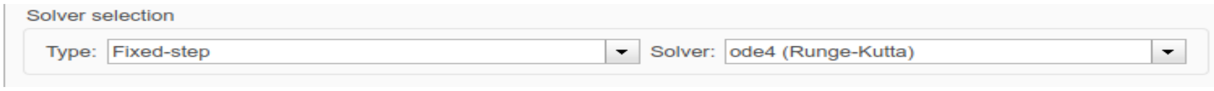
b. Magnetizing Inductance =

$$L_m = \frac{V_L D}{f \Delta I} = 22.2\mu H$$

c. Switching time period = $T = \frac{1}{f} = 50\ \mu sec$

4. SNAPSHOT OF THE SIMULATED CIRCUIT:

Considering diode $V_{f} = 0.8$ V, & solver configuration as-



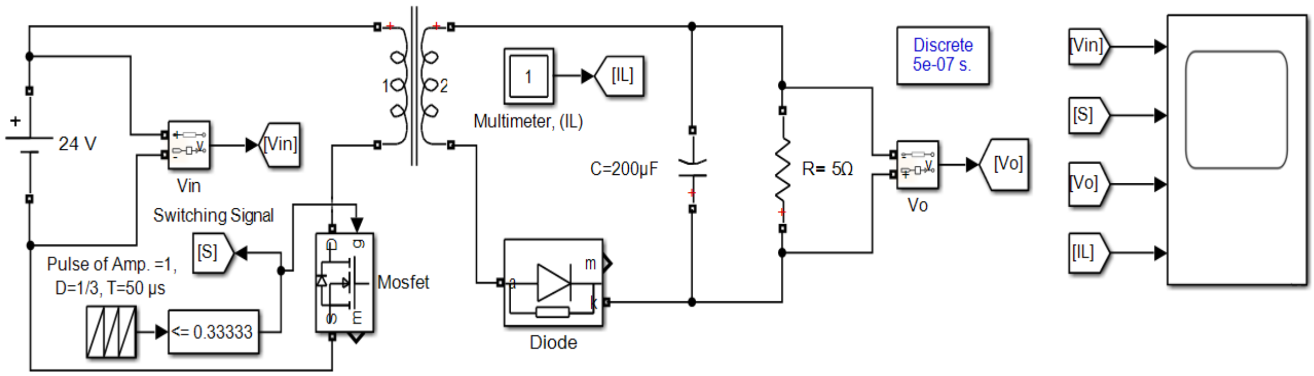
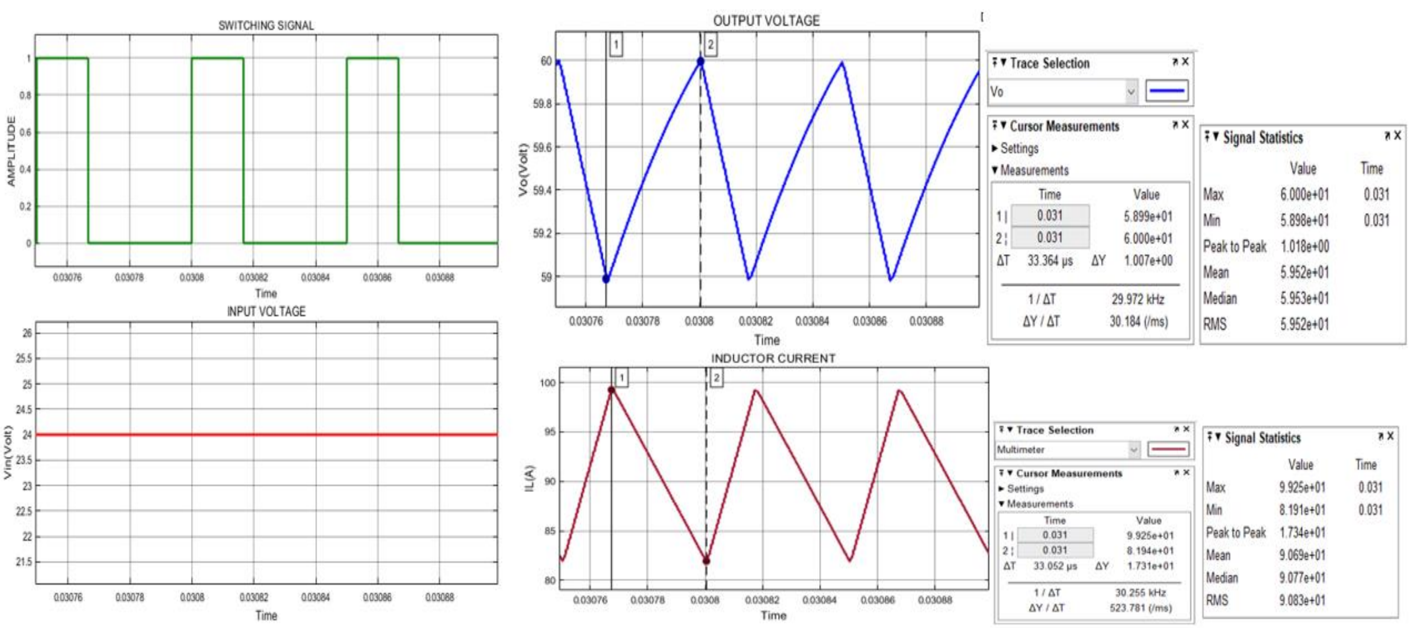


Fig 3: simulated circuit diagram

5. WAVEFORMS OBTAINED:



6. SIMULATION RESULT:

Parameter	Theoretical value	Practical value	Ripple value
Output voltage	60V	58.97V	.95V
Inductor avarage current	90A	86.41A	17.32A

2. SEPIC CONVERTER

7. **PARAMETERS:** Input voltage = 48 V, switching frequency = 50 kHz, Duty ratio = 2/3, Resistance = 10 Ω, Capacitance =200 μF (both C1 & C2)), Ripple inductor current 20% of the average value (for both L1 & L2).

8. **CIRCUIT DIAGRAM:**

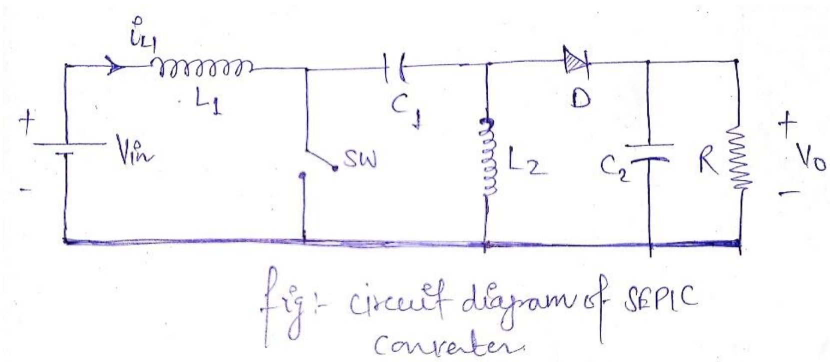


Fig:1 Circuit diagram of SEPIC converter

9. **THEORETICAL WAVEFORMS OF FLYBACK CONVERTER:**

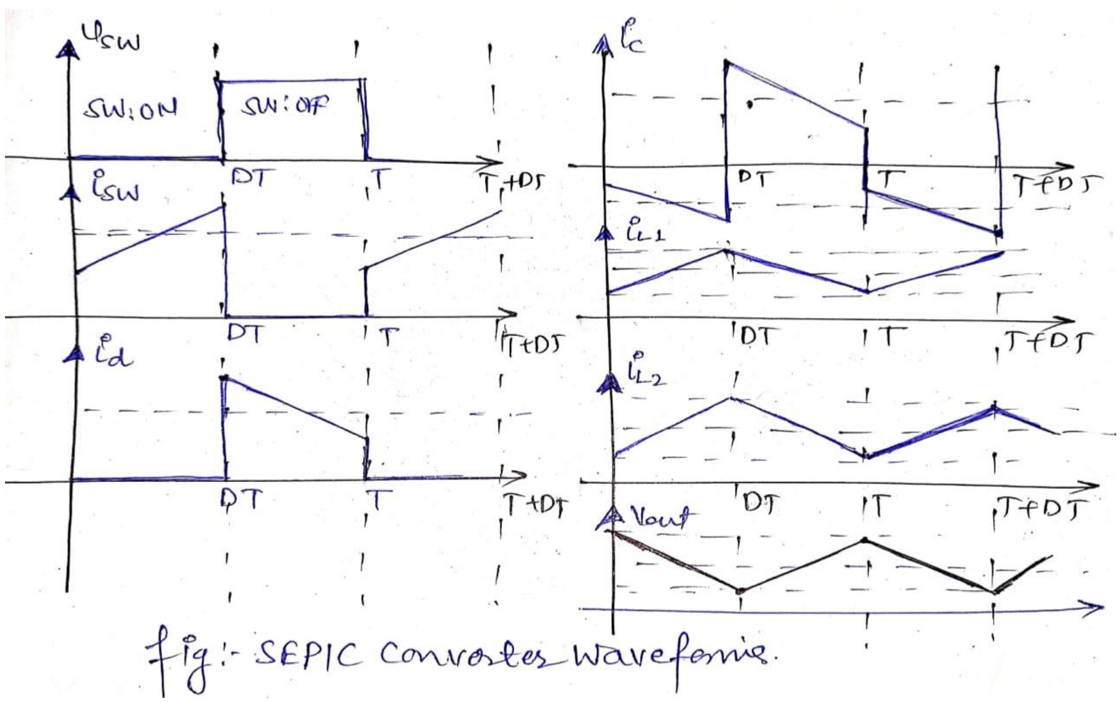


Fig 2: theoretical waveforms of SEPIC converter

10. **DESIGN PARAMETERS:**

d. The value of output voltage =

$$V_0 = \frac{V_s D}{1-D} = 96\text{V}$$

e. Incdctance of Inductors =

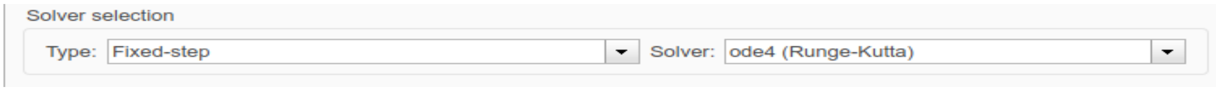
$$L_1 = \frac{V_s D}{\Delta I_{L_1} f} = 166.66\ \mu\text{H}$$

$$L_2 = \frac{V_s D}{\Delta I_{L_2} f} = 333.33\ \mu\text{H}$$

f. Switching time period = $T = \frac{1}{f} = 20\ \mu sec$

11. SNAPSHOT OF THE SIMULATED CIRCUIT:

Considering diode V_{f} = 0.8 V, & solver configuration as-



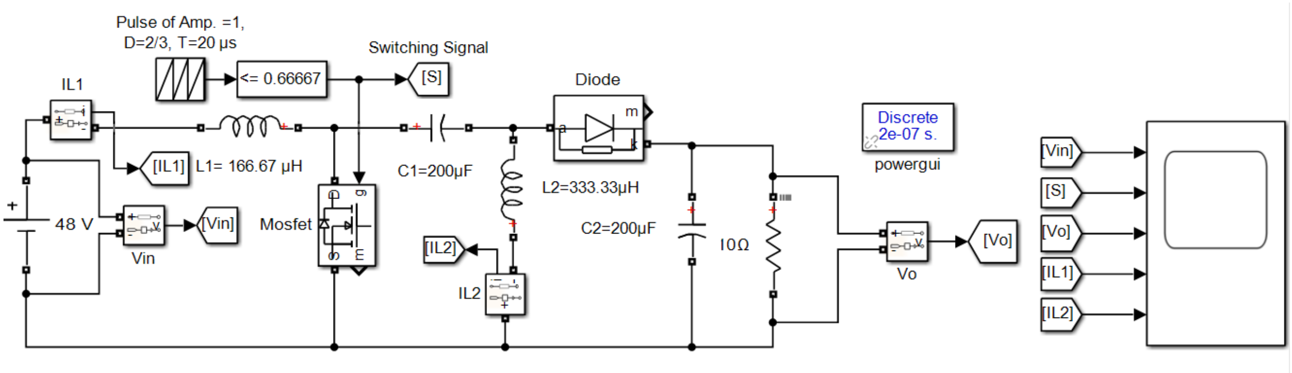
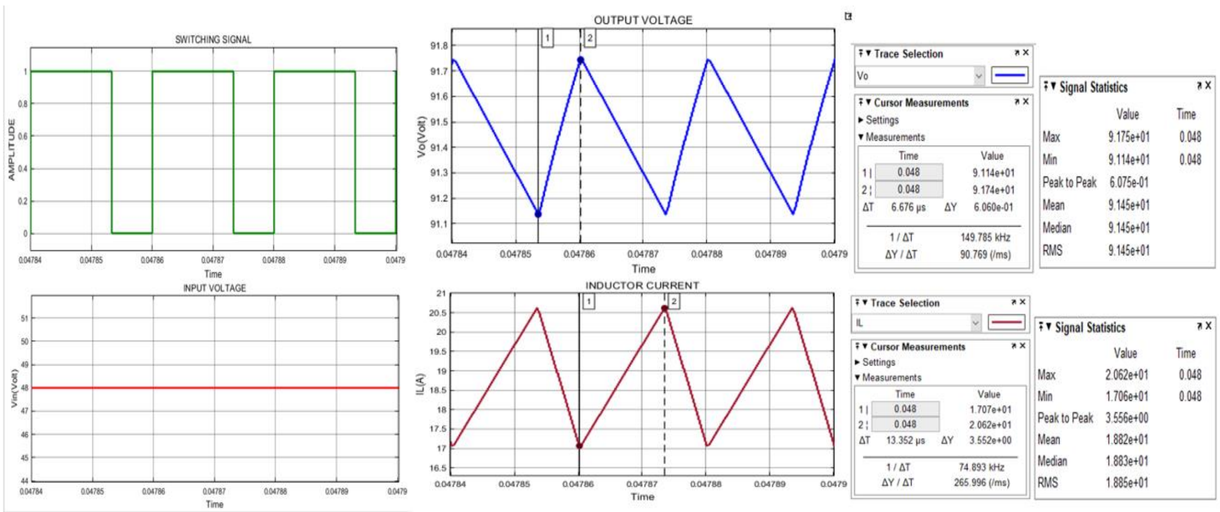
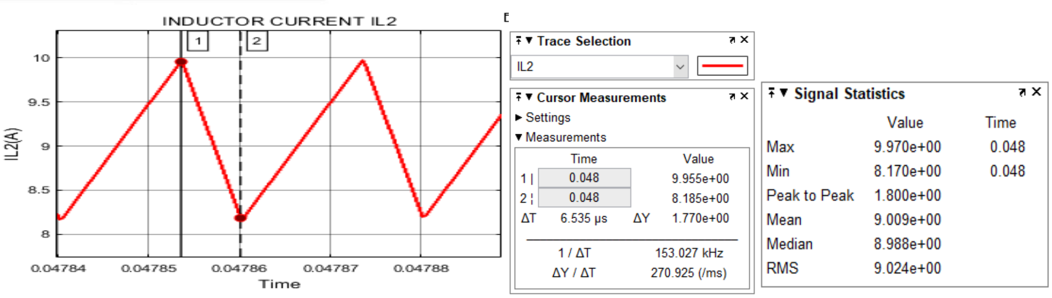


Fig 3: simulated circuit diagram

12. WAVEFORMS OBTAINED:





13. SIMULATION RESULT:

Parameter	Theoretical value	Practical value	Ripple value
Output voltage	96 V	91.45 V	.607 V
Inductor avarage current I_{L1}	19.2 A	18.82 A	3.55 A
Inductor avarage current I_{L2}	9.6 A	9.009 A	1.8 A

Submitted by – Shivraj Vishwakarma,

M. Tech. 1st Year

Roll No. - 224102112

EEED, Power Engg.

EXPERIMENT No. 3

CONTINUOUS AND DISCONTINUOUS CONDUCTION MODES OF BASIC DC - DC CONVERTERS USING MATLAB/SIMULINK

Objective:

To study the Continuous and Discontinuous Conduction modes of basic DC - DC converters viz. buck, boost, buck-boost converters using MATLAB/SIMULINK

1. Buck Converter

Parameters:

Input voltage: **48V**; Switching Frequency: **50 kHz**; Duty Ratio: **0.5;** Load Resistance: **5 Ω**;

Capacitor: **200 μF,** Inductor: Case-1, **$L=10*L_c$**, Case-2, **$L=L_c$,** Case-3, **$L= L_c / 10$**

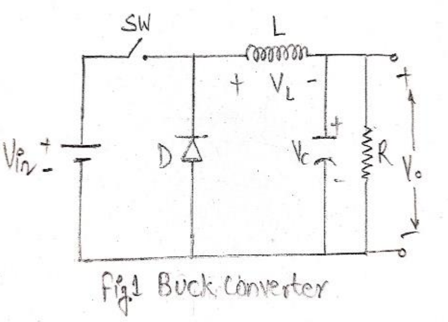
Theory: -

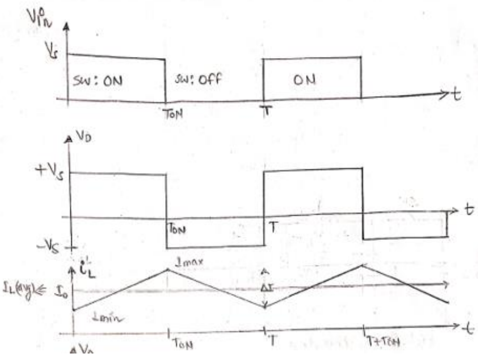
A buck converter is a step-down DC to DC converter. The switching action can be implemented by a BJT, a MOSFET, or an IGBT. Figure 1 shows a simplified block diagram of a buck converter that accepts a DC input and uses pulse-width modulation (PWM) of switching frequency to control the switch. An external diode, together with external inductor and output capacitor, produces the regulated dc output. Buck, or step-down converters produce an average output voltage lower than the input source voltage. The output voltage can be represented as, **$V_o = D*V_{in}$** where D is duty ratio defined as-

CCM and DCM:

The buck converter can operate in two different modes; continuous conduction mode (CCM) and discontinuous conduction mode (DCM). A buck converter operates in continuous mode if the current through the inductor never falls to zero during the commutation cycle. In DCM, the current through the inductor falls to zero during part of the period.

CIRCUIT DIAGRAM & WAVEFORMS: -





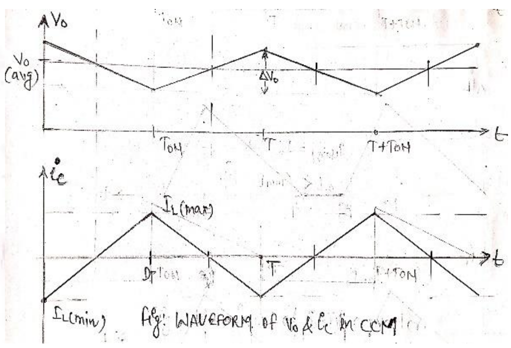
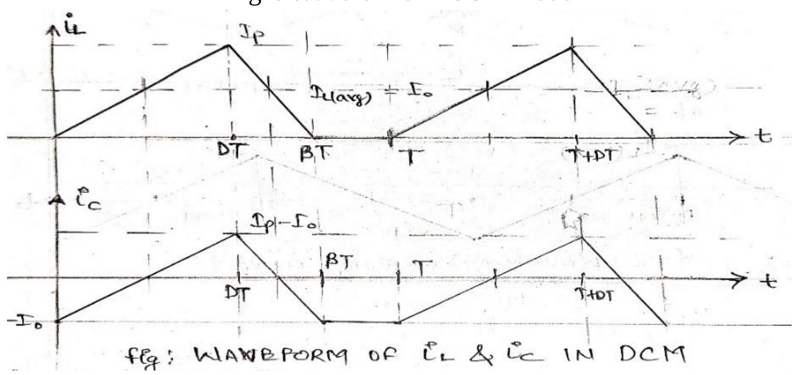


Fig1: Waveforms in CCM mode



DESIGN PARAMETER CALCULATIONS: -

INDUCTOR:

For critical Inductance, $I_{L\,(avg.)} = \Delta I_L \Rightarrow L_c = \frac{(1-D)*R}{2f} \Rightarrow L_c = 25\ \mu H$

CASE 1: When L= 10*25μH $\Rightarrow$ L = 250 μH (CCM)

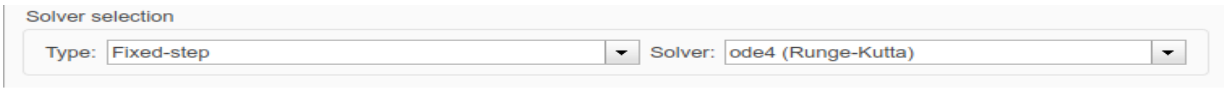
Output voltage: $V_o = D*V_{in} \Rightarrow$ Vo = 24 V

Ripple in Inductor Current $\Delta I_L = \frac{(1-D)*V_o}{fL} \Rightarrow \Delta I_L = 0.96$ A

Ripple in Output Voltage $\Delta V_o = \frac{\Delta I_L}{8fC} \Rightarrow \Delta V_O = 12$ mV

SIMULATION CIRCUIT:

Considering diode $V_f = 0.8$ V, & solver configuration as-



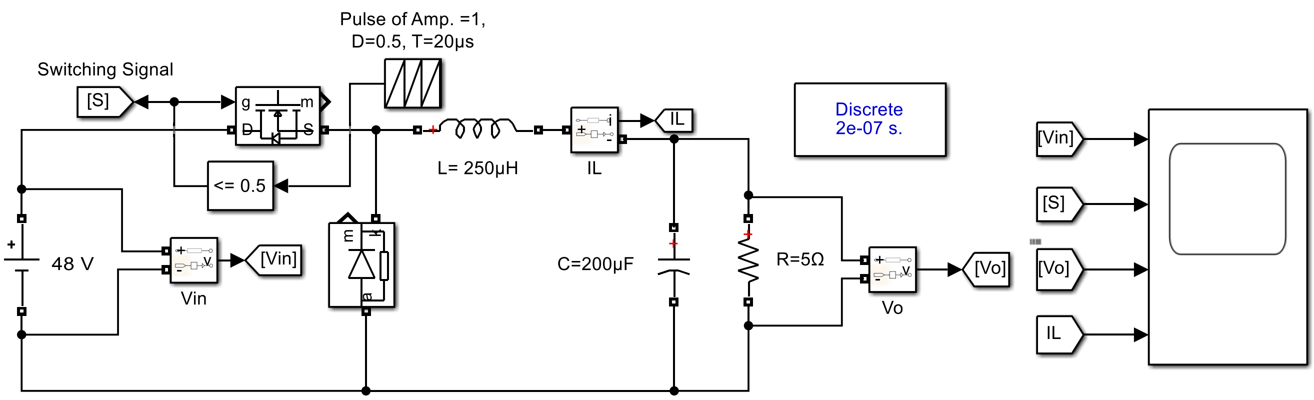
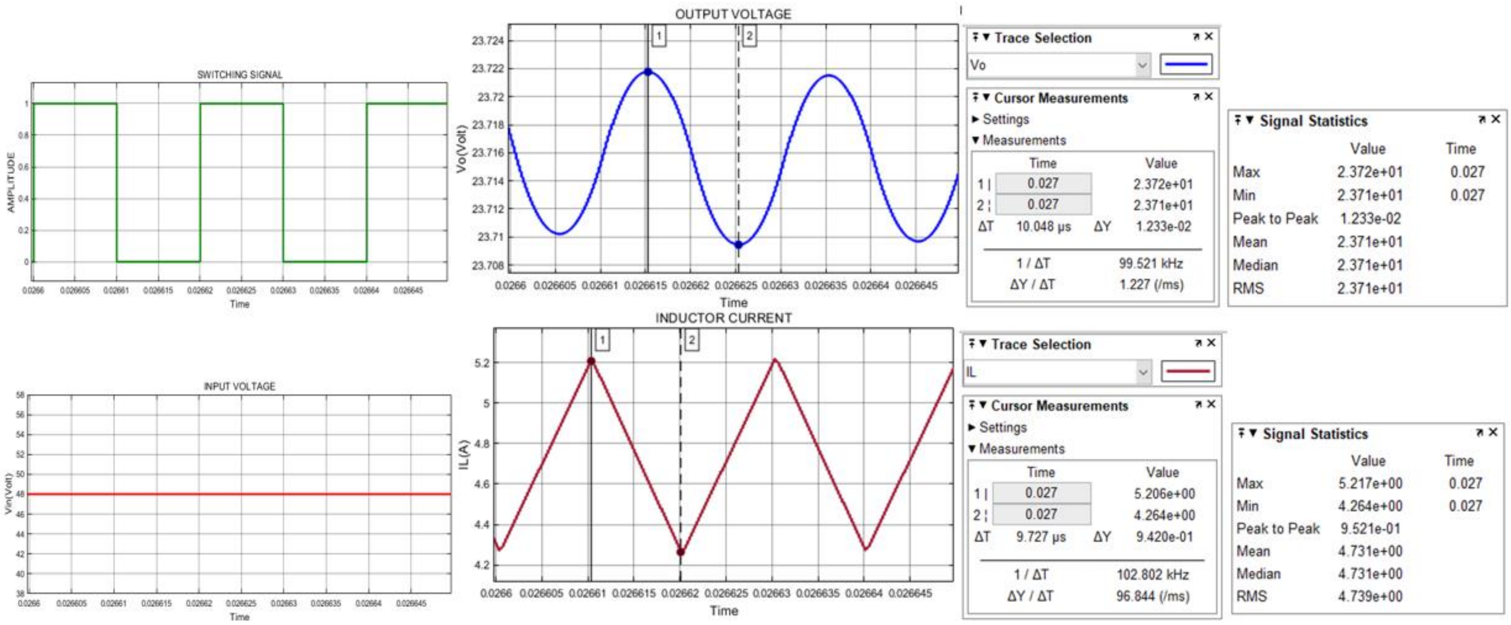


Fig3: Simulation Model of Buck Converter

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current $\Delta I_L = 0.952$ A

Ripple in Output Voltage $\Delta V_o = 12.33$ mV

CASE 2: When L= L_c $\Rightarrow$ L = 25 μH (*Boundary*)

Output voltage: $V_o = D*V_{in} \Rightarrow V_o = 24$ V

Ripple in Inductor Current $\Delta I_L = \frac{(1-D)*V_O}{2fL} \Rightarrow \Delta I_L = 9.6$ A

Ripple in Output Voltage $\Delta V_o = \frac{\Delta I_L}{8fC} \Rightarrow \Delta V_O = 120$ mV

SIMULATION CIRCUIT:

Considering diode $V_f = 0.8$ V, & solver configuration as-

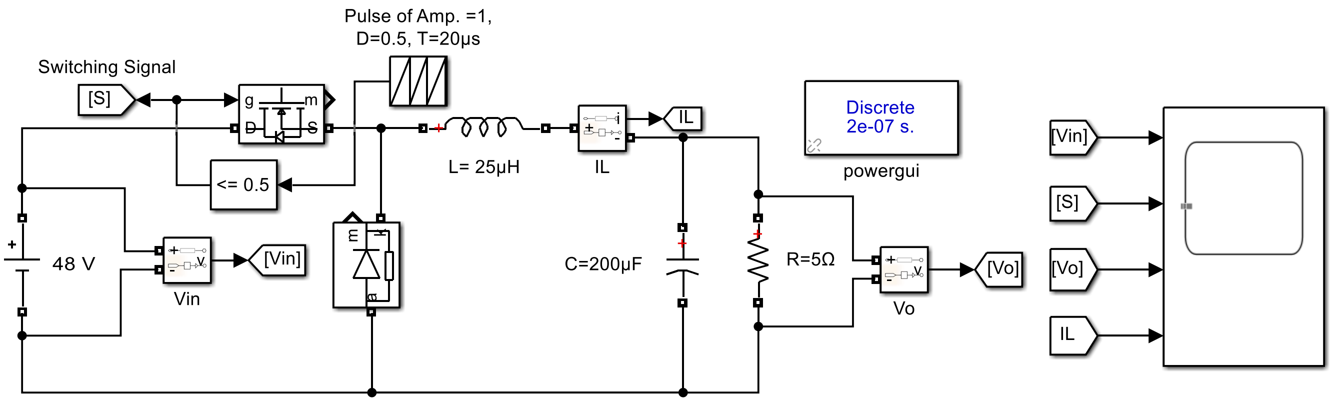
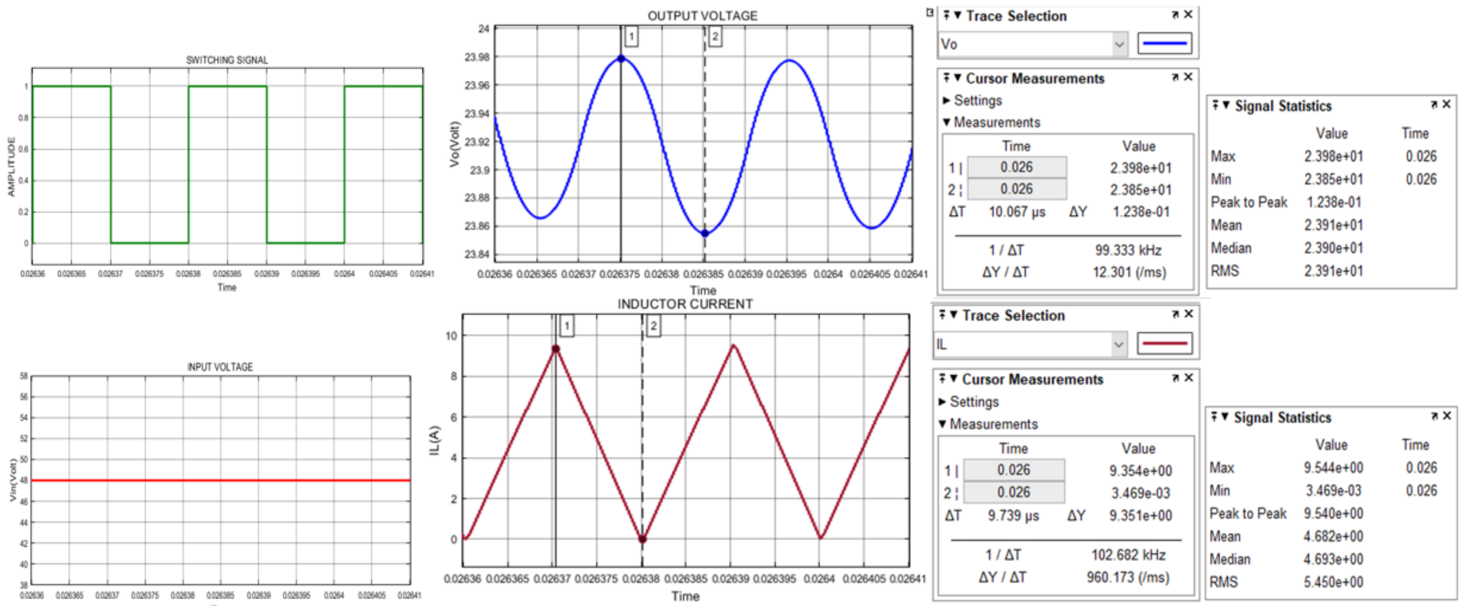


Fig3: Simulation Model of Buck Converter at Boundary of CCM & DCM

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current $\Delta I_L = 9.54$ A

Ripple in Output Voltage $\Delta V_o = 123.8$ mV

CASE 3: When L= $\frac{L_c}{10}$ $\Rightarrow$ L = 2.5 µH (DCM)

Output voltage: In DCM Mode for constant D,

$$\frac{V_o}{V_{in}} = \frac{2}{1+\sqrt{1+\frac{4K}{D^2}}} \quad \text{where } K = \frac{2L}{RT_s} \Rightarrow V_o = 40.997 \text{ V}$$

Since in DCM,

$$V_o = \frac{D}{\beta} * V_{in} \Rightarrow \beta = 0.5854,$$

Ripple in inductor current = Peak value of inductor current,

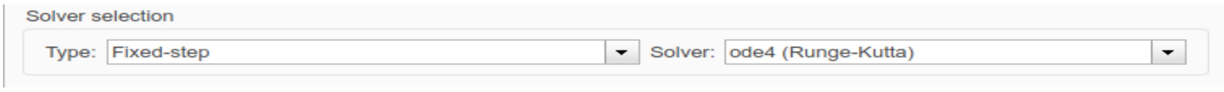
$$\Delta I_L = I_p = \frac{(\beta - D)V_o}{fL} = 28.012 \text{ A}$$

Ripple in Output Voltage

$$\Delta V_o = \frac{I_o}{4fC}(2-\beta)^2 \Rightarrow \Delta V_o = 410.2 \text{ mV}$$

SIMULATION CIRCUIT:

Considering diode $V_f = 0.8$ V, & solver configuration as-



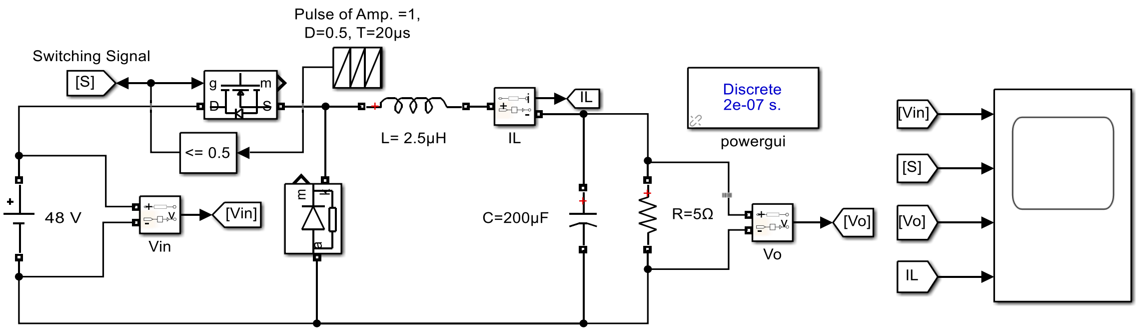
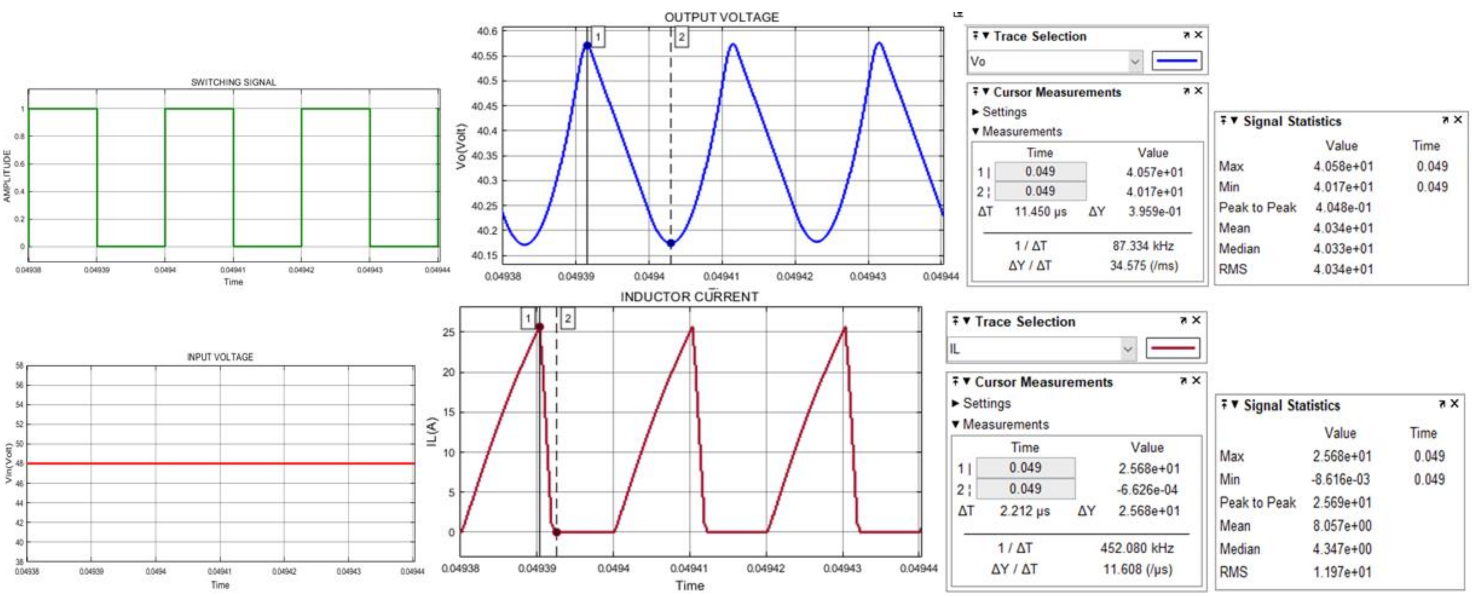


Fig3: Simulation Model of Buck Converter in DCM

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current ΔI_L = 25.69 A

Ripple in Output Voltage ΔV_o = 404.8 Mv

2. Boost Converter

Parameters:

Input voltage: **24V**; Switching Frequency: **50 kHz**; Duty Ratio: **0.5;** Load Resistance: **10 Ω**;

Capacitor: **200 µF,** Inductor: Case-1, **$L=10*L_c$**, Case-2, **$L=L_c$,** Case-3, **$L= L_c / 10$**

Theory: -

A boost converter's output voltage is always higher than the input voltage. Figure 1 shows the schematics of a boost converter**.** The diode provides a path for the inductor current when the switch is opened and is reverse biased when the switch is closed.

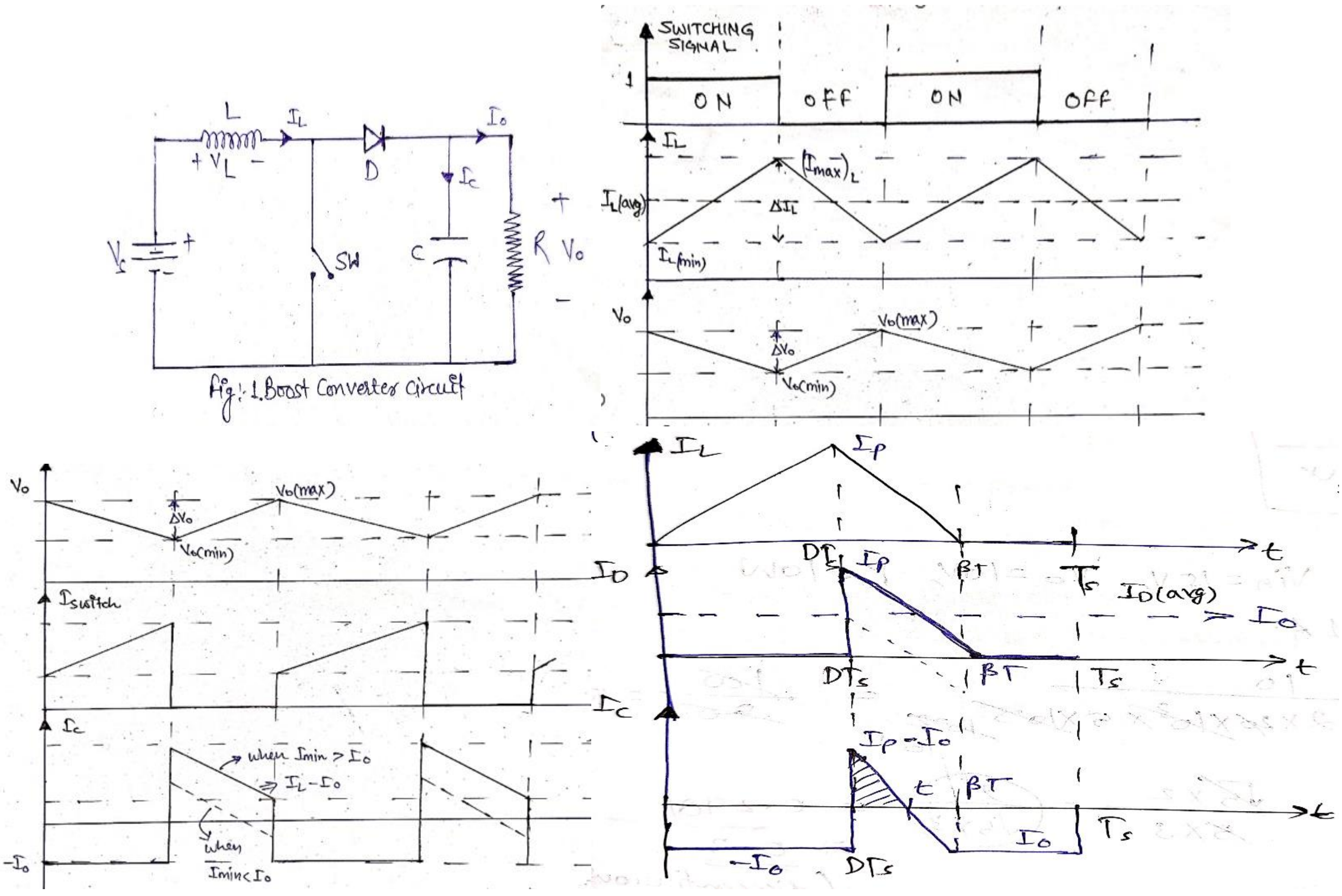
$$V_o = \frac{V_S}{1-D}, \qquad \text{where } D = \frac{T_{on}}{T}$$

CCM, DCM & CRITICAL INDUCTANCE:

- If the inductor current is continuous, the boost converter is operating in continuous conduction mode.
- If the inductor current is reduced to zero, the boost converter is operating in discontinuous mode.
- The minimum inductance to keep the boost converter in continuous conduction mode is the critical inductance. Value of the critical inductance is-

$$Lc = \frac{D(1-D)^2 R}{2f}$$

CIRCUIT DIAGRAM & WAVEFORMS: -



DESIGN PARAMETER CALCULATIONS: -

INDUCTOR: For critical Inductance,

$$I_{L\,(avg.)} = \Delta I_L \Rightarrow L_c = \frac{D(1-D)^2 * R}{2f} \Rightarrow L_c = 12.5\ \mu H$$

CASE 1: When L= 10*12.5 μH ⇒ L = 125 μH (CCM)

Output voltage: $V_o = \frac{V_S}{1-D} \Rightarrow V_o = 48\ V,\ IL_{(avg)} = \frac{I_O}{1-D} = 9.6\ A$

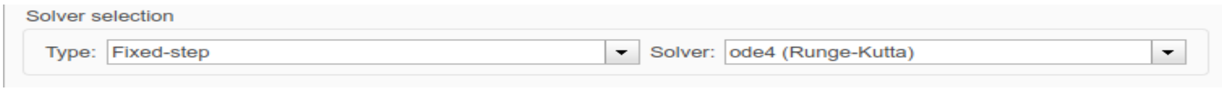
$$\text{Ripple in Inductor Current } \Delta I_L = \frac{D * V_S}{fL} \Rightarrow \Delta I_L = 1.92\ A,$$

$$\text{Since } I_{L\,(min)} = 9.6 - \frac{1.92}{2} = 8.64\ A \Rightarrow I_{L\,(min)} > I_o$$

$$\text{Therefore, Ripple in Output Voltage } \Delta V_o = \frac{DI_O}{fC} \Rightarrow \Delta V_o = 240\ mV$$

SIMULATION CIRCUIT:

Considering diode $V_{f\,=}$ 0.8 V, & solver configuration as-



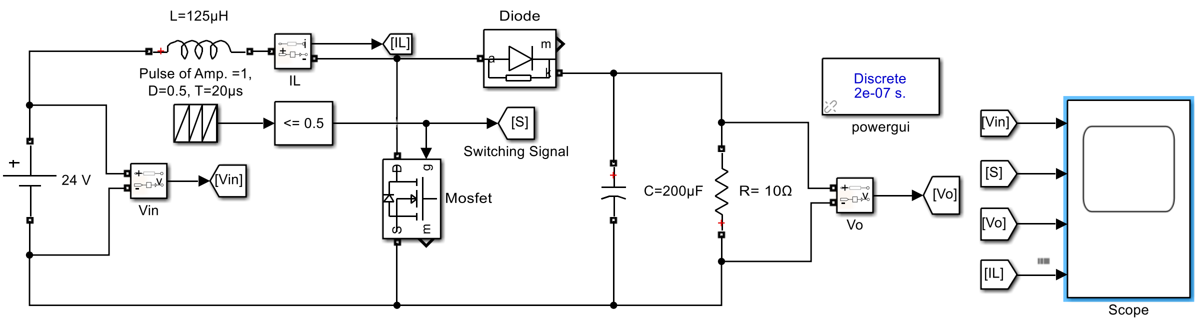
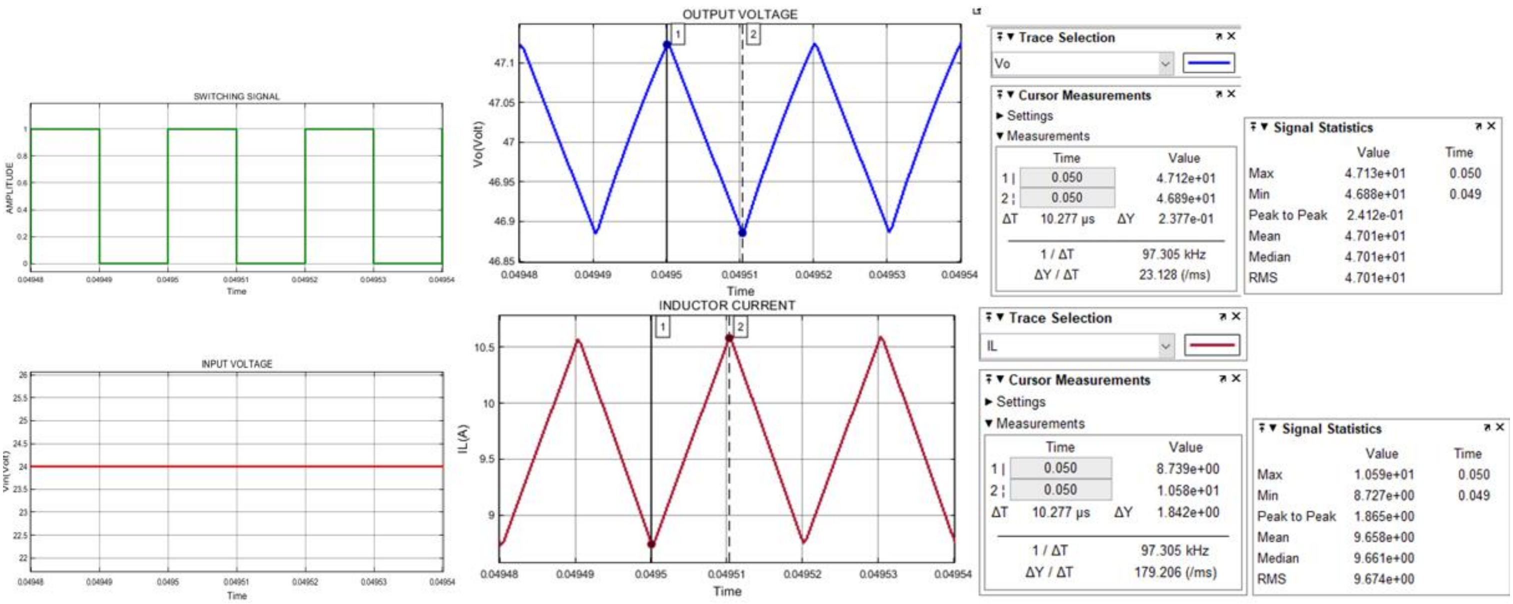


Fig3: Simulation Model of Boost Converter

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current ΔI_L = 1.865 A

Ripple in Output Voltage ΔV_o = 241.2 mV

CASE 2: When L= L_c $\Rightarrow$ L = 12.5 μH $(\boldsymbol{Boundary})$

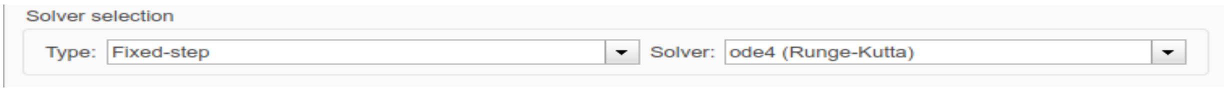
Output voltage: V_o= D*V_{in} $\Rightarrow$ Vo = 24 V, & $I_{L\ (avg)} = \frac{\Delta I_L}{2}$, $I_{L\ (avg)} = \frac{I_o}{1-D}$ = 9.6 A

Ripple in Inductor Current $\Delta \mathbf{I_L} = \frac{DV_S}{fL}$ $\Rightarrow$ ΔI_L = 19.2 A,

Ripple in Output Voltage $\Delta \mathbf{V_o} = \frac{I_o}{4fC}(1+D)^2$ $\Rightarrow$ ΔV_O = 270 mV

SIMULATION CIRCUIT:

Considering diode $V_{f\,=}$ 0.8 V, & solver configuration as-



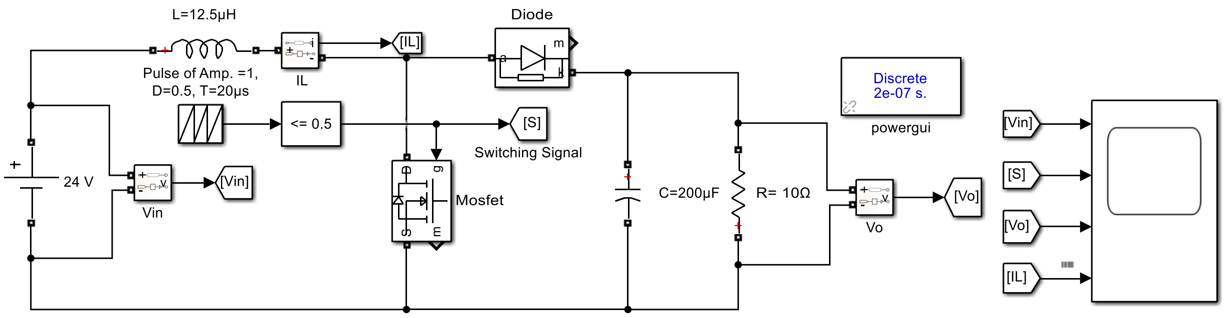
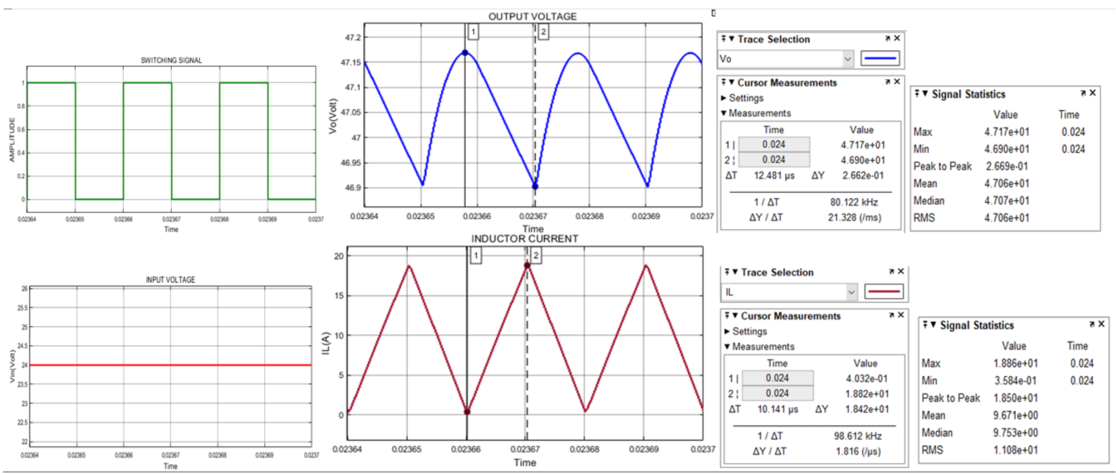


Fig3: Simulation Model of Boost Converter at Boundary of CCM & DCM

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current ΔI_L = 18.5 A

Ripple in Output Voltage ΔV_o = 266.9 mV

CASE 3: When $L = \frac{L_c}{10} \Rightarrow$ L = 1.25 µH (DCM)

Output voltage: In DCM mode for constant D,

$$\frac{V_o}{V_{in}} = \frac{1+\sqrt{1+\frac{4D^2}{K}}}{2}, \text{ where } K = \frac{2L}{RT_s} \Rightarrow V_o = 120\text{ V} \ \& \ I_o = \frac{V_o}{R} = 12\text{ A}$$

Since in DCM,

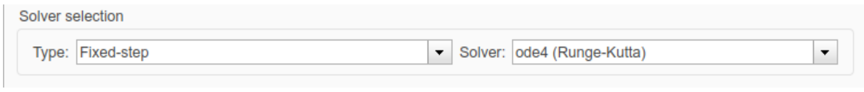
$$V_o = \frac{V_{in}}{1-\frac{D}{\beta}} \Rightarrow \beta = \frac{DV_o}{V_o - V_{in}} \Rightarrow \beta = 0.625$$

Ripple in inductor current = Peak value of inductor current,

$$\Delta I_L = I_p = \frac{DV_s}{fL} = 192\text{ A}$$

Ripple in Output Voltage $\Delta V_o = \frac{I_o}{4fC}\{2-(\beta-D)\}^2 \Rightarrow \Delta V_o = 1054.7$ mV

SIMULATION CIRCUIT: Considering diode $V_f = 0.8$ V, & solver configuration as-



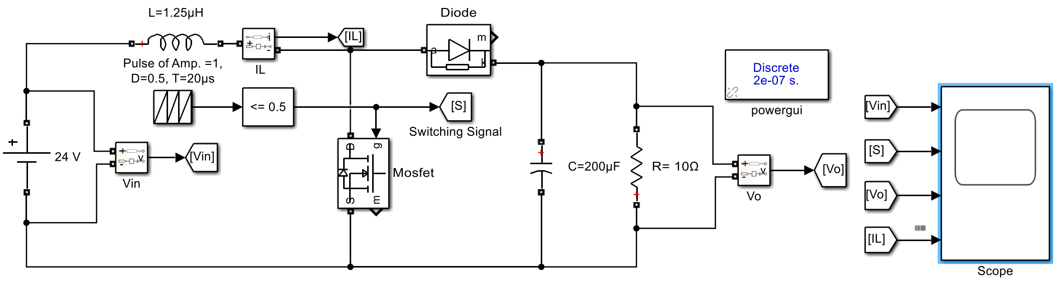
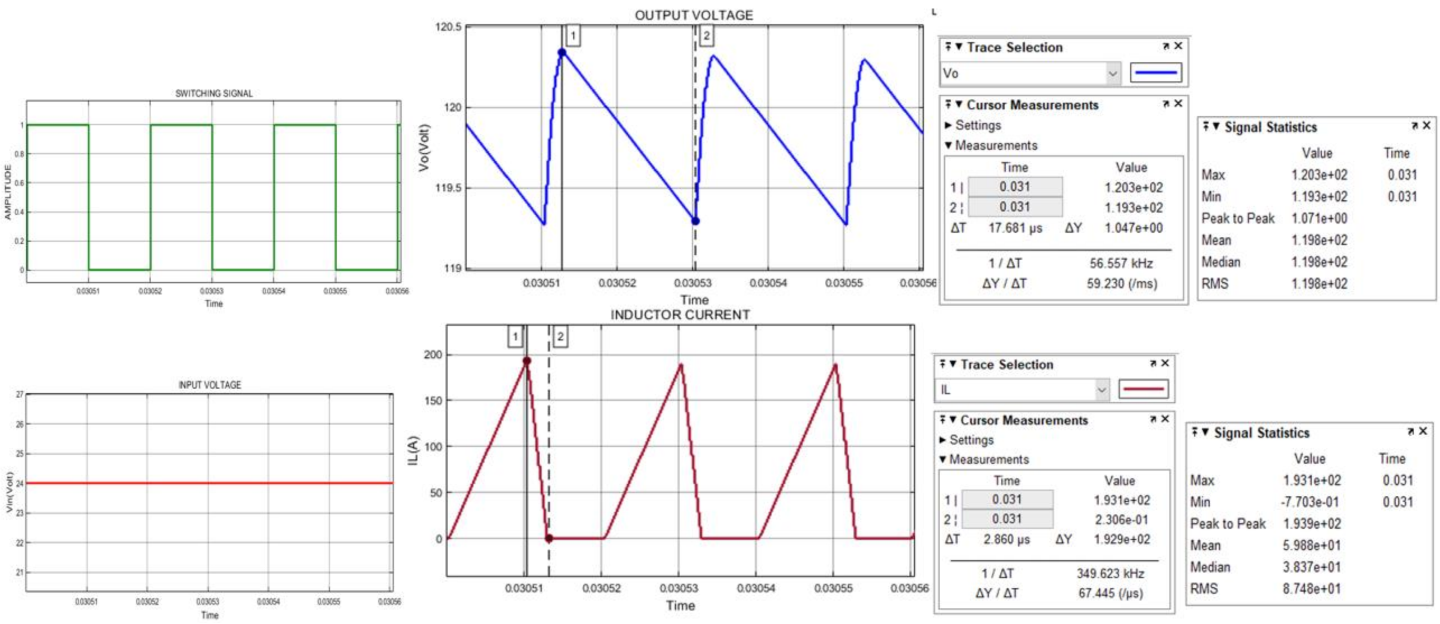


Fig3: Simulation Model of Boost Converter

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current ΔI_L = 193.9 A

Ripple in Output Voltage ΔV_o = 1071 mV

3. Buck - Boost Converter

Parameters:

Input voltage: **100V**; Switching Frequency: **50 kHz**; Duty Ratio: D = $\frac{1}{3}$; Load Resistance: **25 Ω**;

Capacitor: **200 μF,** Inductor: Case-1, **L=10*Lc**, Case-2, **L=Lc,** Case-3, **L= Lc / 10**

Theory: -

The output voltage of a buck-boost converter can be either higher or lower than the input voltage. Ratio of the output voltage over the input voltage is shown below.

$$\frac{V_o}{V_{in}} = \frac{D}{1-D}$$

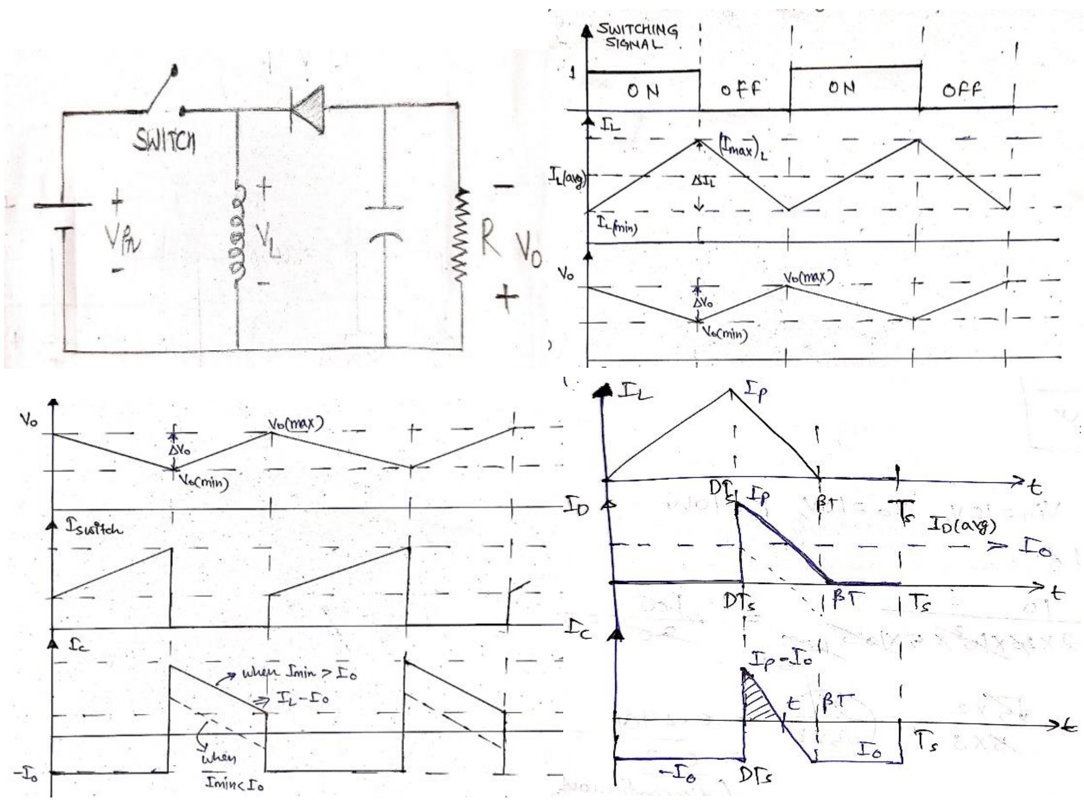
If D>0.5, the output voltage is greater than the input voltage. if D < 0.5, the output voltage is less than the input voltage. (1)

CCM, DCM & CRITICAL INDUCTANCE:

- If the inductor current is continuous, the boost converter is operating in continuous conduction mode.
- If the inductor current is reduced to zero, the boost converter is operating in discontinuous mode.
- The minimum inductance to keep the boost converter in continuous conduction mode is the critical inductance. Value of the critical inductance is-

$$L_c = \frac{(1-D)^2 R}{2f}$$

CIRCUIT DIAGRAM & WAVEFORMS: -



DESIGN PARAMETER CALCULATIONS: -

INDUCTOR: For critical Inductance,

$$I_{L\,(avg.)} = \Delta I_L \Rightarrow L_c = \frac{(1-D)^2 * R}{2f} \Rightarrow L_c = 111.11\ \mu H$$

CASE 1: When L= 10*111.11 μH ⇒ L = 1111.1μH (CCM)

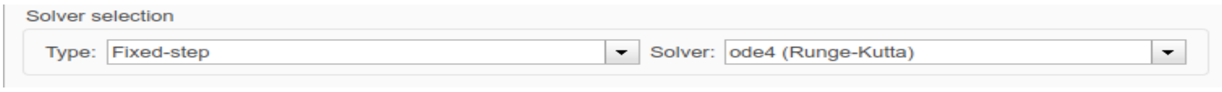
Output voltage: $V_o = \frac{D}{1-D} V_{in} \Rightarrow V_o = 50$ V, $I_{L\,(avg)} = \frac{I_o}{1-D} = 3$ A & $I_o = \frac{V_o}{R} = 2$ A

Ripple in Inductor Current $\Delta I_L = \frac{DV_S}{fL} \Rightarrow \Delta I_L = 0.6$ A, Since $I_{L\,(min)} = 3 - \dfrac{0.6}{2} = 2.7\text{ A} \Rightarrow I_{L\,(min)} > I_o$

Therefore, Ripple in Output Voltage $\Delta V_o = \dfrac{DI_o}{fC} \;\Rightarrow \Delta V_o = 66.66\text{ mV}$

SIMULATION CIRCUIT:

Considering diode $V_{f} = 0.8$ V, & solver configuration as-



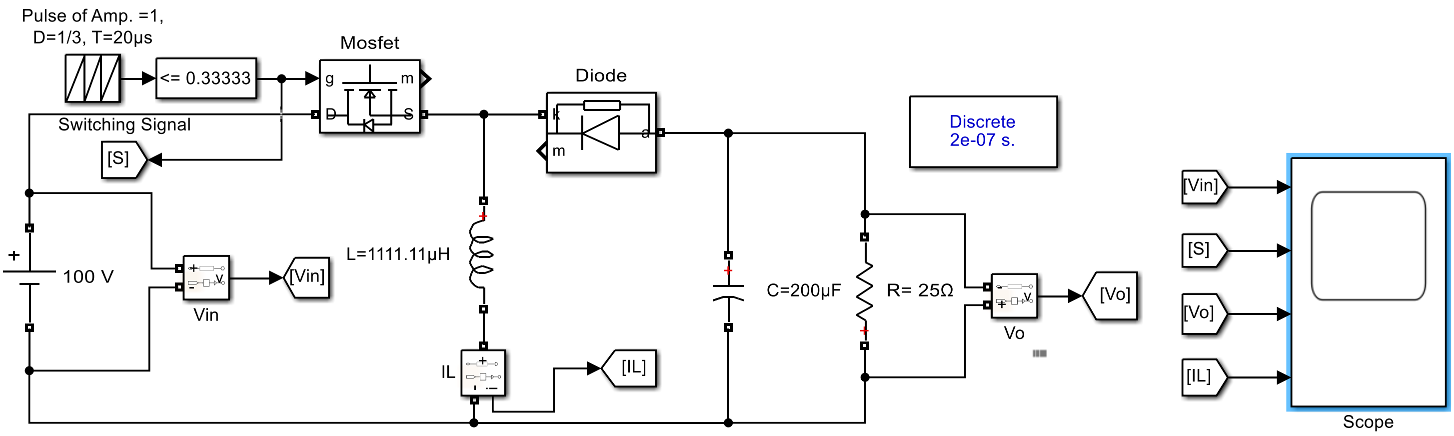
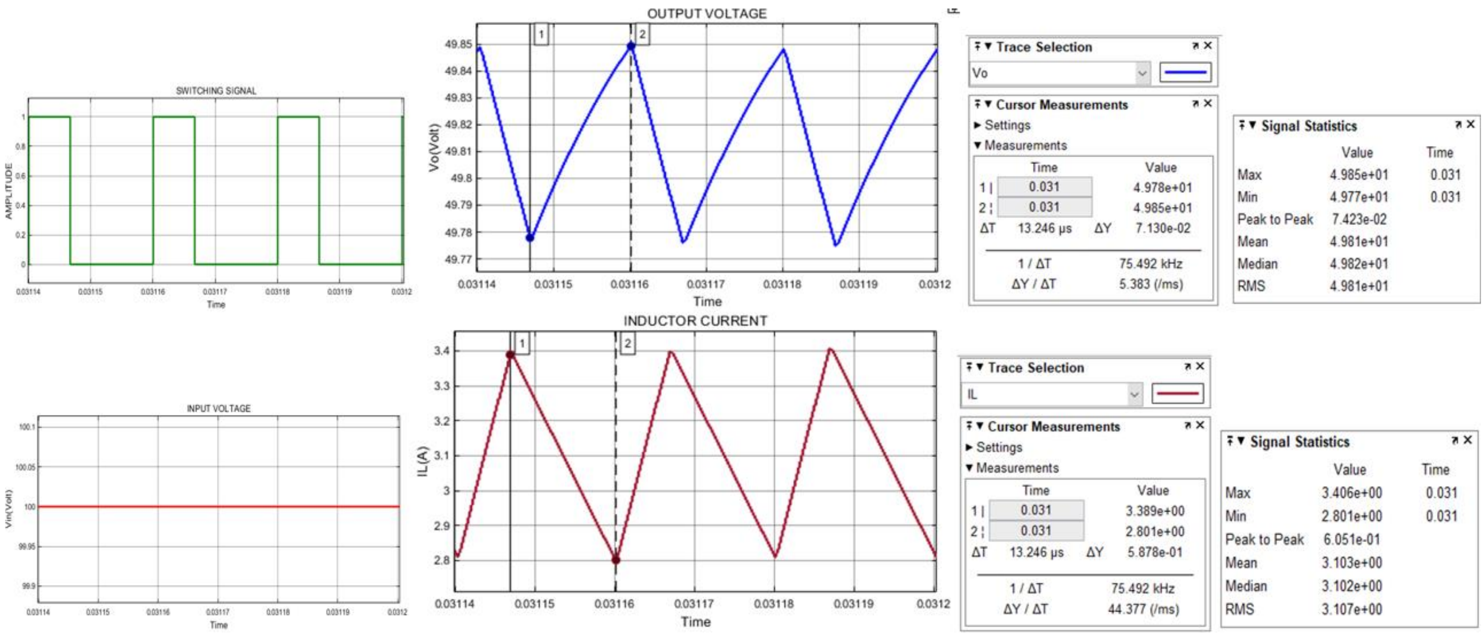


Fig3: Simulation Model of Buck-Boost Converter

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current $\Delta I_L = 0.6051$ A

Ripple in Output Voltage $\Delta V_o = 71.3$ mV

CASE 2: When L= L_c $\Rightarrow$ L = 111.11 μH ($\boldsymbol{Boundary}$)

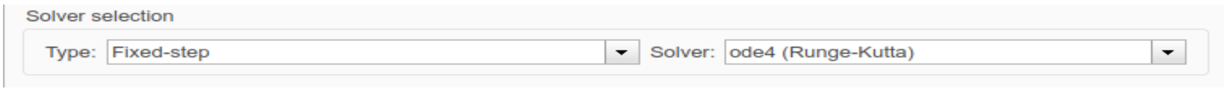
Output voltage: $V_o = \frac{D}{1-D} V_{in} \Rightarrow V_o = 50$ V

Ripple in Inductor Current $\Delta I_L = \frac{(1-D)*V_o}{2fL} \Rightarrow \Delta I_L = 6$ A

Ripple in Output Voltage $\Delta V_o = \frac{I_o}{4fC}(1+D)^2 \Rightarrow \Delta V_O = 88.8$ mV

SIMULATION CIRCUIT:

Considering diode $V_{f} = 0.8$ V, & solver configuration as-



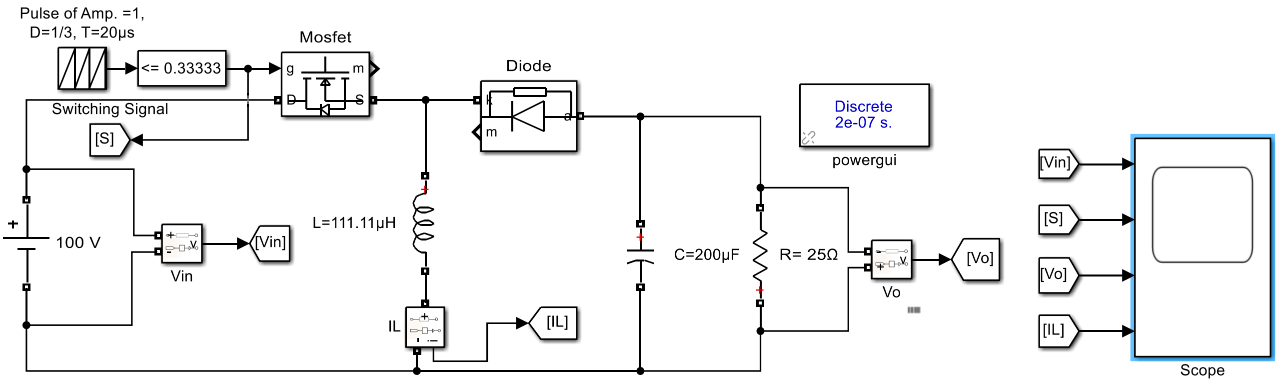
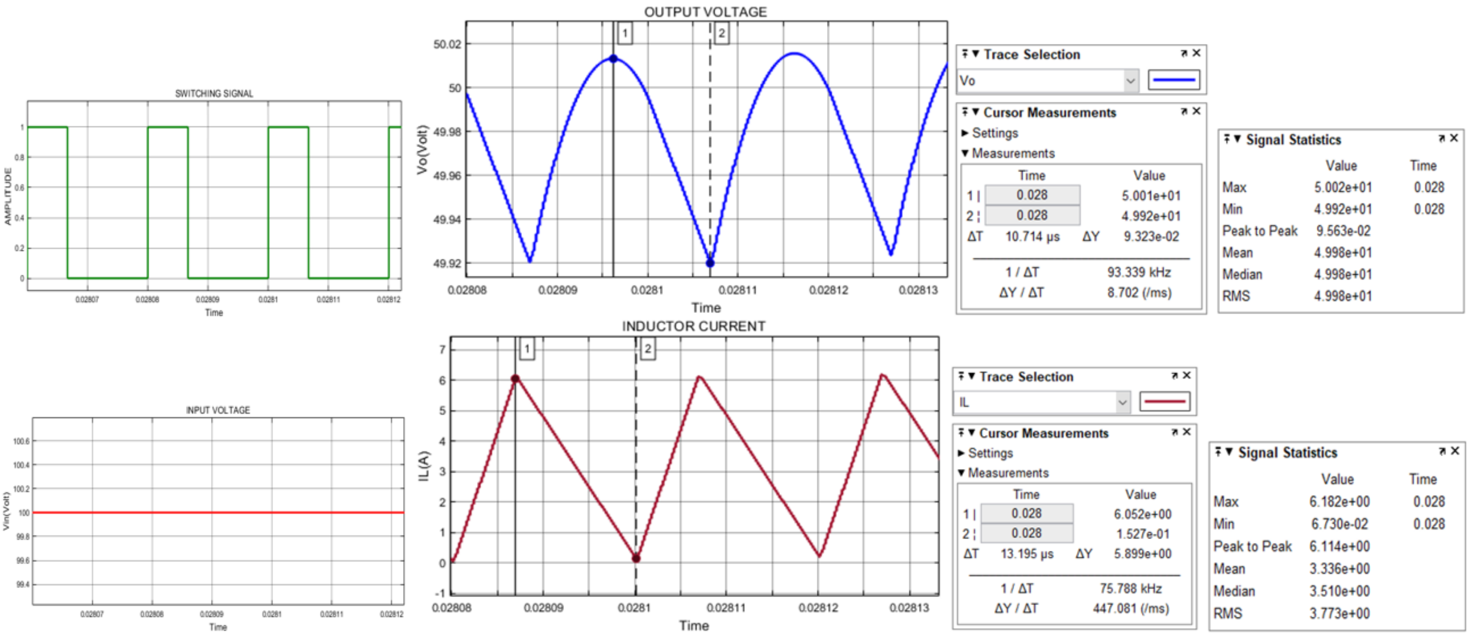


Fig3: Simulation Model of Buck-Boost Converter at Boundary of CCM & DCM

WAVEFORMS OBTAIED:



RESULTS AFTER SIMULATION: -

Ripple in Inductor Current $\Delta I_L = 6.11$ A

Ripple in Output Voltage $\Delta V_o = 93.23$ mV

CASE 3: When L= $\frac{L_c}{10}$ $\Rightarrow$ L = 11.111 μH (DCM)

Output voltage: In DCM mode for constant D,

$$\frac{V_o}{V_{in}} = \frac{D}{\sqrt{K}}, \text{ where } K = \frac{2L}{RT_s} \Rightarrow V_o = 158.12 \text{ V} \ \& \ I_o = \frac{V_o}{R} = 6.32 \text{ A}$$

Since in DCM,

$$V_o = \frac{D}{\beta - D} V_{in} \quad \Rightarrow \beta = \frac{D(V_{in}+V_o)}{V_o} \Rightarrow \beta = 0.544$$

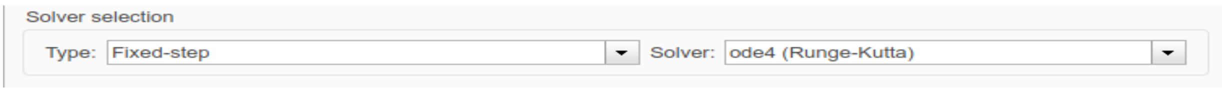
Ripple in inductor current = Peak value of inductor current,

$$\Delta I_L = I_p = \frac{DV_s}{fL} = 60 \text{ A}$$

Ripple in Output Voltage $\Delta V_o = \frac{I_o}{4fC}\{2-(\beta - D)\}^2 \Rightarrow \Delta V_o = 505.9$ mV

SIMULATION CIRCUIT:

Considering diode $V_f = 0.8$ V, & solver configuration as-



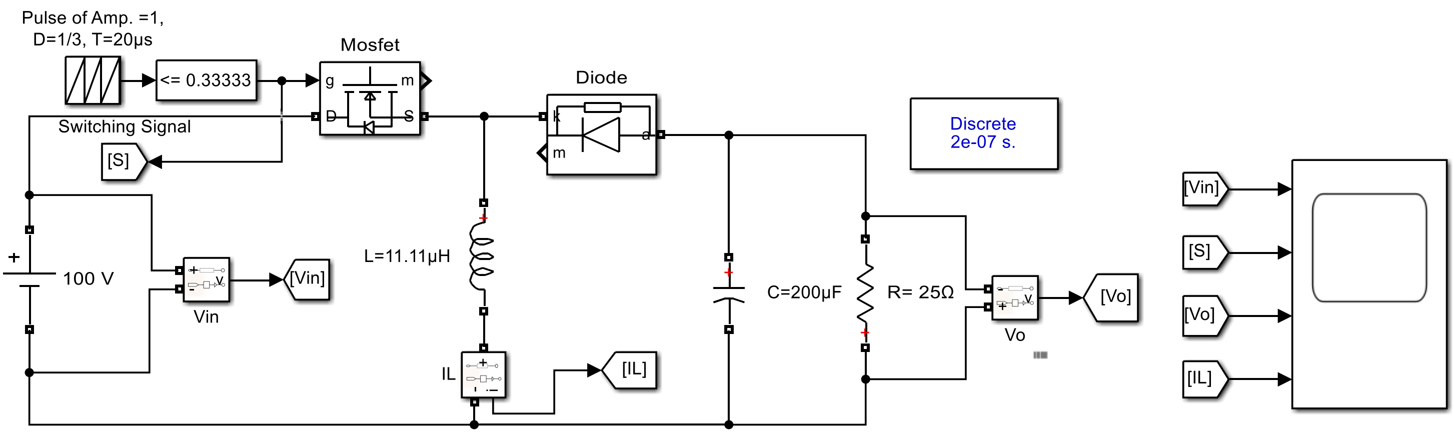
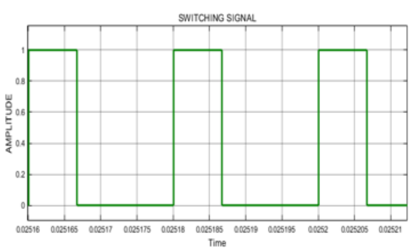
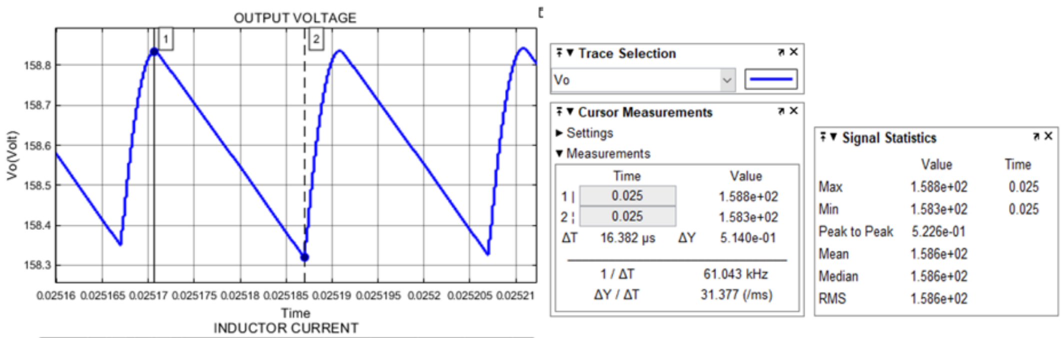
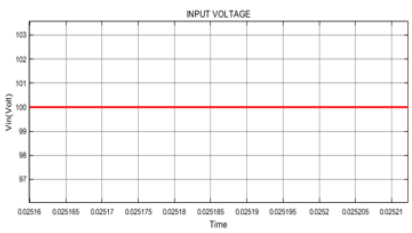


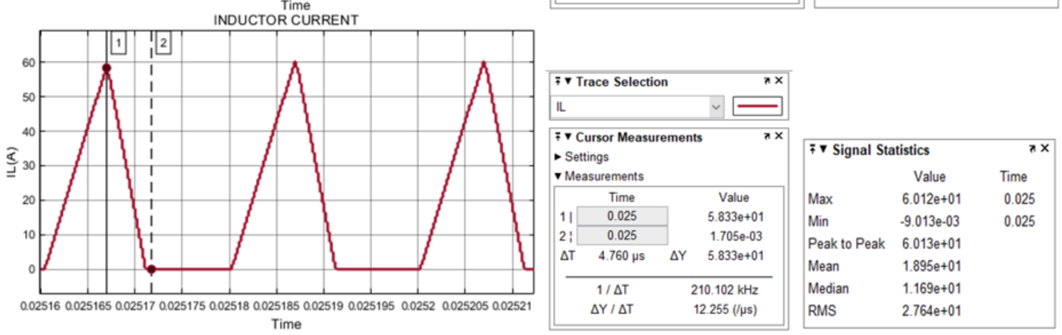
Fig3: Simulation Model of Buck- Boost Converter

WAVEFORMS OBTAIED:









RESULTS AFTER SIMULATION: -

Ripple in Inductor Current ΔI_L = 60.13 A

Ripple in Output Voltage ΔV_o = 514 mV

Submitted by – Shivraj Vishwakarma,

M. Tech. 1st Year,

Power Engg.

Roll No. - 224102112

EXPERIMENT No. 2

SIMULATION OF BOOST CONVERTER USING MATLAB/SIMULINK

Objective: To Design & Simulate a Boost Converter circuit using MATLAB/SIMULINK.

Parameters of the Buck Converter: Input voltage: **24V**; Output Voltage: **48V**; Output Power: **100W**; Switching Frequency: **100kHz**; Ripple in Inductor Current: **25%**; Ripple in Output Voltage: **0.1%**;

Theory: -

A boost converter's output voltage is always higher than the input voltage. Figure 1 shows the schematics of a boost converter. It has a dc input voltage, a transistor working as a switch, an inductor and a capacitor forming a low pass filter to smooth out the output voltage, and a load resistor. The diode provides a path for the inductor current when the switch is opened and is reverse biased when the switch is closed.

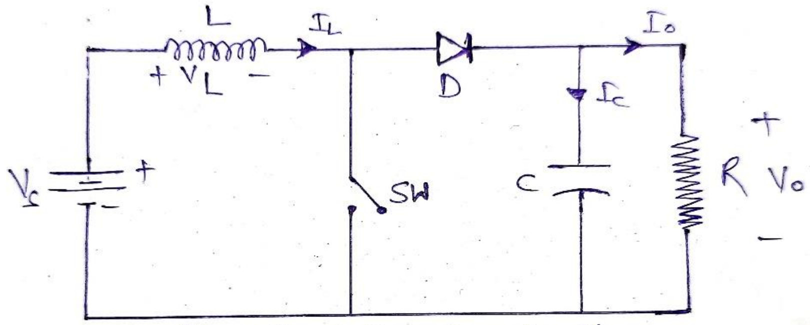


Fig:- 1.Boost Converter circuit

When the switch is closed, the diode is reverse biased. The equivalent circuit is shown in Figure 2. When the switch is open, the diode is forward biased. The equivalent circuit is shown in Figure 3.

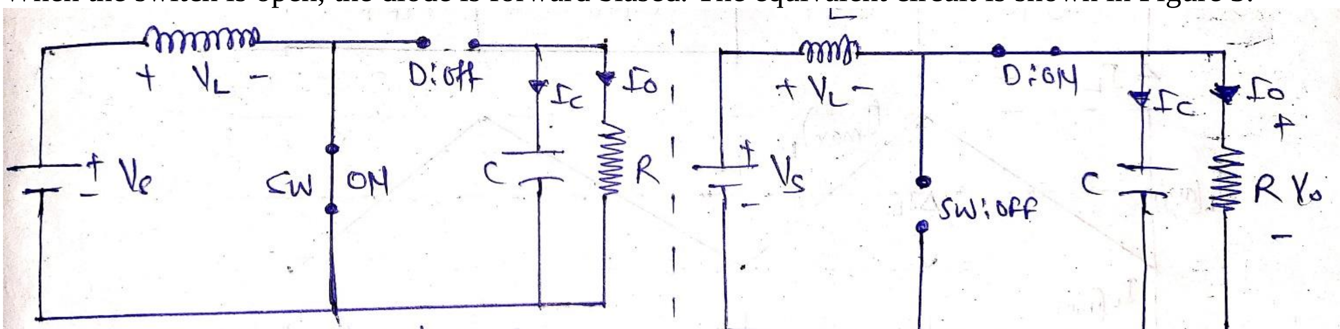


Fig2:- switch ON, diode: off

Fig 3:- SW: off, diode: ON.

Output voltage of a boost converter is controlled by a pulse width modulated (PWM) signal shown in figure 4. The duty cycle is the ratio between the on time and the switching period shown in (2). By adjusting the duty cycle, we can obtain desired output voltage, which is shown in (1). When D increases, the output voltage increases. When D decreases, the output voltage decreases.

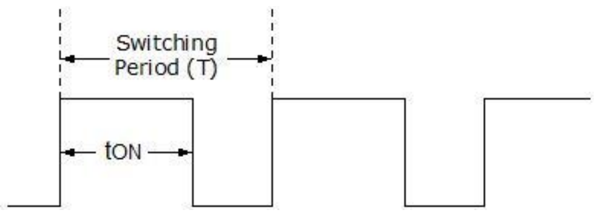


Figure 4. Pulse width modulated (PWM) Signal

$$V_o = \frac{V_s}{1-D}, \quad ..(1) \qquad \text{where } D = \frac{T_{on}}{T} \quad ..(2)$$

CRITICAL INDUCTANCE:

If the inductor current is continuous, the boost converter is operating in continuous conduction mode. If the inductor current is reduced to zero, the boost converter is operating in discontinuous mode. We would like to keep the boost converter operating in continuous conduction mode. The minimum inductance to keep the boost converter in continuous conduction mode is the critical inductance. Value of the critical inductance is shown in (3).

$$Lc = \frac{D(1-D)^2 R}{2f}$$

WAVEFORMS: -

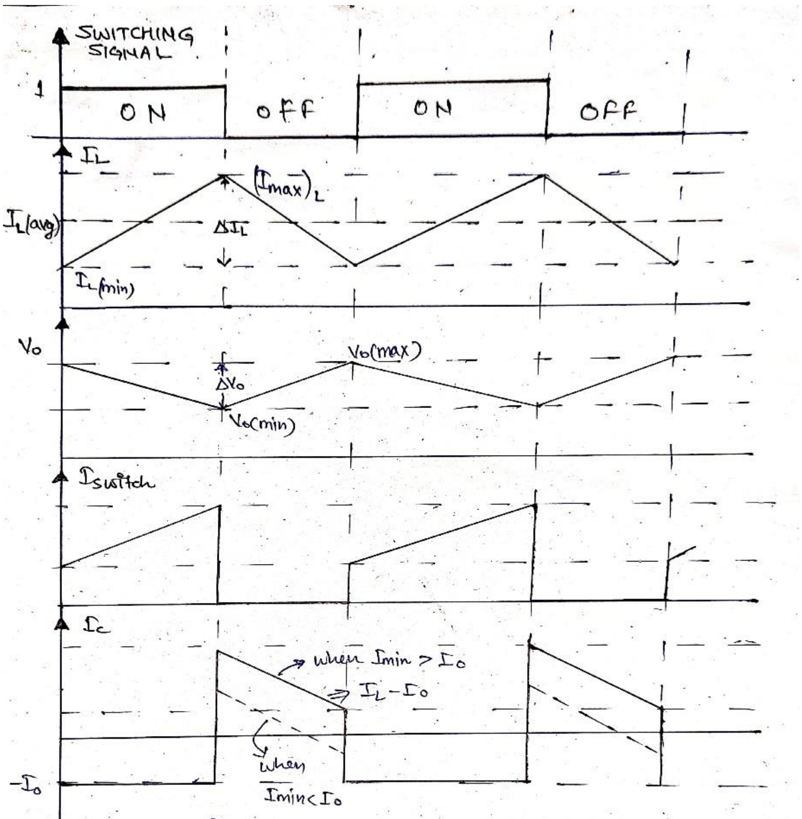


fig: WAVEFORMS OF BOOST CONVERTER

Designing Parameters for Buck Converter:

The peak-to-peak inductor current is often a design criterion in the design of a boost converter. It is also called the current ripple. The current ripple is inversely proportional to the inductance and the switching frequency. To reduce the current ripple, we can increase the inductance or the switching frequency.

CALCULATIONS: -

Using given values as Vo = 48 V, f_{sh}= 100kHz, Po= 100 W, ΔI_L= 25% of $I_{L\,(avg)}$, ΔV_o =.1% of V_o

1. Duty Ratio D = $\frac{V_o - V_{in}}{V_o} = \frac{24}{48}$ = 0.5,

2. Average output current I_o = $\frac{P_o}{V_o} = \frac{100}{48}$ = 2.083 A,

3. Average inductor current $I_L = \frac{I_o}{1-D} = \frac{2.083}{1-0.5} = 4.166$ A,

4. Ripple in inductor current $\Delta I_L = \frac{1}{4} * 4.166 = 1.0416$ A,

5. Now $L = \frac{DV_s}{f\,\Delta I_L} = \frac{\frac{1}{2}*24}{100*10^3*1.0416} = 115.207\,\mu H$

6. $\Delta Vo = 0.1\%$ of 48 V = .048 V, $C = \frac{DI_o}{f\,\Delta V_o} = \frac{0.5*2.083}{100*10^3*0.048} = 217.01\,\mu F$

7. Load Resistance, $R = \frac{V_o^2}{P_o} = \frac{2304}{100} = 23.04\ \Omega$

SIMULATION CIRCUIT:

Considering diode $V_f = 0.8$ V, & solver configuration as-

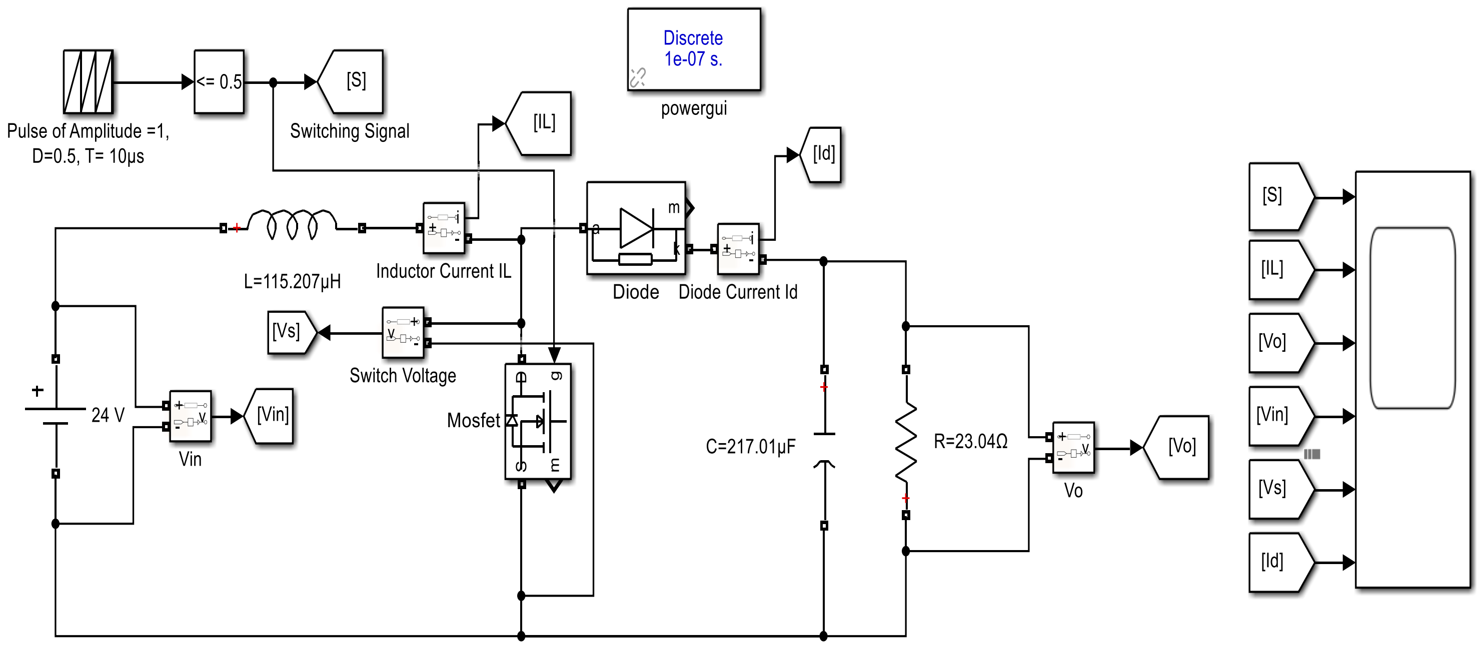
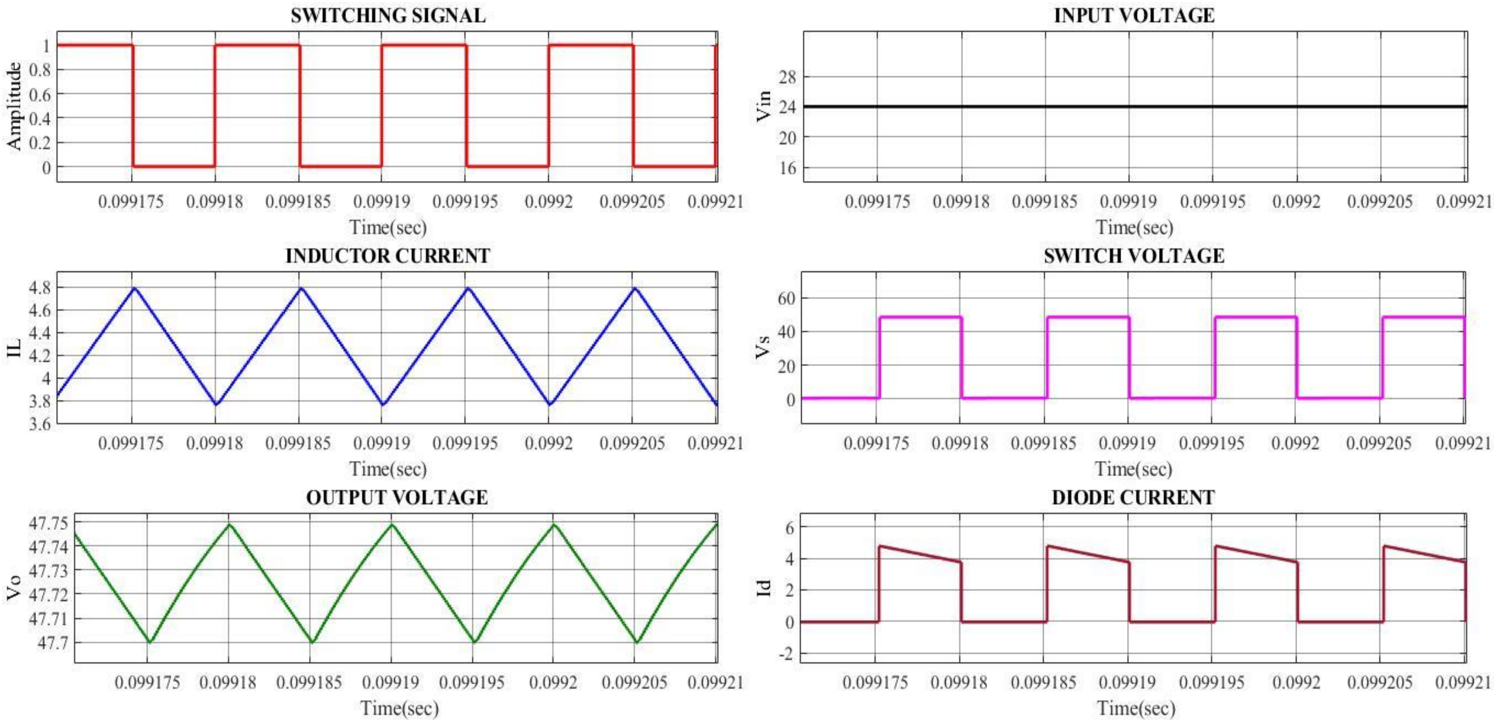


Fig3: Simulation Model of Boost Converter

RESULTS OBTAIED:

Steady State Waveform:



CALCULATIONS AFTER SIMULATION: -

Current through Inductor:

$I_{L\,(max)}$ = 4.8 A, $I_{L\,(min)}$ = 3.78 A,

Avg. Current through Inductor I_L = (4.80+3.78)/2 = 4.29 A

Ripple in Inductor Current,

$\Delta I_{L\,(PEAK\,-\,PEAK)}$ = 4.8 – 3.78 = **1.02 A (23.77% of I_L)**

Output voltage:

$V_{o(max)}$ = 47.749 V, $V_{o(min)}$ = 47.7 V

Avg. Output Voltage = (47.7 + 47.749)/2 = **47.7245 V**

Ripple in Output Voltage

$\Delta V_{o(peak\text{-}peak)}$ = **0.049 V (0.107% of Vo)**

CONCLUSION:

1. *Ripple in inductor Current – **23.77% of I_L***
2. *Ripple in output voltage – **0.107% of V_o***

Submitted by – Shivraj Vishwakarma,
M. Tech. 1st Year,
Power Engg.
Roll No. 224102112

EXPERIMENT No. 1

SIMULATION OF BUCK CONVERTER USING MATLAB/SIMULINK

Objective: To Design & Simulate a Buck Converter circuit using MATLAB/SIMULINK.

Parameters of the Buck Converter: Input voltage: **24V**; Output Voltage: **12V**; Output Power: **100W**; Switching Frequency: **100kHz**; Ripple in Inductor Current: **25%**; Ripple in Output Voltage: **0.1%**;

Theory: -

A buck converter is a step-down DC to DC converter. For a DC–DC converter, input and output voltages are both DC. It uses a power semiconductor device as a switch to turn on and off the DC supply to the load. The switching action can be implemented by a BJT, a MOSFET, or an IGBT. Figure 1 shows a simplified block diagram of a buck converter that accepts a DC input and uses pulse-width modulation (PWM) of switching frequency to control the switch. An external diode, together with external inductor and output capacitor, produces the regulated dc output. Buck, or step-down converters produce an average output voltage lower than the input source voltage.

The output voltage can be represented as, V_o **= D*Vin**

Where D is duty ratio defined as

$$D = \frac{Vo}{Vin} = \frac{Ton}{(Ton + Toff)}$$

CCM and DCM:

The buck converter can operate in two different modes; continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The difference between the two is that in CCM the current in the inductor does not fall to zero. A buck converter operates in continuous mode if the current through the inductor never falls to zero during the commutation cycle. In DCM, the current through the inductor falls to zero during part of the period. Practically, converter can operate in either operation modes. Figure 2 shows CCM and DCM mode.

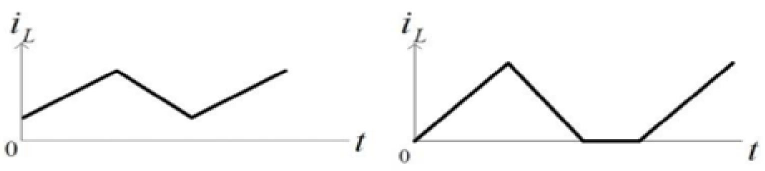


Figure: CCM & DCM Mode

CIRCUIT DIAGRAM & WAVEFORMS: -

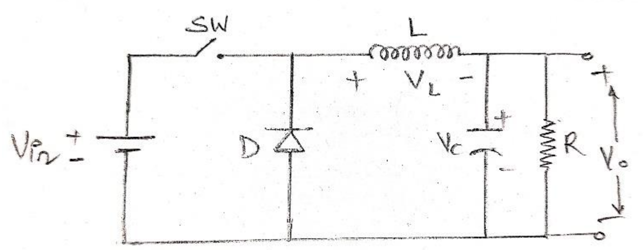


Fig.1 Buck Converter

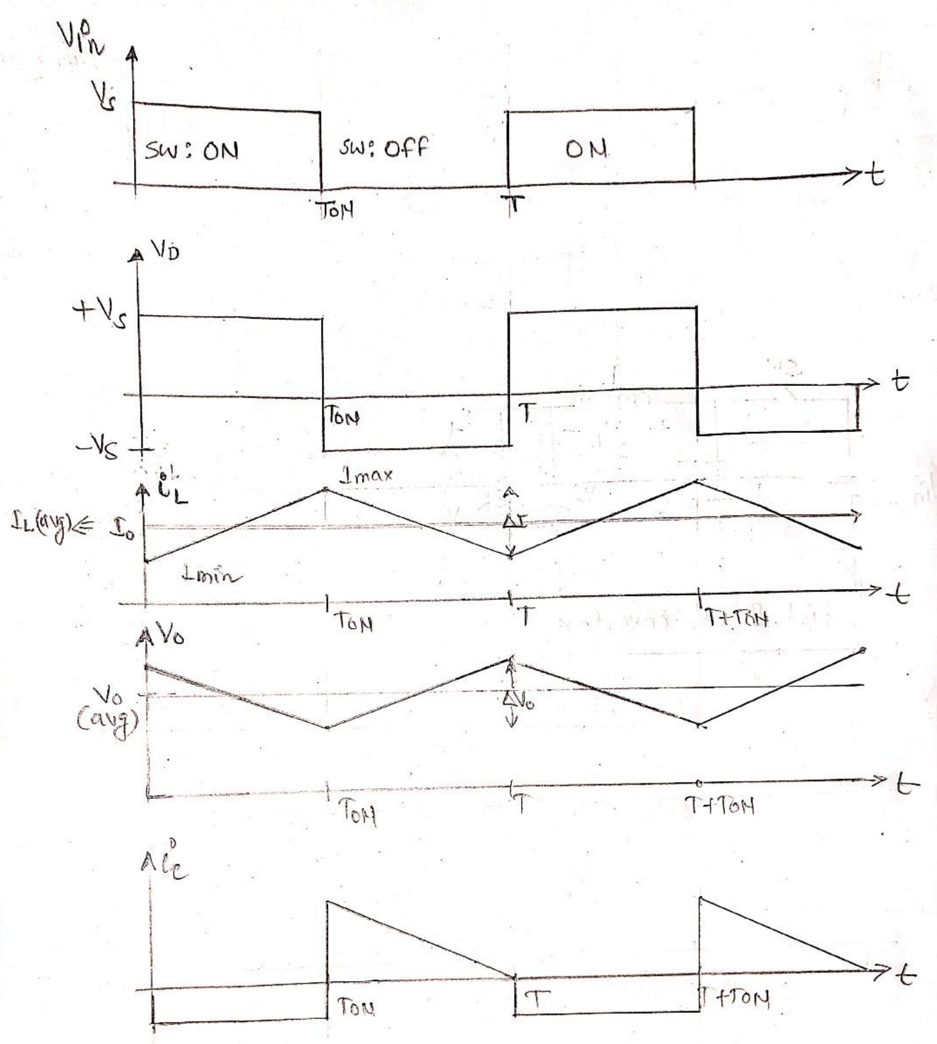
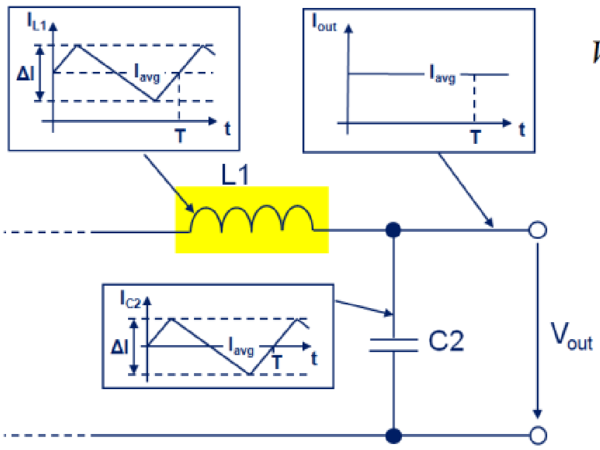


fig:- Waveforms of Buck converter.

Designing Parameters for Buck Converter:

Since in OFF state of switch Voltage across inductor = output voltage, so using this concept we can calculate the inductance of Inductor required.



$$V_{L1} = L_1 \cdot \frac{di_{L1}}{dt}$$

$$= L_1 \cdot \frac{\Delta I_{L1}}{(1-D) \cdot T} = V_{out}$$

$$L_1 = \frac{V_{out} \cdot (1-D)}{f_{sw} \cdot \Delta I_{L1}}$$

Similarly, we can calculate value of capacitance also, so finally these formulas can be used to calculate the value of Inductance & Capacitance required.

$$L = \frac{V_{out} \times (V_{in} - V_{out})}{\Delta I_L \times f_s \times V_{in}}$$

Where

V_{in} = typical input voltage

V_{out} = desired output voltage

f_s = minimum switching frequency of the converter

ΔI_L = estimated inductor ripple current

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_{out}}$$

Where

ΔI_L = estimated inductor ripple current

f_s = minimum switching frequency of the converter

ΔV_{out} = desired output voltage ripple

CALCULATIONS: -

Using given values as Vo = 12 V, f_{sh}= 100kHz, Po= 100 W, ΔI_o = 25%, ΔV_o =.1%

1. Duty Ratio

D = 0.5

2. INDUCTANCE-

Ripple in Inductor Current

$\boldsymbol{\Delta I_L}$ = 25/12

= 2.08 A & hence,

L = 28.8μH

3. CAPACITANCE

Ripple in Output Voltage

ΔV_o = 1% of 12 V = 0.012V & hence **C = 217μF**

4. Load Resistance,

R_L (Fixed) = V_O/I_{DC}= **1.44Ω**

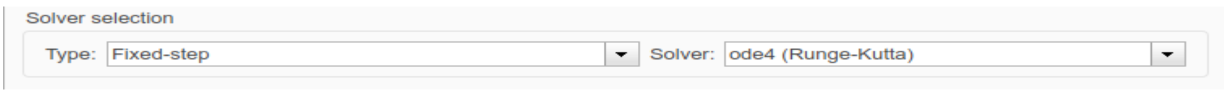
5. Avg output Current,

$I_{DC} = P/V_O$

I_{DC} = **8.33Amp**.

SIMULATION CIRCUIT:

Considering diode V_f = 0.8 V, & solver configuration as-



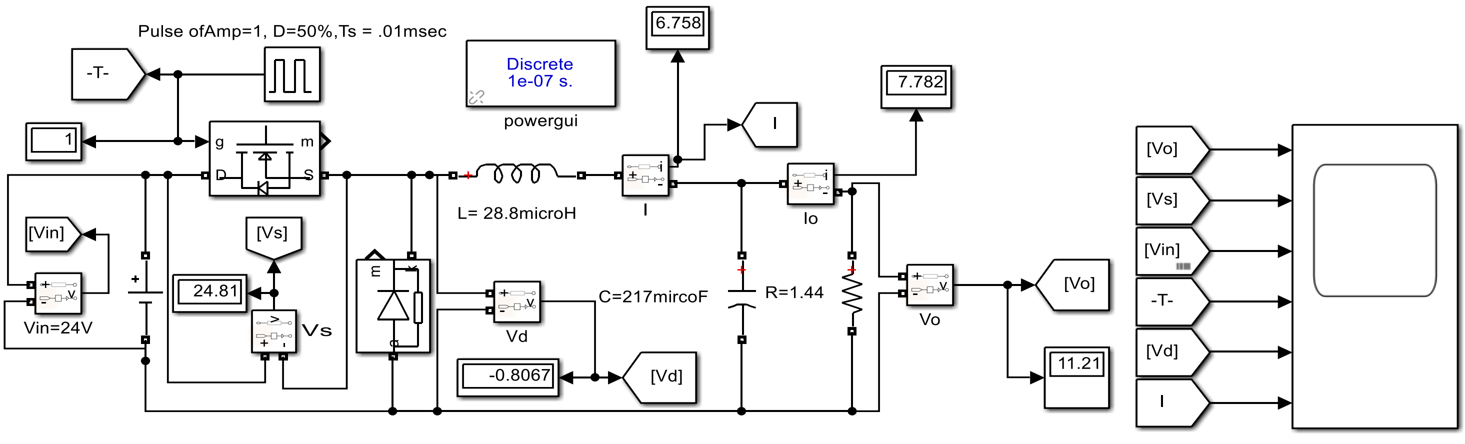
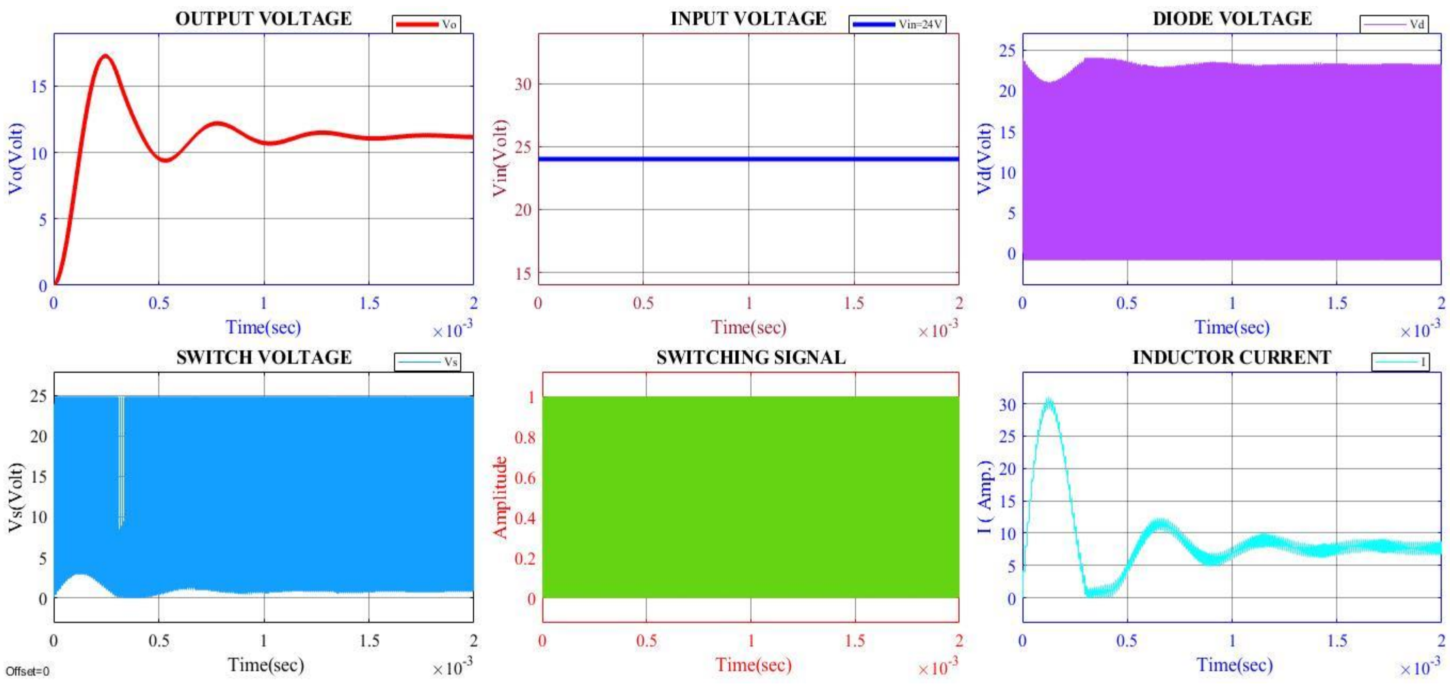


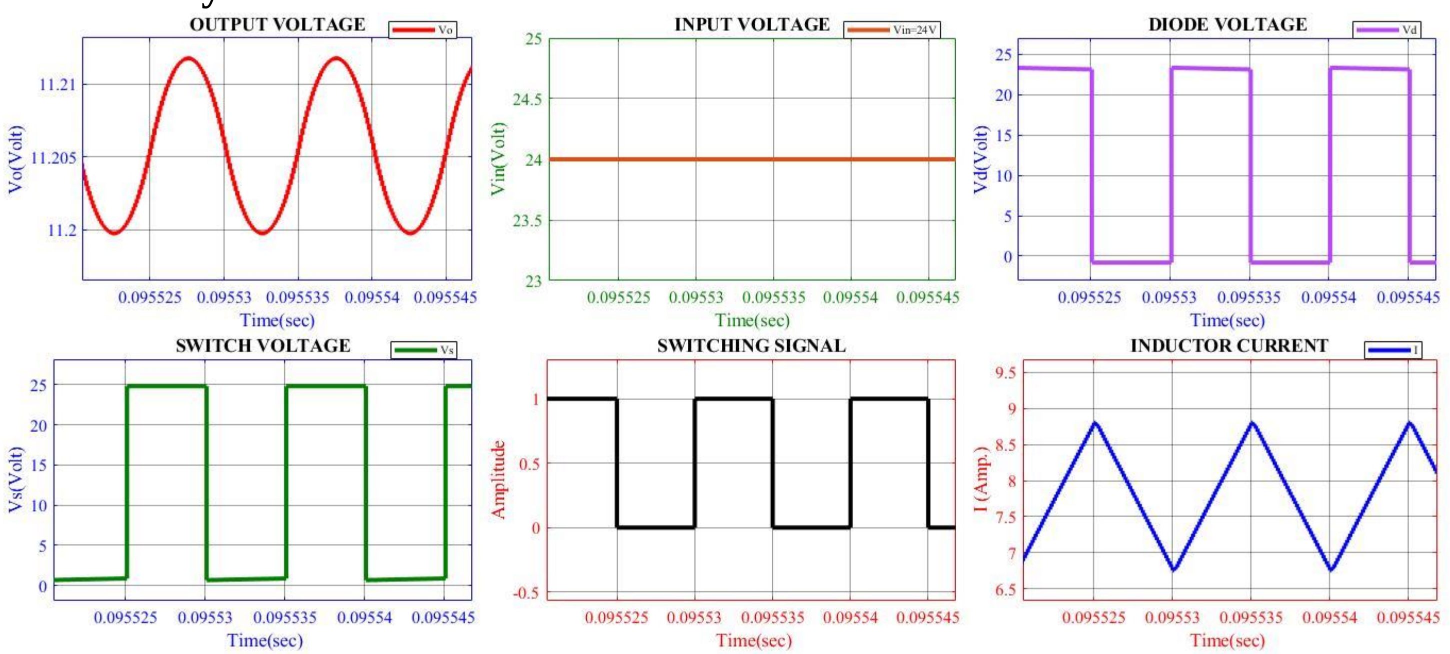
Fig3: Simulation Model of Buck Converter

RESULTS OBTAIED:

1. Transient State Waveform:



2. Steady State Waveform:



CALCULATIONS AFTER SIMULATION: -

Current through Inductor:

Avg Current through Inductor

I_{DC} = **6.758 A**mp.

Ripple in Inductor Current,

$I_{L\,(max)}$ = 8.80 A,

$I_{L\,(min)}$ = 6.75 A,

$\Delta I_{L\,(PEAK\,-\,PEAK)}$ = 8.8 - 6.75

= **2.05 A (26.34% of Io)**

Output voltage:

Avg. Output Voltage = **11.21 V**

Ripple in Output Voltage

$V_{o(max)}$ = 11.2116 V,

$Vo_{(min)}$ = 11.1996 V

$\Delta V_{o(peak\text{-}peak)}$ = **0.012 V (0.107% of Vo)**

6. **Average Output Current Io** = **7.782 A**
7. **Average Output Power Po** = **87.24 W**

CONCLUSION:

1. *Ripple in inductor Current – **26.4% of I_o***
2. *Ripple in output voltage – **0.107% of V_o***

Submitted by – Shivraj Vishwakarma,
M. Tech. 1st Year,
Power Engg.
Roll No. 224102112