Cell Balancing using Flyback Converters in current control mode

ADVANCED TOPICS IN POWER ELECTRONICS

ELL856

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Introduction

The aim of the project is to achieve cell balancing in a 3s1p battery pack being charged using a current source using 3 bi-directional flyback converter and one two switch bi-directional flyback converter. The circuit of these two converters are shown below.

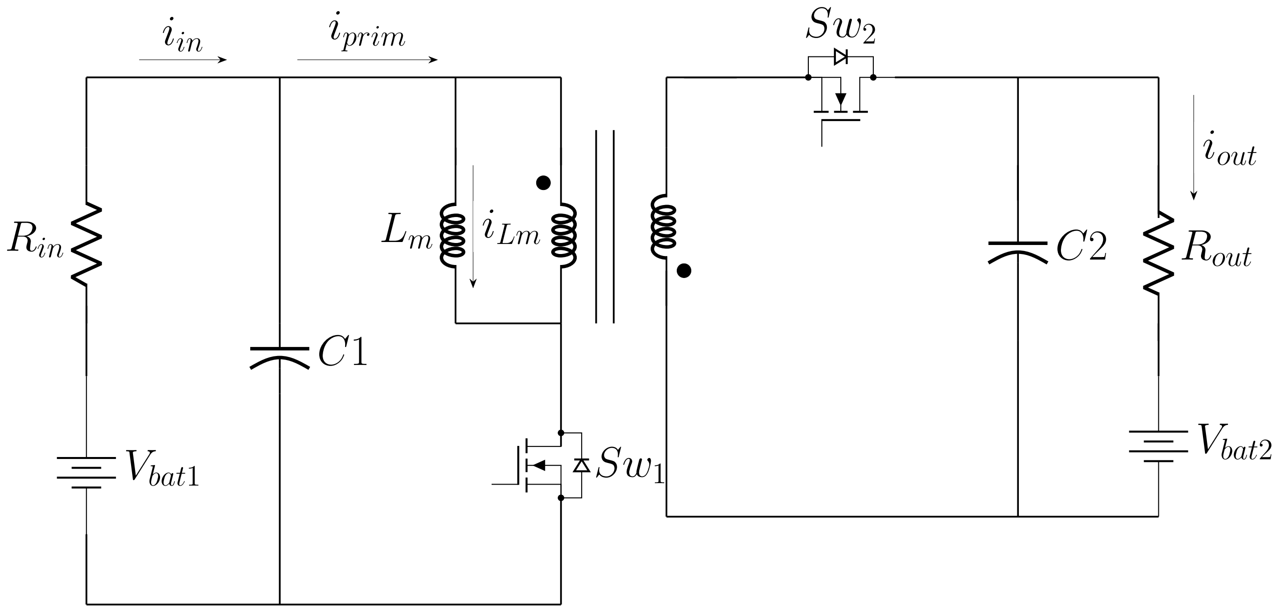

Figure 1: Bi-directional Flyback Converter

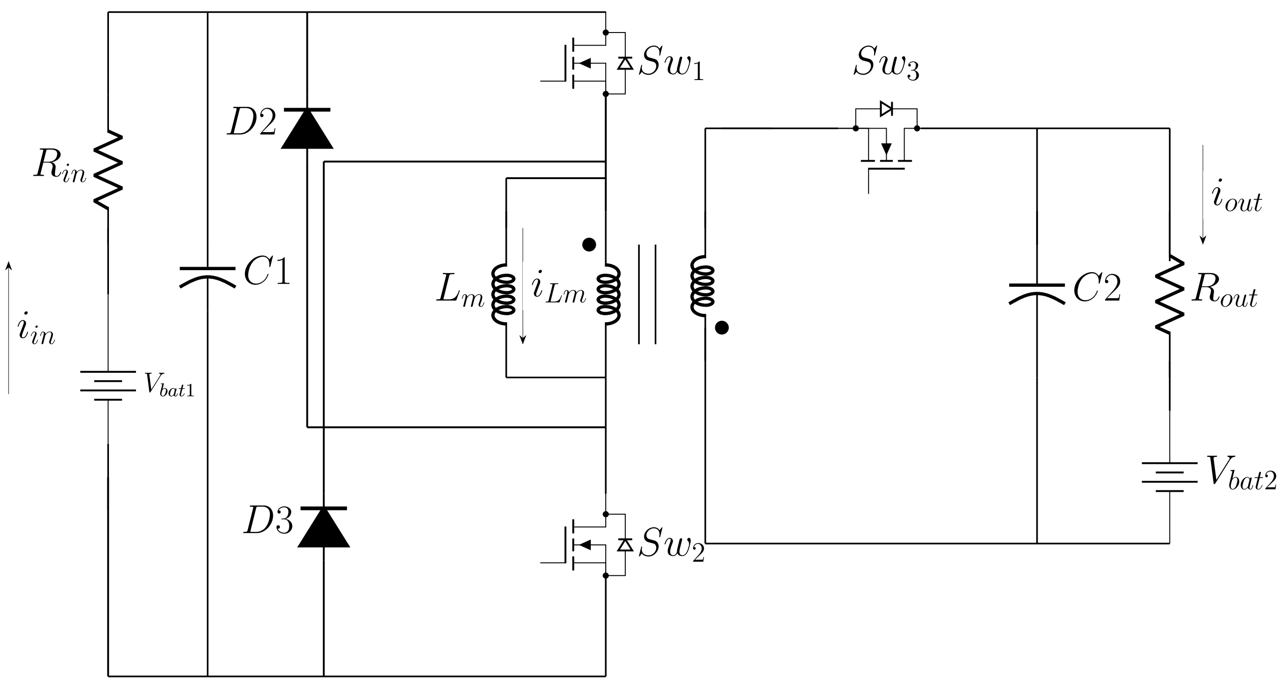

Figure 2: Two Switch bi-directional Flyback Converter

NOTE: L_m is just for representation purpose. In reality, it is the magnetizing inductance of the transformer/coupled inductor. Each transformer has a turns ratio of $1:n$

All the converter will run in current mode control to control the input current (I_{in}) of the converters.

Specifications given for the design are :

1. Each cell voltage = 3.7V
2. Charging current = 2.5A
3. Switching frequency = 250kHz
4. Type of battery pack : 3s1p

1 Methodology

Each flyback converter will have a sensor to sense to the input current which will be compared to the reference current (can be set as per our need) and the error will be fed to the controller. Depending on this error, the controller will produce the required duty ratio.
Before designing the controller we need to model our converter.
NOTE: The modelling will be done for the case of charging/discharging of a battery i.e., the modelling will consider the fact that there are two batteries with finite internal resistance at input and output terminals of the converter.

1.1 Modelling of flyback converter

Since, all the cells are identical, let us say the voltage of input cell be v_{bat1}, output cell be v_{bat2}, output capacitor voltage be v_c, inductor current be i_{Lm} and internal resistance be R_{in}.
To avoid lot of complications, I ignored the effect of input capacitor owing to the fact that if I can control the current waveform without a filter then the controller will act suitably in presence of capacitor filter at input because its impedance is low near the bandwidth of loop and thus this input filter won't affect the design/model a lot. Let us write the dynamic equations now for flyback converter:
During $0 \le t < DT_s$

$$v_{Lm} = v_{bat1} - i_{Lm}R_{in} \tag{1}$$

$$i_C = -\frac{v_c - v_{bat2}}{R_{out}} \tag{2}$$

$$i_{in} = i_{Lm} \tag{3}$$

During $DT_s \le t < T_s$

$$v_{Lm} = -\frac{v_c}{n} \tag{4}$$

$$i_C = \frac{i_{Lm}}{n} - \frac{v_c - v_{bat2}}{R_{out}} \tag{5}$$

$$i_{in} = 0 \tag{6}$$

If the values of L_m, C_1 and C_2 are properly chosen then there will be a very small ripple on i_{Lm} and v_c.So, we can replace i_{Lm} with $\langle i_{Lm}(t)\rangle_{T_s}$ and v_c with $\langle v_c(t)\rangle_{T_s}$

During $0 \le t < DT_s$

$$v_{Lm} = \langle v_{bat1}(t)\rangle_{T_s} - \langle i_{Lm}(t)\rangle_{T_s}R_{in} \tag{7}$$

$$i_C = -\frac{\langle v_c(t)\rangle_{T_s} - \langle v_{bat2}(t)\rangle_{T_s}}{R_{out}} \tag{8}$$

$$i_{in} = \langle i_{Lm}(t)\rangle_{T_s} \tag{9}$$

During $DT_s \le t < T_s$

$$v_{Lm} = -\frac{\langle v_c(t)\rangle_{T_s}}{n} \tag{10}$$

$$i_C = \frac{\langle i_{Lm}(t)\rangle_{T_s}}{n} - \frac{\langle v_c(t)\rangle_{T_s} - \langle v_{bat2}(t)\rangle_{T_s}}{R_{out}} \tag{11}$$

$$i_{in} = 0 \tag{12}$$

Now perturbing and linearizing the equation and neglecting second order terms gives:

$$L_m\frac{dI_{Lm}}{dt} + L_m\frac{d\widetilde{i_{Lm}}}{dt} = \left[DV_{bat1} - DI_{Lm}R_{in} - D'\frac{V_c}{n}\right] + \widetilde{d}\left[V_{bat1} - I_{Lm}R_{on} + \frac{V_c}{n}\right] + D\widetilde{v_{bat1}} - DR_{in}\widetilde{i_{Lm}} - \frac{D'}{n}\widetilde{v_c} \tag{13}$$

$$C_2\frac{dV_c}{dt}+C_2\frac{d\widetilde{v_c}}{dt}=\left[\frac{D'}{n}I_{Lm}-\frac{V_c-V_{bat2}}{R_{out}}\right]-\widetilde{d}\left[\frac{I_{Lm}}{n}\right]+\frac{\widetilde{V_{bat2}}}{R_{out}}+\frac{D'}{n}\widetilde{i_{Lm}}-\frac{\widetilde{v_c}}{R_{out}} \tag{14}$$

$$I_{in}+\widetilde{i_{in}}=DI_{in}+I_{Lm}\widetilde{d}+D\widetilde{i_{Lm}} \tag{15}$$

DC terms will be zero and thus we can get a set of DC relations and dynamic small signal equations.
DC equations:
On simplifying the DC terms we get,

$$V_c=\frac{DV_{bat1}+\frac{nD}{D'}\frac{R_{in}}{R_{out}}V_{bat2}}{\frac{D'}{n}+\frac{nD}{D'}\frac{R_{in}}{R_{out}}} \tag{16}$$

$$I_{Lm}=\frac{n}{D'}\frac{DV_{bat1}-\frac{D'}{n}V_{bat2}}{R_{out}(\frac{D'}{n}+\frac{nDR_{in}}{D'R_{out}})}\quad and\quad I_{in}=\frac{nD}{D'}\frac{DV_{bat1}-\frac{D'}{n}V_{bat2}}{R_{out}(\frac{D'}{n}+\frac{nDR_{in}}{D'R_{out}})} \tag{17}$$

Small signal AC dynamic equations: Note that over the time scale the duty changes is much smaller than the time scale where the voltages of input and output side battery changes. So, we can take $\widetilde{V_{bat2}}=\widetilde{V_{bat1}}=0$

$$L_m\frac{d\widetilde{i_{Lm}}}{dt}=\frac{V_c}{nD}\widetilde{d}-DR_{in}\widetilde{i_{Lm}}-\frac{D'}{n}\widetilde{v_c} \tag{18}$$

$$C_2\frac{d\widetilde{v_c}}{dt}=-\frac{I_{Lm}}{n}\widetilde{d}+\frac{D'}{n}\widetilde{i_{Lm}}-\frac{\widetilde{v_c}}{R_{out}} \tag{19}$$

$$and,\widetilde{i_{in}}=I_{Lm}\widetilde{d}+D\widetilde{i_{Lm}} \tag{20}$$

Hence, the required plant transfer function for current mode control is:

$$\frac{\widetilde{i_{Lm}}(s)}{\widetilde{d}(s)}=\left[\frac{\frac{V_c}{nD}+\frac{D'R_{out}I_{Lm}}{n^2}}{DR_{in}+\frac{D'^2R_{out}}{n^2}}\right]\frac{1+\frac{sCR_{out}\frac{V}{nD}}{\frac{V_c}{nD}+\frac{D'R_{out}I_{Lm}}{n^2}}}{1+s\frac{(L_m+DR_{in}R_{out}C_2)}{DR_{in}+\frac{D'^2R_{out}}{n^2}}+s^2\frac{L_mC_2R_{out}}{DR_{in}+\frac{D'^2R_{out}}{n^2}}} \tag{21}$$

$$\frac{\widetilde{i_{in}}(s)}{\widetilde{d}(s)}=I_{Lm}-D\frac{\widetilde{i_{Lm}}(s)}{\widetilde{d}(s)} \tag{22}$$

1.2 Modelling of two switch flyback converter:

We can observe that if we can ensure that diodes do not turn on then this converter is equivalent to flyback converter during CCM operation.
So, the two switch flyback converter will have the same transfer functions given that diode does not conduct during any period of time. This can be ensured by choosing the turns ratio appropriately so that the diodes are never in forward biased condition. Thus, we do not need to model the converter again.

1.3 Controller Design methodology:

As per the requirement we want to control the input current so that bidirectional power flow is possible. So, we will design the controller first depending on the values of parameter like crossover frequency and phase margin (has been shown later in 1.5) and then following logic will be implemented:

- Whenever the reference current will be positive, we will give the duty pulse from the controller to Sw_1 (in case of flyback converter) and to $Sw_1\ and\ Sw_2$ (in case of two switch flyback converter) on the primary side and the body diodes will be conducting in the secondary side. In this case, primary current will be controlled.
- Whenever the reference current will be negative, we will give the duty pulse from the controller to Sw_2 (in case of flyback converter) and to Sw_3 (in case of two switch flyback converter) on the secondary side and the body diodes will be conducting in the primary side. In this case, secondary current will be controlled.
- Anti windup mechanism will be implemented to reduce the settling time due to unnecessary over integration in integrator part of PI compensator (reason for using PI compensator will be discussed in 1.5).

1.4 Choosing the components value:

1.4.1 For flyback converter:

The specifications are:

1. Input cell voltage, $V_{bat1} = 3.7V$
2. Output cell voltage, $V_{bat2} = 3.7V$
3. Average input current, $I_{in} = 0.2A/0.1A/-0.1A/-0.2A$
4. Switching frequency, $f_{sw} = 250kHz$

The following values were chosen for the quantities that were not specified:

1. Pulse width modulator peak voltage, $V_m = 5V$
2. Reference voltage for 0.2A current, $V_{ref} = 5V$
3. Inductor current ripple (pk-pk), $\Delta i_{Lm} = 0.01A$
4. Capacitor voltage ripple (pk-pk) , $\Delta v_c = 0.02V$
5. Internal resistance of each cell, $R_{int} = 100m\Omega$

Choice of turns ratio of transformer:
Since, output cell and input cell has roughly same voltage, we can choose the turns ratio as 1:1 to get a duty ratio near to 0.5. This duty will help to avoid stress on one of the devices to carry current for larger duration.

Calculation for Inductor value:
Absolute value of ripple = 0.01A
Duty ratio, $D = 0.5021$ (This can be calculated using input current equation in equation 17)
Output voltage, V_c = 3.7103V (This can be calculated using voltage equation in equation 16)
From equation 10

$$L_m \frac{\Delta i_{Lm}}{D'Ts} = V_c \tag{23}$$

$$\implies L_m = \frac{3.7103 * 0.4979}{0.01 * 250 * 10^3} \tag{24}$$

$$\implies L_m = 738.95\mu H \tag{25}$$

Calculation of capacitor value:
From equation 8

$$C_2 \frac{\Delta v_c}{DTs} = -\frac{V_c - V_{bat}}{Rout} \tag{26}$$

$$\implies C_2 = \frac{0.0103 * 0.5021}{0.02 * 0.1 * 250 * 10^3} \tag{27}$$

$$\implies C_2 = 10.360\mu F \tag{28}$$

Since, the circuit is symmetric and the duty ratio is close to 0.5, we can say that same value of capacitor would work for input side as well.
Thus, for the flyback converter the value of passives for the converter are:
$L_m = 738.95\mu H, C_1 = C_2 = 10.36\mu F.$

Choice of sensor gain for current sensing:
Since, 0.2A of average input current is going to be drawn in the input side at max. So, let us say that 5V corresponds to this value of current.
Hence, $R_{sense} = 25V/A$.
NOTE: This R_{sense} is not a 25Ω resistor but gain of a sensing circuit realised using, say, sense resistors and op-amps.

1.4.2 For two switch flyback converter:

The specifications are:

1. Input cell voltage, $V_{bat1} = 3.7V$
2. Output cell voltage, $V_{bat2} = 11.1V$ (since the battery pack is a 3s1p structure)
3. Average input current, $I_{in} = 0.1A/-0.1A$
4. Switching frequency, $f_{sw} = 250kHz$

The following values were chosen for the quantities that were not specified:

1. Pulse width modulator peak voltage, $V_m = 5V$
2. Reference voltage for 0.1A current, $V_{ref} = 5V$
3. Inductor current ripple (pk-pk), $\Delta i_{Lm} = 0.01A$
4. Capacitor voltage ripple (pk-pk) , $\Delta v_c = 0.02V$
5. Internal resistance of each cell, $R_{int} = 100m\Omega$

Choice of turns ratio of transformer:
Since, output voltage is 3 times the input voltage, we could have taken a turns ratio of 1:3, so that the reflected voltage in the primary side is roughly around 3.7V but during negative current reference this might lead to forward biasing of diode which we do not want.
So, I chose a turns ratio of 1:4 to avoid the possibility of forward biasing the diode in the range of duty we operate.
Although this would lead to a duty value different from 0.5 but if we allow the diodes to conduct, the conduction losses in diodes will be higher as compared to the conduction losses of MOSFETs which will lead to poor efficiency of the converter.

Calculation for Inductor value:
Absolute value of ripple = 0.01A
Duty ratio, $D = 0.4305$ (This can be calculated using input current equation in equation 17)
Output voltage, V_c = 11.1109V (This can be calculated using voltage equation in equation 16)
From equation 10

$$L_m \frac{\Delta i_{Lm}}{D'Ts} = V_c \tag{29}$$

$$\implies L_m = \frac{11.1109 * 0.5695}{0.01 * 250 * 10^3} \tag{30}$$

$$\implies L_m = 2.5310mH \tag{31}$$

Calculation of output capacitor value:
From equation 8

$$C_2 \frac{\Delta v_c}{DTs} = -\frac{V_c - V_{bat2}}{Rout} \tag{32}$$

$$\implies C_2 = \frac{0.0109 * 0.4305}{0.02 * 0.3 * 250 * 10^3} \tag{33}$$

$$\implies C_2 = 3.115\mu F \tag{34}$$

Calculation of output capacitor value:
From equation 8

$$C_1 \frac{\Delta v_c}{D'Ts} = -\frac{V_c - V_{bat1}}{Rin} \tag{35}$$

$$\implies C_1 = \frac{0.01 * 0.5695}{0.02 * 0.1 * 250 * 10^3} \tag{36}$$

$$\implies C_1 = 1.139\mu F \tag{37}$$

Thus, for the two switch flyback converter the value of passives for the converter are:
$L_m = 2.5310mH, C_1 = 1.139\mu F \; and \; C_2 = 3.115\mu F.$

Choice of sensor gain for current sensing when reference voltage is positive:
Since, 0.1A of average input current is going to be set at max. So, let us say that 5V corresponds to thus value of current.
Hence, for current sensed on primary side, $R_{sense_{prim}} = 50V/A$.

Choice of sensor gain for current sensing when reference voltage is negative:
The 0.1A of average output current (considering output current because now the output terminal will be supplying power and input side cell will be charged) is achieved at duty of roughly 0.6. And,

$$I_{in} = n\frac{D}{D'}I_{out}$$

So,for current sensed on secondary side, if we want to keep the same magnitude of reference voltage for -0.1A, $R_{sense_{sec}} = 130V/A$.

1.5 Controller design:

1.5.1 For flyback converter

On plugging the values from 1.4.1 in equation 22, we get the plant transfer function as:

$$\frac{\widetilde{i_{in}}(s)}{\widetilde{d}(s)} = 49.7469\frac{\left(1+\dfrac{s}{9.6520\times10^5}\right)\left(1+\dfrac{s}{2.437\times10^4}\right)}{\left(1+\dfrac{s}{9.6524\times10^5}\right)\left(1+\dfrac{s}{101.5}\right)} \tag{38}$$

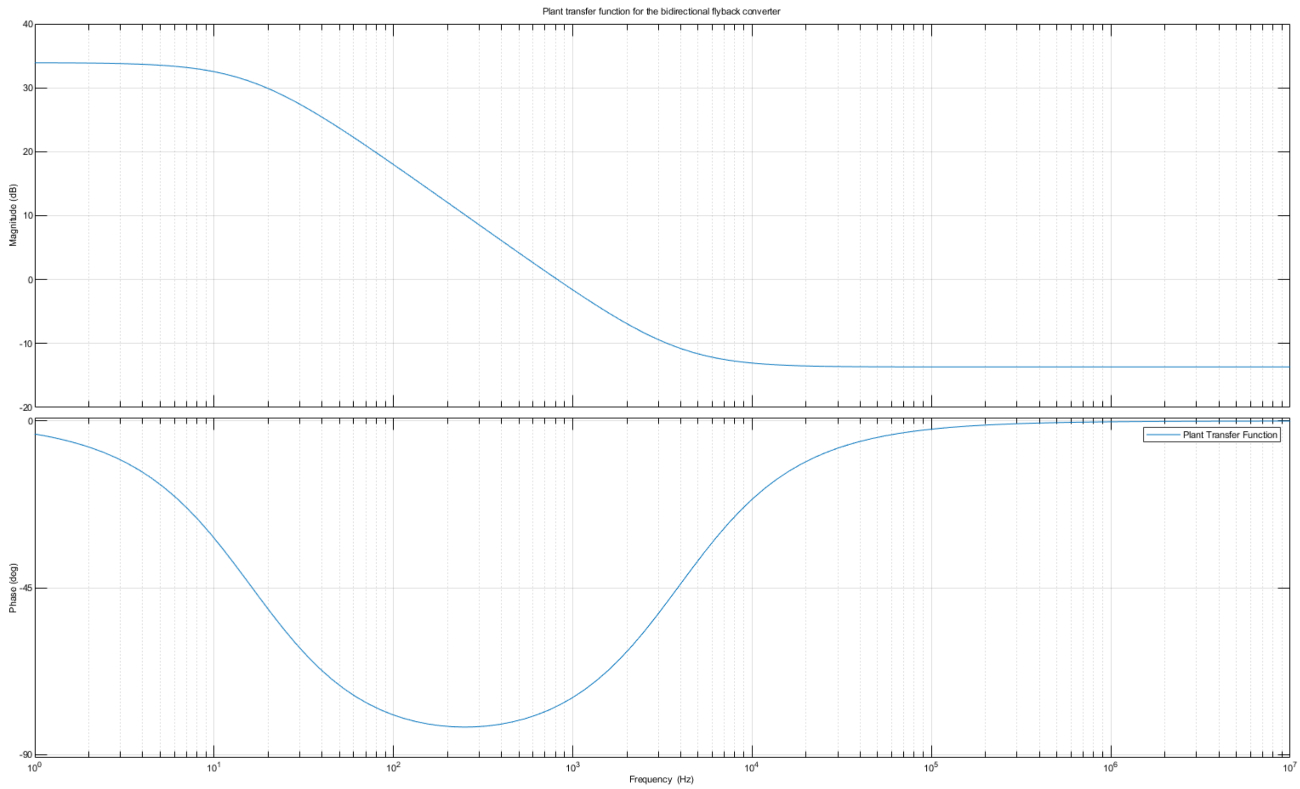

Figure 3: Bode plot for plant transfer function of flyback converter

So, uncompensated loop gain is:

$$T_{ui}(s) = 248.7343 \frac{\left(1 + \dfrac{s}{9.6520 \times 10^5}\right)\left(1 + \dfrac{s}{2.437 \times 10^4}\right)}{\left(1 + \dfrac{s}{9.6524 \times 10^5}\right)\left(1 + \dfrac{s}{101.5}\right)} \tag{39}$$

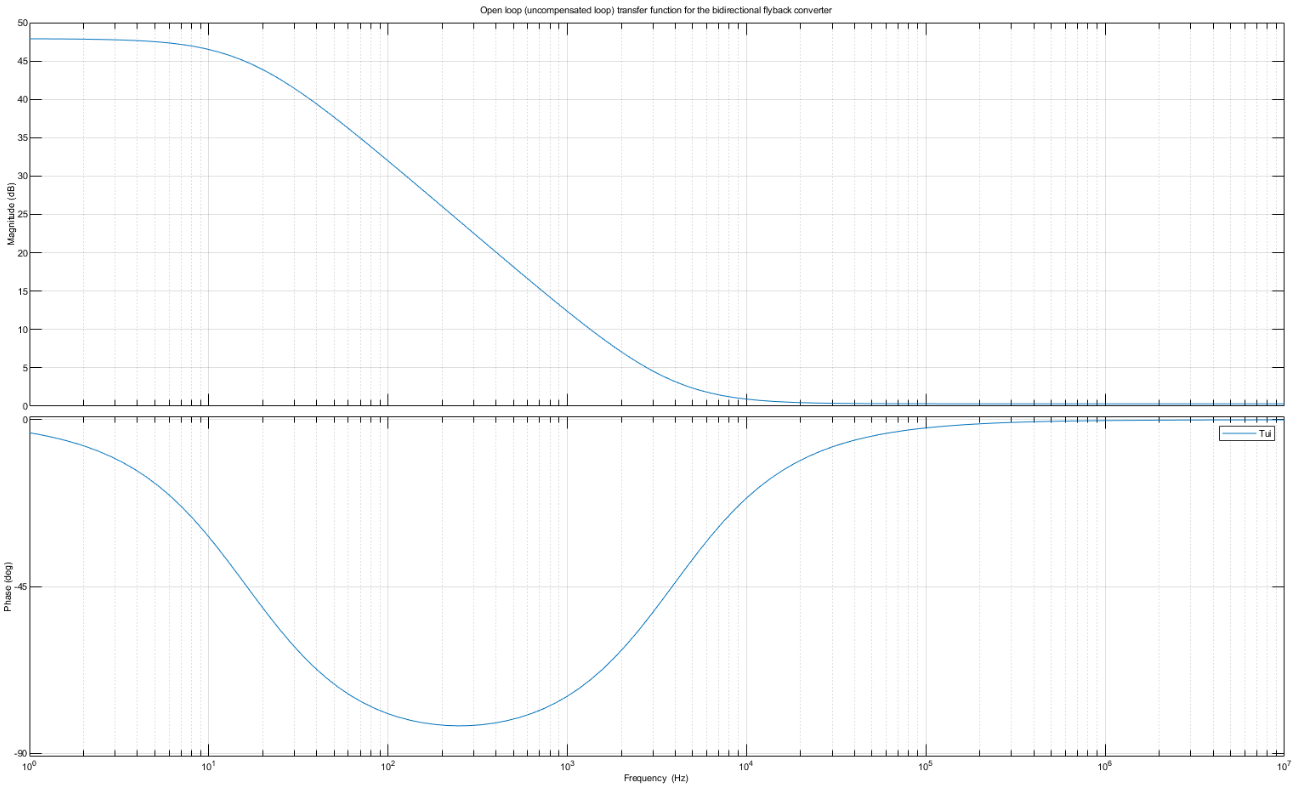

Figure 4: Bode plot of uncompensated loop gain of Flyback converter

Specs for the current controller:

1. Crossover frequency, $f_c = 20kHz$
2. Phase margin, $\phi_m = 60°$
3. High frequency roll-off of the controller = -20dB/decade
4. Zero steady state error

Designing the controller transfer function:
As can be seen from the bode plot in Figure 4, the phase of the open loop is close to $0°$ and thus a PI compensator with a low pass characteristic at high frequency can be used.
General form of the transfer function is:

$$G_c = G_{c0} \frac{1 + \dfrac{\omega_{Lv}}{s}}{1 + \dfrac{s}{\omega_{filter}}} \tag{40}$$

On computing the values required to achieve the specified crossover frequency and the phase margin, the final controller look like:

$$G_c = 0.3282 \frac{1 + \dfrac{4.69 \times 10^5}{s}}{1 + \dfrac{s}{1.885 \times 10^5}} \tag{41}$$

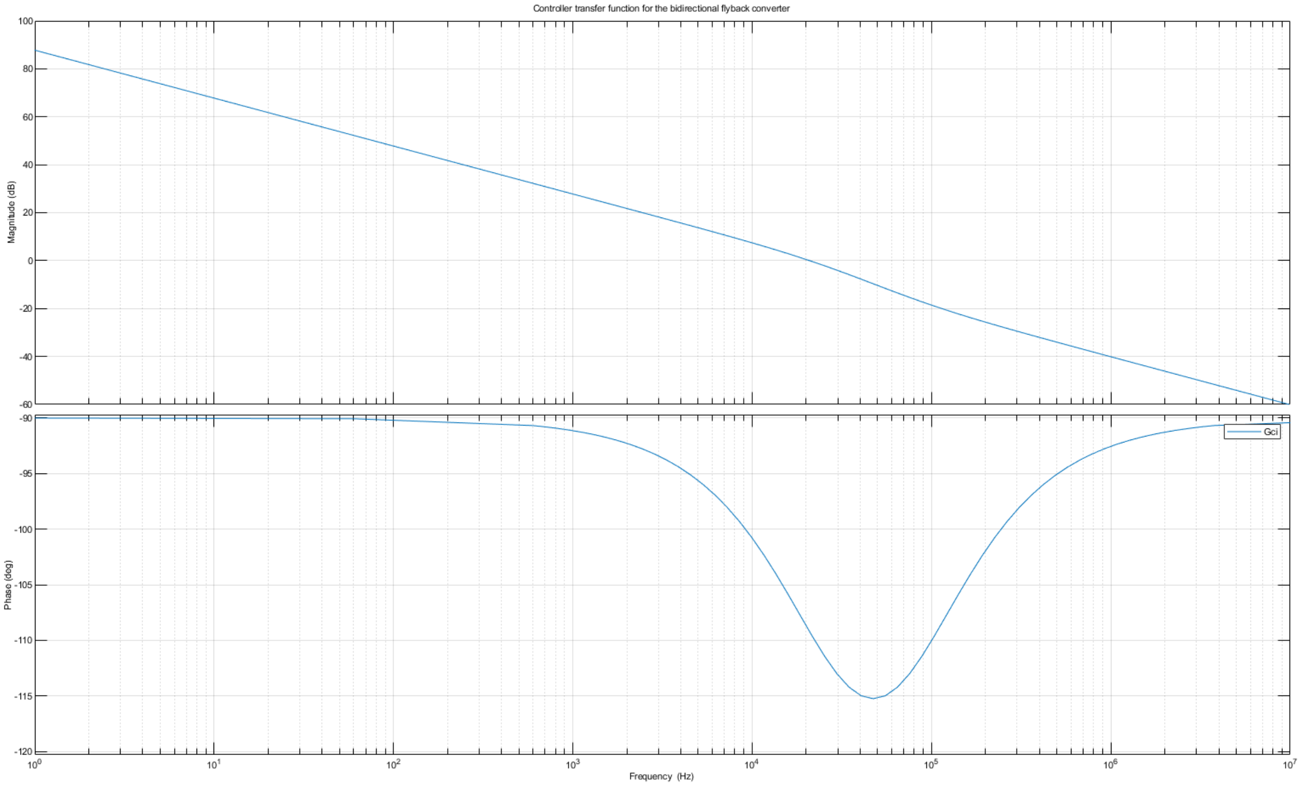

Figure 5: Bode plot of current controller for Flyback converter

After inserting the current controller in the loop, the open loop (compensated) transfer function is:

$$T_{ci}(s) = 81.63459726 \frac{\left(1+\dfrac{s}{9.6520\times 10^5}\right)\left(1+\dfrac{s}{2.437\times 10^4}\right)\left(1+\dfrac{4.69\times 10^5}{s}\right)}{\left(1+\dfrac{s}{9.6524\times 10^5}\right)\left(1+\dfrac{s}{101.5}\right)\left(1+\dfrac{s}{1.885\times 10^5}\right)} \tag{42}$$

The bode plot plot for this transfer function is shown in Figure 6
Thus, the closed loop transfer function (CLTF) looks like:

$$CLTF = \frac{T_{ci}(s)}{1+T_{ci}(s)} \tag{43}$$

where T_{ci} is given by Equation 42.
The bode plot for the CLTF of the Flyback converter for the designed controller is shown is Figure 7

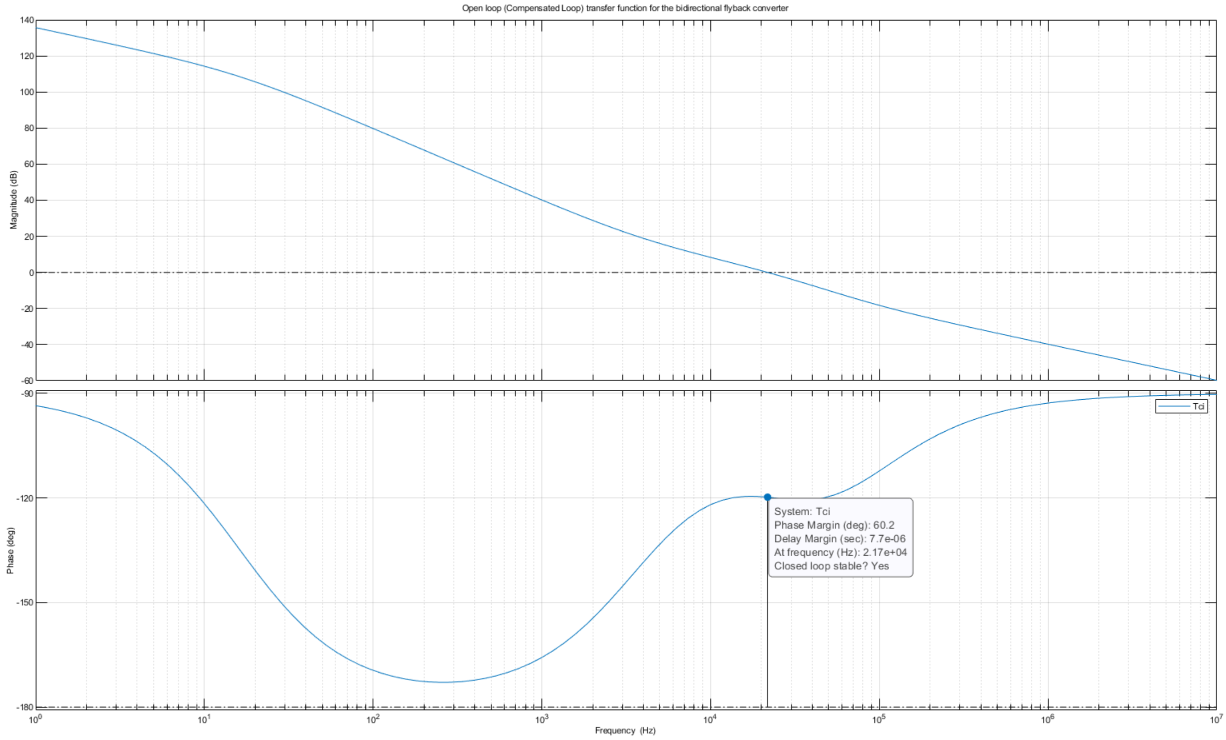

Figure 6: Bode plot of compensated loop gain of Flyback converter

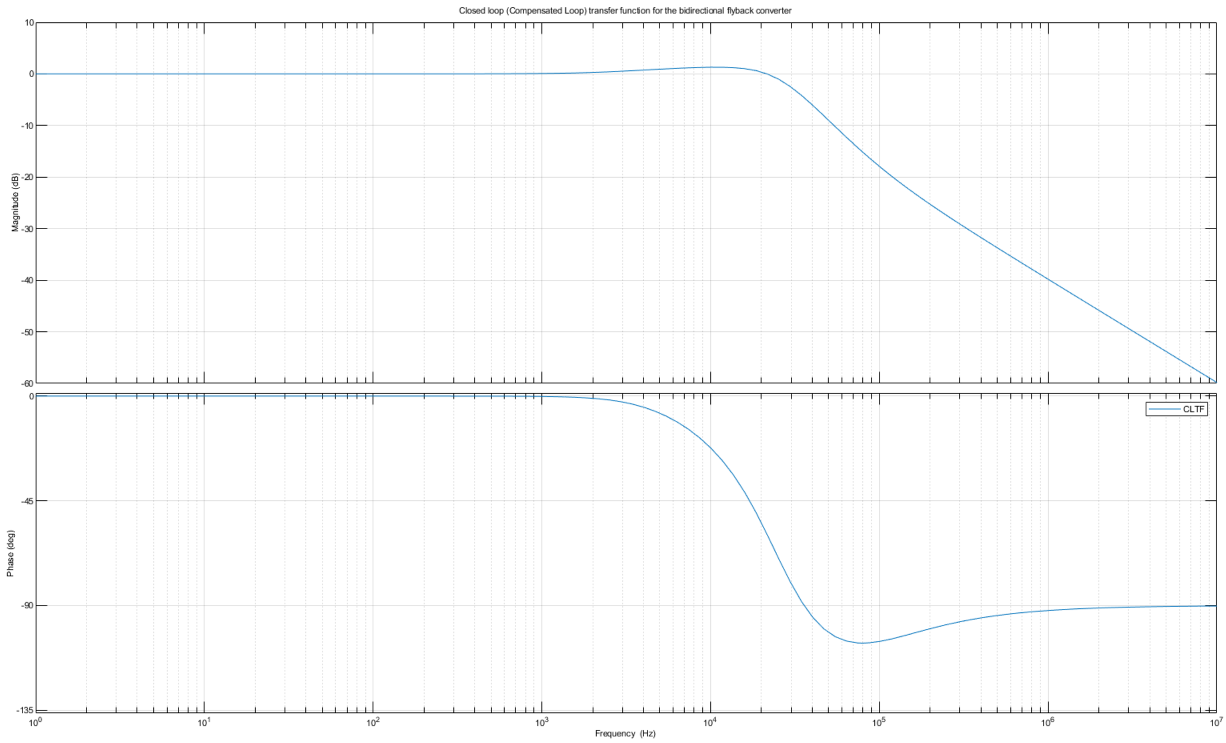

Figure 7: Bode plot of closed loop transfer function for Flyback converter

1.5.2 For two switch flyback converter

On plugging the values from 1.4.2 in equation 22, we get the plant transfer function as:

$$\frac{\widetilde{i_{in}}(s)}{\widetilde{d}(s)} = 56.7983 \frac{\left(1 + \frac{s}{1.193385 \times 10^6}\right)\left(1 + \frac{s}{4835.442}\right)}{\left(1 + \frac{s}{1.193387 \times 10^6}\right)\left(1 + \frac{s}{19.4003}\right)} \tag{44}$$

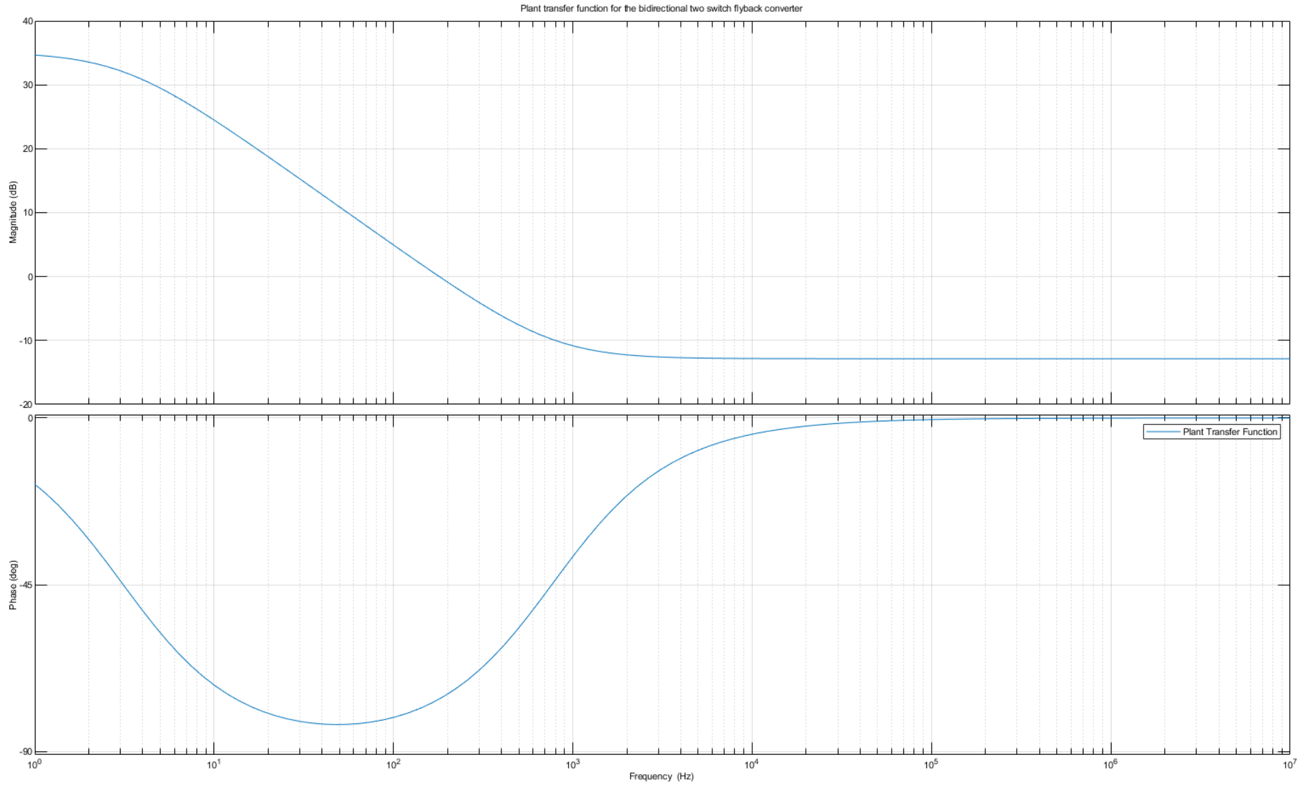

Figure 8: Bode plot for plant transfer function of two switch flyback converter

So, uncompensated loop gain is:

$$T_{ui}(s) = 567.9829 \frac{\left(1 + \frac{s}{1.193385 \times 10^6}\right)\left(1 + \frac{s}{4835.442}\right)}{\left(1 + \frac{s}{1.193387 \times 10^6}\right)\left(1 + \frac{s}{19.4003}\right)} \tag{45}$$

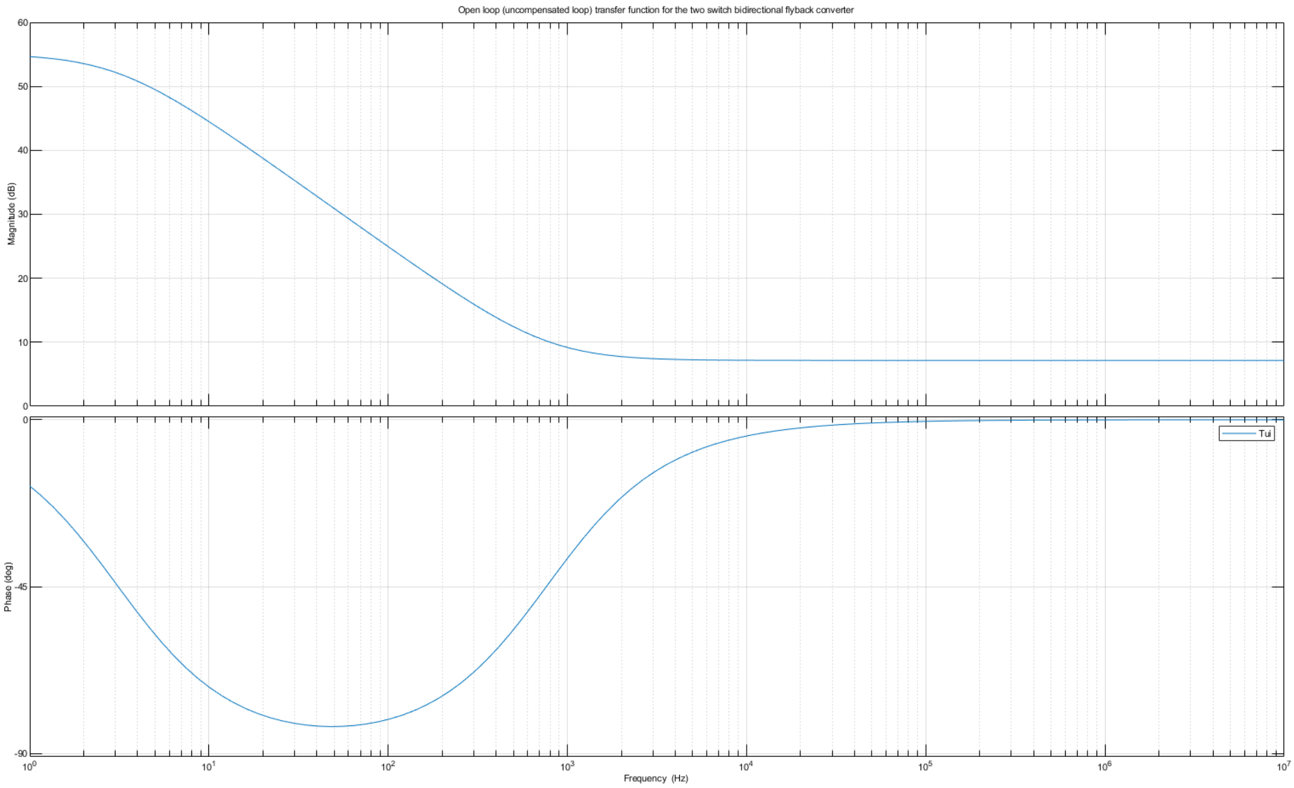

Figure 9: Bode plot of uncompensated loop gain of two switch flyback converter

Specs for the current controller:

1. Crossover frequency, $f_c = 40kHz$
2. Phase margin, $\phi_m = 60°$
3. High frequency roll-off of the controller = -20dB/decade
4. Zero steady state error

Designing the controller transfer function:
As can be seen from the bode plot in Figure 9, the phase of the open loop is close to $0°$ and thus a PI compensator with a low pass characteristic at high frequency can be used.
General form of the transfer function is same as in Equation 40

On computing the values required to achieve the specified crossover frequency and the phase margin, the final controller look like:

$$G_c = 1.3704 \frac{1 + \frac{2.1777 \times 10^5}{s}}{1 + \frac{s}{6.283 \times 10^4}} \tag{46}$$

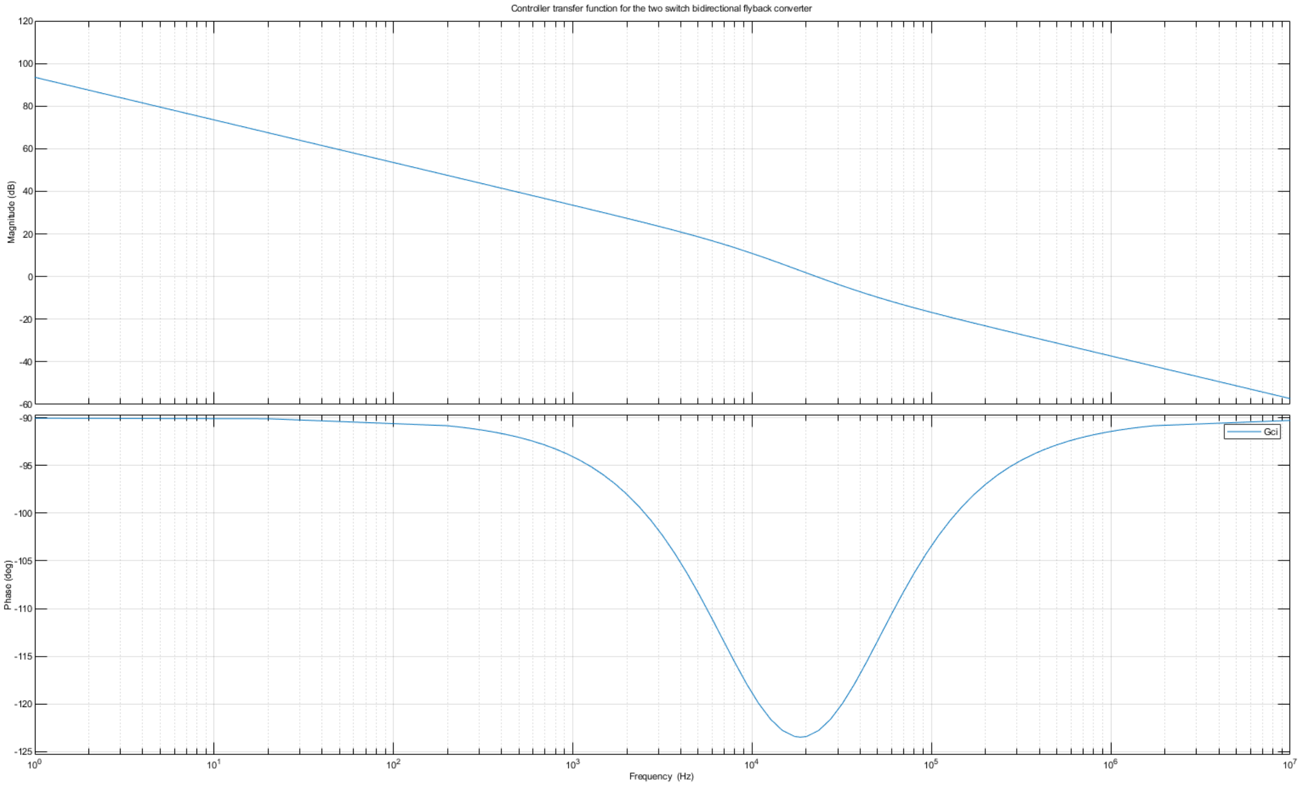

Figure 10: Bode plot of current controller for two switch flyback converter

After inserting the current controller in the loop, the open loop (compensated) transfer function is:

$$T_{ci}(s) = 778.3888\frac{\left(1+\dfrac{s}{1.193385\times10^{6}}\right)\left(1+\dfrac{s}{4835.442}\right)\left(1+\dfrac{2.1777\times10^{5}}{s}\right)}{\left(1+\dfrac{s}{1.193387\times10^{6}}\right)\left(1+\dfrac{s}{19.4003}\right)\left(1+\dfrac{s}{6.283\times10^{4}}\right)} \tag{47}$$

The bode plot plot for this transfer function is shown in Figure 11
Thus, the closed loop transfer function (CLTF) looks like:

$$CLTF = \frac{T_{ci}(s)}{1+T_{ci}(s)} \tag{48}$$

where T_{ci} is given by Equation 47.
The bode plot for the CLTF of the two switch Flyback converter for the designed controller is shown is Figure 12

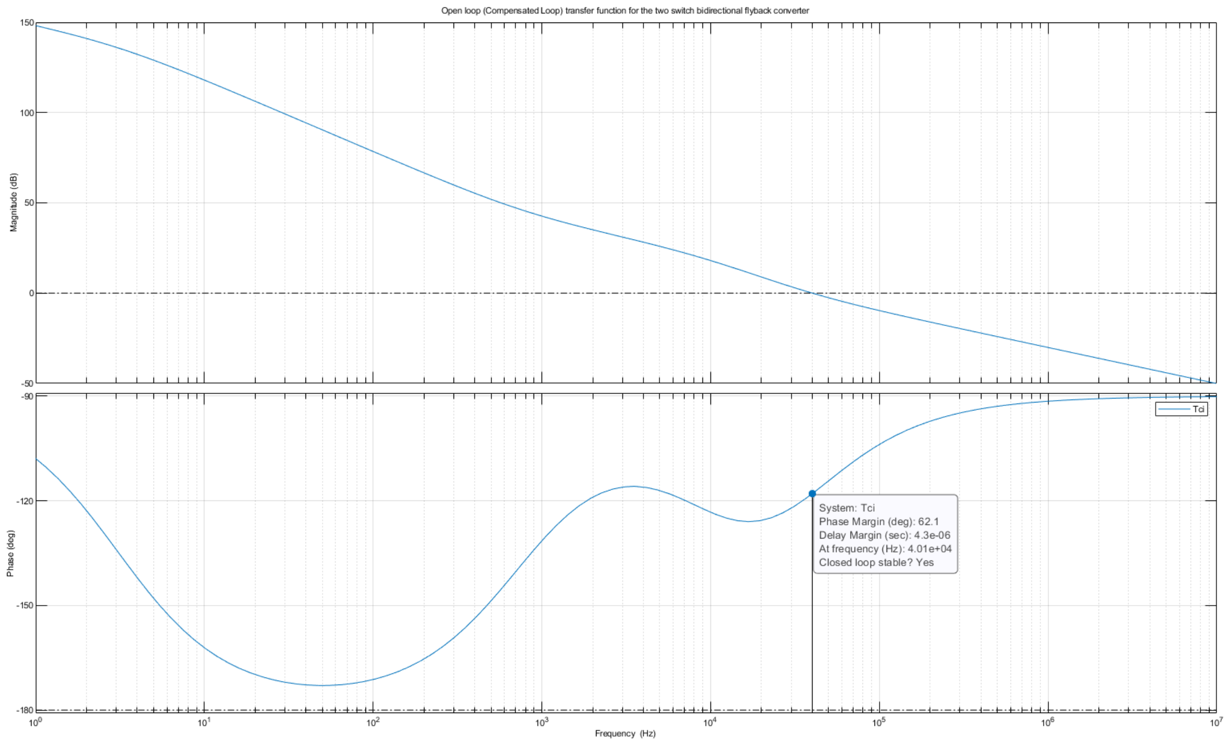

Figure 11: Bode plot of compensated loop gain of two switch Flyback converter

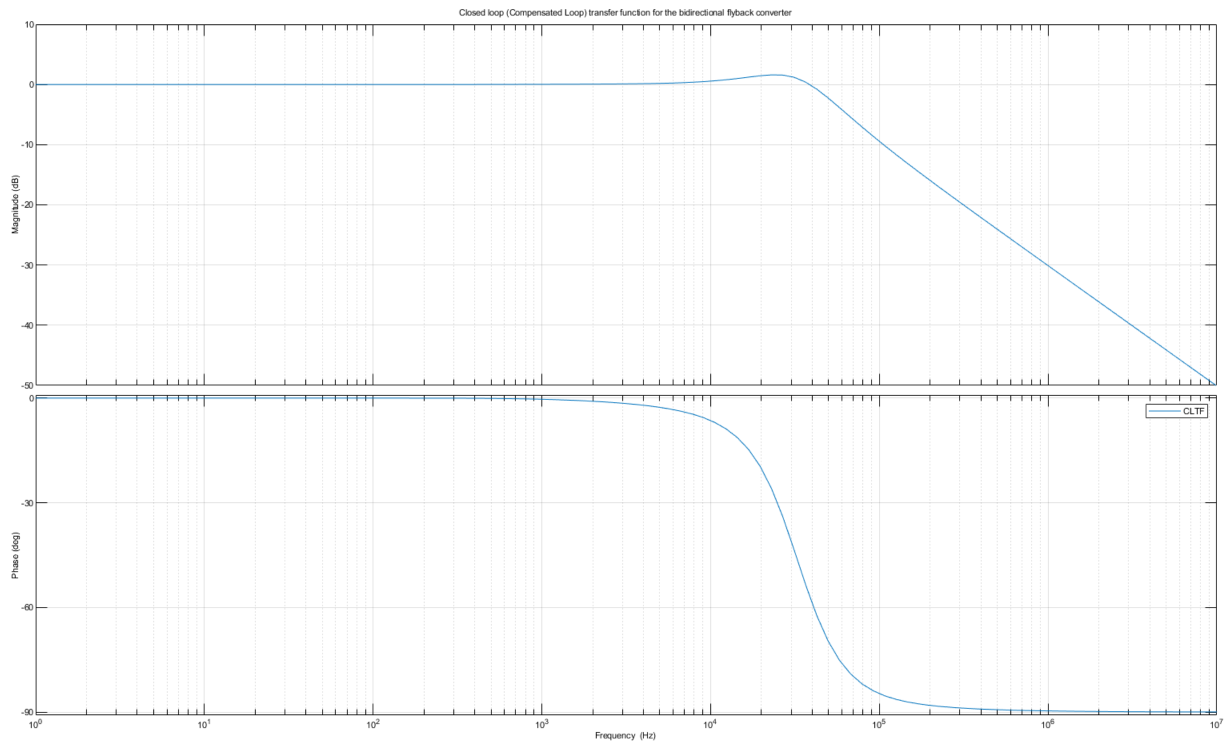

Figure 12: Bode plot of closed loop transfer function for two switch Flyback converter

2 Results

2.1 Results of the simulation for flyback converter:

2.1.1 Schematic for the circuit designed in Simulink is:

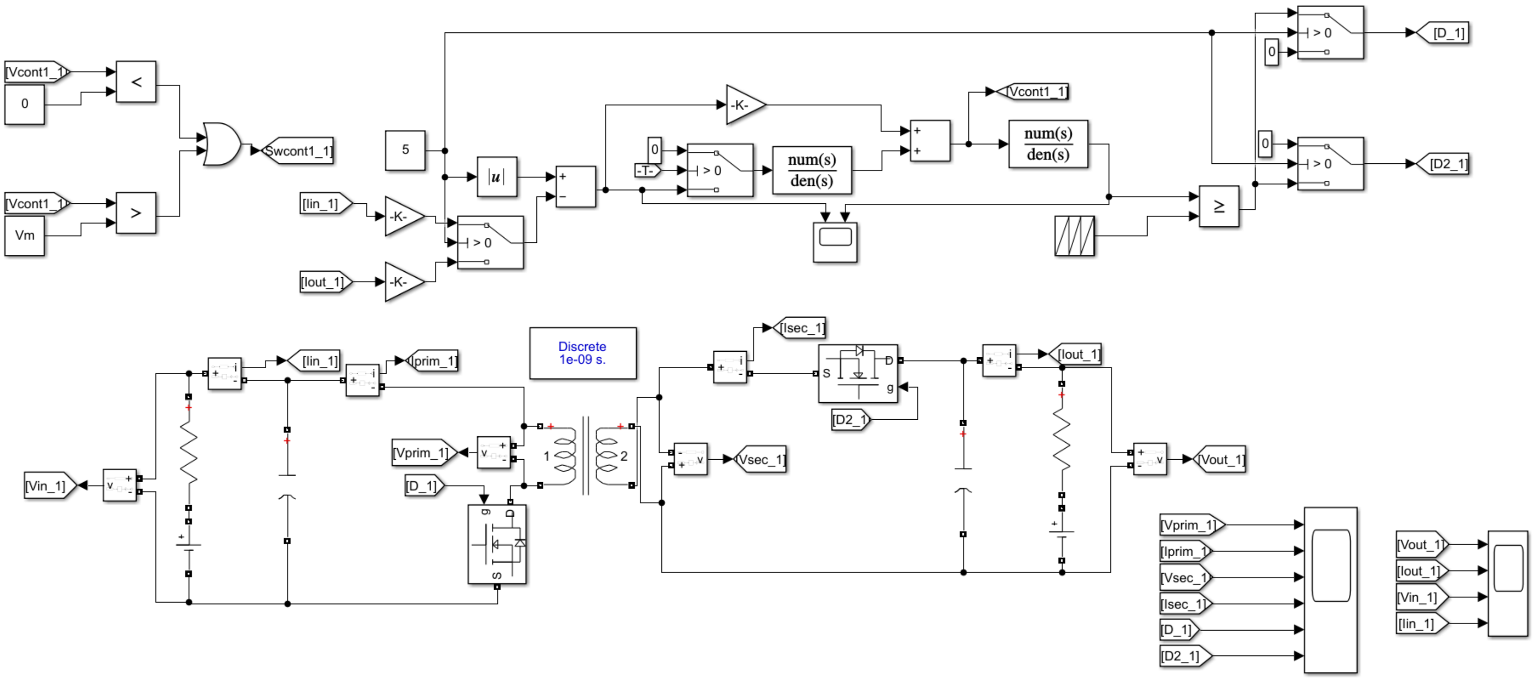

Figure 13: Schematic of the bidirectional flyback converter

The schematic shown in figure 13 was used for the simulation purposes. The component values were derived from the MATLAB workspace using a script which has been attached in the appendix A of the report.
All the relevant waveforms have been attached in later pages to show the bidirectional flow of power and proper implementation of the scheme discussed in Section 1.3.

2.1.2 Waveform for converter when input current reference is 0.1A

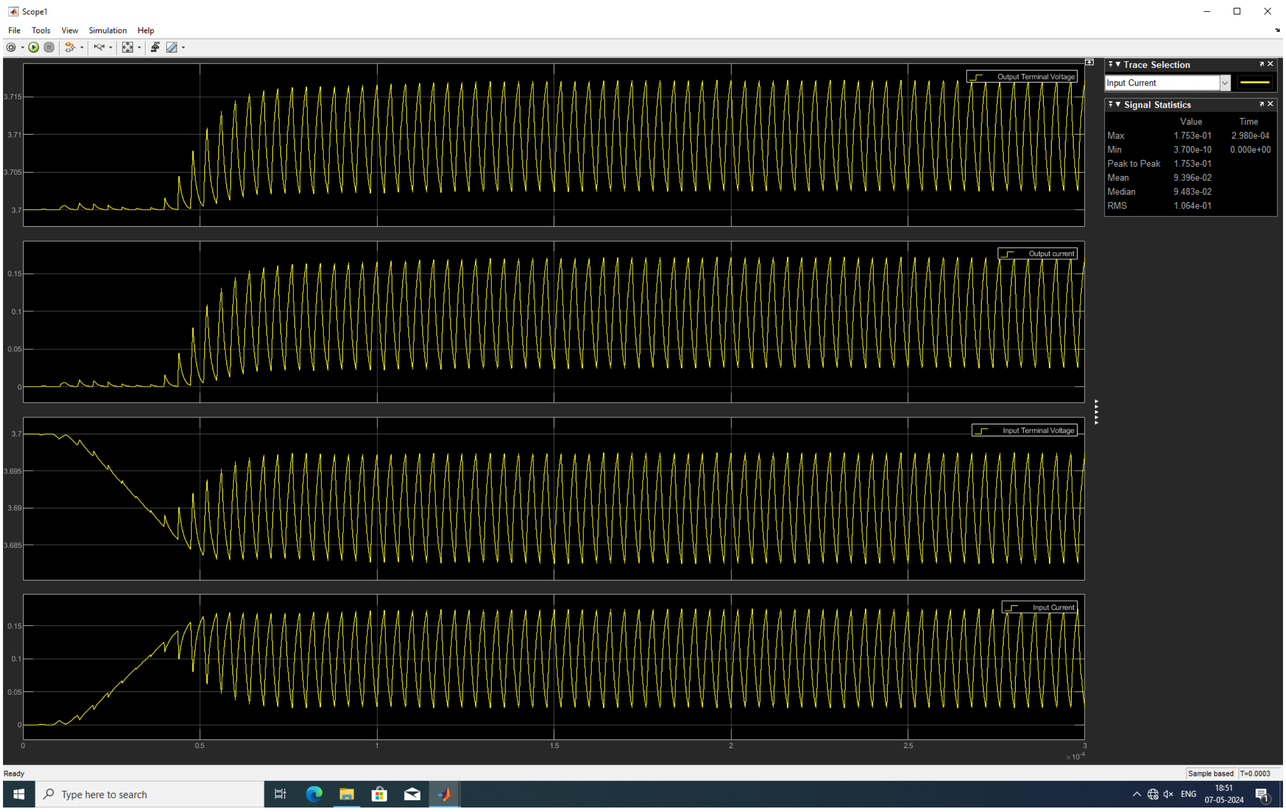

Figure 14: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the bidirectional flyback converter when $I_{ref} = 0.1A$

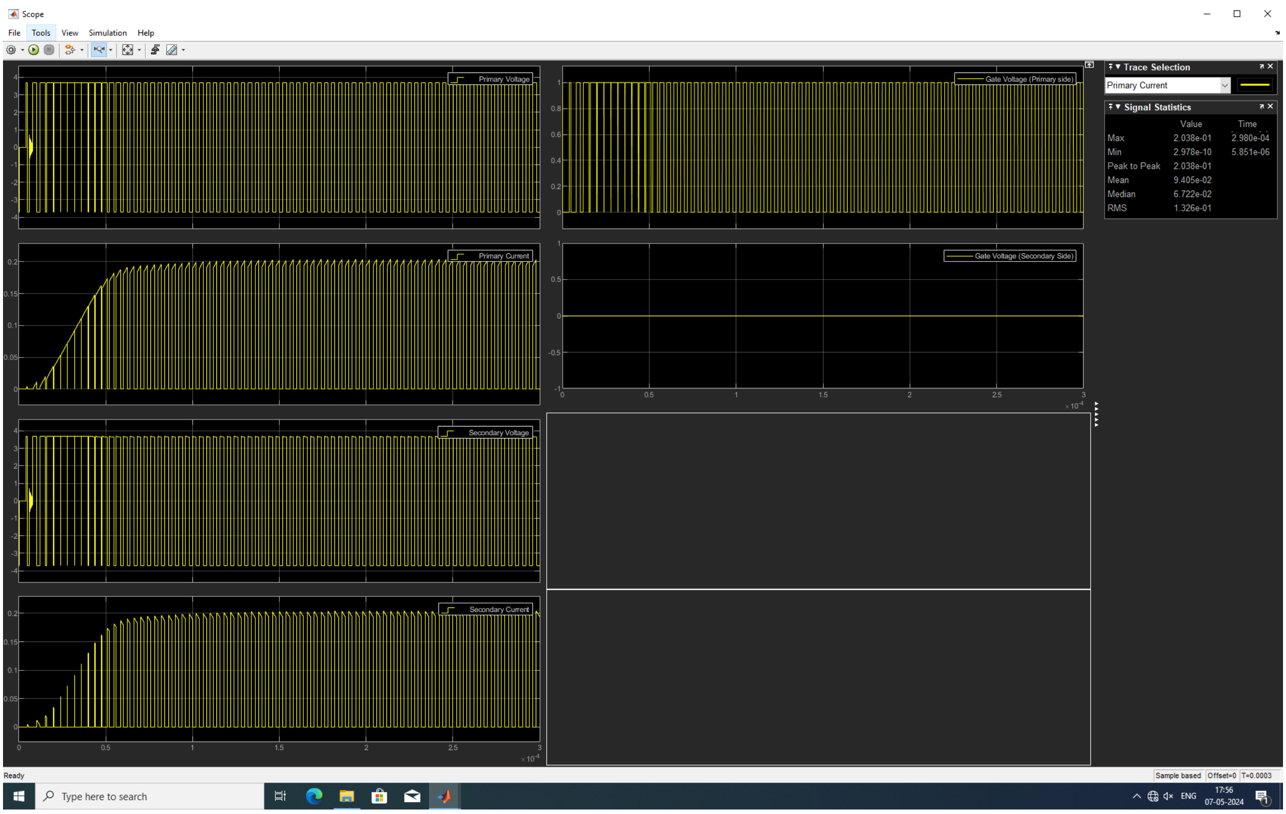

Figure 15: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the bidirectional flyback converter when $I_{ref} = 0.1A$

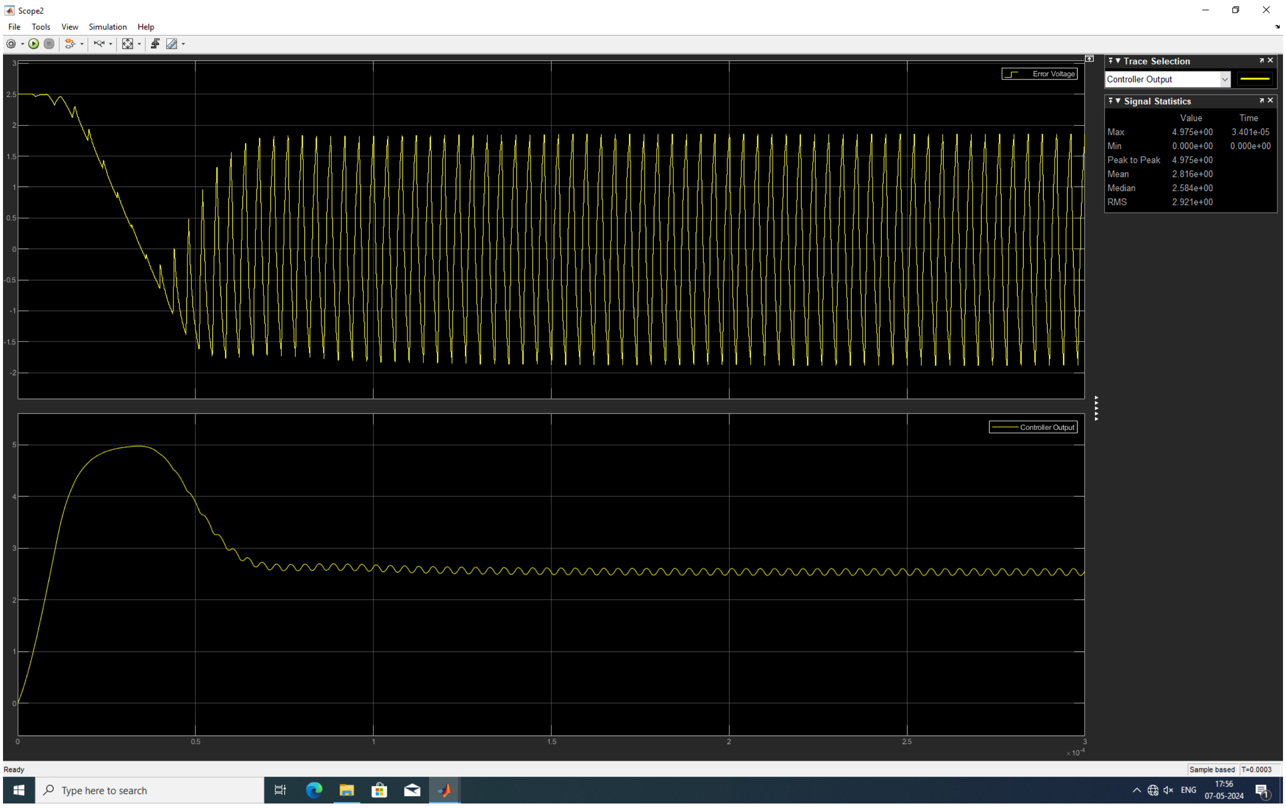

Figure 16: Waveform of error voltage and controller output for the bidirectional flyback converter when $I_{ref} = 0.1A$

2.1.3 Waveform for converter when input current reference is -0.1A

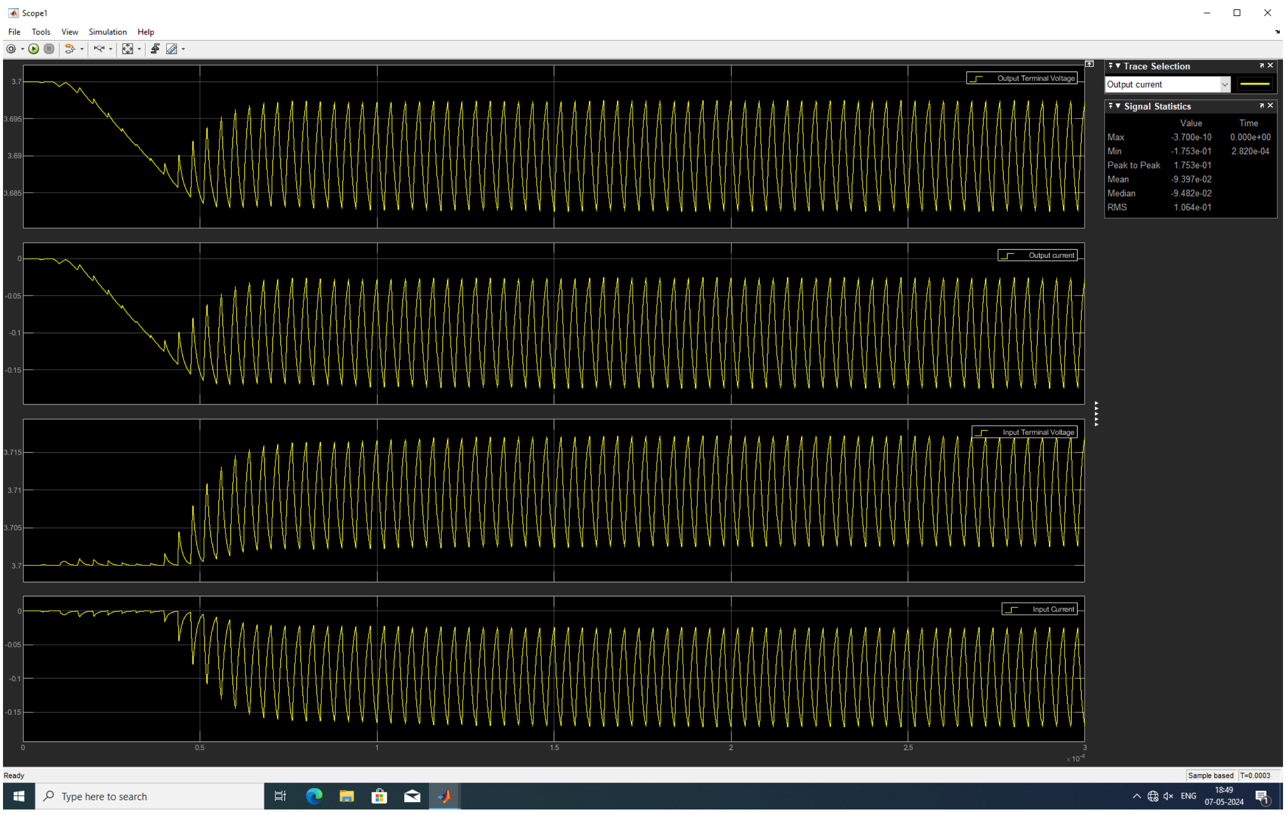

Figure 17: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the bidirectional flyback converter when $I_{ref} = -0.1A$

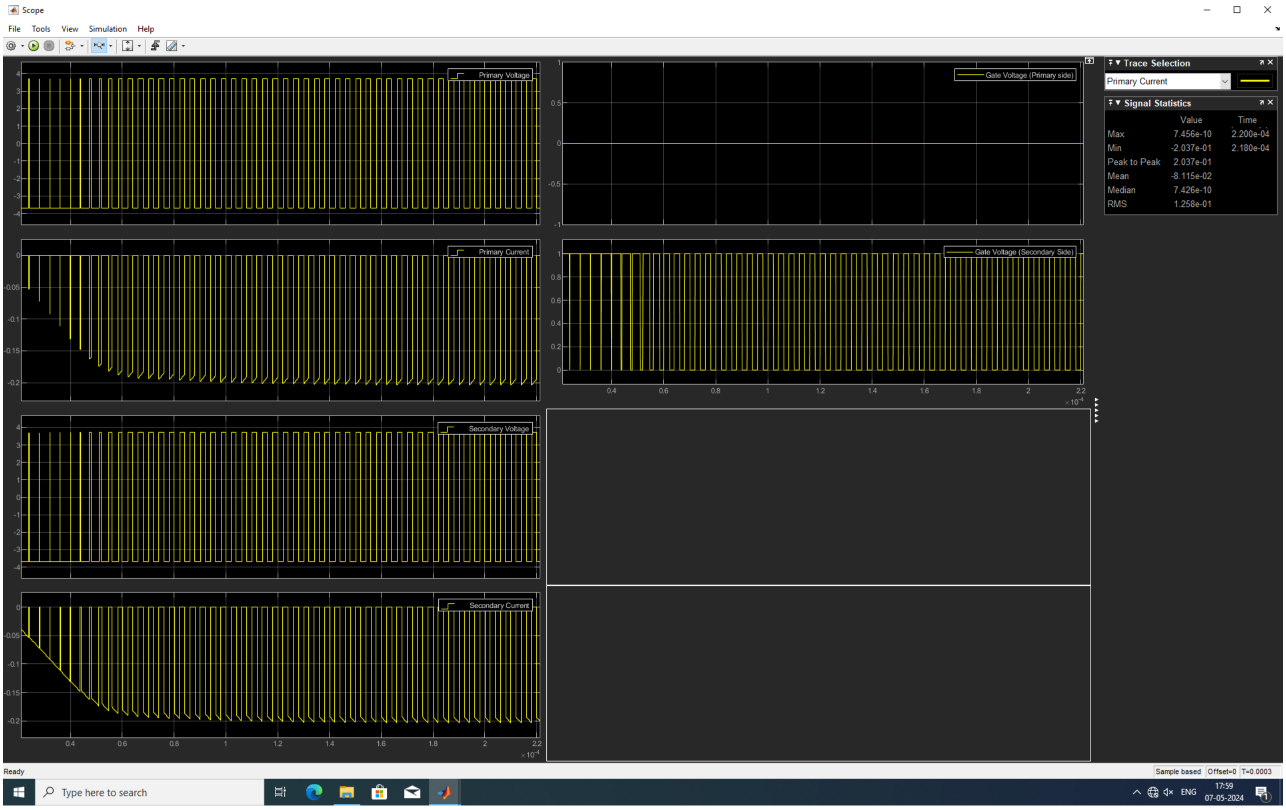

Figure 18: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the bidirectional flyback converter when $I_{ref} = -0.1A$

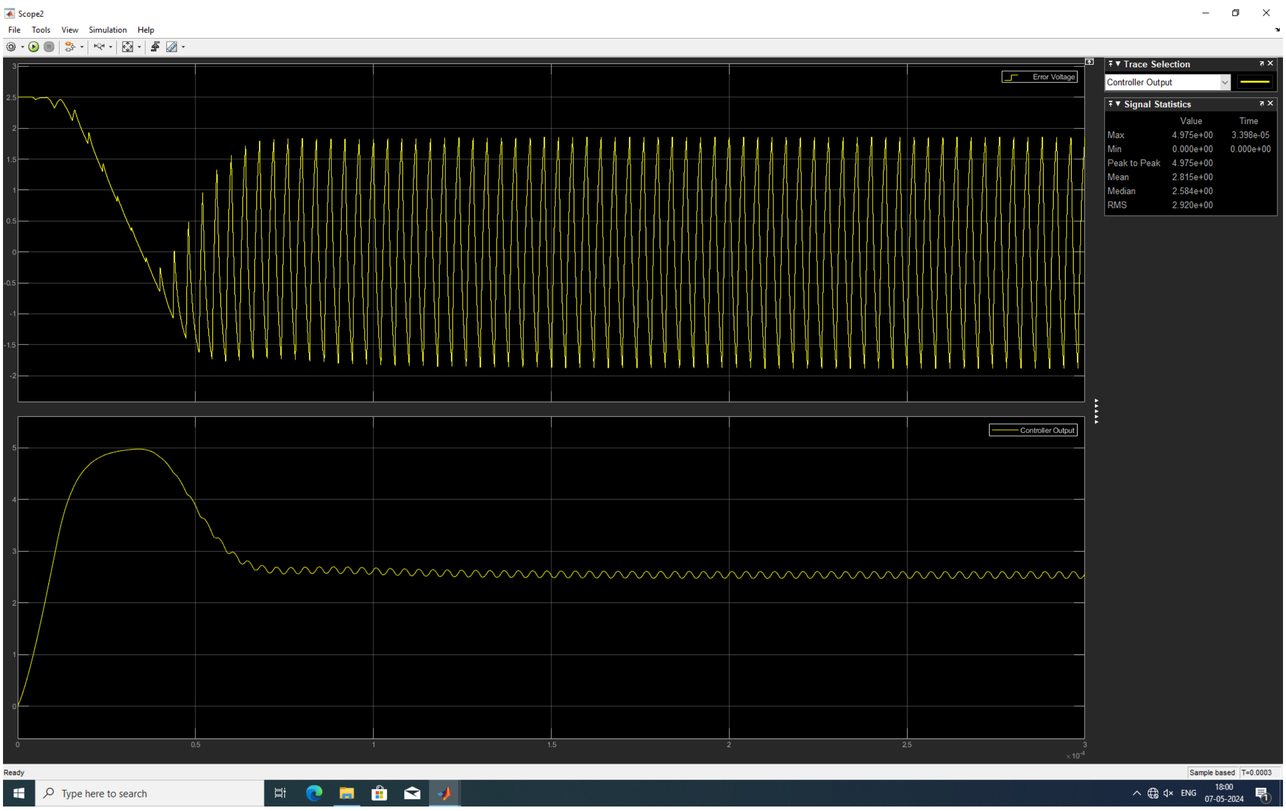

Figure 19: Waveform of error voltage and controller output for the bidirectional flyback converter when $I_{ref} = -0.1A$

2.2 Results of the simulation for two switch flyback converter:

2.2.1 Schematic for the circuit designed in Simulink is:

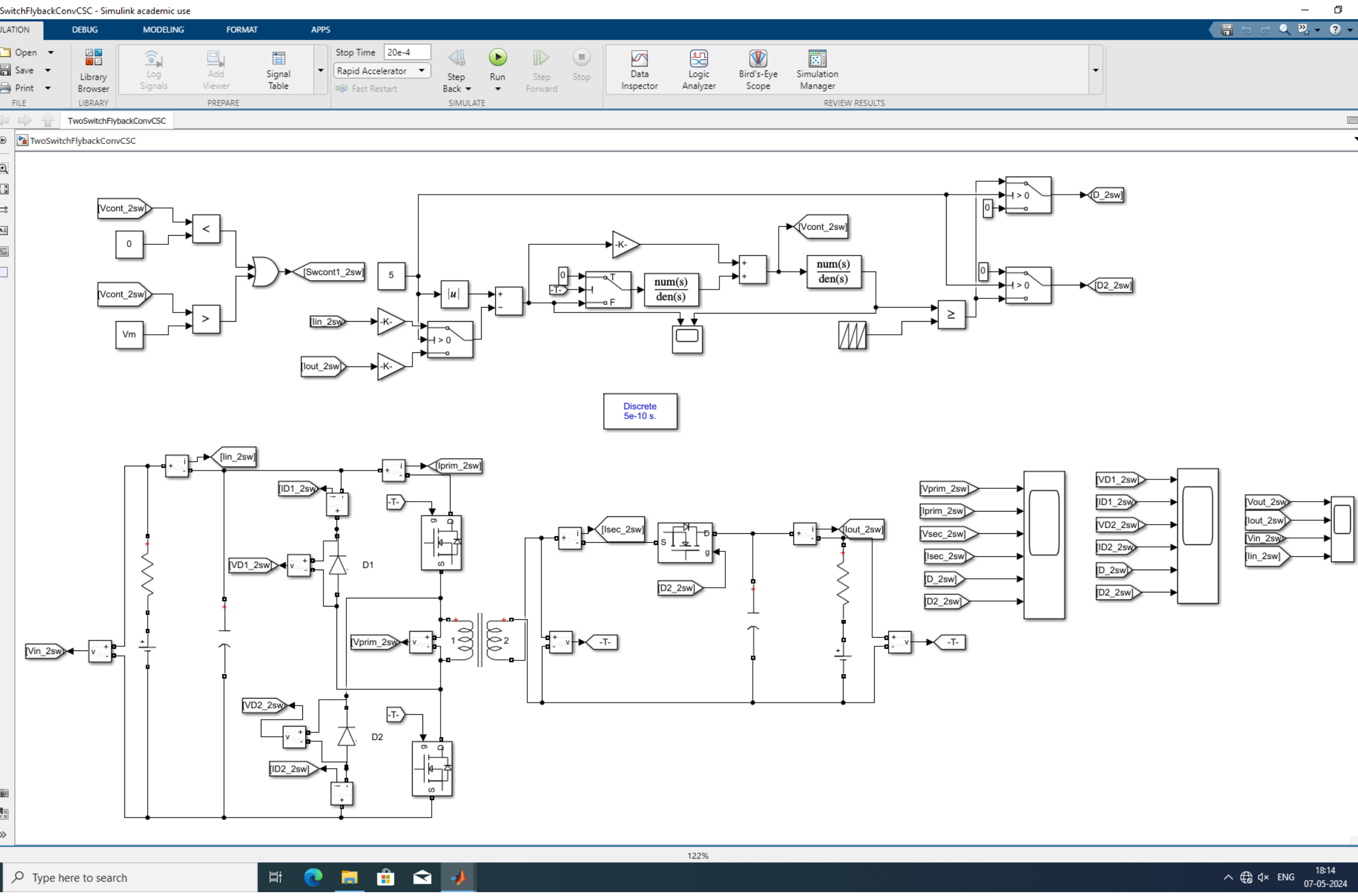

Figure 20: Schematic of the two switch bidirectional flyback converter

The schematic shown in figure 20 was used for the simulation purposes. The component values were derived from the MATLAB workspace using a script which has been attached in the appendix A of the report.
All the relevant waveforms have been attached in later pages to show the bidirectional flow of power and proper implementation of the scheme discussed in Section 1.3.

2.2.2 Waveform for converter when input current reference is 0.1A

Figure 21: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$

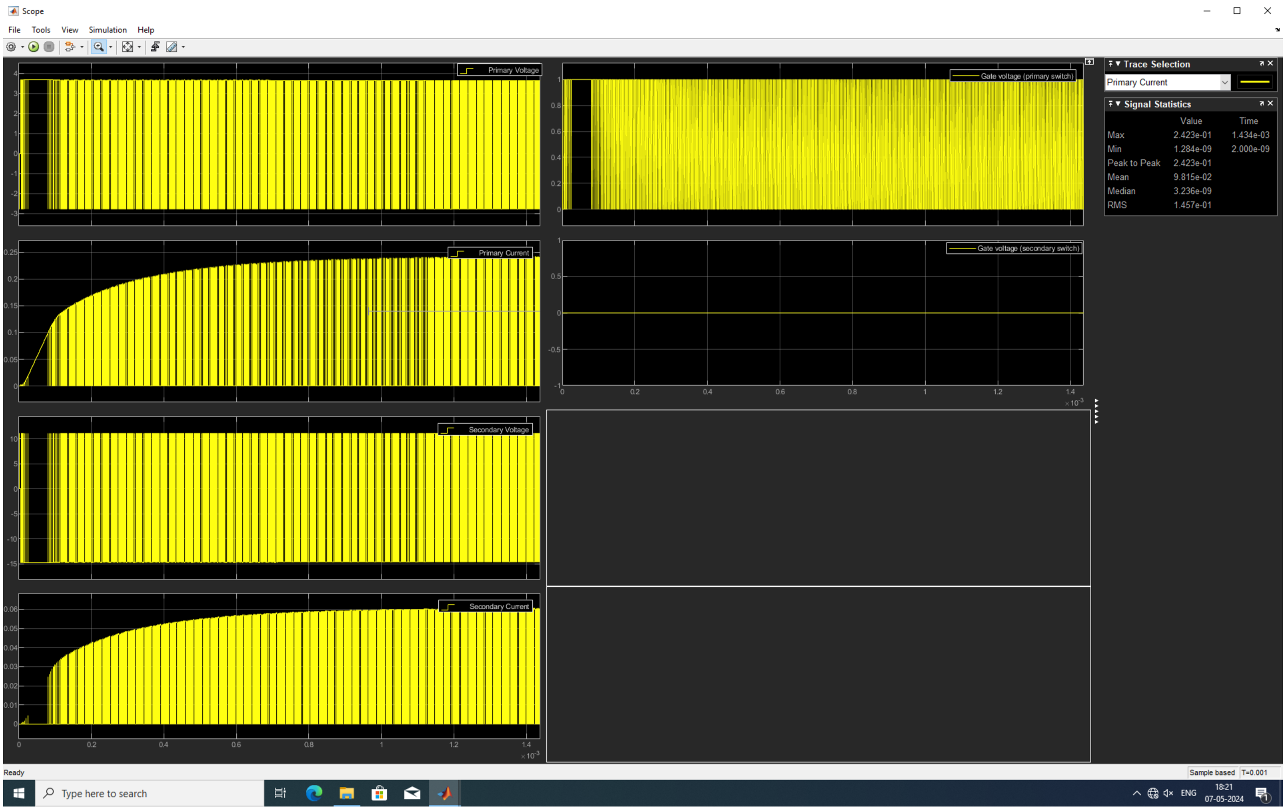

Figure 22: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$

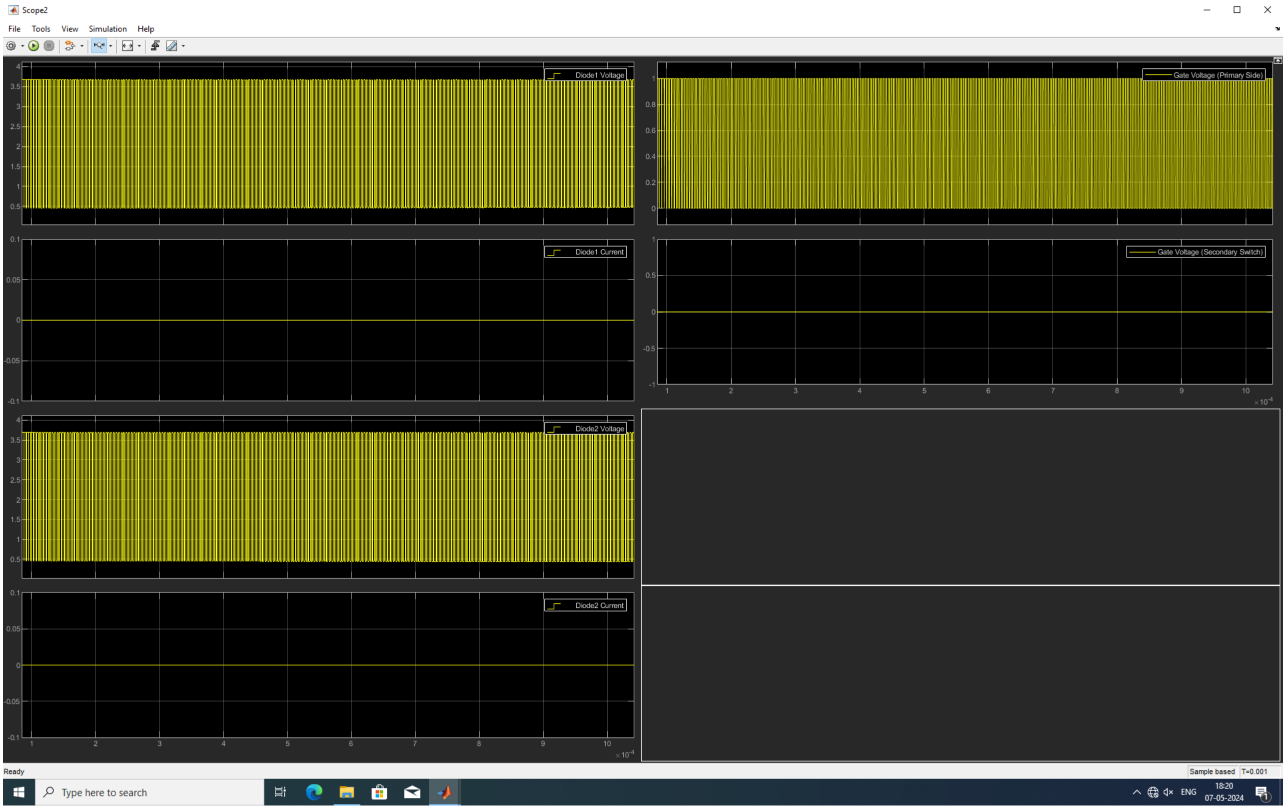

Figure 23: Waveform of diode (D1 and D2) voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$

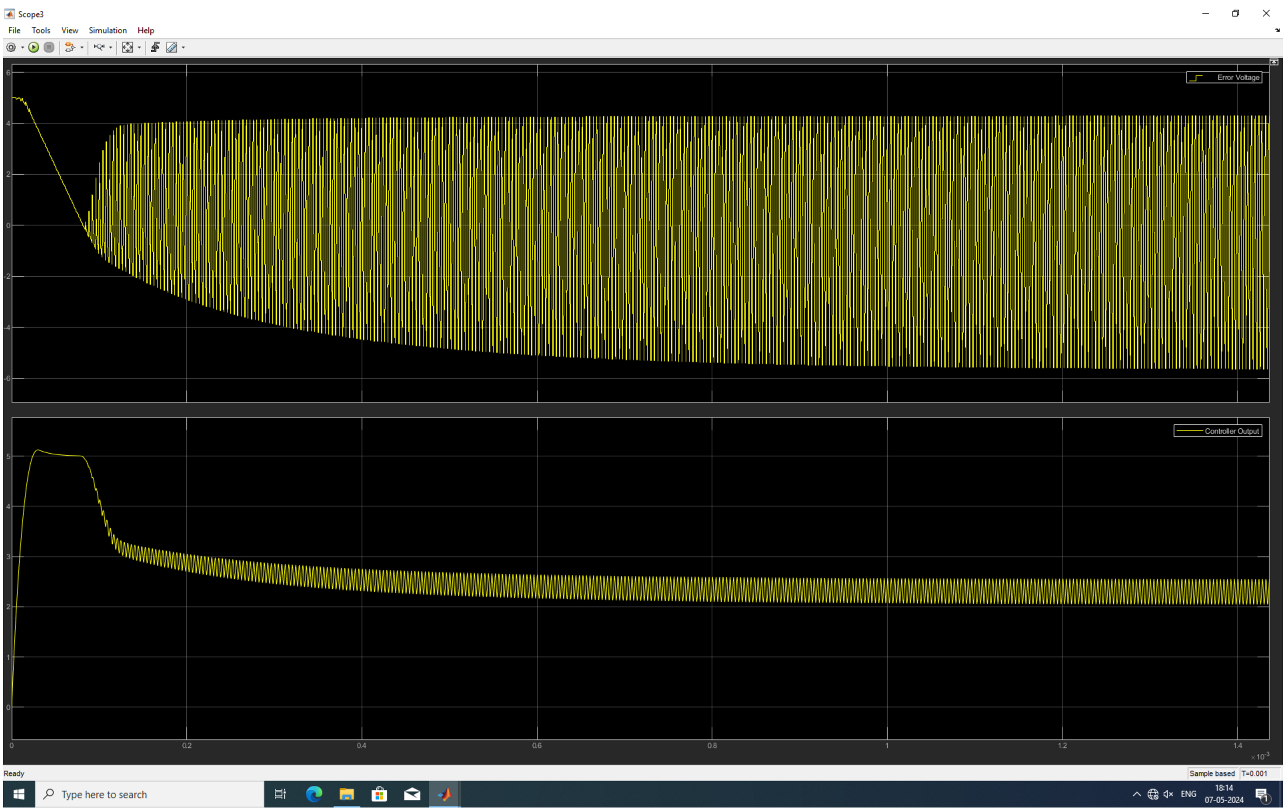

Figure 24: Waveform of error voltage and controller output for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$

2.2.3 Waveform for converter when input current reference is -0.1A

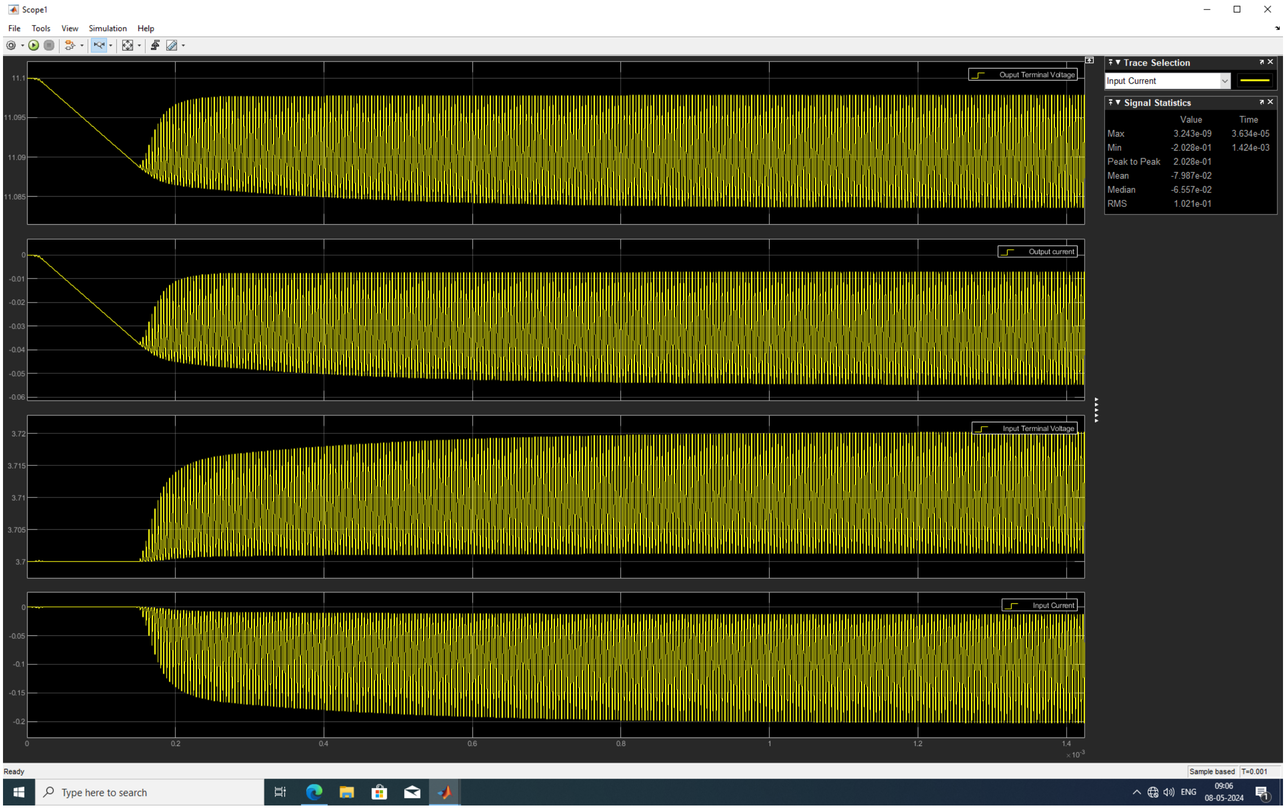

Figure 25: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$

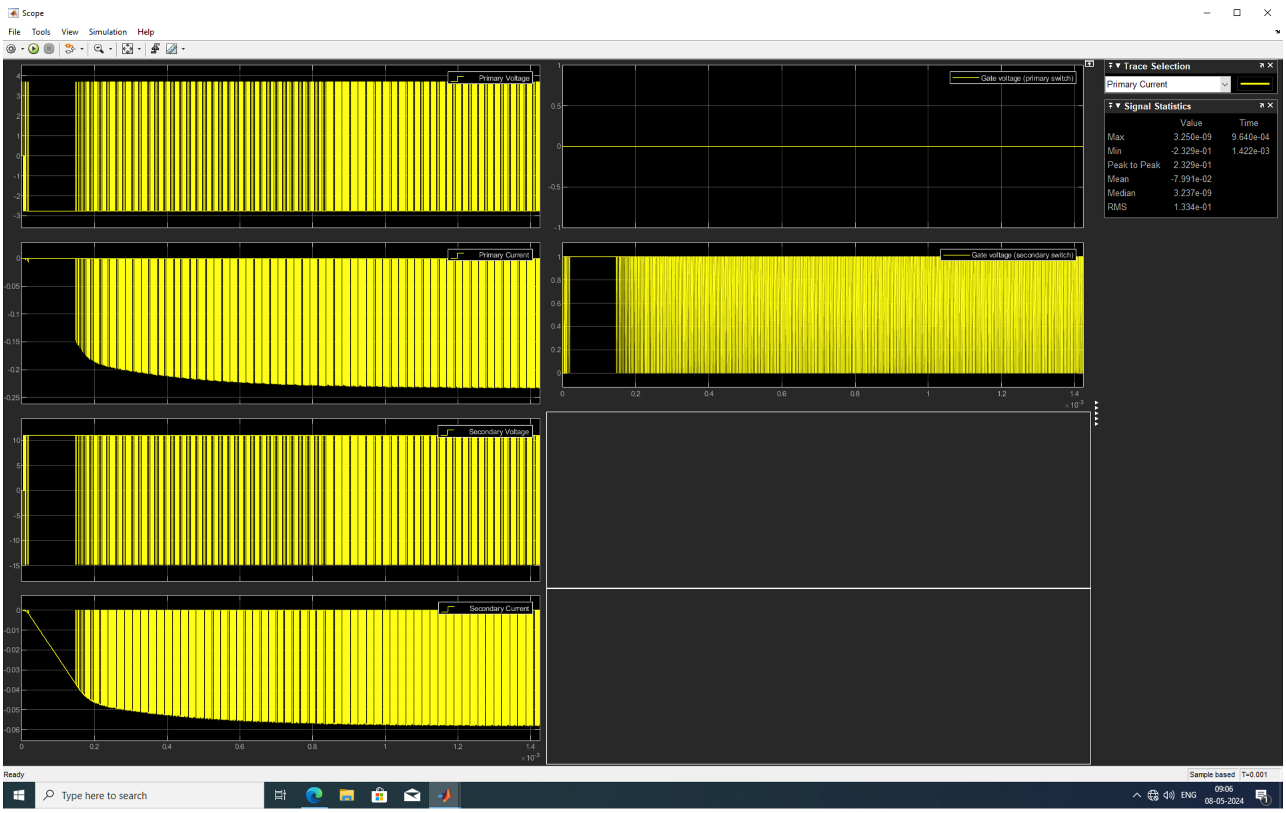

Figure 26: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$

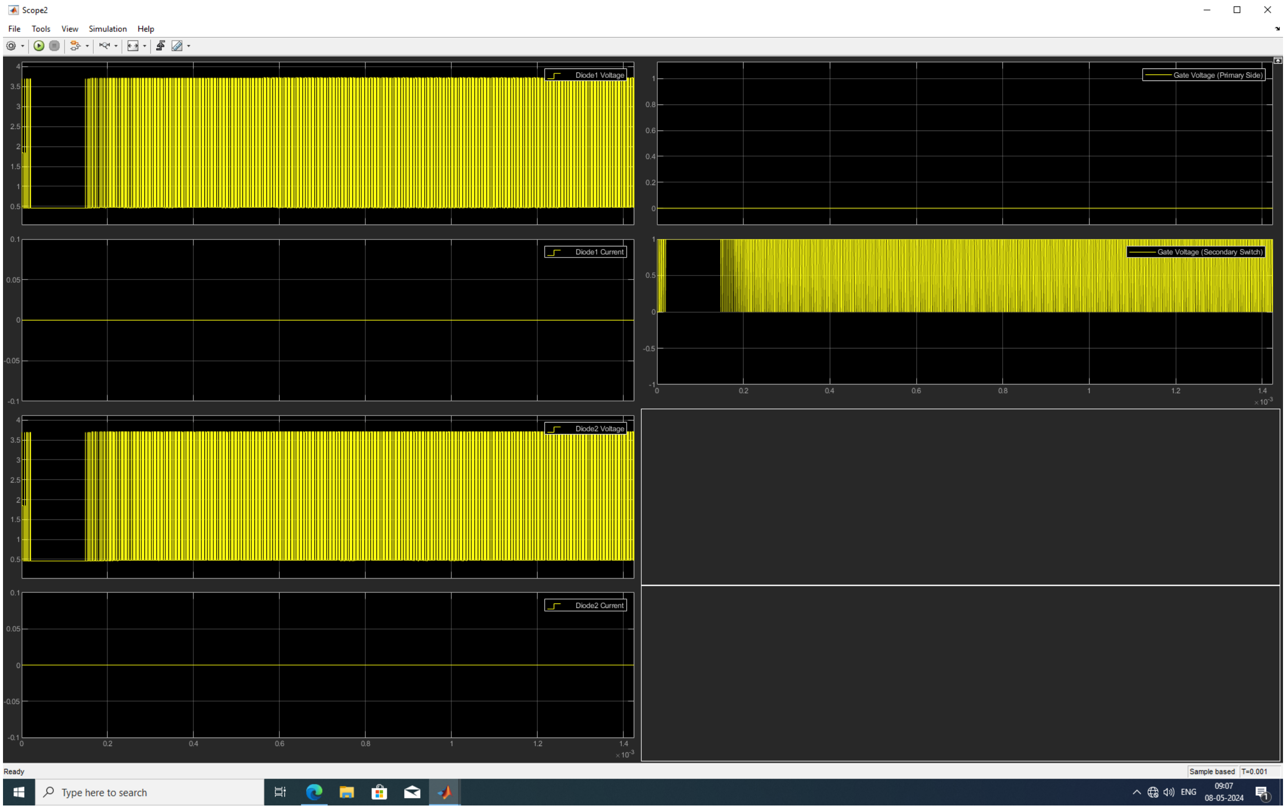

Figure 27: Waveform of diode (D1 and D2) voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$

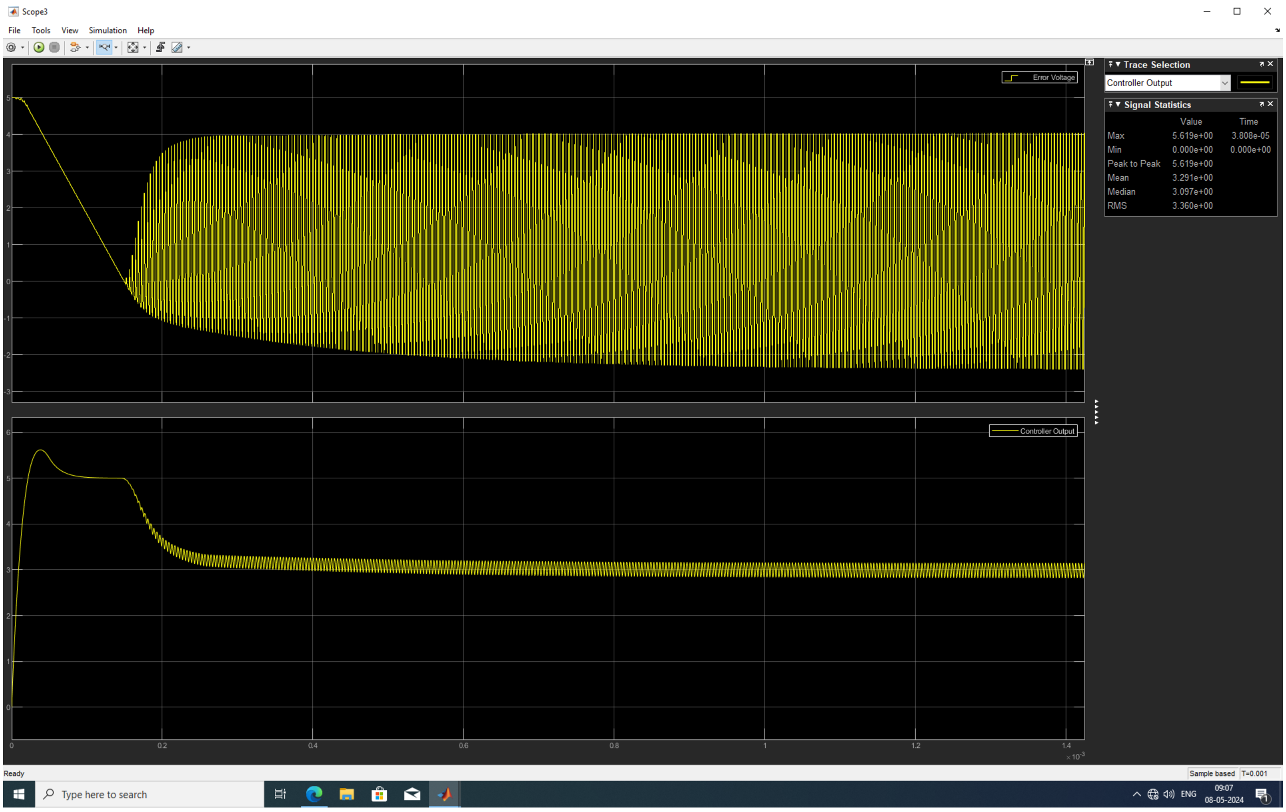

Figure 28: Waveform of error voltage and controller output for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$

2.3 Result of the simulation when 3 bidirectional flyback converters are connected to the 3 cells of 3s1p battery pack

2.3.1 Schematic for the circuit designed in Simulink is:

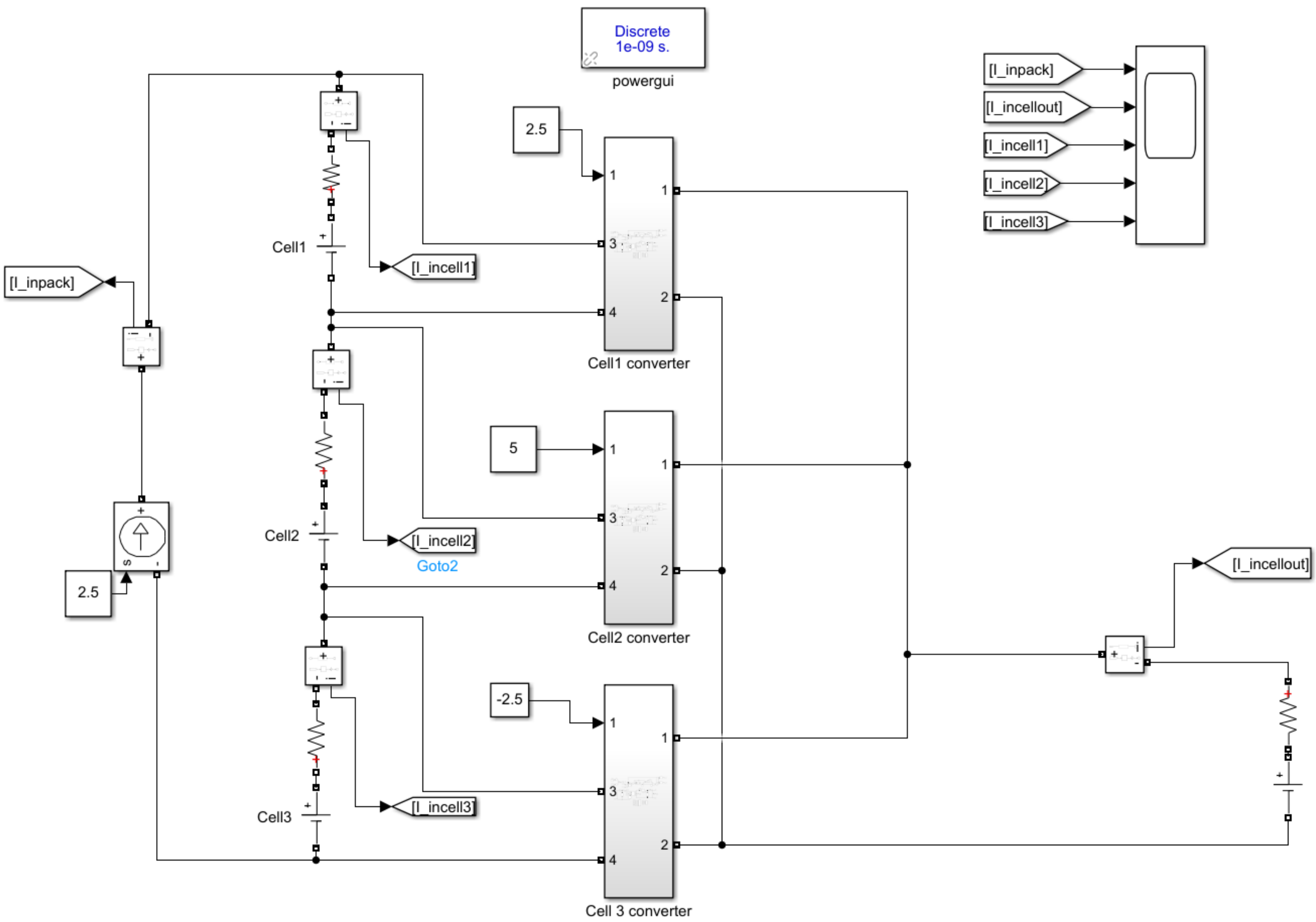

Figure 29: Schematic of the 3s1p battery pack connected to 3 flyback converters

The schematic shown in figure 29 was used for the simulation purposes. The component values were derived from the MATLAB workspace using a script which has been attached in the appendix A of the report.
The current reference has been set to $0.1A, 0.2A, -0.1A$ for the cell1,cell2 and cell3 respectively.
From here, we will refer 'Converter connected to cell **i**' as '**cell i converter**'.
All the relevant waveforms have been attached in later pages to show the working of converters when attached to a battery pack.

2.3.2 Waveform when only 3 flyback converter is connected to the battery pack

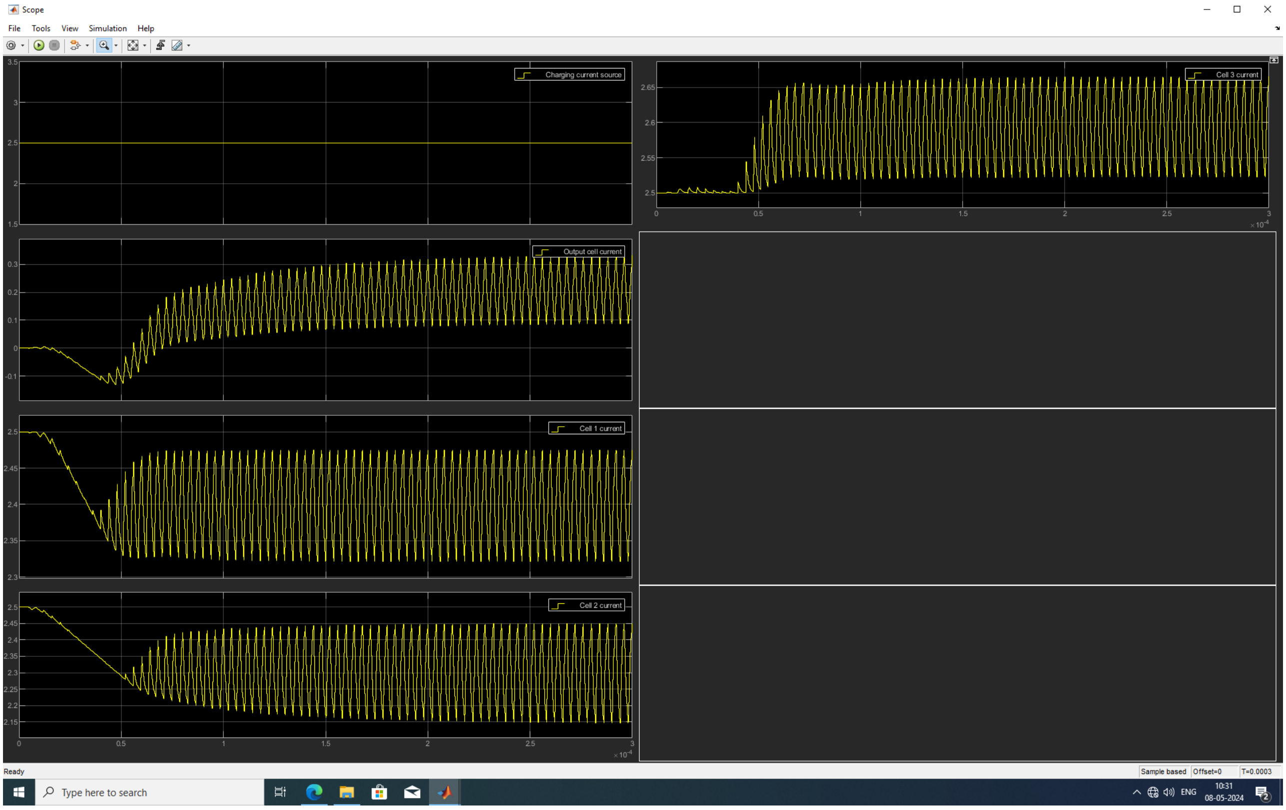

Figure 30: Waveform of current from charging current source, output cell current, cell1 current, cell2 current, cell3 current for the battery pack when 3 flyback converters are used

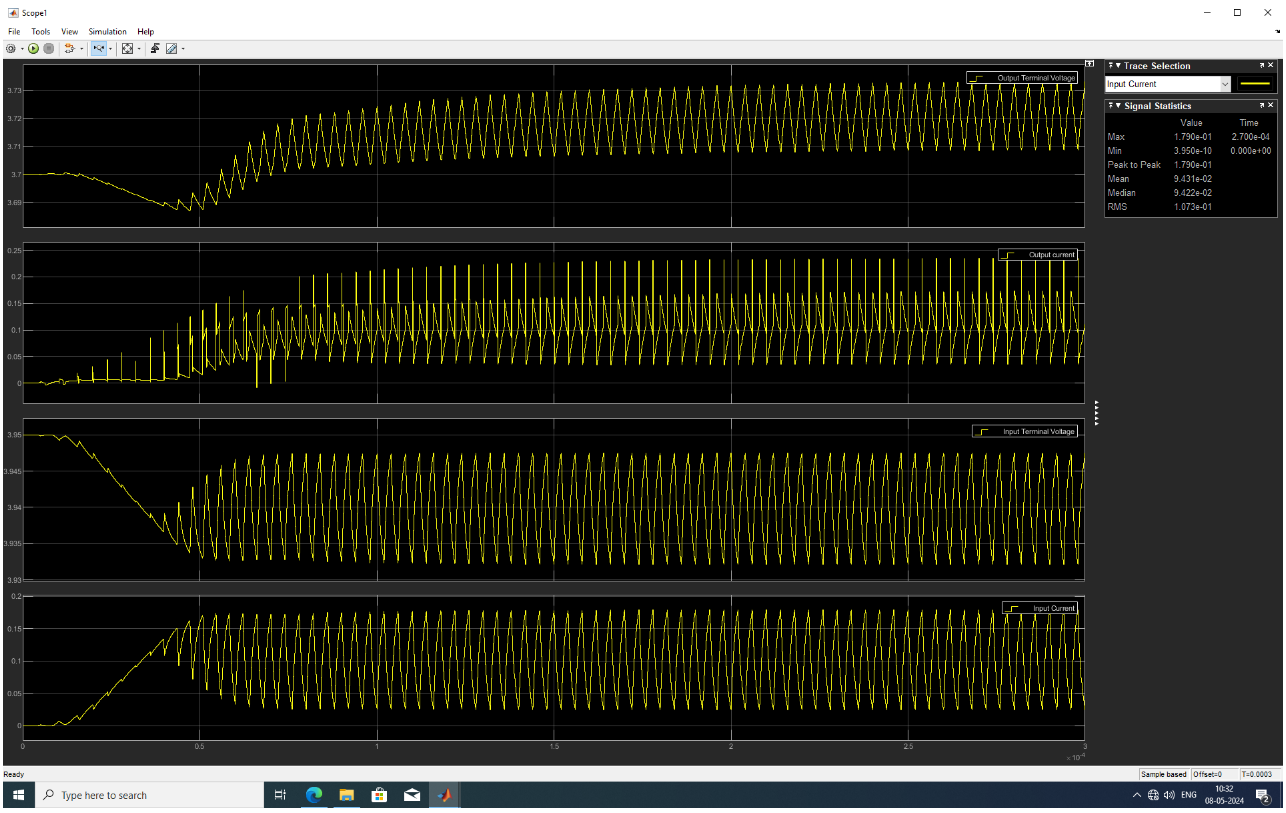

Figure 31: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 1 converter with $I_{ref} = 0.1A$

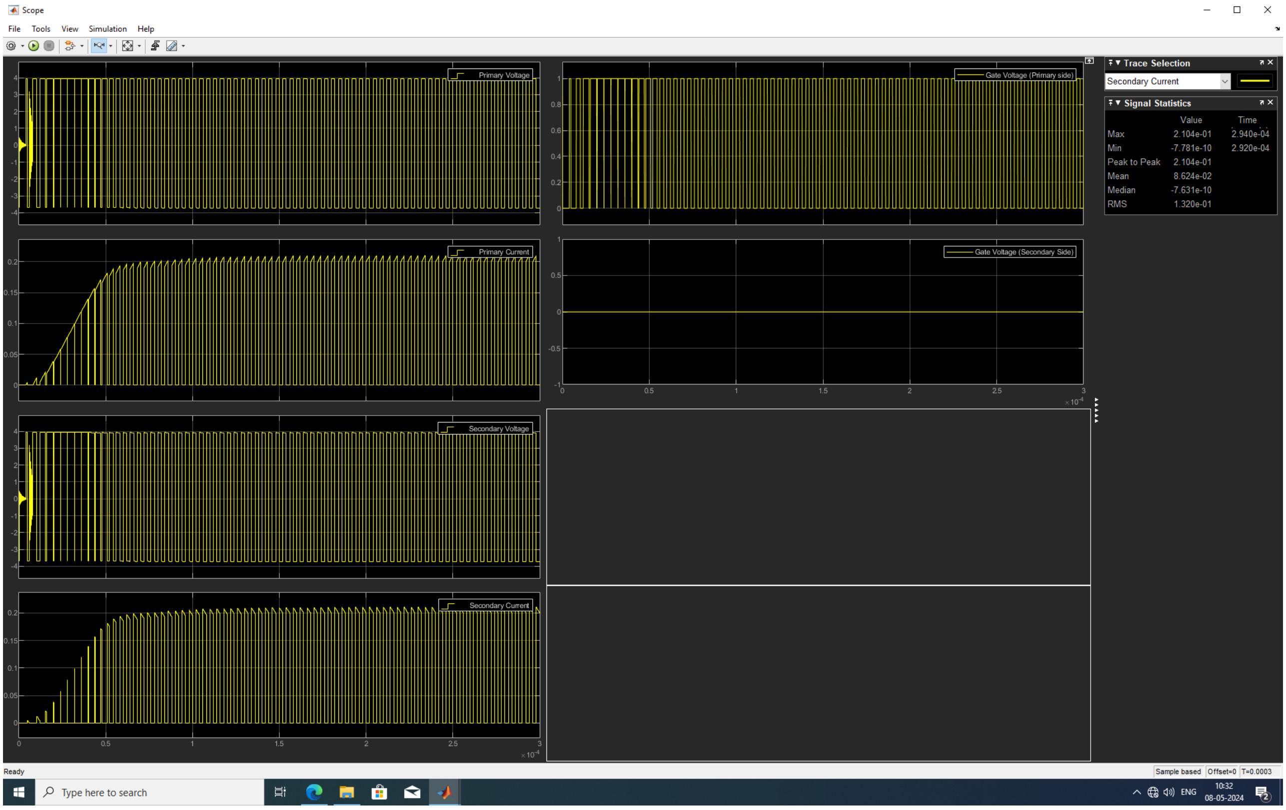

Figure 32: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 1 converter with $I_{ref} = 0.1A$

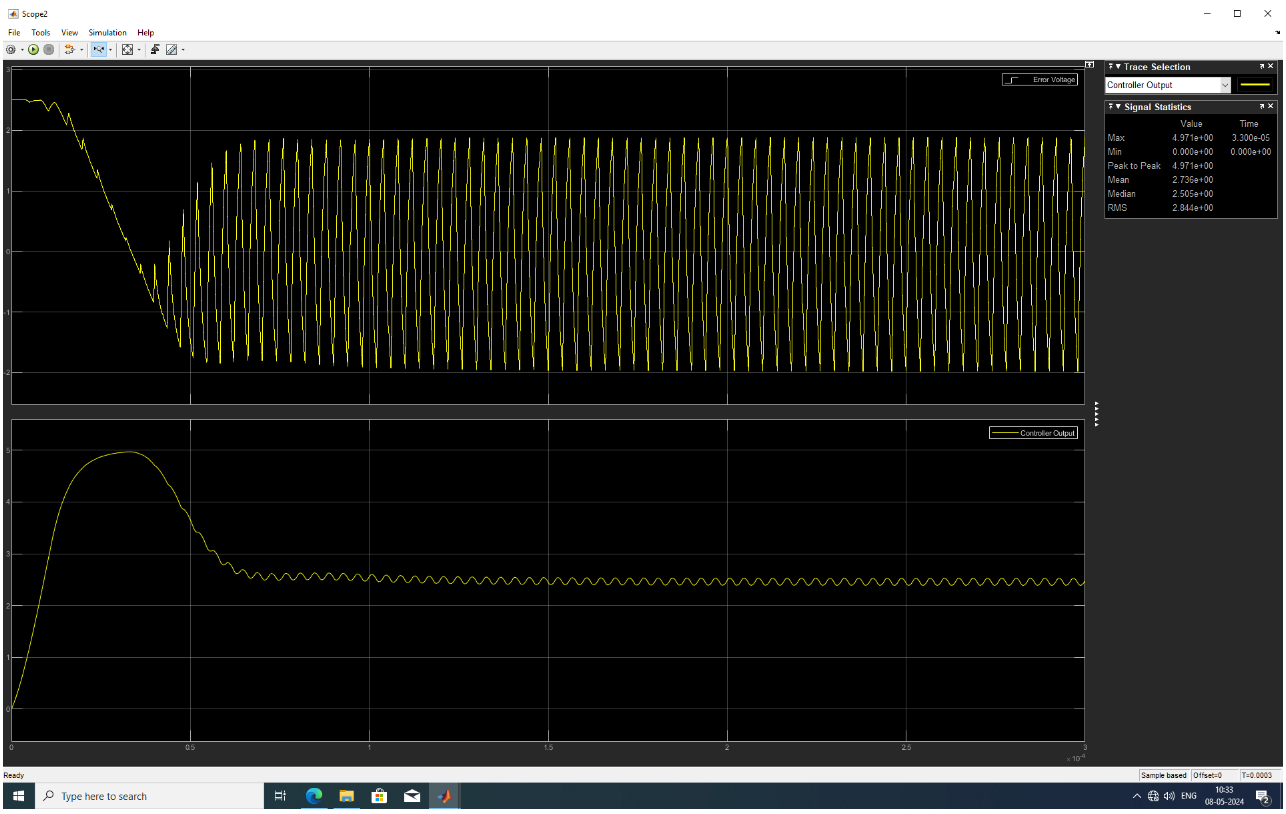

Figure 33: Waveform of error voltage and controller output for the cell 1 converter with $I_{ref} = 0.1A$

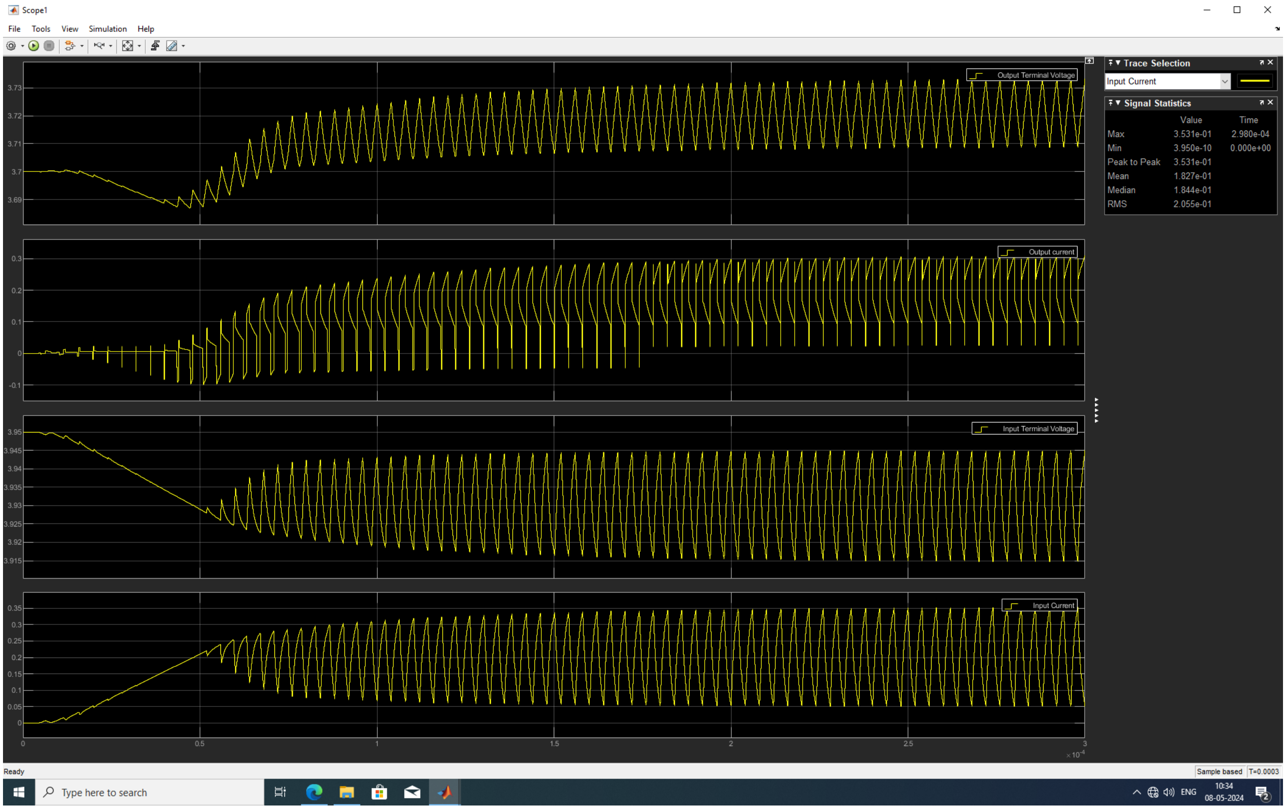

Figure 34: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 2 converter with $I_{ref} = 0.2A$

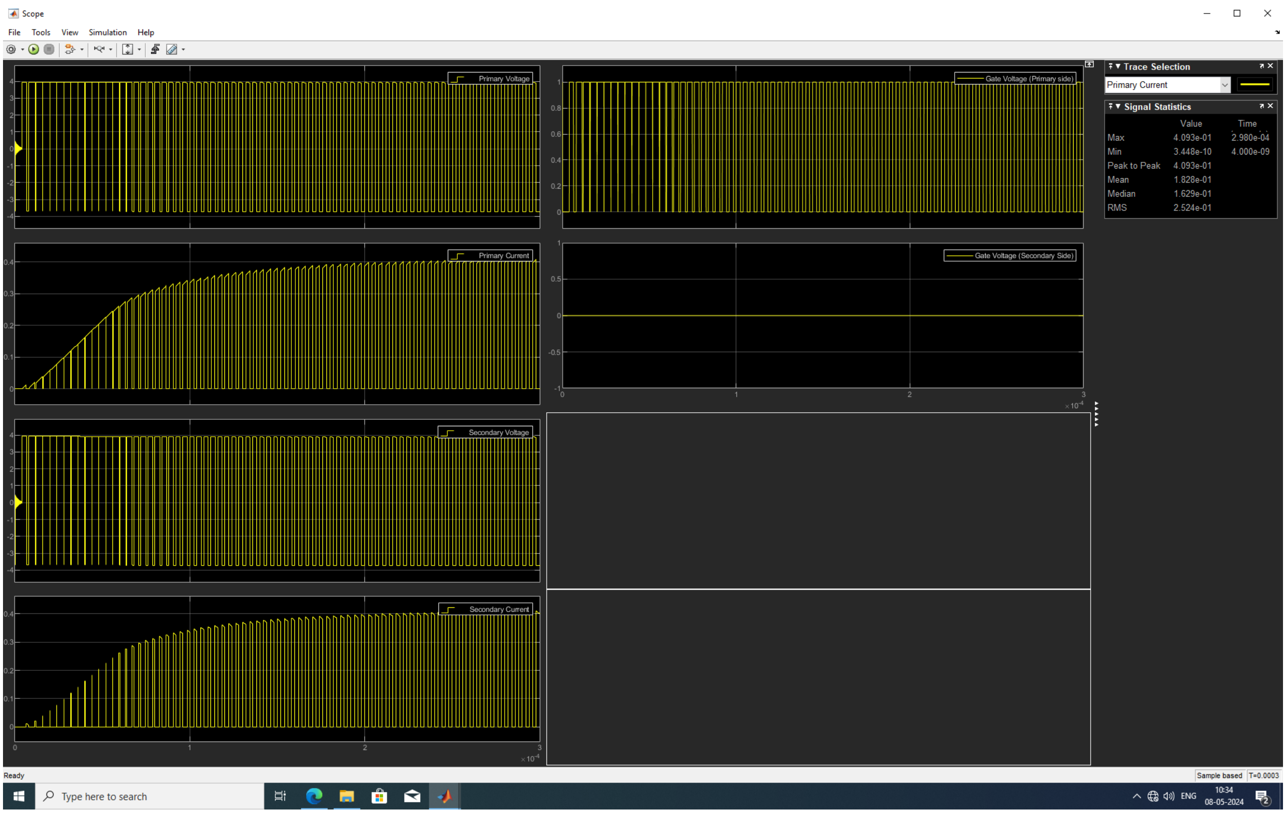

Figure 35: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 2 converter with $I_{ref} = 0.2A$

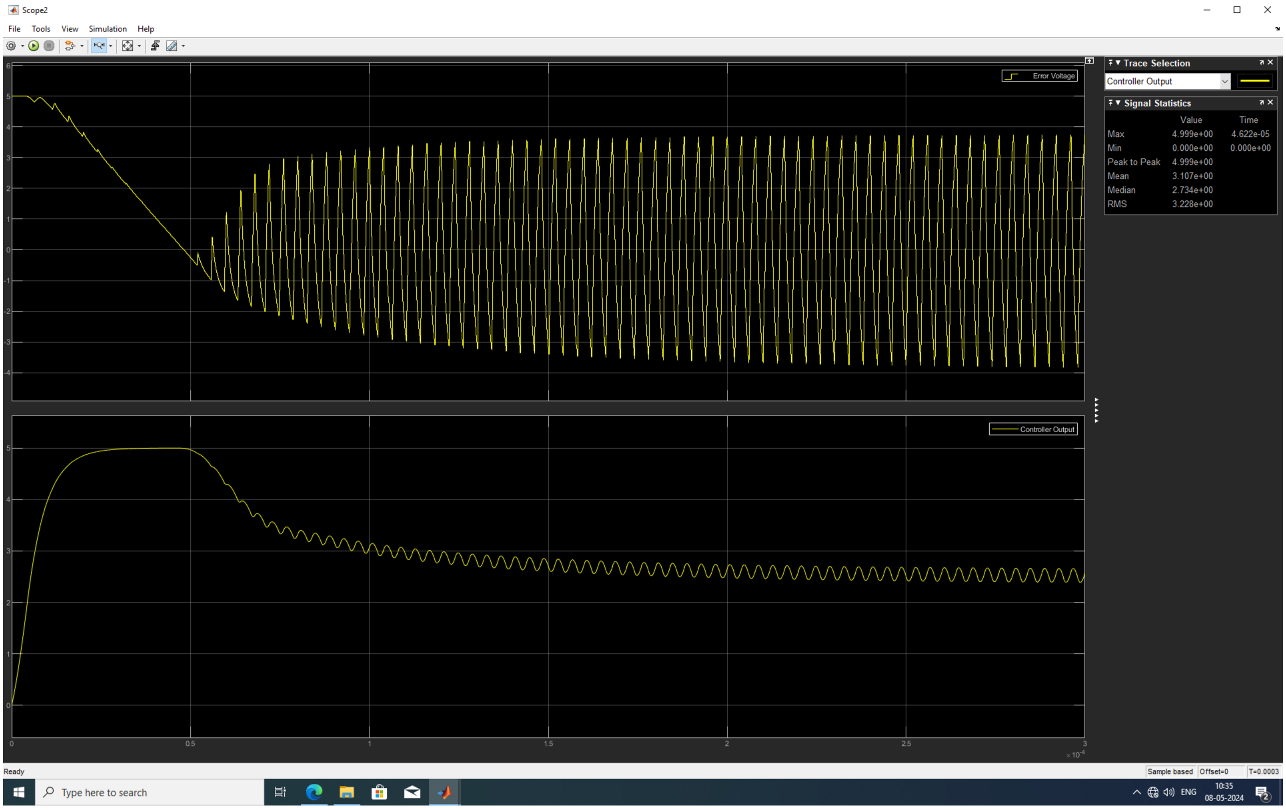

Figure 36: Waveform of error voltage and controller output for the cell 2 converter with $I_{ref} = 0.2A$

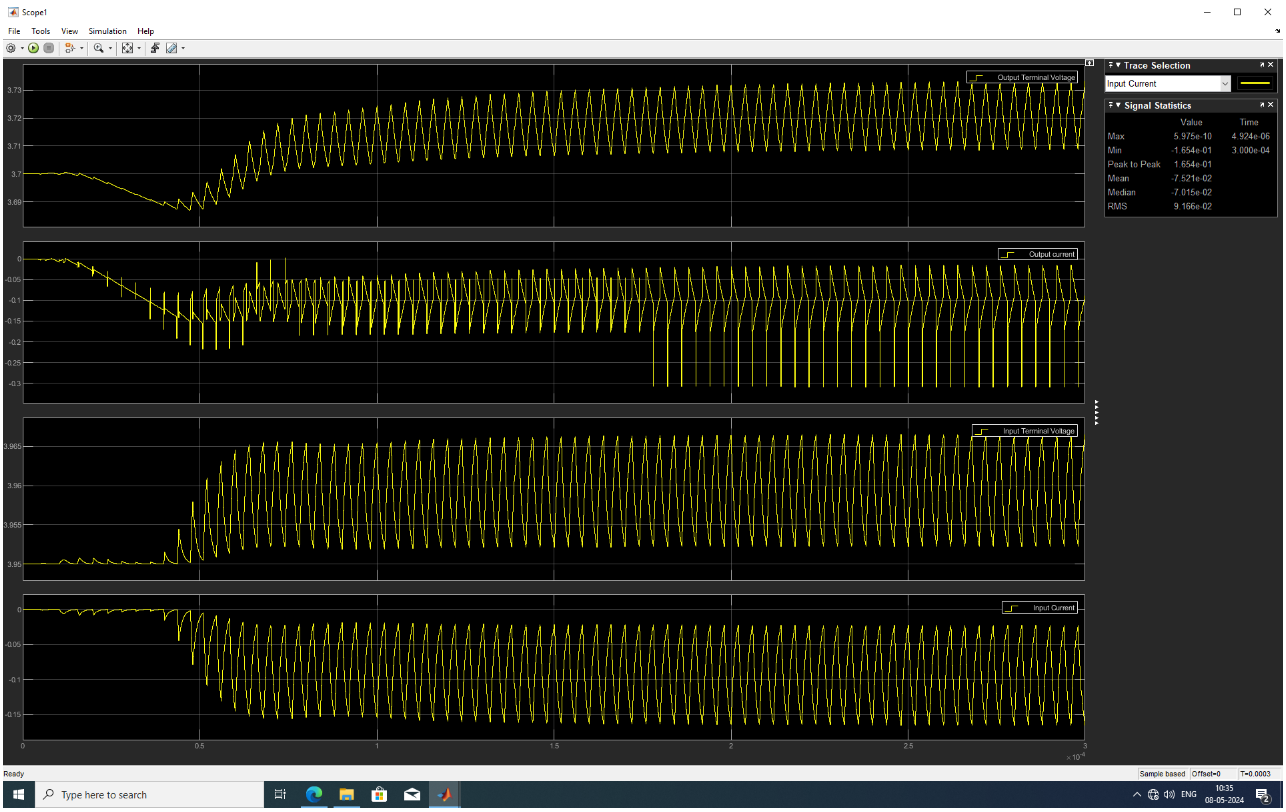

Figure 37: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 3 converter with $I_{ref} = -0.1A$

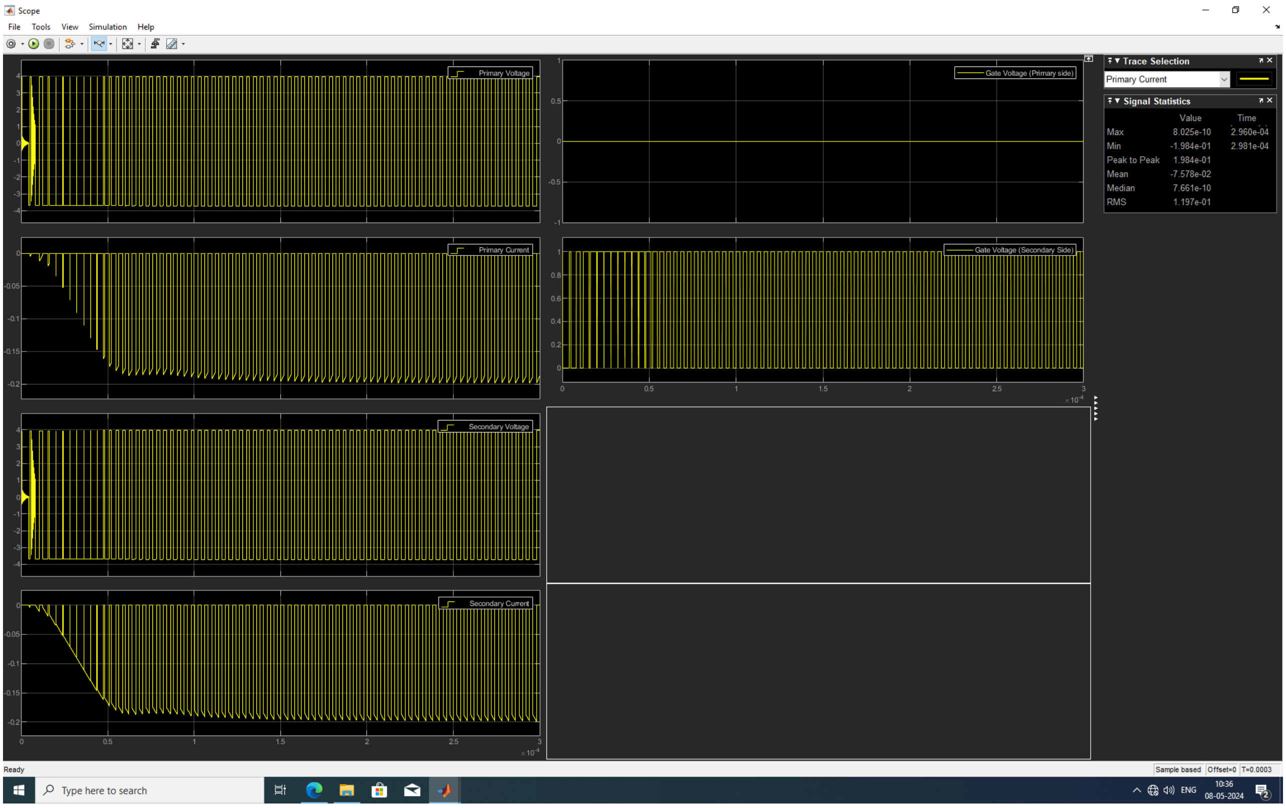

Figure 38: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 3 converter with $I_{ref} = -0.1A$

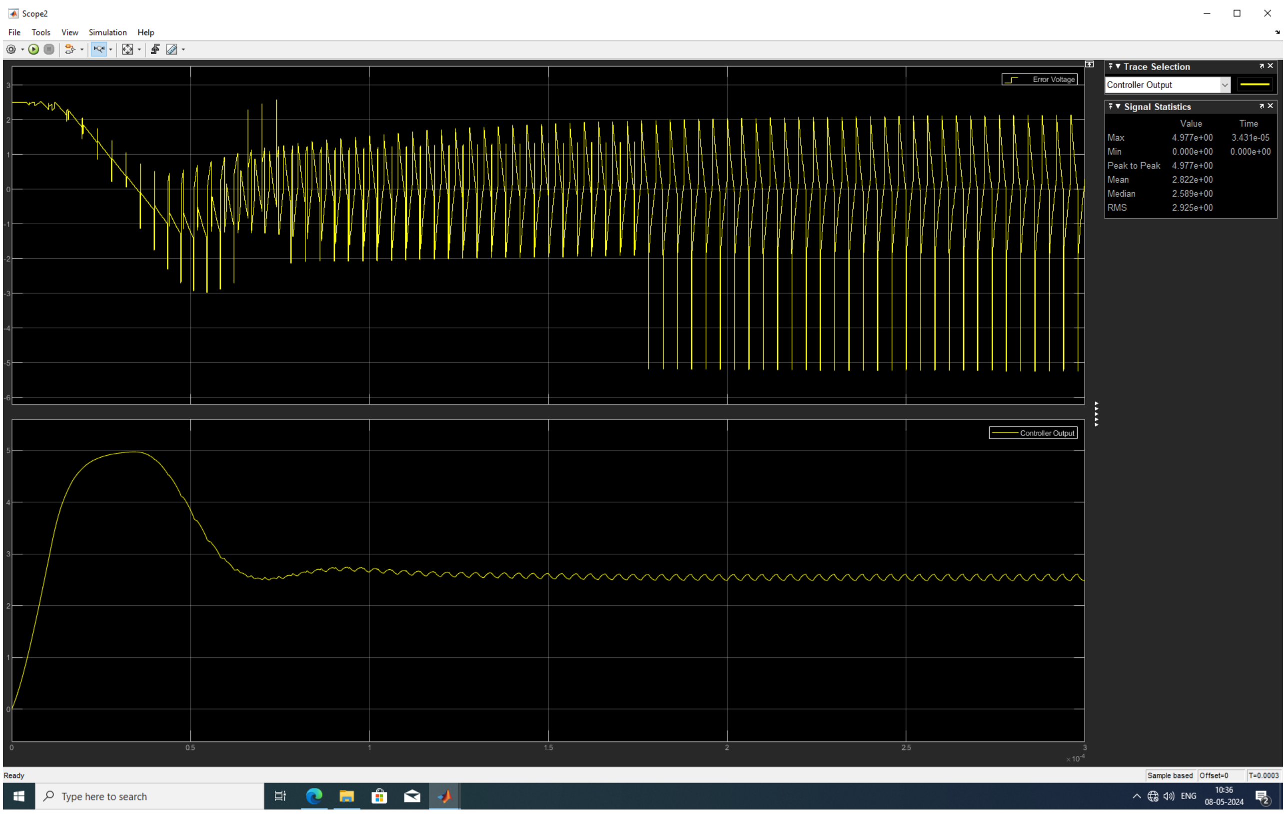

Figure 39: Waveform of error voltage and controller output for the cell 3 converter with $I_{ref} = -0.1A$

2.4 Result of the simulation when 3 bidirectional flyback converters and 1 two-switch bidirectional flyback converter are connected (as specified) to the 3 cells of 3s1p battery pack

2.4.1 Schematic for the circuit designed in Simulink is:

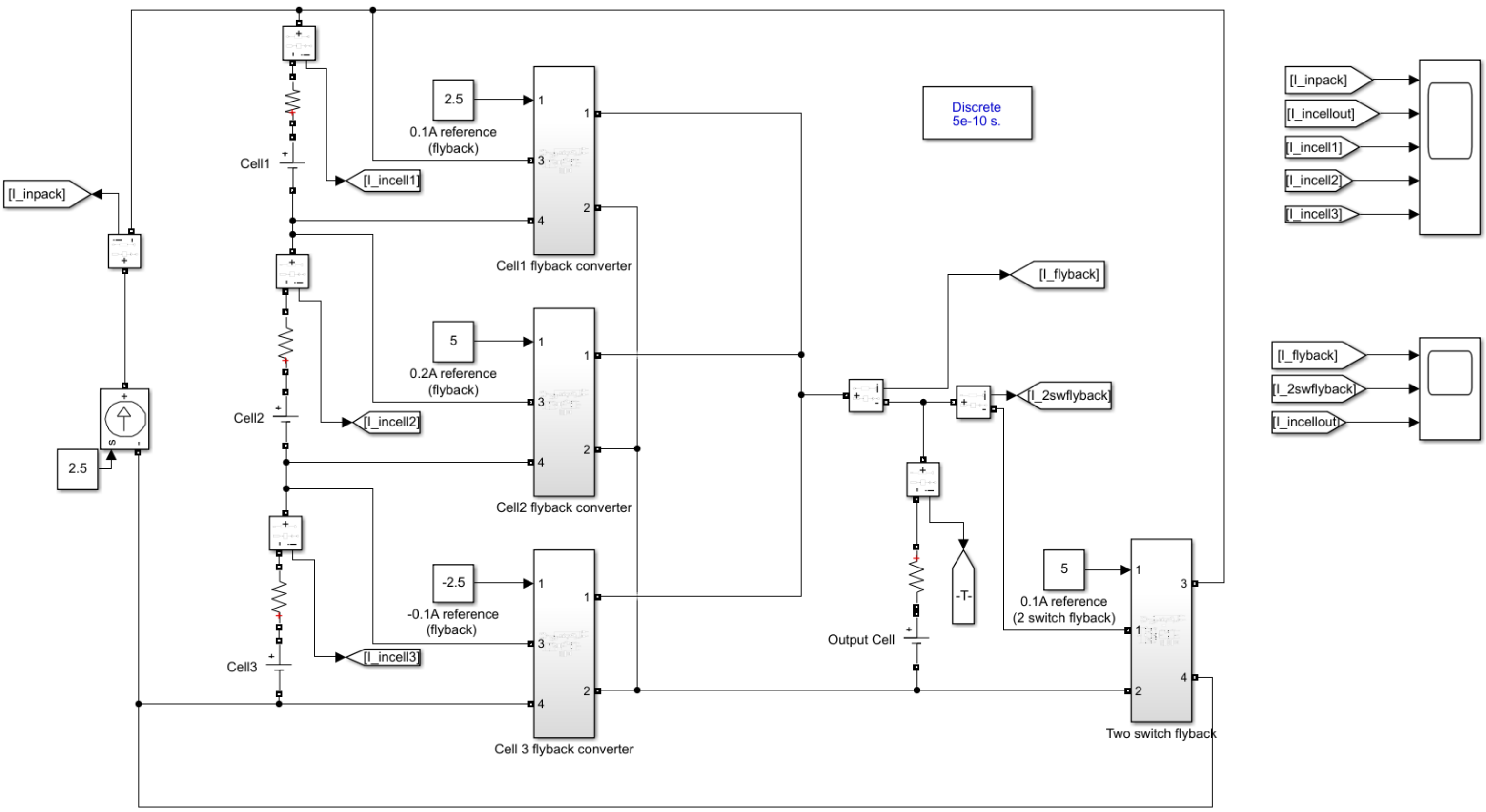

Figure 40: Schematic of the 3s1p battery pack connected to 3 flyback converters and a two-switch bi directional flyback converter

The schematic shown in figure 40 was used for the simulation purposes. The component values were derived from the MATLAB workspace using a script which has been attached in the appendix A of the report.
The current reference for flyback converters has been set to $0.1A, 0.2A, -0.1A$ for the cell1,cell2 and cell3 respectively and $0.1A/-0.1A$ for the two switch flyback converter connected to output cell.
All the relevant waveforms have been attached in later pages to show the working of all converters when attached to a battery pack. **NOTE: The references for the 3 flyback converters that were present earlier are kept same.**

2.4.2 Waveform when 3 flyback converter and a two switch flyback converter is connected to the battery pack and $I_{ref} = 0.1A$ for the two switch flyback converter

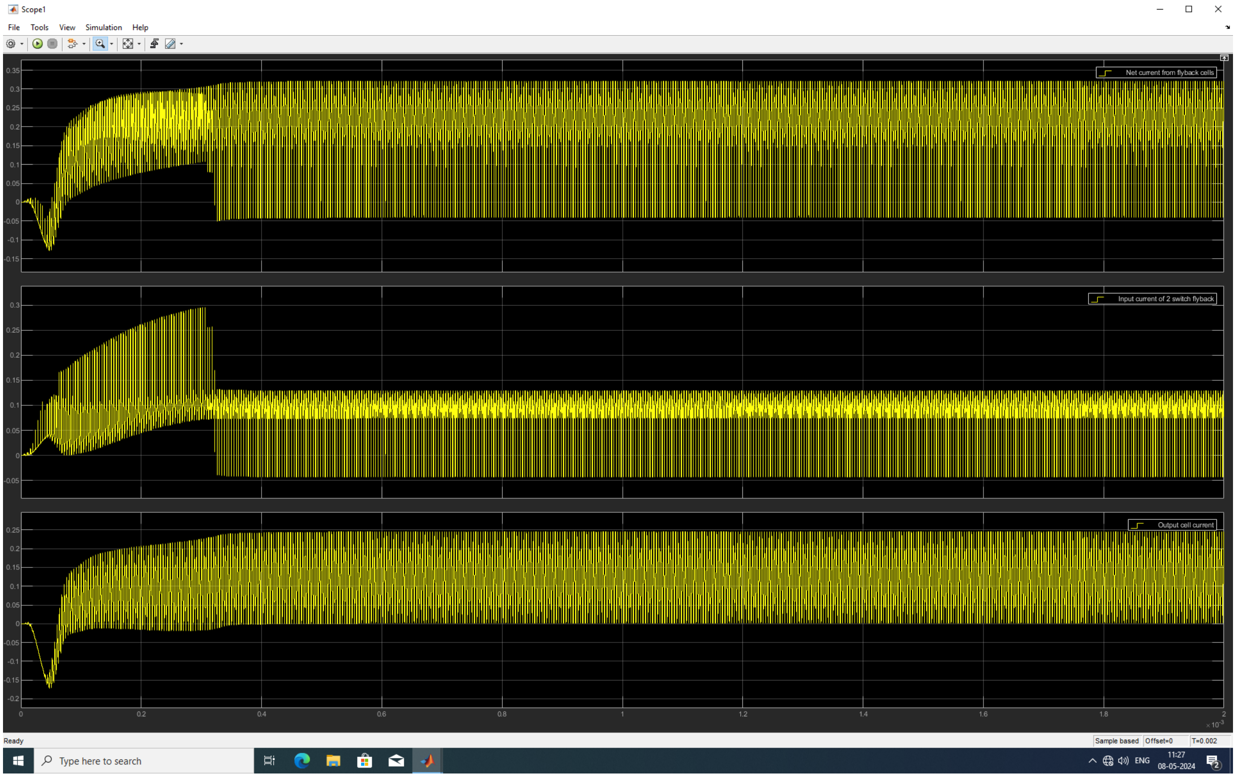

Figure 41: Waveform of net current from flyback,input current of two switch flyback , output cell current for the battery pack when $I_{ref} = 0.1A$ for the two switch flyback converter

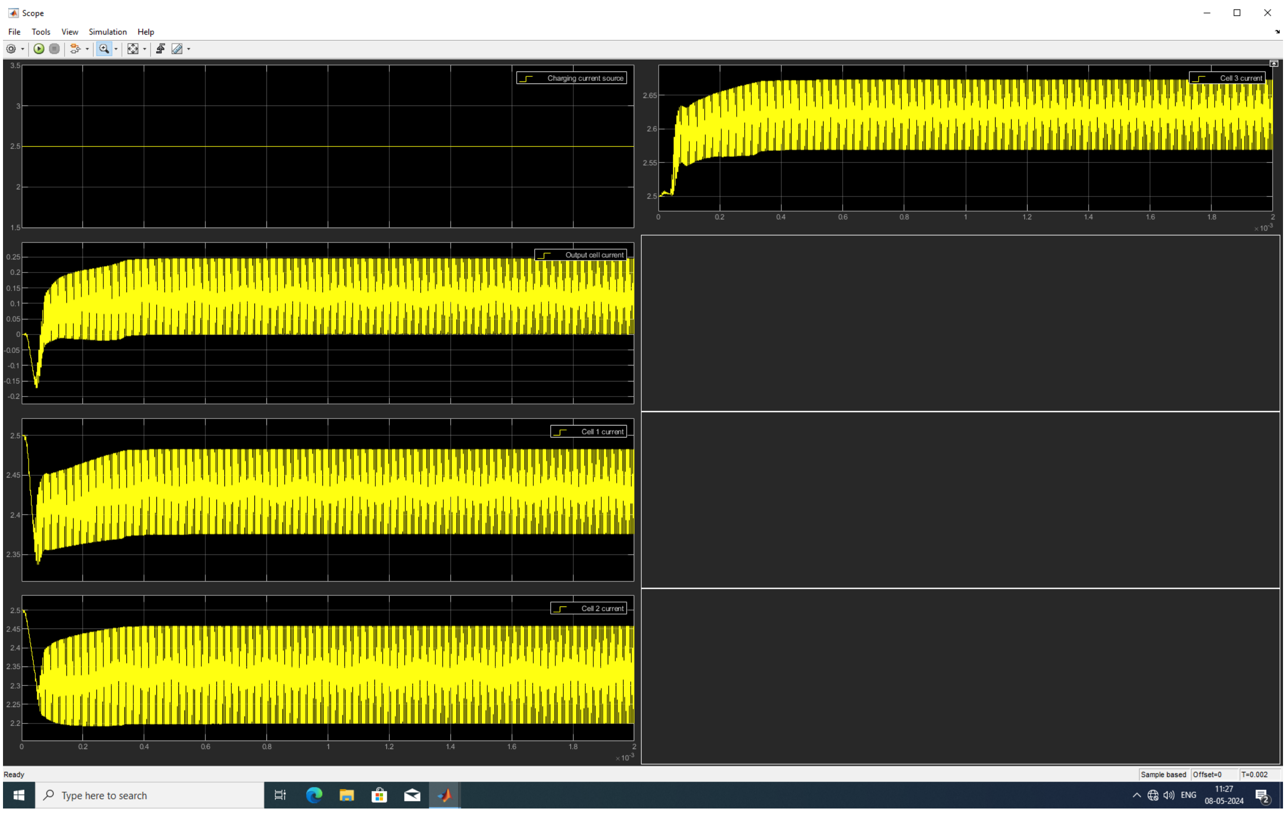

Figure 42: Waveform of current from charging current source, output cell current, cell1 current, cell2 current, cell3 current for the battery pack when $I_{ref} = 0.1A$ for the two switch flyback converter

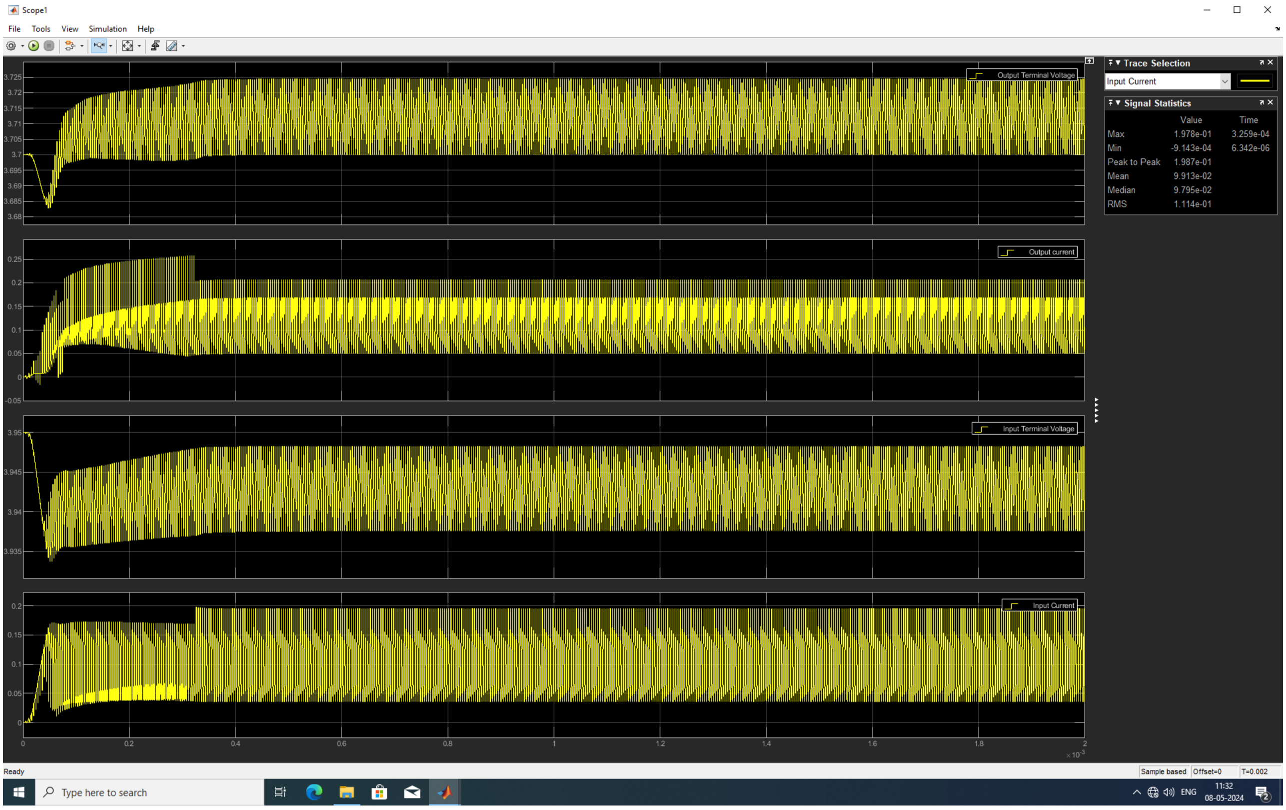

Figure 43: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 1 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

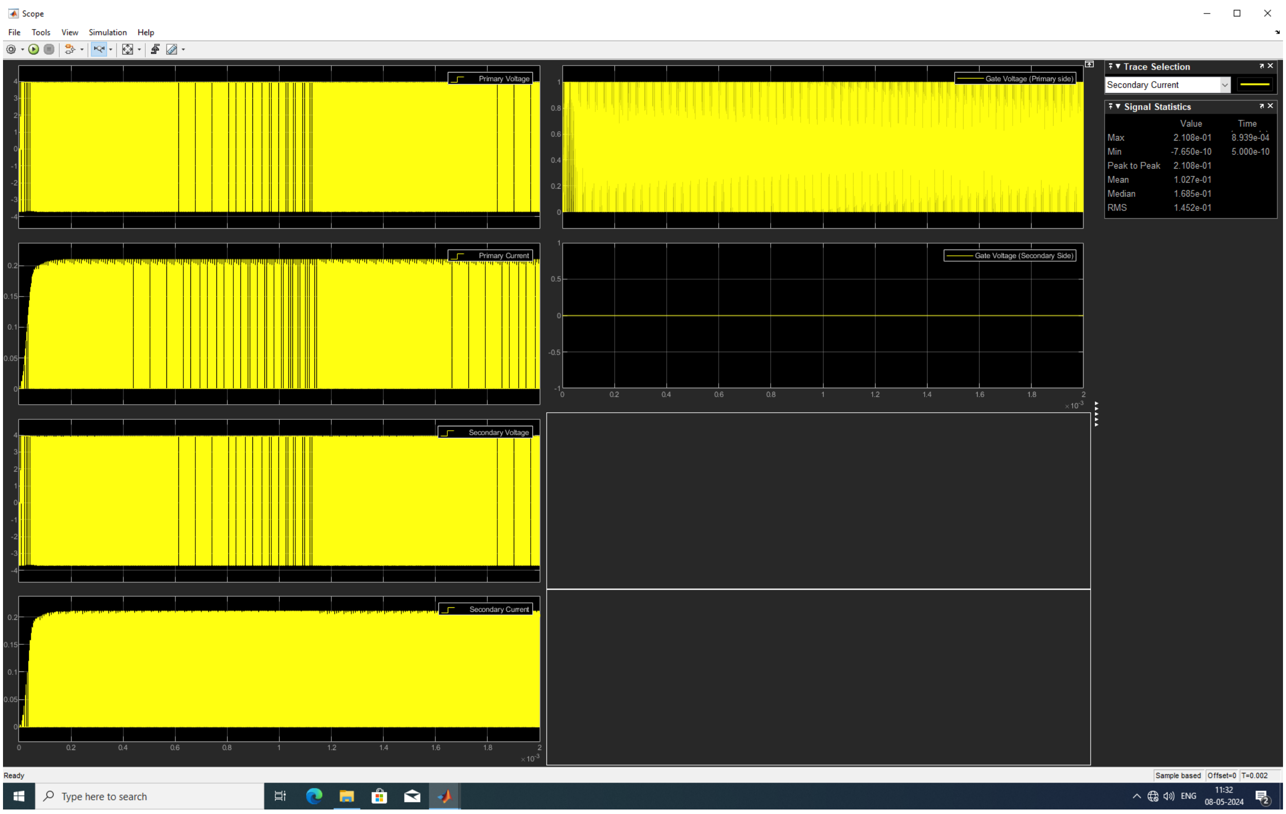

Figure 44: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 1 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

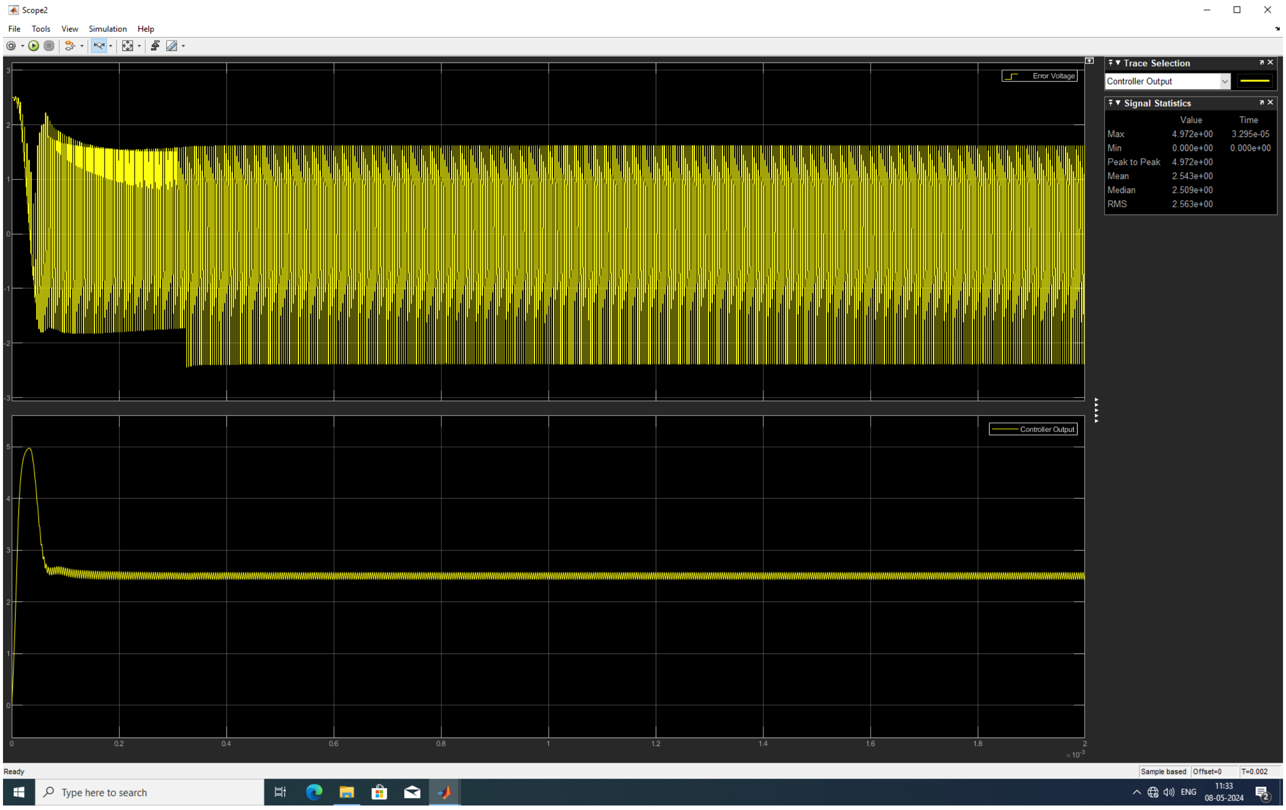

Figure 45: Waveform of error voltage and controller output for the cell 1 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

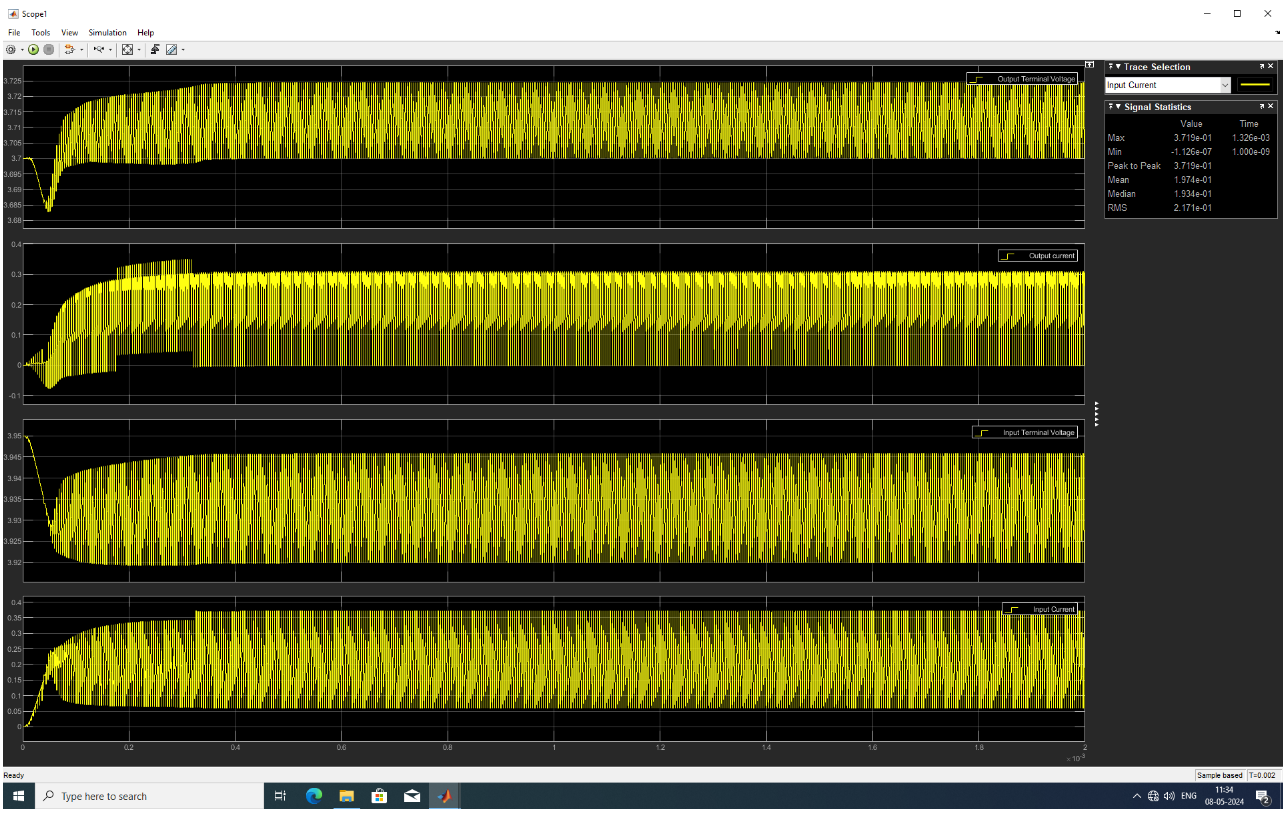

Figure 46: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 2 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

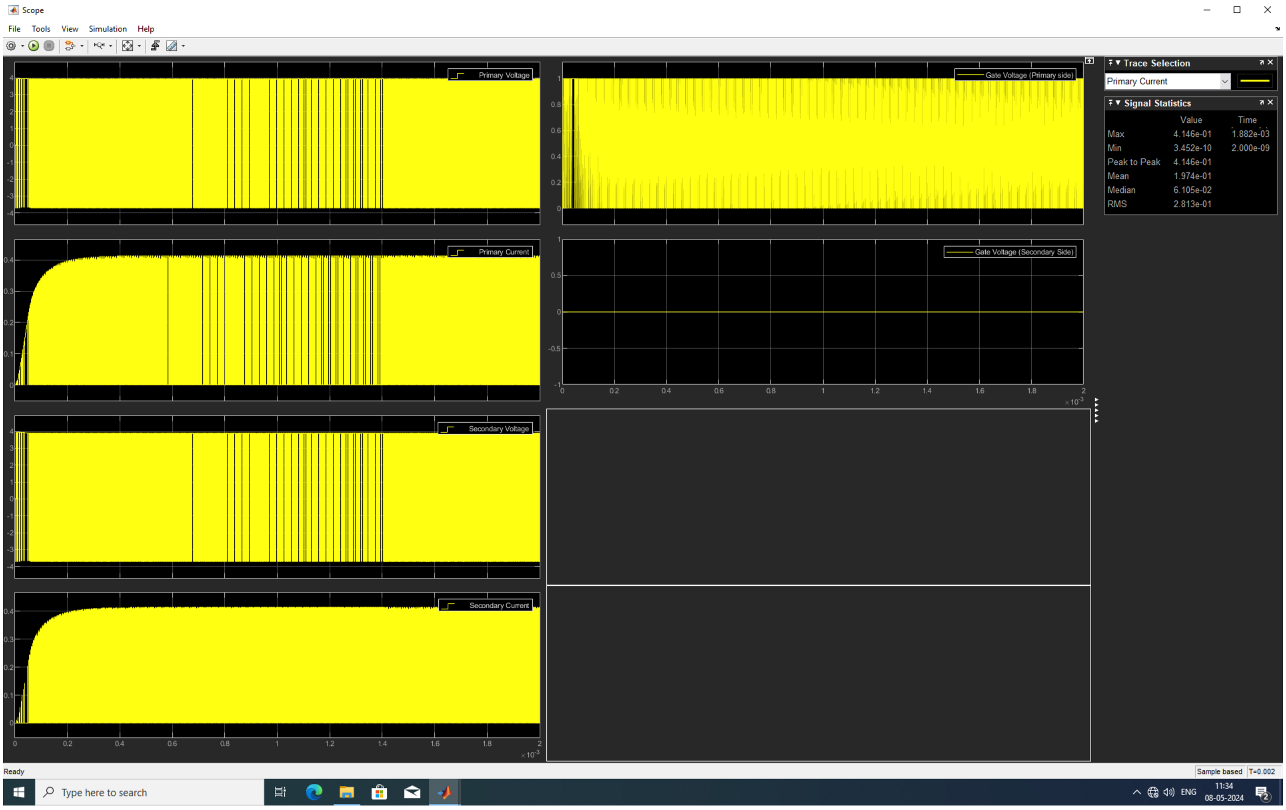

Figure 47: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 2 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

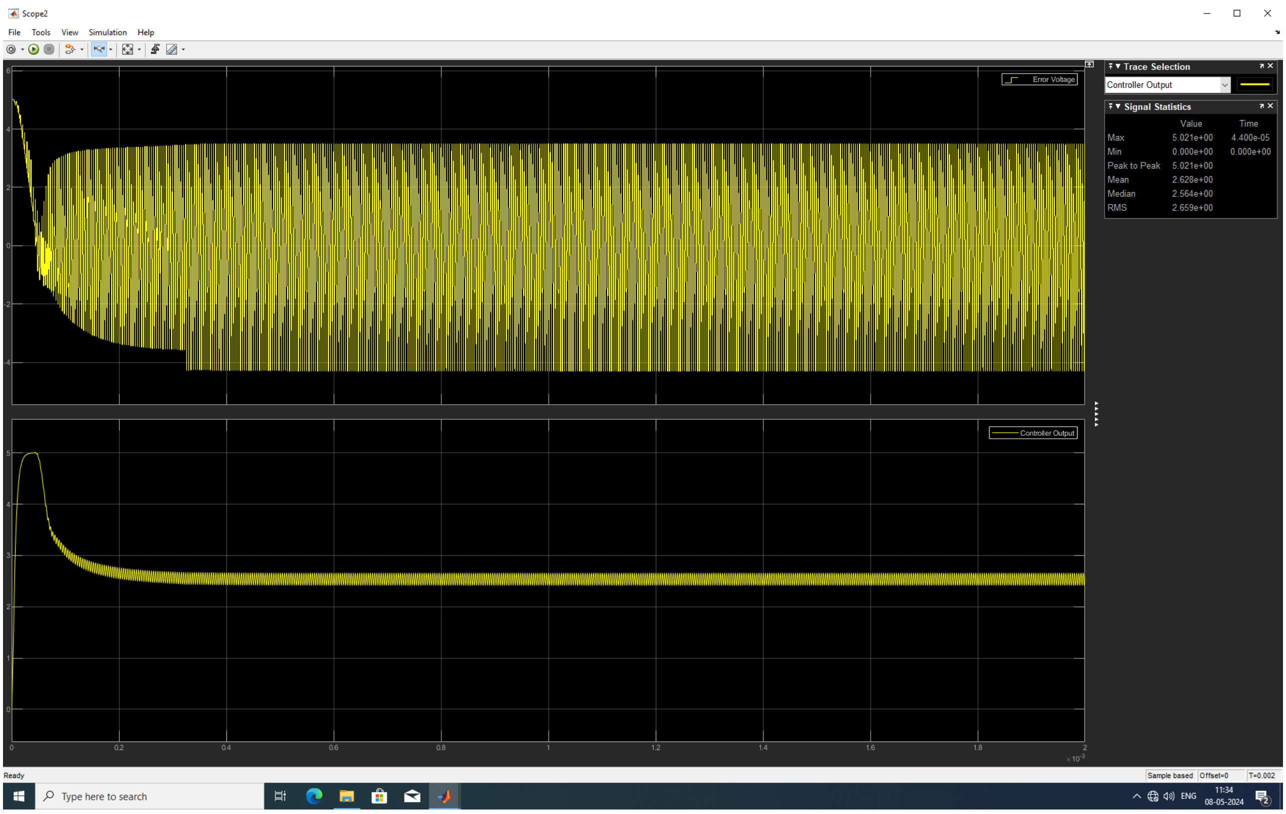

Figure 48: Waveform of error voltage and controller output for the cell 2 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

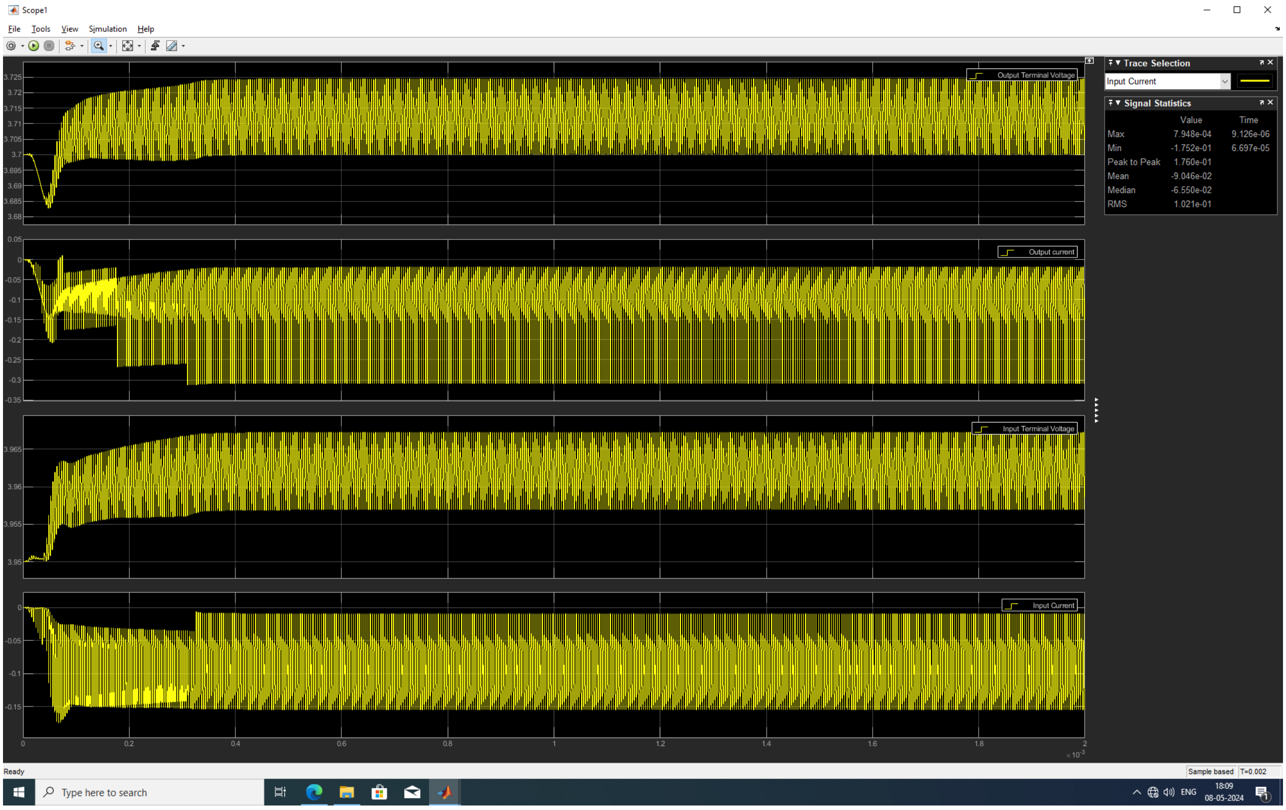

Figure 49: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 3 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

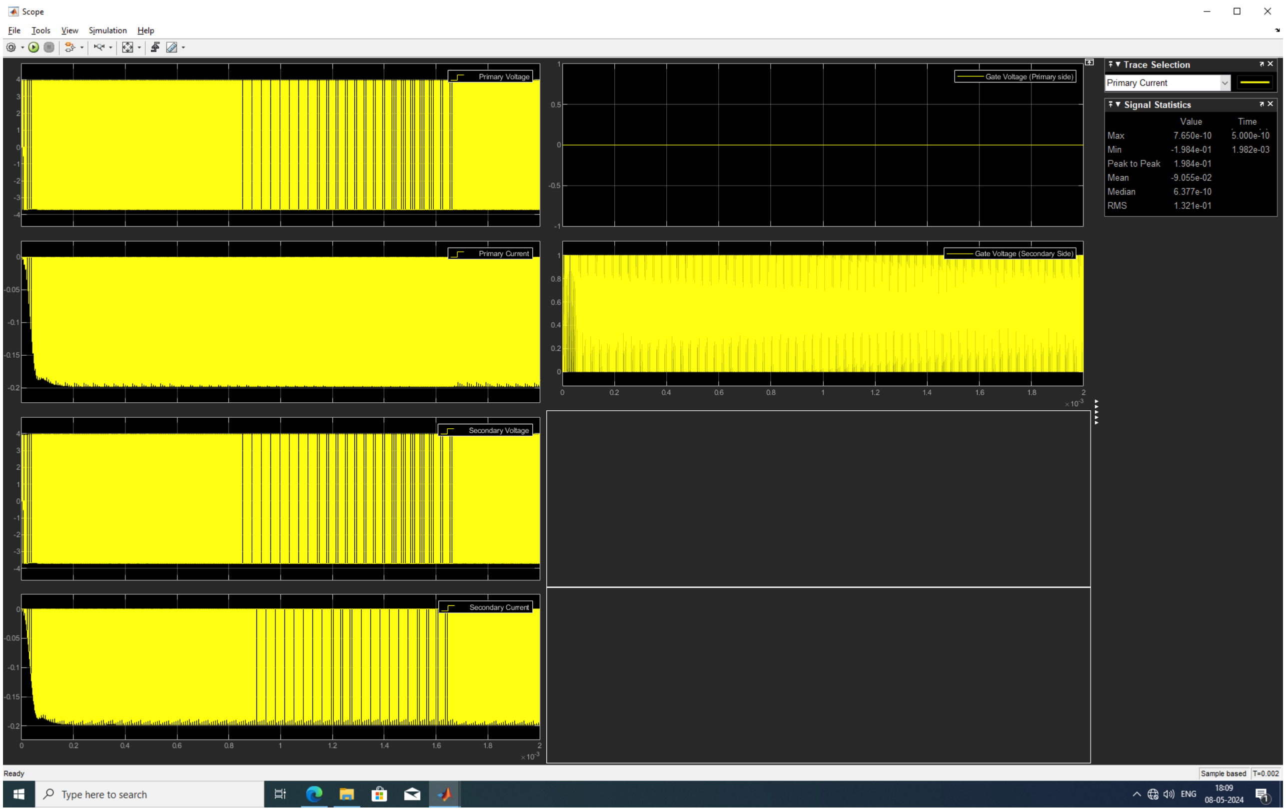

Figure 50: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 3 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

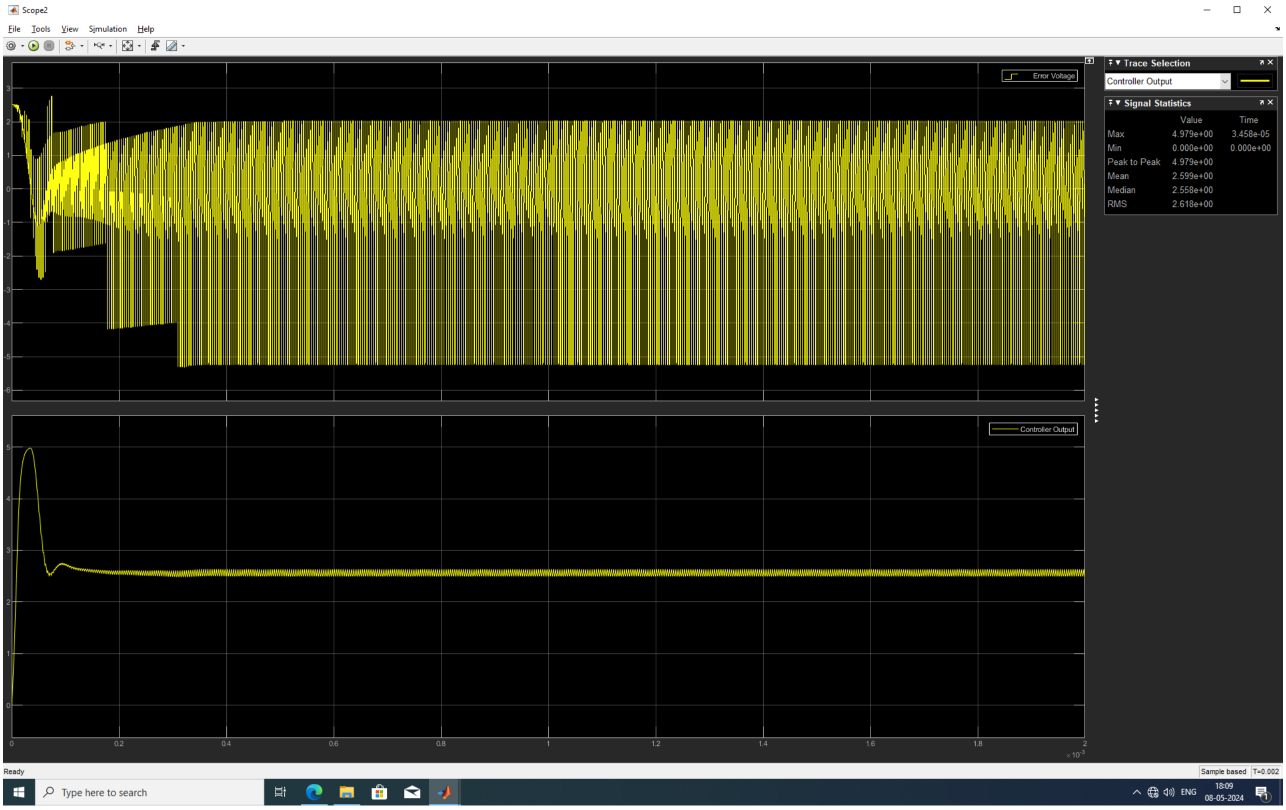

Figure 51: Waveform of error voltage and controller output for the cell 3 converter with $I_{ref} = 0.1A$ for the two switch flyback converter

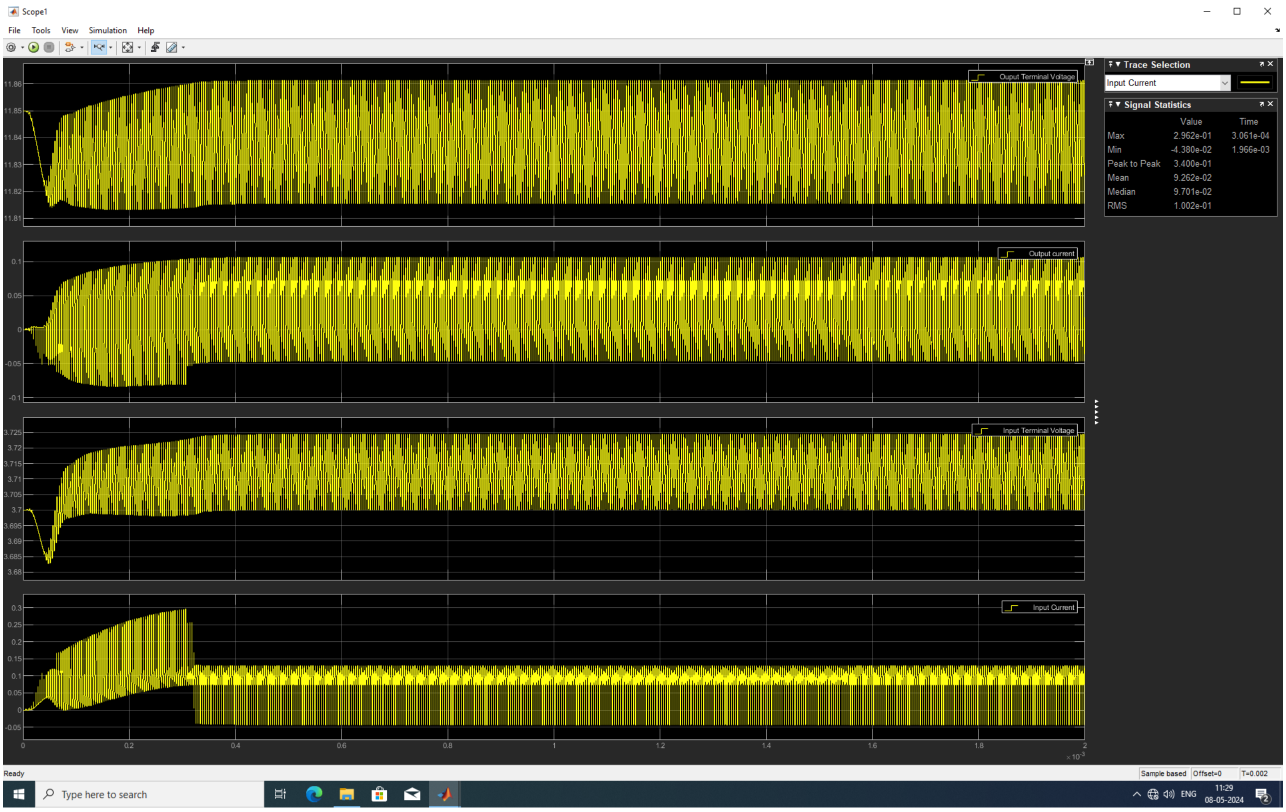

Figure 52: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$ for the two switch flyback converter

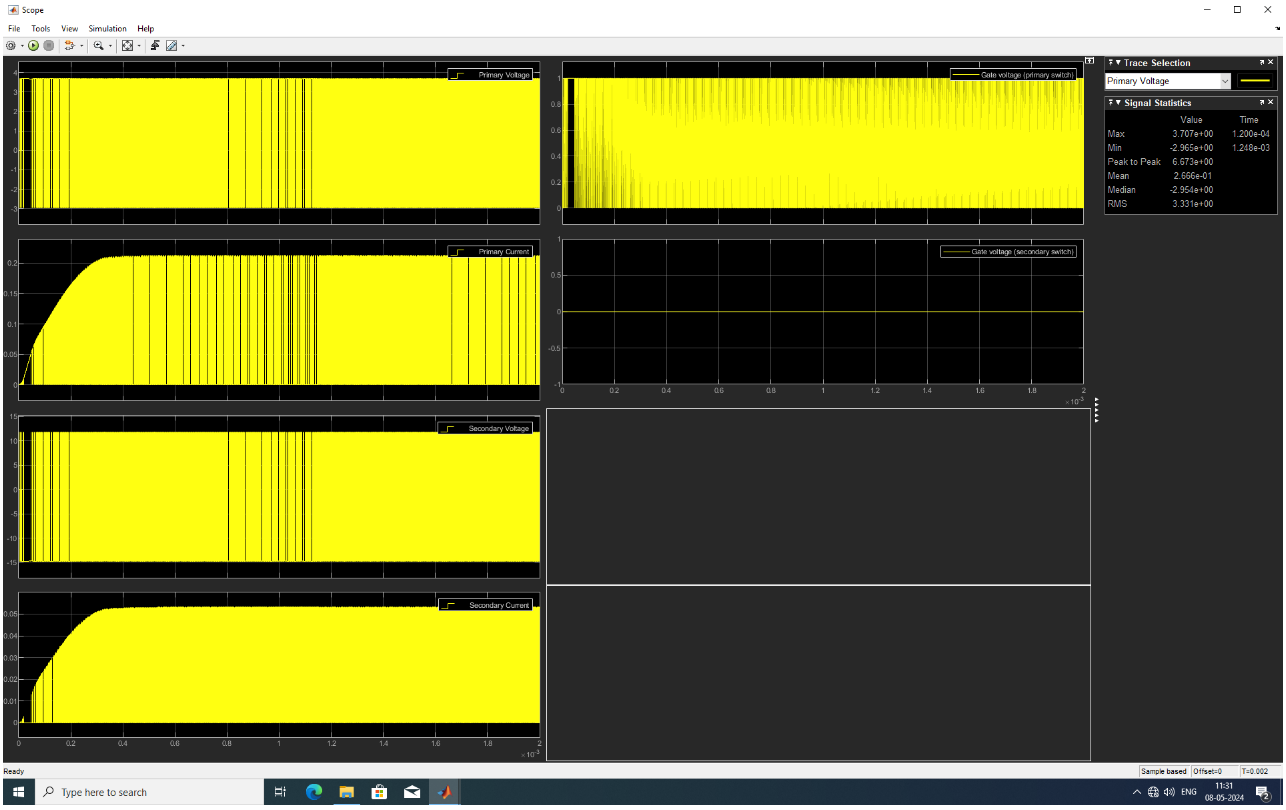

Figure 53: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$ for the two switch flyback converter

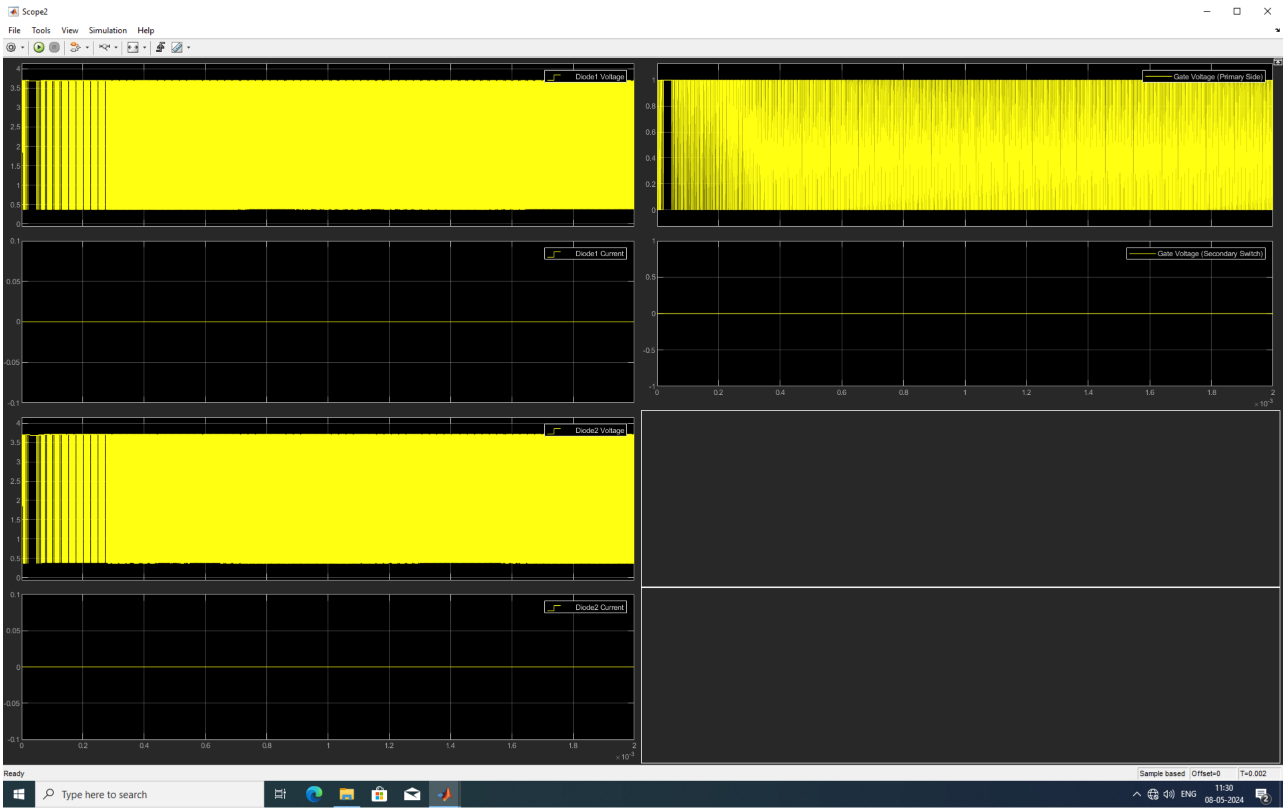

Figure 54: Waveform of diode (D1 and D2) voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$ for the two switch flyback converter

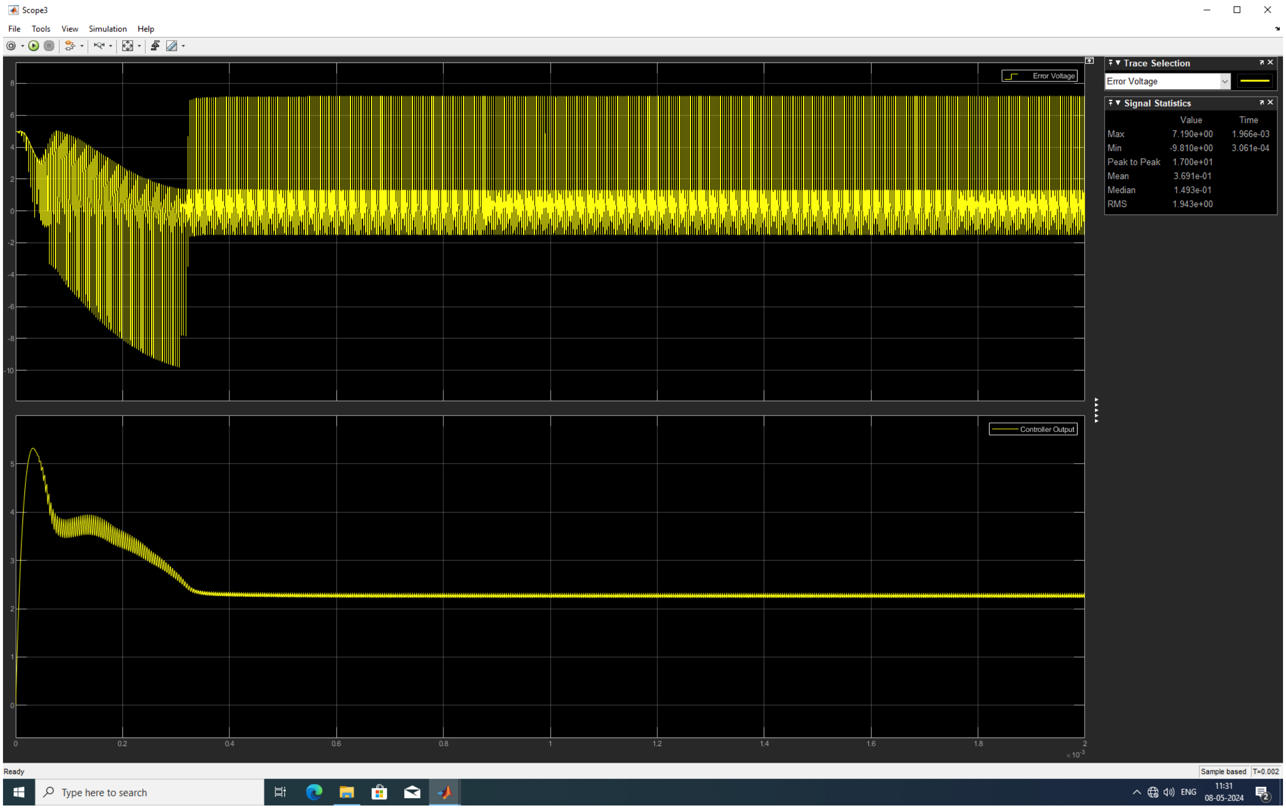

Figure 55: Waveform of error voltage and controller output for the two switch bidirectional flyback converter when $I_{ref} = 0.1A$ for the two switch flyback converter

2.4.3 Waveform when 3 flyback converter and a two switch flyback converter is connected to the battery pack and $I_{ref} = -0.1A$ for the two switch flyback converter

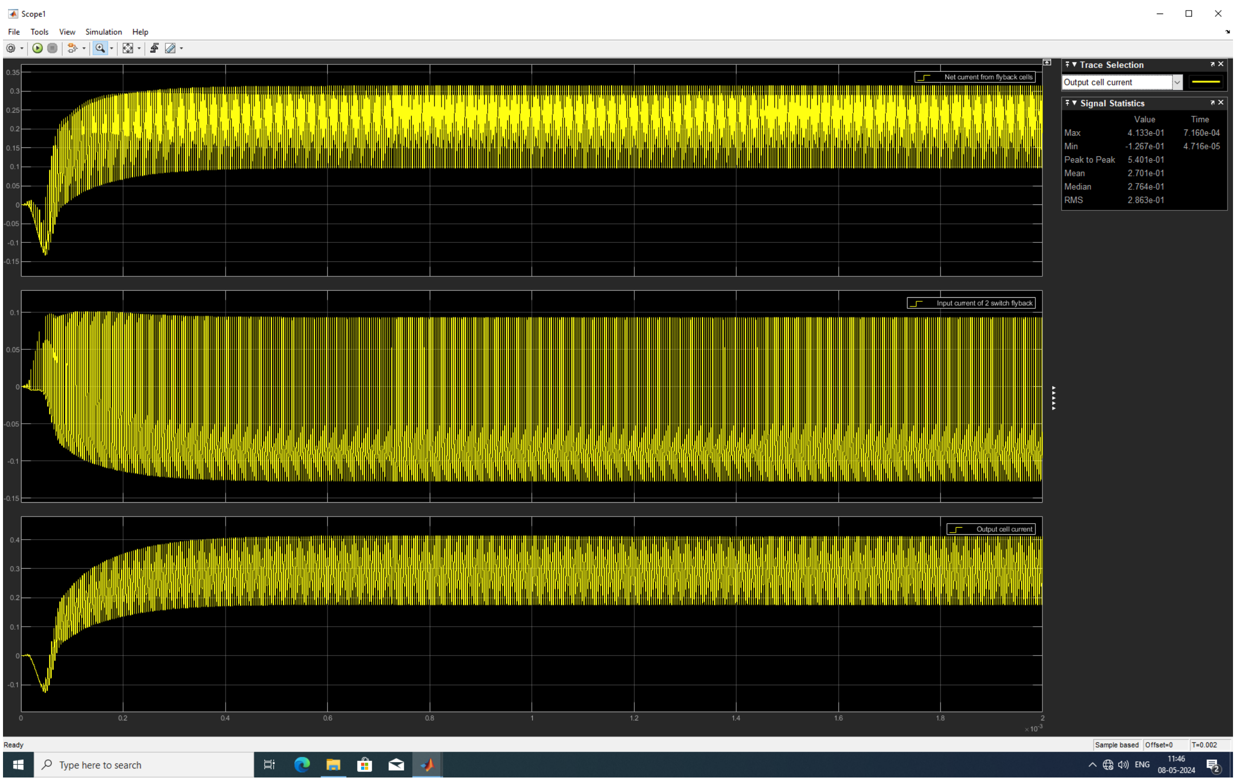

Figure 56: Waveform of net current from flyback,input current of two switch flyback , output cell current for the battery pack when $I_{ref} = -0.1A$ for the two switch flyback converter

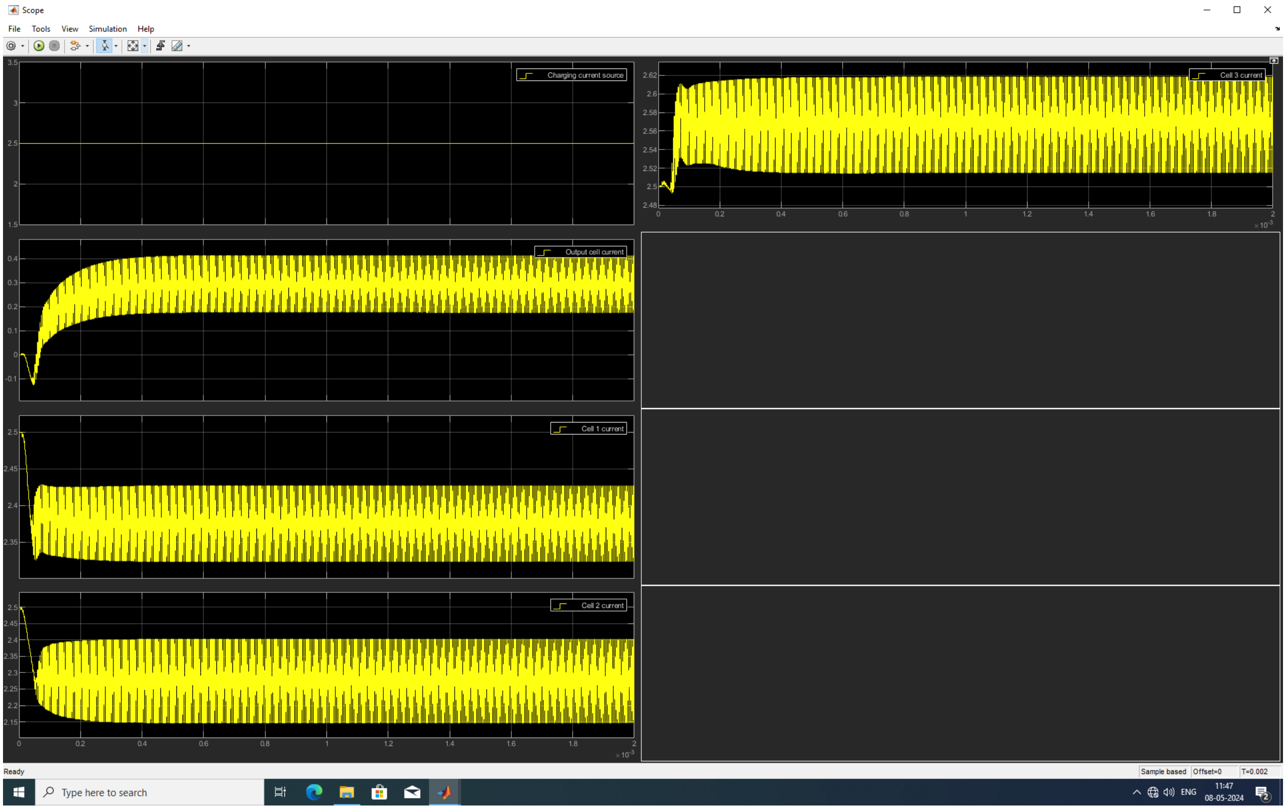

Figure 57: Waveform of current from charging current source, output cell current, cell1 current, cell2 current, cell3 current for the battery pack when $I_{ref} = -0.1A$ for the two switch flyback converter

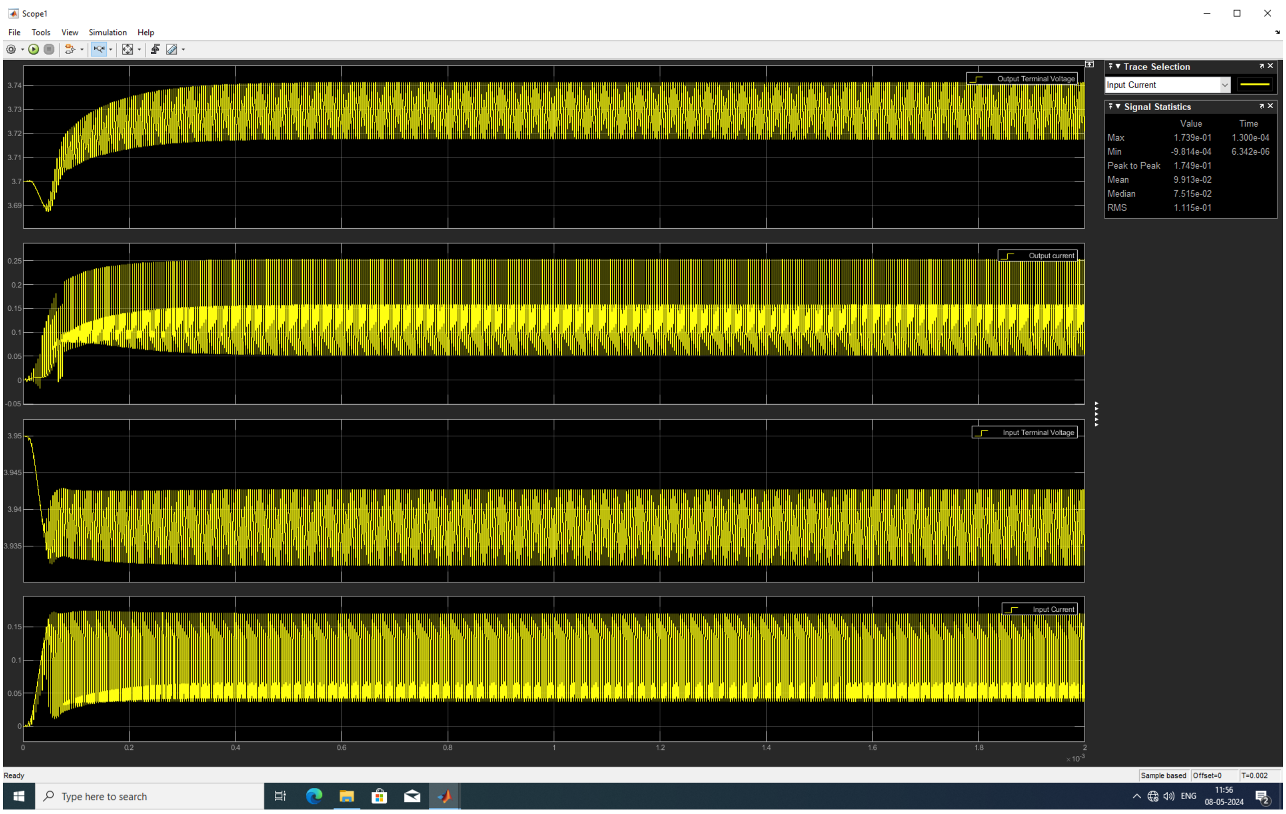

Figure 58: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 1 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

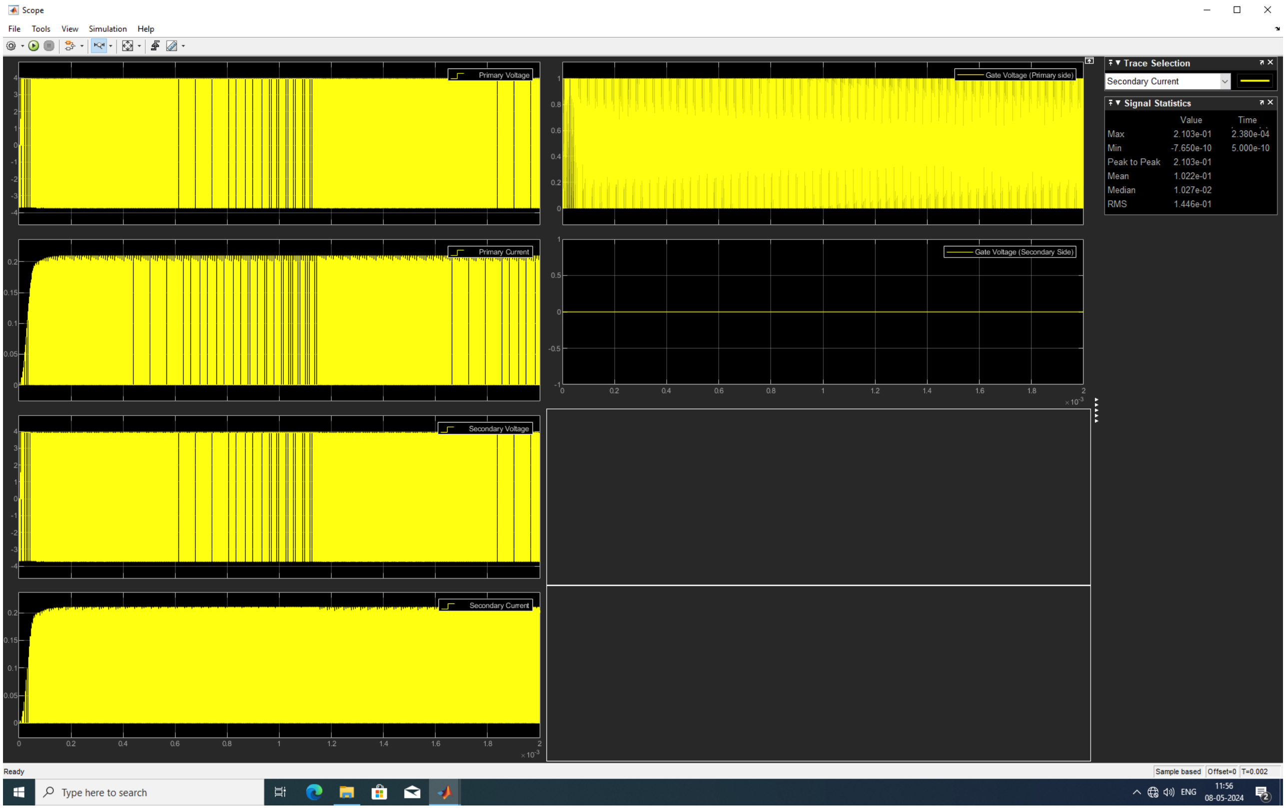

Figure 59: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 1 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

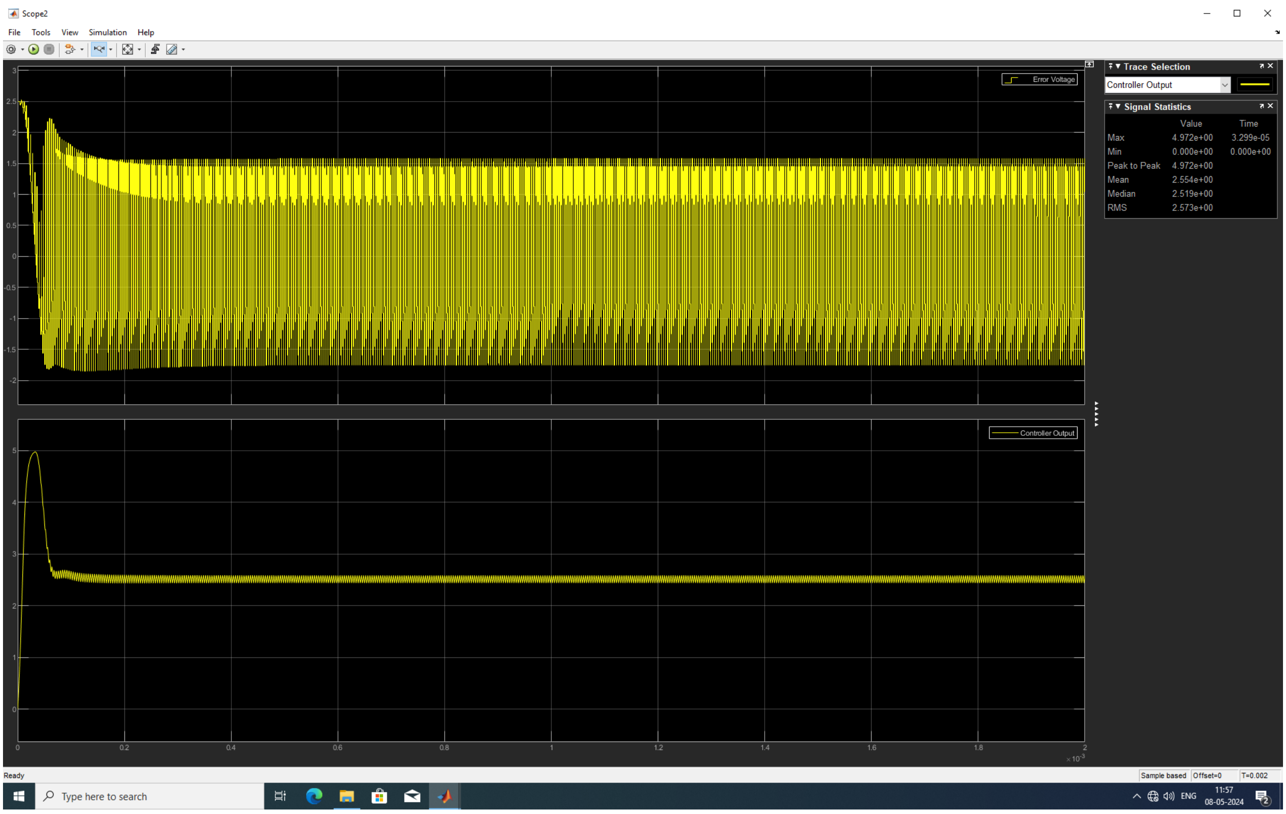

Figure 60: Waveform of error voltage and controller output for the cell 1 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

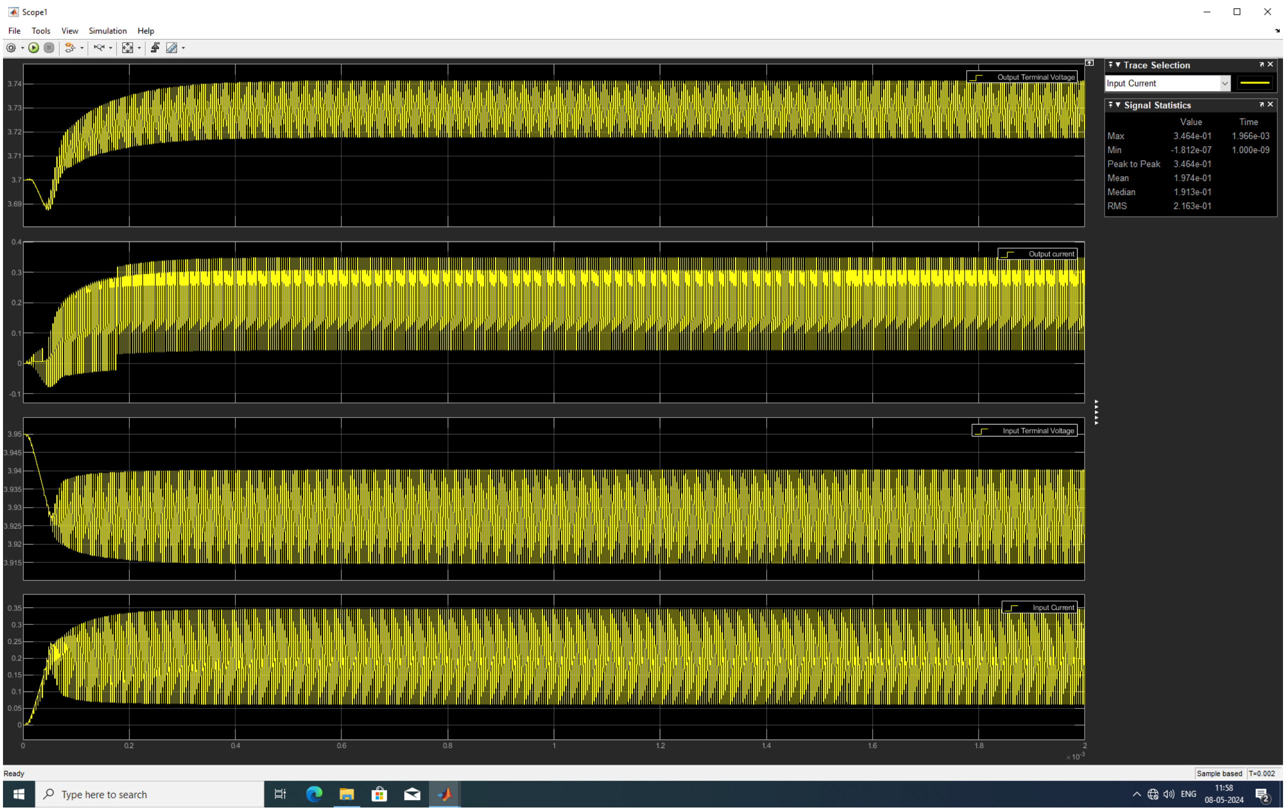

Figure 61: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 2 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

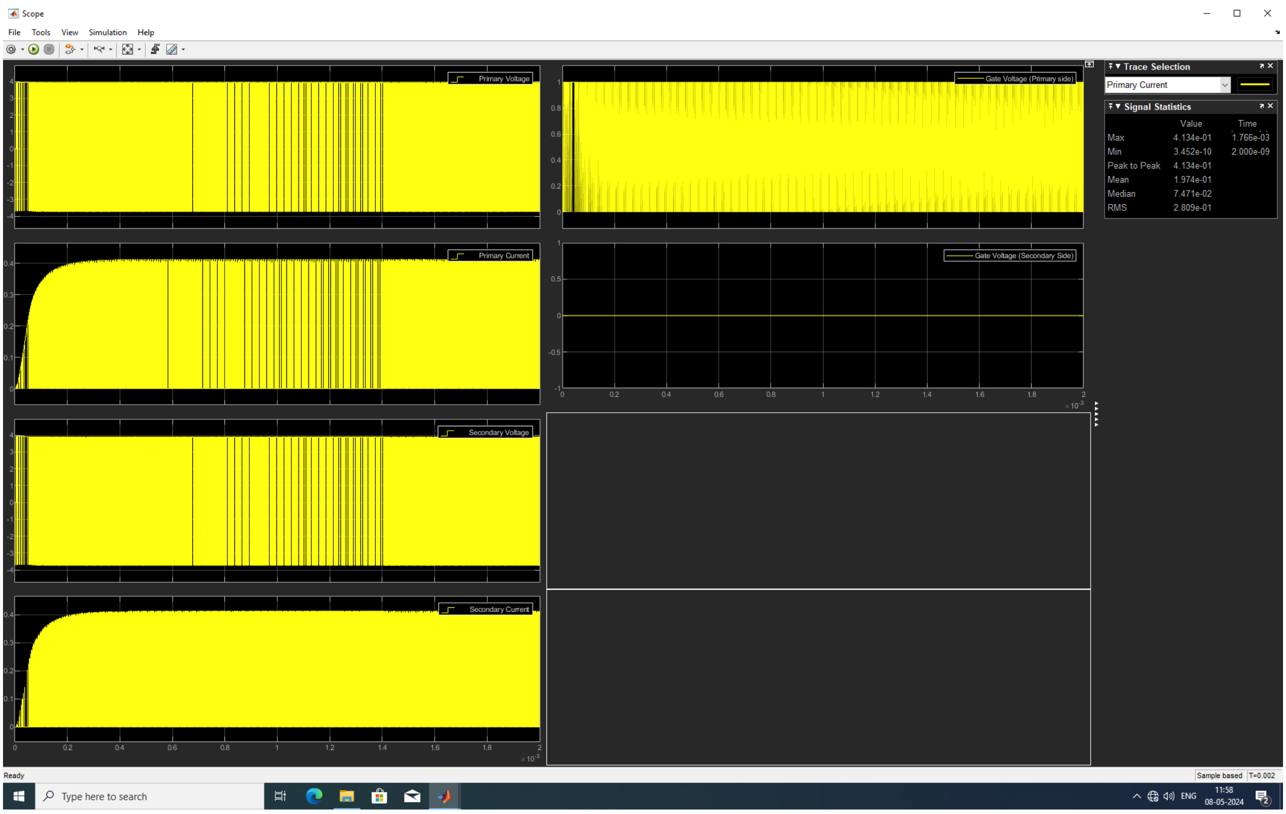

Figure 62: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 2 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

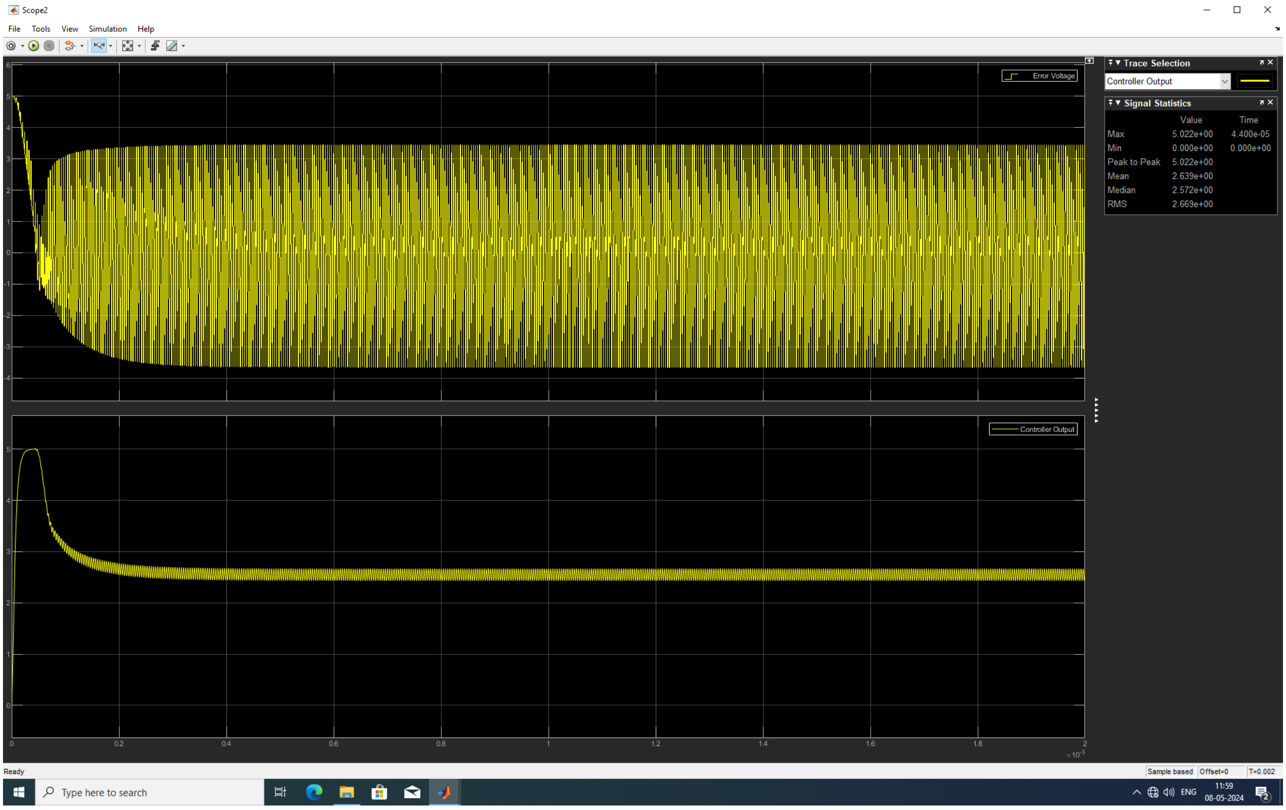

Figure 63: Waveform of error voltage and controller output for the cell 2 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

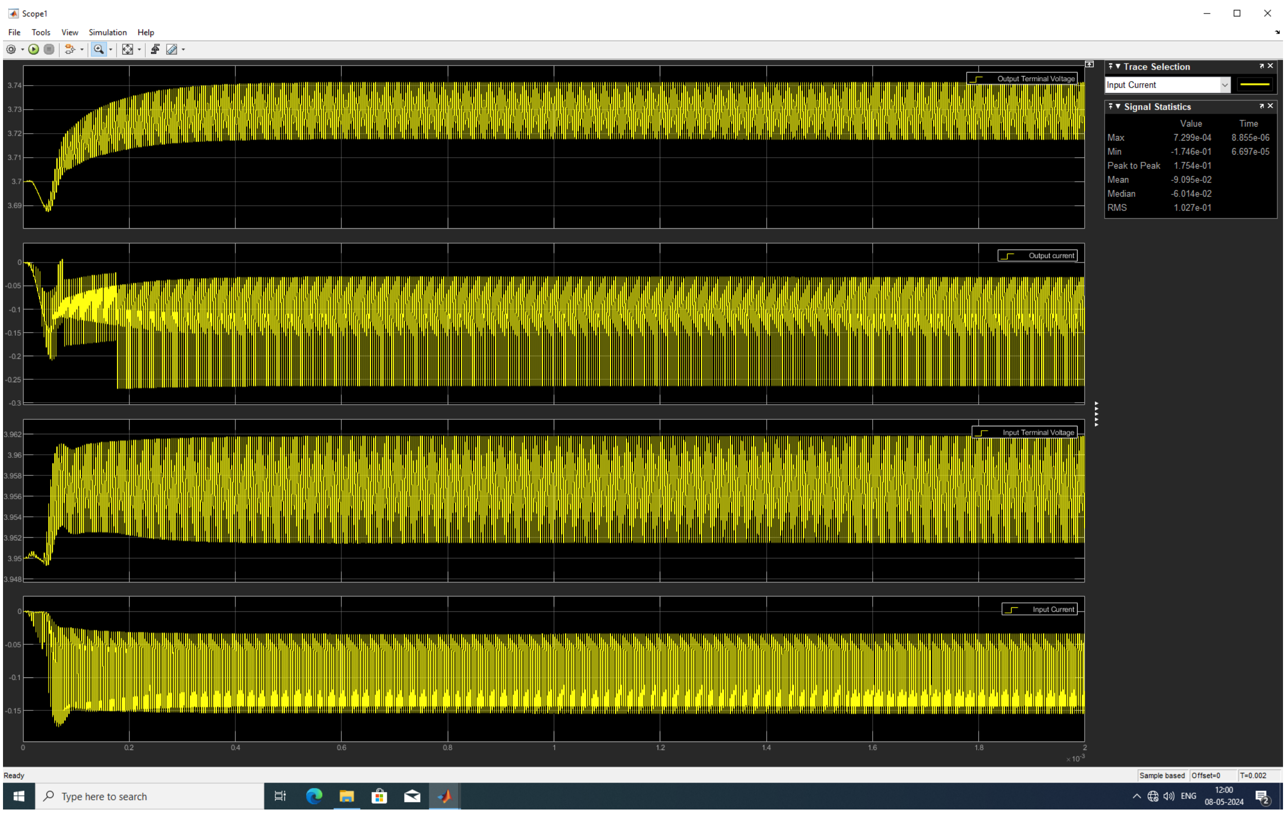

Figure 64: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the cell 3 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

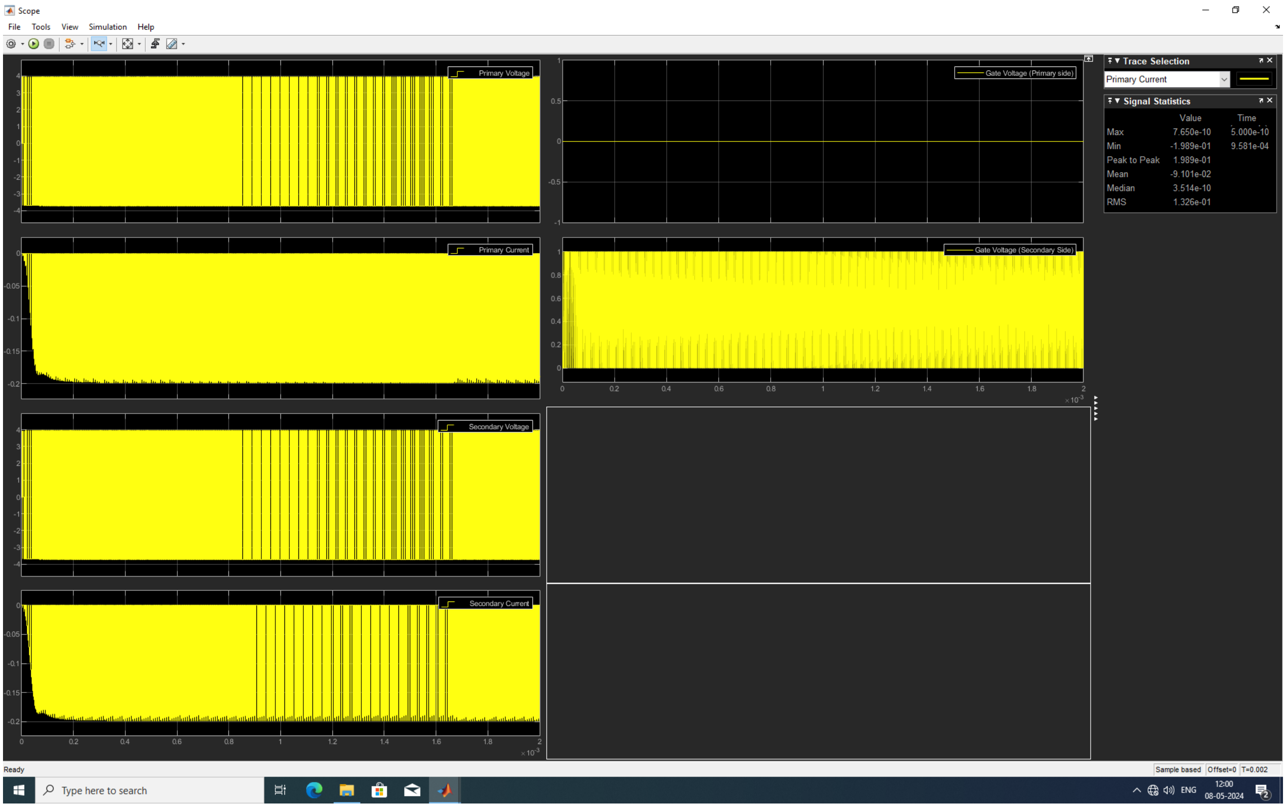

Figure 65: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the cell 3 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

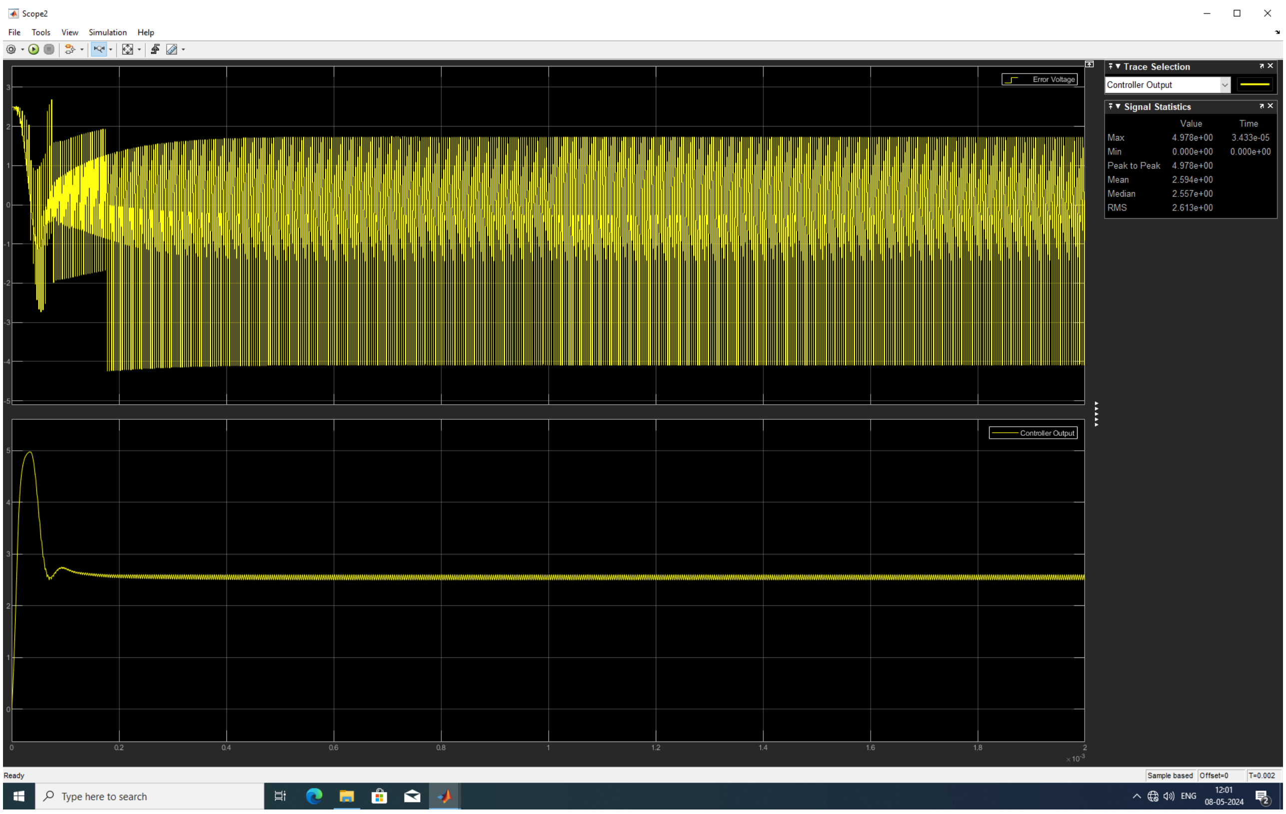

Figure 66: Waveform of error voltage and controller output for the cell 3 converter with $I_{ref} = -0.1A$ for the two switch flyback converter

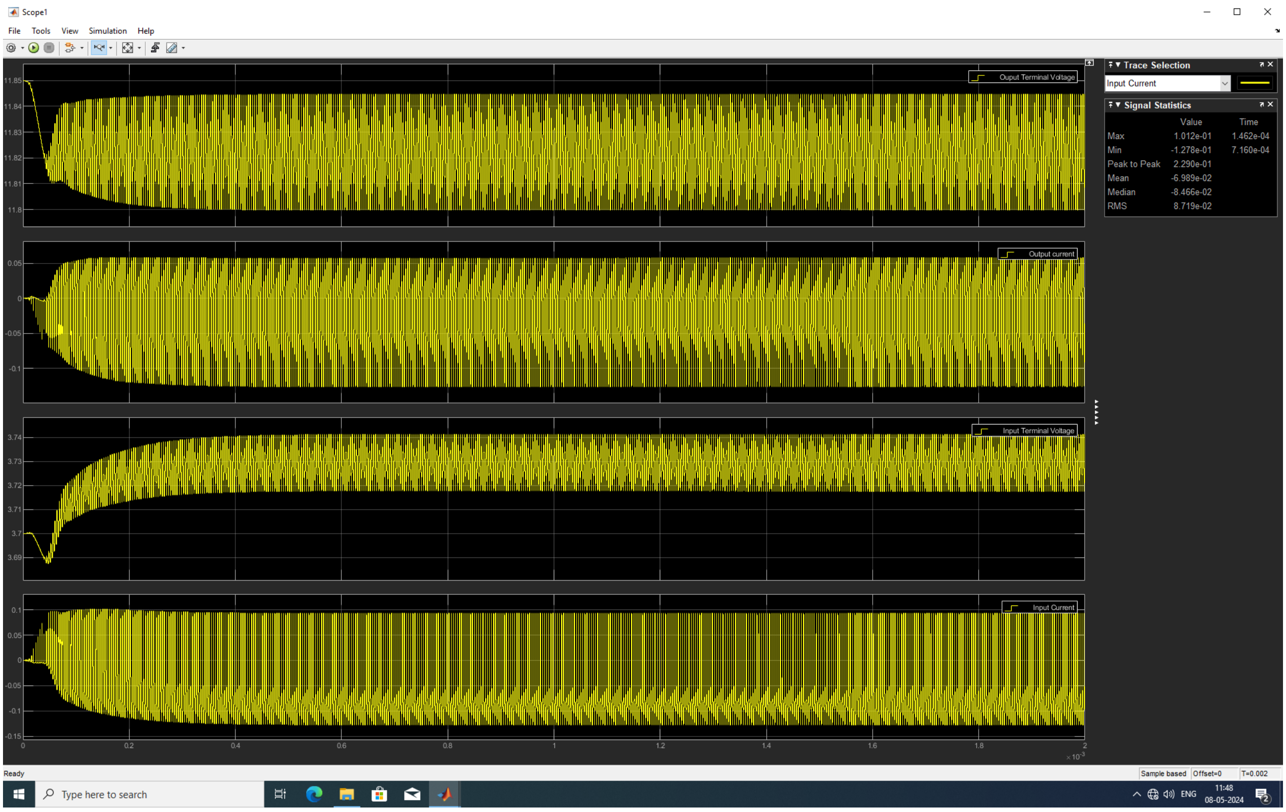

Figure 67: Waveform of output terminal voltage, output current, input terminal voltage, and input current for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$ for the two switch flyback converter

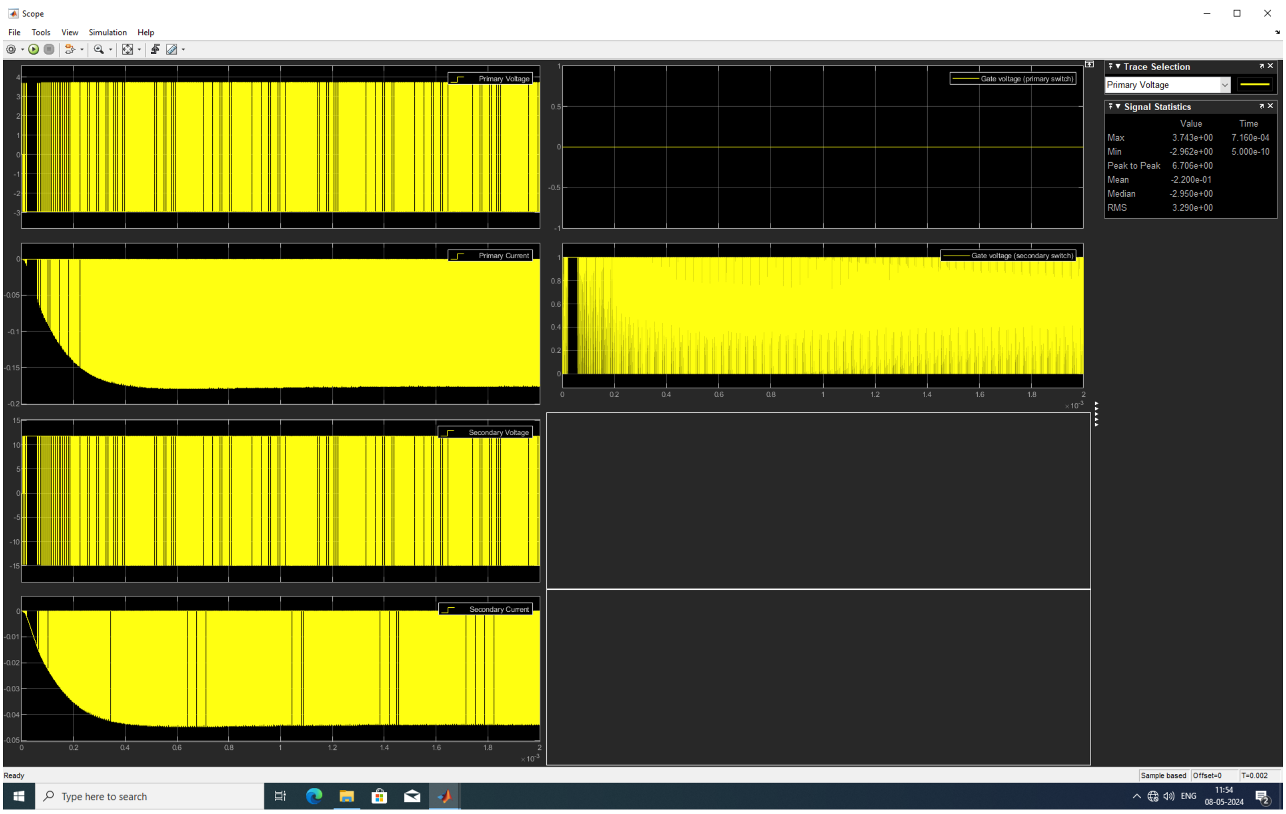

Figure 68: Waveform of primary voltage and current, secondary voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$ for the two switch flyback converter

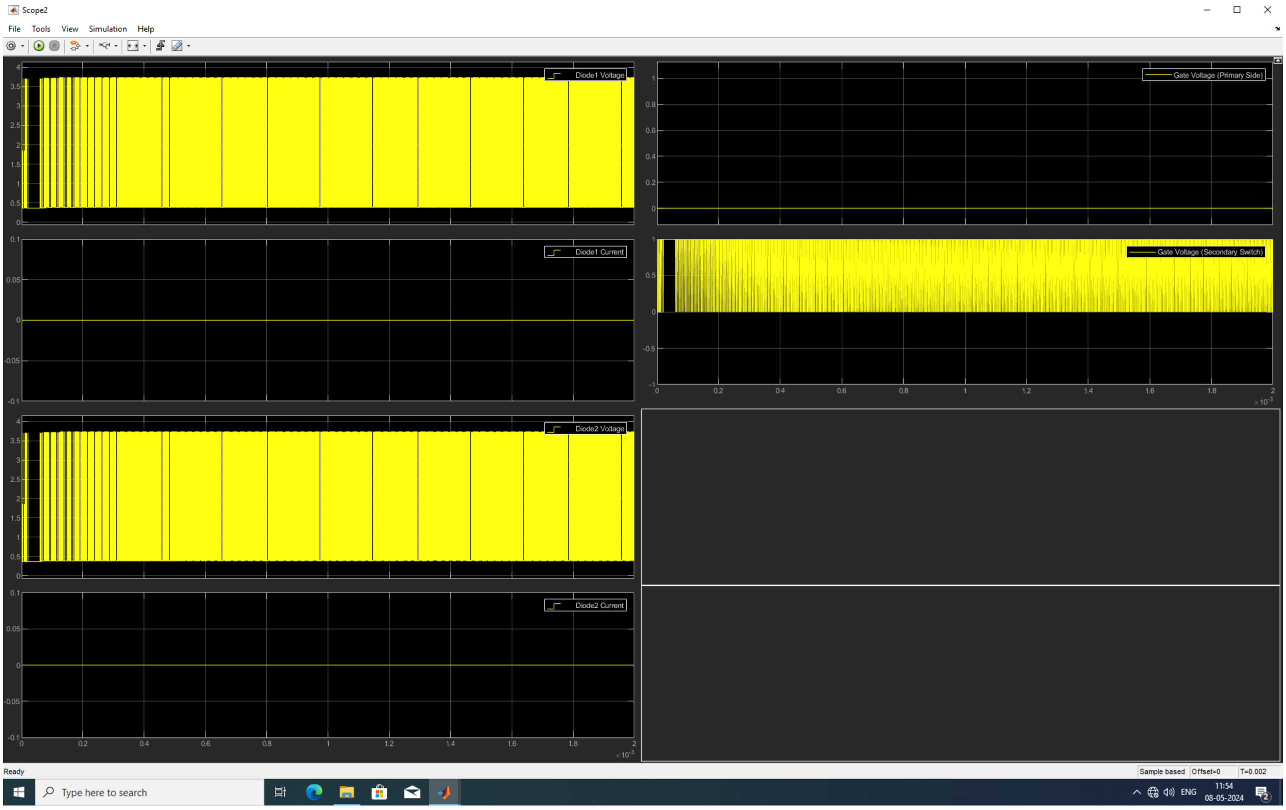

Figure 69: Waveform of diode (D1 and D2) voltage and current, Gate pulses for both switches for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$ for the two switch flyback converter

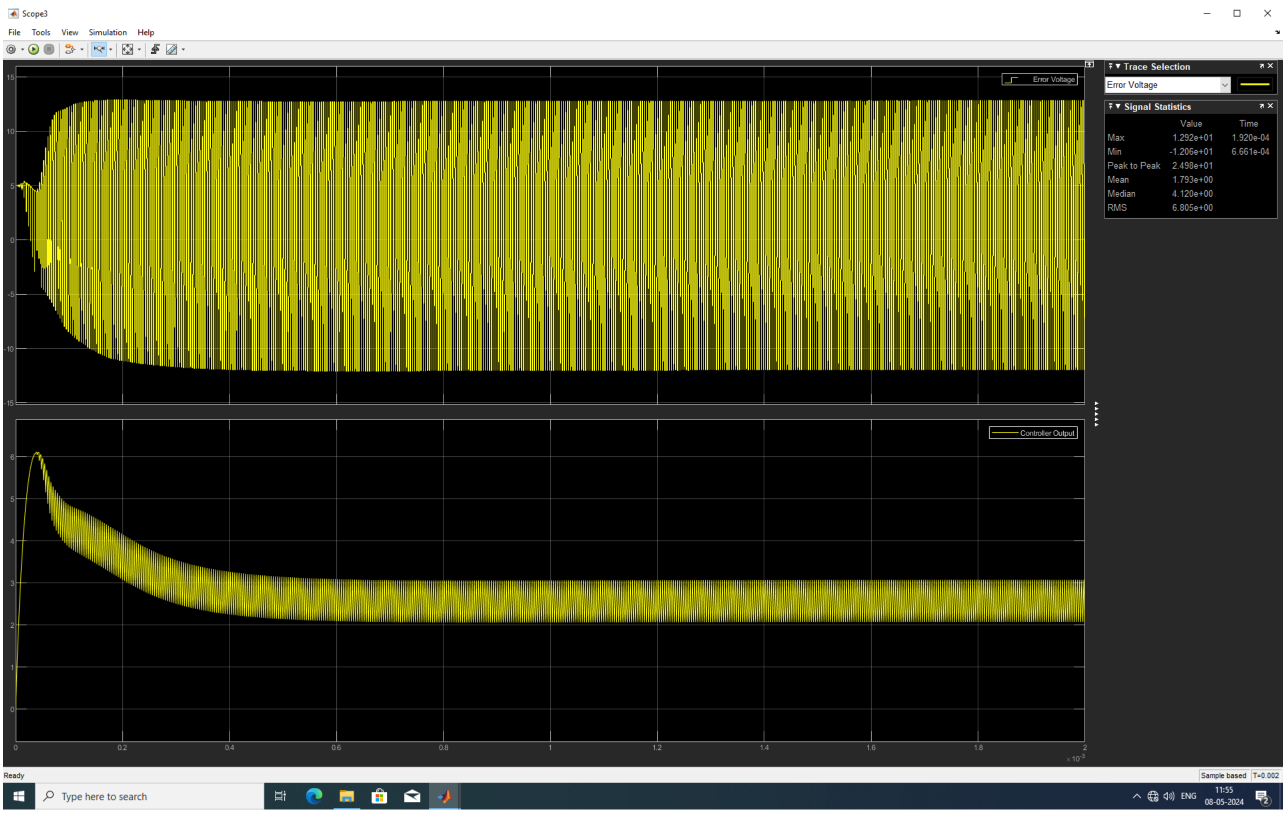

Figure 70: Waveform of error voltage and controller output for the two switch bidirectional flyback converter when $I_{ref} = -0.1A$ for the two switch flyback converter

3 Discussion

- One can see that when the converters are connected to the battery pack, the current waveforms in the cells are smoother and does not have spikes, but the current in converters have some spikes.
- This can be attributed to the fact that there is a mismatch in duty of the converters. Since, the 3 flyback converter are attached to the common output so to maintain smoother current in cell the converters has to carry some excess current and that is why there are spikes.
- Also, observe that when two switch flyback converter is not connected the input current of flyback converter is also smooth but when we connect the two switch flyback converter then there are spikes in input current of flyback converter as well. This is happening because the sudden changes in output current of the flyback converters is fed to input of two switch flyback converter and the same is reflected in the output of two switch flyback which indeed is connected to the input of flyback converters and thus these spikes are reflected there as well.
  Due to this we might need to increase device ratings, there can be EMI issues due to these spikes in current and therefore this need a careful treatment.

Solution: One of the solution could be to design filters for the input and output currents of all the converters to make the current smoother (not done here but can be done if required).

4 Conclusion

From the bode plots and waveforms attached in the report, one can conclude that designed controllers are working perfectly (both independently and after integrating the components in the system). Thus, we have achieved the specifications and control objectives and these schematic and controller design with appropriate circuit implementation can be used to implement a real system as per our need. One need to add circuits for gate driver components and protection circuit for the converter.

Appendices

A MATLAB Script for the design

```
%Flyback Converter
Vin = 3.7;
Vbat = 3.7;
Rin = 100e-3;
Rout = Rin;
D = 0.5021;
Dp = 1-D;
n = 1;
delIlm = 0.01;
delVc = 0.02;
fs = 250e3;

Vc = (D*Vin + n*D*Rin*Vbat/Dp/Rout)/(Dp/n + n*D*Rin/Dp/Rout);
Iin = (D/Dp)* (Vc-Vbat)/Rout;
Ilm = Iin/D;
Lm = Vc*Dp/delIlm/fs;
C = D/fs*(Vc-Vbat)/Rout/delVc;

s = tf('s');
opts = bodeoptions;
opts.freqUnits = 'Hz';
opts.xLim = [100, 1000e3];
opts.grid = 'on';
%Plant Transfer function initialisation
GiLmd0 = (Vc/n/D + Dp*Rout*Ilm/n/n)/((D*Rin+Dp*Dp*Rout/n/n));
wz = (Vc/n/D + Dp*Rout*Ilm/n/n)/(C*Rout*Vc/n/D);
w0 = sqrt((D*Rin+Dp*Dp*Rout/n/n)/Lm/C/Rout);
Q = (D*Rin + Dp*Dp*Rout/n/n)/(Lm + D*Rin*Rout*C)/w0;
GiLmd = GiLmd0*(1+s/wz)/(1+(s/Q/w0)+(s/w0)^2);
Rsense = 5/0.2;
Vm = 5;
% bode(GiLmd,opts);

Giind = Ilm + D*GiLmd;
Tuiind = Giind*Rsense/Vm;

%Controller design
fc = 20e3;
wLv = 2*pi*fc*tan(75*pi/180);
wpfilter = 2*pi*30e3;
Gfilter = 1/(1+s/wpfilter);
Gcinf = (abs(evalfr(Tuiind,1i*2*pi*fc)))/sqrt(1+(wLv/2/pi/fc)^2)/abs(evalfr(Gfilter,1i*2*pi*fc
    ));
Gc = Gcinf*(1+wLv/s)*Gfilter;                % final controller for glyback converter
opts.xLim = [1,100e5];
bode(Gc*Tuiind,opts);


%Two switch flyback
Vin2 = 3.7;
Vbat2 = 3*3.7;
Rin2 = 100e-3;
Rout2 = 3*Rin2;
D2 = 0.4303;
Dp2 = 1-D2;
n2 = 4;
delIlm2 = 0.01;
delVc2= 0.02;
fs = 250e3;

Vc2 = (D2*Vin2+ n2*D2*Rin2*Vbat2/Dp2/Rout2)/(Dp2/n2 + n2*D2*Rin2/Dp2/Rout2);
Iin2 = n2*(D2/Dp2)* (Vc2-Vbat2)/Rout2;
Ilm2 = Iin2/D2;
Lm2 = Vc2*Dp2/delIlm2/fs;
C2 = D2/fs*(Vc2-Vbat2)/Rout2/delVc2;

GiLmd02 = (Vc2/n2/D2 + Dp2*Rout2*Ilm2/n2/n2)/((D2*Rin2+Dp2*Dp2*Rout2/n2/n2));
wz2 = (Vc2/n2/D2 + Dp2*Rout2*Ilm2/n2/n2)/(C2*Rout2*Vc2/n2/D2);
w02 = sqrt((D2*Rin2+Dp2*Dp2*Rout2/n2/n2)/Lm2/C2/Rout2);
Q2 = (D2*Rin2 + Dp2*Dp2*Rout2/n2/n2)/(Lm2 + D2*Rin2*Rout2*C2)/w02;
```

```
GiLmd2 = GiLmd02*(1+s/wz2)/(1+(s/Q2/w02)+(s/w02)^2);
% bode(GiLmd2,opts);
Rsense2 = 5/0.1;
Vm = 5;

Giind2 = Ilm2 + D2*GiLmd2;
Tuiind2 = Giind2*Rsense2/Vm;
bode(Tuiind2,opts);

%Controller design
fc = 20e3;
wLv2 = 2*pi*fc*tan(60*pi/180);
wpfilter2 = 2*pi*10e3;
Gfilter2 = 1/(1+s/wpfilter2);
Gcinf2 = (abs(evalfr(Tuiind2,1i*2*pi*fc)))/sqrt(1+(wLv2/2/pi/fc)^2)/abs(evalfr(Gfilter,1i*2*pi
    *fc));
Gc2 = Gcinf2*(1+wLv2/s)*Gfilter2;           %final controller for two switch flyback
% opts.xLim = [1,100e5];
% bode(Gc2*Tuiind2,opts);
```