Attempt to calculate flyback converter output ripple

By K. B.

October 24th, 2023

1 Flyback converter working cycle analysis attempt

"ON" Phase MOSFET swithced "ON", primary current increases to its threshold level, energy stored in magnetic field.

"OFF1" Phase Secondary coil gets energised and then demagnetizes, output capacitors receive charge. Reflected voltage across auxilary coil switches "OFF" MOSFET.

"FEEDBACK" Phase Shunt regulator switched "ON", Output capacitors discharges. C2 discharge path to ground activated by feedback signal, so MOSFET's gate voltage not rising.

"OFF2" Phase Shunt regulator switched "OFF", C2 capacotor recharges and MOSFET's gate voltage rises back to threshold level.

2 Calculations attempt

2.1 Setup

Item	Value	Comment
C_2	0.022 µF	
C_{EC3}	330 µF	
C_{EC4}	470 µF	
L_P	997 µH	
N_{Aux}	6 turns	Auxilary coil winding
N_P	72 turns	Primary coil winding
N_{S1}	15 turns	Secondary (1st) coil winding
N_{S2}	7 turns	Secondary (2nd) coil winding
$R1$	1 MΩ	
$R2$	1 kΩ	
$R5$	220 Ω	
$R6$	0.47 Ω	
$R7$	1 MΩ	
$R11$	3.9 kΩ	
$R13$	3 kΩ	
$R14$	49.9 kΩ	
$R_{DS(ON)}$	2.5 Ω	MOSFET's DS "ON" reistanse
R_{L_P}	0.7 Ω	
R_{L_S}	0.6 Ω	
V_{AC}	220 Vrms	
$V_{BE(Sat)}$	0.7 V	Transistor base-emitter saturation voltage
V_{F_D}	0.7 V	Diode forward voltage
$V_{F_{LED}}$	1.3 V	Optocoupler's LED forward voltage
$V_{GS(Th)}$	4 V	MOSFET's gate threshold voltage
$V_{K(IC2)}$	2 V	Shunt regulator cathode voltage
$V_{Ref(Typ)}$	2.495 V	Shunt regulator reference voltage
$V_{F_{DW2}}$	0.7 V	DW2 forvard voltage
$V_{Z_{DW1}}$	17.9 V	DW1 Zener voltage

DC Voltage from bulk capacitor EC1

$$V_m = \sqrt{2}V_{AC} = \sqrt{2} \cdot 220V_{rms} = 311.13V$$

$$V_{DC} = V_m - 2V_{FD} = 311.13V - 2 \cdot 0.7V \approx 310V$$

Zeners DW1 and DW2 clamping voltage

$$V_{DW} = Vz_{DW1} + V_{F_{DW2}} = 17.9V + 0.7V = 18.6V$$

EC3 and EC4 output capcitors equivalent capacitance

$$C_{EC} = \frac{C_{EC3}C_{EC4}}{C_{EC3} + C_{EC4}} = \frac{330\mu F \cdot 470\mu F}{330\mu F + 470\mu F} = 194\mu F$$

Output EC capacitors threshol voltage

$$V_{OUT(Th)} = V_{EC(Th)} = V_{Ref(Typ)}\frac{R14 + R11}{R11} = 2.495V \cdot \frac{49.9k\Omega + 3.9k\Omega}{3.9k\Omega} = 34.42V$$

Secondary coil effective inductance

$$L_S = \frac{L_P}{(N_P/N_S)^2} = \frac{997\mu H}{(72/22)^2} = 93\mu H$$

Total resistance of primaty coil loop when MOSFET is "ON"

$$R_{P(Loop)} = R_{L_P} + R_{DS(ON)} + R6 = 0.7\Omega + 2.5\Omega + 0.47\Omega = 3.67\Omega$$

Maximum current in primary coil loop

$$I_{L_P(Max)} = \frac{V_{DC}}{R_{P(Loop)}} = \frac{310V}{3.67\Omega} = 84.5A$$

Threshold current for primary coil loop

$$I_{L_P(Th)} = \frac{V_{BE(Sat)}}{R6} = \frac{0.7V}{0.47\Omega} \approx 1.5A$$

Time constant for primary coil

$$\tau_{L_P} = \frac{L_p}{R_{P(Loop)}} = \frac{997\mu H}{3.67\Omega} = 272\mu S$$

Capacitor C2 time constants "A": Zeners - "OFF"; Q2,Q3 - "OFF" (Charging from DC)

$$\tau_{C2_A} = (R_1 + R_7 + R_2)C_2 = (1M\Omega + 1M\Omega + 1k\Omega) \cdot 0.022\mu F = 44022\mu S$$

"B": Zeners - "ON"; Q2,Q3 - "OFF" (Discharging with zener current)

$$\tau_{C2_B} = R_2C_2 = 0.022\mu F \cdot 1k\Omega = 22\mu S$$

"C": Zeners - ""OFF"; Q2,Q3 - "ON" (Discharging via path opened by transistors)

$$\tau_{C2_C} = (R_2 + R_5 + R_6)C_2 = (1k\Omega + 220\Omega + 0.47\Omega) \cdot 0.022\mu F = 26.9\mu S$$

Output ECs capacitors time constants "VD" - Discharge via R11,R14 voltage divider

$$\tau_{VD} = (R_{14} + R_{11})C_{EC} = (3.9k\Omega + 49.9k\Omega) \cdot 194\mu F = 10.43S$$

"Led" - Discharge via R13 and Led

$$\tau_{LED} = R_{13}C_{EC} = 3k\Omega \cdot 194\mu F = 582mS$$

2.2 "ON" Phase

Duration: $\mathrm{T_{ON}}$;

Initial time moment: $\mathrm{t_{on(i)}}$ - MOSFET just switches "ON"

Final moment: $\mathrm{t_{on(f)}}$- Primary coil current just reached threshold value

Known/definite values

$$V_{EC}(t_{on(i)}) = V_{EC(Th)} = 34.42V$$

$$I_{L_P}(t_{on(i)}) = 0A$$

$$I_{L_P}(t_{on(f)}) = I_{L_P(Th)} = 1.5A$$

$$V_{C2}(t_{on(i)}) = -V_{GS(Th)} = -4V$$

Primary coil induced voltage @$\mathbf{t_{on(i)}}$

$$V_{L_P}(t_{on(i)}) = -V_{DC} = -310V$$

Auxiliary coil induced voltage @$\mathbf{t_{on(i)}}$

$$V_{Aux}(t_{on(i)}) = \frac{N_{Aux}}{N_P} V_{L_P}(t_{on(i)}) = \frac{6}{72} \cdot (-310V) = -25.8V$$

Voltage from transformer's pin2 @$\mathbf{t_{on(i)}}$

$$V_{TR2}(t_{on(i)}) = -V_{Aux}(t_{on(i)}) = -(-25.8V) = 25.8V$$

Voltage on MOSFET's gate @$\mathbf{t_{on(i)}}$ (transformer's pin2 voltage clamped by Zeners)

$$V_{GS}(t_{on(i)}) = V_{DW} = 18.6V$$

Primary coil current rising time $\mathbf{T_{ON}}$

$$T_{ON} = \tau_{L_P} ln \frac{(I_{L_P}(t_{on(i)}) - I_{L_P(Max)})}{(I_{L_P}(t_{on(f)}) - I_{L_P(Max)})} = 272\mu S \cdot ln \frac{(0 - 84.5A)}{(1.5A - 84.5A)} = 4.8\mu S$$

Primary coil induced voltage @$\mathbf{t_{on(f)}}$

$$V_{L_P}(t_{on(f)}) = V_{L_P}(t_{on(s)}) e^{-\frac{T_{ON}}{\tau_{L_P}}} = -310V \cdot e^{-\frac{4.9\mu S}{272\mu S}} = -304.5V$$

Auxiliary coil induced voltage @$\mathbf{t_{on(f)}}$

$$V_{Aux}(t_{on(f)}) = \frac{N_{Aux}}{N_P} V_{L_P}(t_{on(f)}) = \frac{6}{72} \cdot (-304.5V) = -25.4V$$

Voltage from transformer's pin2 @$\mathbf{t_{on(f)}}$

$$V_{TR2}(t_{on(f)}) = -V_{Aux}(t_{on(f)}) = -(-25.4V) = 25.4V$$

Voltage across C2 @$\mathbf{t_{on(f)}}$calculations:

$$v_{TR2}(t) - v_{R_2}(t) - v_{C_2}(t) - V_{DW} = 0$$

$$V_{TR2}(t_{on(i)}) e^{-\frac{t}{\tau_{Lp}}} - iR_2 - v_{C_2}(t) - V_{DW} = 0$$

$$V_{TR2}(t_{on(i)}) e^{-\frac{t}{\tau_{Lp}}} - C_2 \frac{dv_{C_2}(t)}{dt} R_2 - v_{C_2}(t) - V_{DW} = 0$$

$$-R_2 C_2 \frac{dv_{C_2}(t)}{dt} - v_{C_2}(t) = V_{DW} - V_{TR2}(t_{on(i)}) e^{-\frac{t}{\tau_{Lp}}}$$

$$-\tau_{c2_B} \frac{dv_{C_2}(t)}{dt} - v_{C_2}(t) = V_{DW} - V_{TR2}(t_{on(i)}) e^{-\frac{t}{\tau_{Lp}}}$$

$$\frac{dv_{C_2}(t)}{dt} = \frac{1}{\tau_{c2_B}} [-v_{C_2}(t) + V_{TR2}(t_{on(i)}) e^{-\frac{t}{\tau_{Lp}}} - V_{DW}]$$

Numerical solution for differential equation. Octave code:

```
clear all
clc

tau_Lp = 272*10^-6;     % S
tau_C2B = 22*10^-6;     % S
TON = 4.8*10^-6;        % S
Vc2_i = -4;                 % V, C2 voltage at start
VDW = 18.6;             % V
Vtr2_i = 25.8;          % V, Vtr2 voltage at start
```

```
ptsNum = 100;            % number of time points for calculations

% time points (need for numeric calculations)
tspan = linspace(0,TON,ptsNum);

% Differential equation for C2 voltage
% (in a form of anonymus function in a form necessary for ode45 solver)
dvdt = @(t,v) (1/tau_C2B)*(-v+Vtr2_i*exp(-t/tau_Lp)-VDW);

% Solved using ode45 solver for time period equivalent TON in lenght
[T,V] = ode45(dvdt, tspan, Vc2_i);

% Plot
plot(T,V)

% Voltage of C2 at the end of TON period
% is last element of array of voltages calculated for time span
% length of TON
ton_f = T(ptsNum,1);
v_ton_f = V(ptsNum,1);

% Display answer
disp("**************************************")
disp("C2 voltage at the end of TON period is:")
disp(v_ton_f)
disp("Volts;")
disp("After:")
disp(ton_f)
disp("Seconds;")
disp("**************************************")
```

Calculated C2 voltage is

$$V_{C2}(t_{on(f)}) = -1.85V$$

Enenergy stored in manetic field during $\mathbf{T_{ON}}$

$$v_{L_P}(t) = V_{DC}e^{-\frac{t}{\tau_{L_P}}} \tag{1}$$

$$i_{L_P}(t) = I_{L_P(Max)}(1 - e^{-\frac{t}{\tau_{L_P}}}) \tag{2}$$

$$p_{L_P}(t) = v_{L_P}(t)i_{L_P}(t) \tag{3}$$

$$E_{L_P} = \int p_{L_P}(t)dt \tag{4}$$

Solving integral from $t_{on(i)}$to $t_{on(f)}$(=T_{ON}):

$$\Delta E_{L_P} = \int_0^{T_{ON}} p_{L_P}(t)dt = \int_0^{T_{ON}} V_{DC}e^{-\frac{t}{\tau_{L_P}}} I_{L_P(Max)}(1 - e^{-\frac{t}{\tau_{L_P}}})dt$$

Numerical solution for integral. Octave code:

```
clear all
clc

I_Lp_Max = 84.5;          % A
tau_Lp = 272*10^-6;       % S
TON = 4.8*10^-6;          % S
VDC = 310;                % V
ptsNum = 100;             % number of time points for calculations

% Function to integrate
p_Lp = @(t) VDC.*exp(-t./tau_Lp).*I_Lp_Max.*(1-exp(-t./tau_Lp));

% Integration
deltaE = integral(p_Lp, 0, TON);

% Display answer
disp("**************************************************")
disp("Energy stored in magnetic field during TON period")
disp(deltaE)
disp("Joules;")
disp("**************************************************")
```

Calculated energy:

$$\Delta E_{L_P} \approx 1090\mu J$$

Calculations of output EC capacitors voltage, energy and charge @$\mathbf{t_{on(f)}}$

$$V_{EC}(t_{on(f)}) = V_{EC}(t_{on(i)})e^{-\frac{T_{ON}}{\tau_{VD}}} = 34.42V \cdot e^{-\frac{4.8\mu S}{10.43S}} \approx 34.42V$$

$$E_{EC}(t_{on(f)}) = \frac{1}{2}C_{EC}V_{EC}^2(t_{on(f)}) = \frac{1}{2} \cdot 194\mu F \cdot (34.42V)^2 = 114919\mu J$$

$$Q_{EC}(t_{on(f)}) = C_{EC}V_{EC}(t_{on(f)}) = 194\mu F \cdot 34.42V = 6678\mu C$$

2.3 "OFF1" Phase

Duration: T_{OFF1};

Initial time moment: $t_{off1(i)}$ - Secondary coil just started to conduct (reflected voltage switches OFF MOSFET)

Final moment: $t_{off2(f)}$- Secondary coil just finished demagnetisation

Known/definite values

$$I_{L_S}(t_{off1(f)}) = 0A$$

$$V_{EC}(t_{off1(i)}) = V_{EC}(t_{on(f)}) = 34.42V$$

$$E_{EC}(t_{off1(i)}) = E_{EC}(t_{on(f)}) = 114919\mu J$$

$$Q_{EC}(t_{off1(i)}) = Q_{EC}(t_{on(f)}) = 6678\mu C$$

$$V_{C2}(t_{off1(i)}) = V_{C2}(t_{on(f)}) = -1.85V$$

Current in secondary coil @ $t_{off1(i)}$

$$I_{L_S}(t_{off1(i)}) = \sqrt{\frac{2\Delta E_{L_P}}{L_S}} = \sqrt{\frac{2 \cdot 1090\mu J}{93\mu H}} = 4.84A$$

EC capacitors voltage, energy and charge @ $t_{off1(f)}$

$$E_{EC}(t_{off1(f)}) = E_{EC}(t_{off1(i)}) + \Delta E_{L_P} = 114919\mu J + 1090\mu J = 116009\mu J$$

$$V_{EC}(t_{off1(f)}) = \sqrt{\frac{2E_{EC}(t_{off1(f)})}{C_{EC}}} = \sqrt{\frac{2 \cdot 116009\mu J}{194\mu F}} = 34.58V$$

$$Q_{EC}(t_{off1(f)}) = C_{EC}V_{EC}(t_{off1(f)}) = 194\mu F \cdot 34.58V = 6709\mu C$$

$$\Delta Q_{EC} = Q_{EC}(t_{off1(f)}) - Q_{EC}(t_{off1(s)}) = 6709\mu C - 6678\mu C = 31\mu C$$

$$\Delta V_{EC} = V_{EC}(t_{off1(f)}) - V_{EC}(t_{off1(s)}) = 34.58V - 34.42V = 0.16V$$

Secondary coil demagnetization time $\mathbf{T_{OFF1}}$ Using RLC series circuit formula

$$V_{EC}(t_{off1(s)}) = L_S \frac{di}{dt}$$

$$\frac{di}{dt} = -\frac{V_{EC}(t_{off1(s)})}{L_S}$$

$$\omega_0 = \frac{1}{\sqrt{L_s C_{EC}}}$$

$$\alpha = \frac{Rs}{2L_S}$$

$$\beta = \sqrt{\alpha^2 - \omega_0^2}$$

Formula for current:

$$i = A_1 e^{(-\alpha+\beta)t} + A_2 e^{(-\alpha-\beta)t}$$

boundary conditions: at t=$\mathrm{t_{off1(s)}}$: i= $I_{L_S}(t_{off1(s)})$, $\frac{di}{dt} = -\frac{V_{EC}(t_{off1(s)})}{L_S}$ from which:

$$\begin{cases} I_{L_S}(t_{off1(s)}) = A_1 + A_2 \\ -\frac{V_{EC}(t_{off1(s)})}{L_S} = A_1(-\alpha+\beta)e^{(-\alpha+\beta)t} + A_2(-\alpha-\beta)e^{(-\alpha-\beta)t} \end{cases}$$

$$A_1 = \frac{-\frac{V_{EC}(t_{off1(s)})}{L_S} + (\alpha+\beta)\cdot I_{L_S}(t_{off1(s)})}{2\beta} =$$

$$A_2 = I_{L_S}(t_{off1(s)}) - A_1$$

Now, demagnetisation stops when secondary coil current transfer charge ΔQ_{EC} into capacitors

$$\Delta Q_{EC} = \int_0^{T_{OFF1}} i dt = \int_0^{T_{OFF1}} (A_1 e^{(-\alpha+\beta)t} + A_2 e^{(-\alpha-\beta)t}) dt$$

Numerical solution of integral equation. Octave code:

```
clear all
clc

Cec = 194*10^-6;          % F
DQ = 31*10^-6;            % C
I_Ls_i = 4.84;            % A
Ls = 93*10^-6;            % H
```

```
Rs = 0.6;                  % Ohm
Vec_i = 34.42;             % V

DIDT = -Vec_i/Ls;
w0 = 1/sqrt(Ls*Cec);
a = Rs/(2*Ls);
b = sqrt(a^2-w0^2);
A1 = (-(Vec_i/Ls)+(a+b)*I_Ls_i)/(2*b);
A2 = I_Ls_i-A1;

% Function to integrate
i_t = @(t) A1*exp((-a+b)*t) + A2*exp((-a-b)*t);

% Integral equation "DQ = integral of i_t from 0 to T"
% in a form suitable for solver fsolve
Q = @(T) (integral(i_t, 0, T)-DQ);

% Initial gues need for solver fsolve
initGuess = 1*10^-6;

% Solution
TOFF1 = fsolve (Q,initGuess);

% Display answer
disp("*********************")
disp("TOFF1 period length is")
disp(TOFF1)
disp("Seconds;")
disp("*********************")
```

Calculated $\mathrm{T_{OFF1}}$:

$$T_{OFF1} = 10.7\mu S$$

Secondary coil induced voltage @$\mathbf{t_{off1(i)}}$

$$V_S(t_{off1(i)}) = L_S\frac{\Delta I_{L_S}}{T_{OFF1}} = L_S\frac{I_{L_S}(t_{off1(i)}) - I_{L_S}(t_{off1(f)})}{T_{OFF1}} = 93\mu H\cdot\frac{4.84A - 0A}{10.7\mu S} = 42.07V$$

Auxilary coil induced voltage and voltage from transformer's pin2 @$\mathbf{t_{off1(i)}}$

$$V_{Aux}(t_{off1(i)}) = \frac{N_{Aux}}{N_S}V_S(t_{off1(i)}) = \frac{6}{22}\cdot 42.07V = 11.47V$$

$$V_{TR2}(t_{off1(i)}) = -V_{Aux}(t_{off1(i)}) = -11.47V$$

Voltage on MOSFET's gate @$\mathbf{t_{off1(i)}}$ (transformer's pin2 coupled via C2)

$$V_{GS}(t_{off1(i)}) = V_{TR2}(t_{off1(i)}) - 11.47V$$

Voltage across C2 @$\mathbf{t_{off1(f)}}$calculations: From. $t_{off1(i)}$to $t_{off1(f)}$voltage from transformer's pin2 decreaces to zero, because @$t_{off1(f)}$of Ls demagnitized amd there is no reflected voltage in auxilary coil. Assume linear decreasing for simplicity

$$v_{TR2}(t) = V_{TR2}(t_{off1(i)}) \cdot (1 - \frac{t}{T_{OFF1}})$$

Set up differential equation:

$$v_{TR2}(t) - v_{R_2}(t) - v_{C_2}(t) - v_{R_7}(t) - v_{R_1}(t) - V_{DC} = 0$$

$$v_{TR2}(t) - i(R_1 + R_2 + R_7) - v_{C_2}(t) - V_{DC} = 0$$

$$v_{TR2}(t) - (R_1 + R_2 + R_7)C_2\frac{v_{C_2}(t)}{dt} - v_{C_2}(t) - V_{DC} = 0$$

$$V_{TR2}(t_{off1(i)}) \cdot (1 - \frac{t}{T_{OFF1}}) - \tau_{C2_A}\frac{v_{C_2}(t)}{dt} - v_{C_2}(t) - V_{DC} = 0$$

$$\tau_{C2_A}\frac{v_{C_2}(t)}{dt} + v_{C_2}(t) = V_{TR2}(t_{off1(i)}) \cdot (1 - \frac{t}{T_{OFF1}}) - V_{DC}$$

$$\frac{v_{C_2}(t)}{dt} = \frac{1}{\tau_{C2_A}}[-v_{C_2}(t) + V_{TR2}(t_{off1(i)}) \cdot (1 - \frac{t}{T_{OFF1}}) - V_{DC}]$$

Numerical solution of differential equation. Octave code:

```
clear all
clc
tau_C2A = 44022*10^-6;        % S
TOFF1 = 10.7*10^-6;           % S
Vc2_i = -1.85;                   % V, C2 voltage at start
VDC = 310;                    % V
Vtr2_i = -11.47;              % V, Vtr2 voltage at start
ptsNum = 100;                 % number of time points for calculations

% time points (need for numeric calculations)
tspan = linspace(0,TOFF1,ptsNum);

% Differential equation for C2 voltage
% (in a form of anonymus function in a form necessary for ode45 solver)
dvdt = @(t,v) (1/tau_C2A)*(-v+Vtr2_i*(1-t/TOFF1)-VDC);
```

```
% Solved using ode45 solver for time period equivalent TOFF1 in lenght
[T,V] = ode45(dvdt, tspan, Vc2_i);

% Plot plot(T,V)

% Voltage of C2 at the end of TON period
% is last element of array of voltages calculated for time span
% length of TOFF1
toff1_f = T(ptsNum,1);
v_toff1_f = V(ptsNum,1);

% Display answer
disp("**************************************")
disp("C2 voltage at the end of TOFF1 period is:")
disp(v_toff1_f)
disp("Volts;")
disp("After:")
disp(toff1_f)
disp("Seconds;")
disp("**************************************")
```

Calculated C2 voltage is

$$V_{C2}(t_{off1(f)}) = -1.93V$$

Voltage on MOSFET's gate @$\mathbf{t_{off1(f)}}$ (controlled by C2)

$$V_{GS}(t_{off1(f)}) = -V_{C2}(t_{off1(f)}) = 1.93V$$

2.4 "FEEDBACK" Phase

Duration: $\mathrm{T_{FB}}$;

Initial time moment: $\mathrm{t_{fb(i)}}$ - EC capacitors voltage just begin to discharge (C2 just pulled of to ground via R5 and R6)

Final moment: $\mathrm{t_{fb(f)}}$- EC capacitors voltage just decreased to threshold value

Known/definite values

$$V_{EC}(t_{fb(i)}) = V_{EC}(t_{off1(i)}) = 34.58V$$

$$V_{C2}(t_{fb(i)}) = V_{C2}(t_{off1(f)}) = -1.93V$$

Output capacitors discharge currents @$\mathbf{t_{fb(i)}}$

$$I_{VD}(t_{fb(i)}) = \frac{V_{EC}(t_{fb(i)})}{R_{14}+R_{11}} = \frac{34.58V}{3.9k\Omega + 49.9k\Omega} = 0.64mA$$

$$I_{LED}(t_{fb(i)}) = \frac{V_{EC}(t_{fb(i)}) - V_{F(LED)} - V_{K(IC2)}}{R_{13}} = \frac{34.58V - 1.3V - 2V}{3k\Omega} = 10.43mA$$

Output capacitors discharge to threshol time $\mathbf{T_{FB}}$ Assume ECs be discharged to threshold level after lost of charge accumulated above threshold level

$$i_{VD}(t) = I_{VD}(t_{fb(i)})e^{-\frac{t}{\tau_{VD}}}$$

$$i_{LED}(t) = I_{LED}(t_{fb(i)})e^{-\frac{t}{\tau_{LED}}}$$

$$\Delta Q_{EC} = \int_0^{T_{FB}} (i_{VD}(t) + i_{LED}(t))dt$$

$$\Delta Q_{EC} = \int_0^{T_{FB}} (I_{VD}(t_{fb(i)})e^{-\frac{t}{\tau_{VD}}} + I_{LED}(t_{fb(i)})e^{-\frac{t}{\tau_{LED}}})dt$$

Numerical solution of integral equation. Octave code:

```
clear all
clc

DQ = 31*10^-6;            % C
I_Led_i = 10.43*10^-3;    % A
I_VD_i = 0.64*10^-3;      % A
tau_Led = 582*10^-3;      % S
tau_VD = 10.43;           % S

% Function to integrate
i_t = @(t) I_VD_i*exp(-t/tau_VD) + I_Led_i*exp(-t/tau_Led);

% Integral equation "DQ = integral of i_t from 0 to T"
% in a form suitable for solver fsolve
Q = @(T) (integral(i_t, 0, T)-DQ);

% Initial gues need for solver fsolve
initGuess = 1*10^-6;

% Solution
TFB = fsolve (Q,initGuess);
```

```
% Display answer
disp("************************")
disp("Feedback period length is")
disp(TFB)
disp("Seconds;")
disp("************************")
```

Calculated T_{FB} is

$$T_{FB} = 2807\mu S$$

Voltage across C2 @$t_{fb(f)}$calculations:

$$V_{C2}(t_{FB(f)}) = V_{C2}(t_{FB(i)})e^{-\frac{T_{FB}}{\tau_{C2_C}}} = -1.93V \cdot e^{-\frac{2807\mu S}{26.9\mu S}} \approx 0V$$

2.5 "OFF2" Phase

Duration: T_{OFF2};

Initial time moment: $t_{off2(i)}$ - C2 just started to recharge.

Final moment: $t_{off2(f)}$- MOSFET's gate just reached threshold level

Known/definite values

$$V_{C2}(t_{off2(i)}) = V_{C2}(t_{fb(f)}) = 0V$$

$$V_{GS}(t_{off2(i)}) = -V_{C2}(t_{off2(i)}) = 0V$$

$$V_{GS}(t_{off2(f)}) = V_{GS(Th)} = 4V$$

$$V_{C2}(t_{off2(f)}) = -V_{GS}(t_{off2(f)}) = -4V$$

Time capacitor C2 recharge to MOSFET's gate threshold T_{OFF2}

$$T_{OFF2} = \tau_{C2_A} ln\frac{(V_{C2}(t_{off2(i)}) - (-V_{DC}))}{(V_{C2}(t_{off2(f)}) - (-V_{DC}))} = 44022\mu S \cdot ln\frac{(0V + 310V)}{(-4V + 310V)} = 572\mu S$$