Analysis and Design of Active Clamped ZVS Current-Fed DC-DC Converter for Fuel-Cell to Utility-Interface Application

Department of Electrical and Computer Engineering

ECE 581 POWER ELECTRONICS

PROJECT REPORT

SUBMITTED BY

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Date: AUG 12TH 2020

PHASE ONE:

1)Explain the operation of the converter for different intervals of operation and give a systematic analysis of the converter.

DETAILED EXPLANATION:

The high-power step-up dc/dc conversion technique finds increasing necessities and power capability demands in applications such as electric vehicles, uninterruptible power
supplies (UPS), servo-drive systems, semiconductor fabrication equipment, and photovoltaic systems, where the low dc input voltage must be converted into the higher dc output voltage A High-frequency (HF) transformer isolated DC-DC converter is part of a fuel-cell to utility-interface power converter, required to translate the level of low fuel-cell stack voltage to meet the peak utility line voltage. Two inductor current fed isolated DC-DC converter is suitable when application requires higher input current and high boost ratio. The underlying concept is derived via duality principle from half bridge voltage fed inverter.
Some of the advantages are:
(1) Voltage stress of each switch is only half of that of single-inductor topology.
(2) Input current is shared by two inductors reducing the current stress, while decreasing the input-output current ripple.
(3) Ripple current through the output filter capacitor is reduced.
(4) The volt-ampere rating of isolation transformer is reduced compared to the conventional push-pull type current-fed converter since the primary does not require a centre-tap.
(5) Output rectifier diodes operate with zero-current switching (ZCS) and voltage across the rectifier diodes is same as the output voltage.
(6) It has higher efficiency, high power density and high component utilization,especially under the low output voltage of the fuel-cell stack and large voltage variations

Limitations: The major limitations of converters are hard switching of HF switches and requirement of an auxiliary circuit to absorb the voltage spike at the switch turn-off.

ASSUMPTIONS MADE FOR ANALYSIS AND OPERATIONS:
The operation and analysis of the converter is presented based on the following assumptions:

(a)Effect of the magnetizing inductance of the HF transformer is neglected.
(b) Switches and diodes are assumed ideal.
(c) Auxiliary capacitor C_a is large enough to maintain constant voltage across it.
(d) Boost inductors are sufficiently large to maintain constant current through them.

CIRCUIT SET-UP AND OVERVEIW FOR ANALYSIS OVER DIFFERENT INTERVALS OF OPERATIONS:

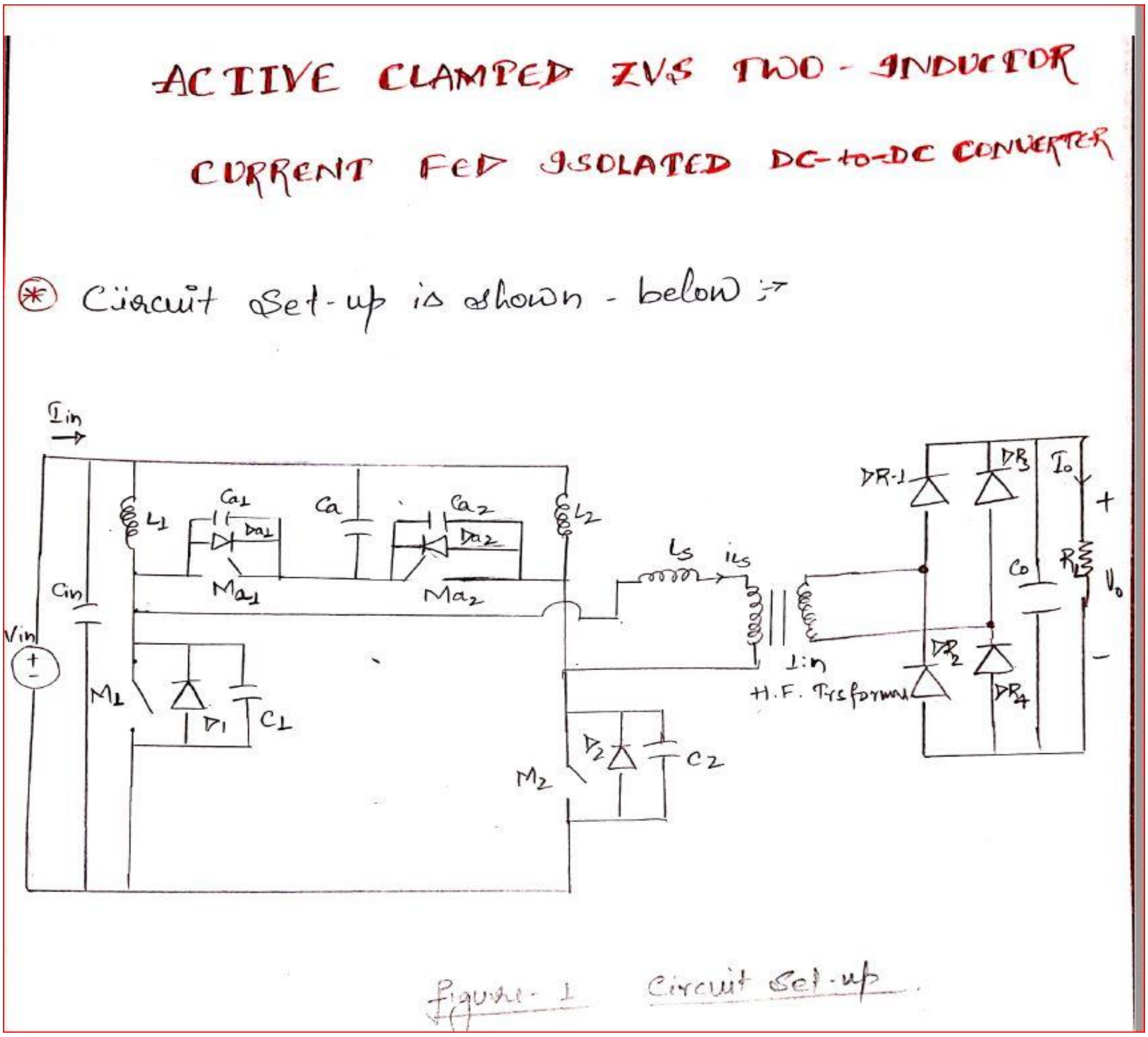


Fig 1 Circuit overview

INTERVAL 1: For the interval ranging from $t_0 < t < t_1$

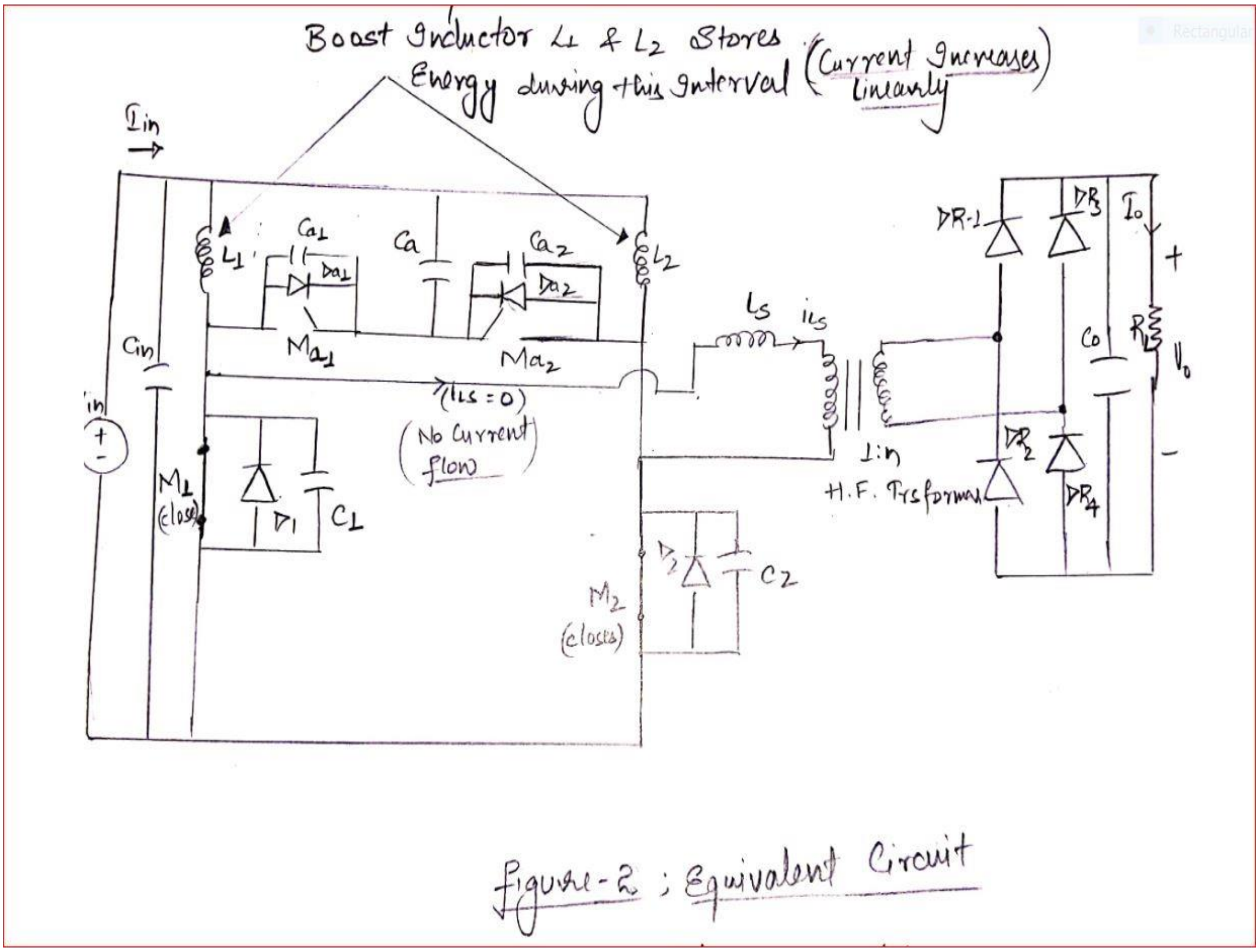


Figure 2 Equivalent circuit during interval 1

Key parameter and operation process during interval 1:

* During this interval $t_0 < t < t_1$, Both Main Switches M_1 & M_2 are Turned-ON (i.e. Gate pulse Corresponding to Switches in Applied), and M_1 & M_2 both switch Closes as shown Above in Equivalent Circuit diagram-2

* By Applying the KVL and finding Voltage Across Auxilary Capacitor C_{a1} (V_{ca}) we get in terms of Voltage Across Auxilary Switches as ⇒

$$\boxed{V_{ca1} = V_{Ma1} = V_{Ma2} = V_{ca} + V_{in} = \frac{V_{in}}{1-D}}$$

here D is Duty Ratio of Main Switches M_1 & M_2.

$D = \frac{T_{ON}}{T_S}$; T_{ON} : Conduction period of switch.
T_S : Switching period.

* RMS & Average Value of Main Switches M_1 & M_2 is Equal to Boost Inductor Current

$$\boxed{i_{M1} = i_{M2} = \frac{I_{in}}{2}}$$

* Current through the Series tank Inductor L_s or High frequency transformer is zero.

i.e. $i_{Ls} = 0$ during this Interval.

* I_L, Load Current is supplied solely by output Capacitor C_o, i.e. power is trsferred to load by o/p Capacitor C_o.

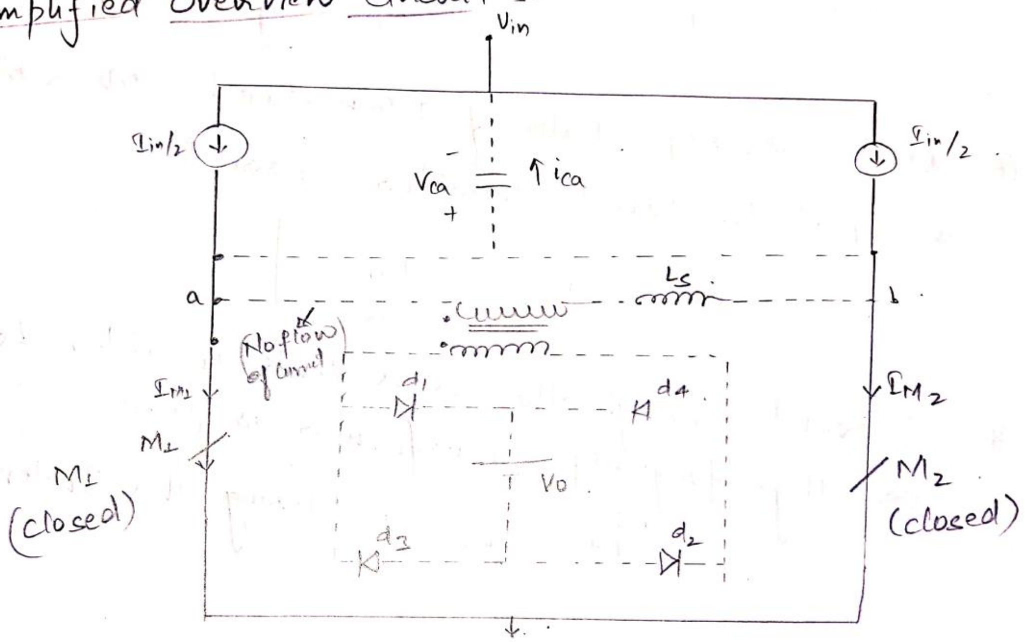
* The Current flowing through Boost Inductor L_1 & L_2 increases linearly during this phase.

* This phase is Considered as "Boosting phase"

* Voltage Across the o/p Rectifier diode.

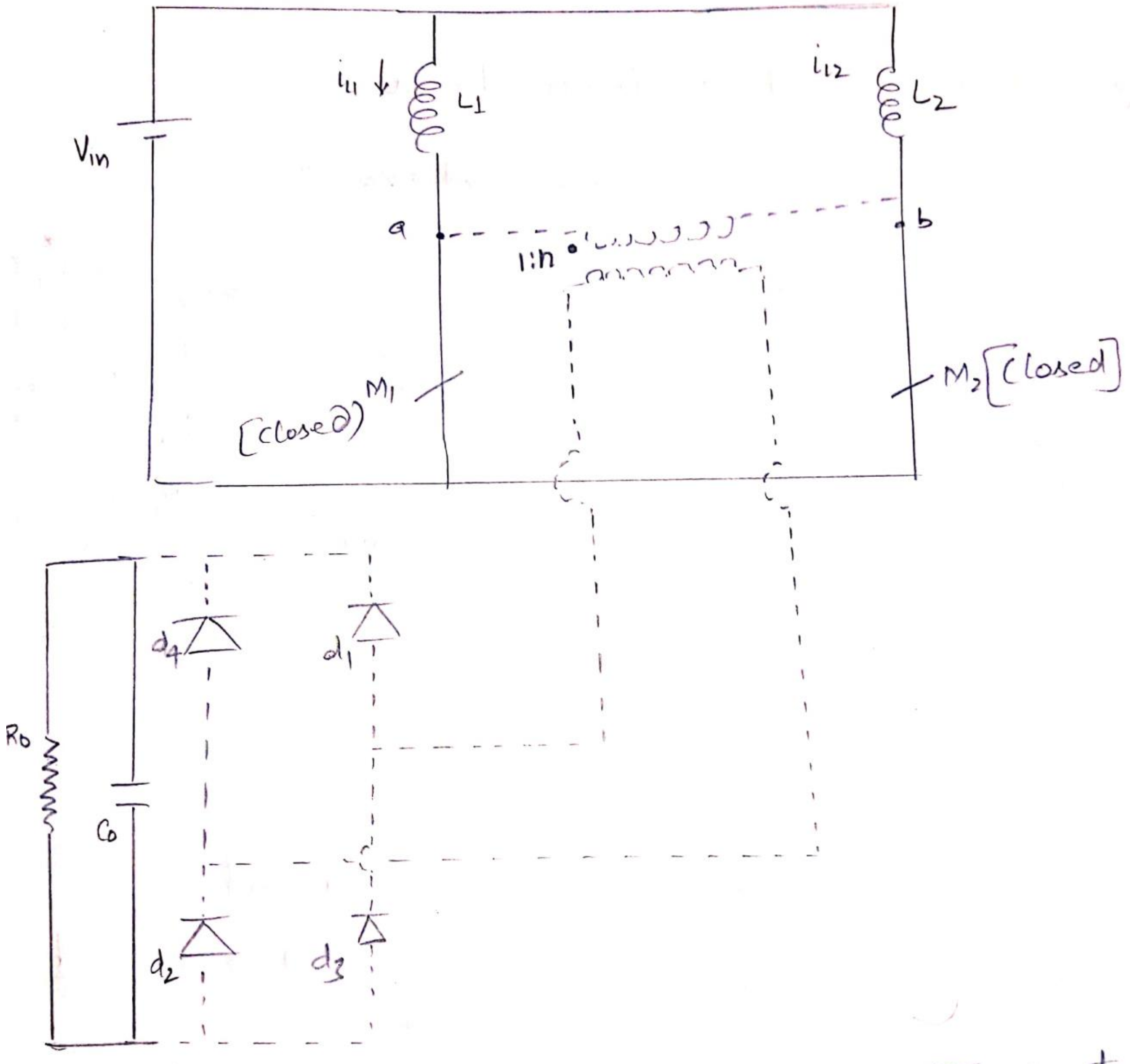
$$\boxed{V_{DR} = \frac{V_o}{2}}$$ during this Interval.

Simplified Overview Circuit ->



Dotted line signifies Circuit Not Active during this Interval.

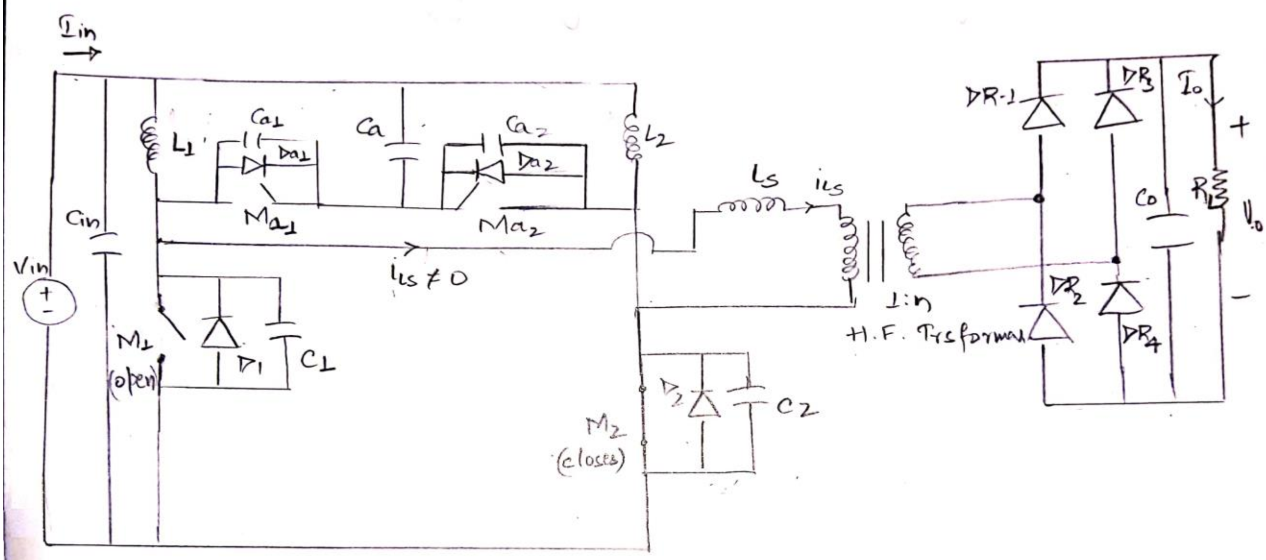
BOOSTING MODE



Dotted part Show's Non-Conducting parts

INTERVAL 2: For time interval ranging $t_1 < t < t_2$

Circuit set-up is shown below :-



Equivalent Ckt during Interval.

Key parameter and operation process during interval 2:

* This phase of operation is Considered as "POWERING PHASE".

* At t_1, M_1 is turned off (as shown Above) and Current I_{L1} Begins to flow through the transformer towards the Load-side Via Rectifier diode.

* The Boost Inductor L_1 Current $\left(\frac{I_{in}}{2}\right)$ Charges the ~~Sun~~ Snubber Capacitor C_1 and discharges the the Auxiliary Snubber Capacitor Ca_1 linearly.

* Current i_{c1} and i_{ca1} are Assumed to be Constant during this interval.

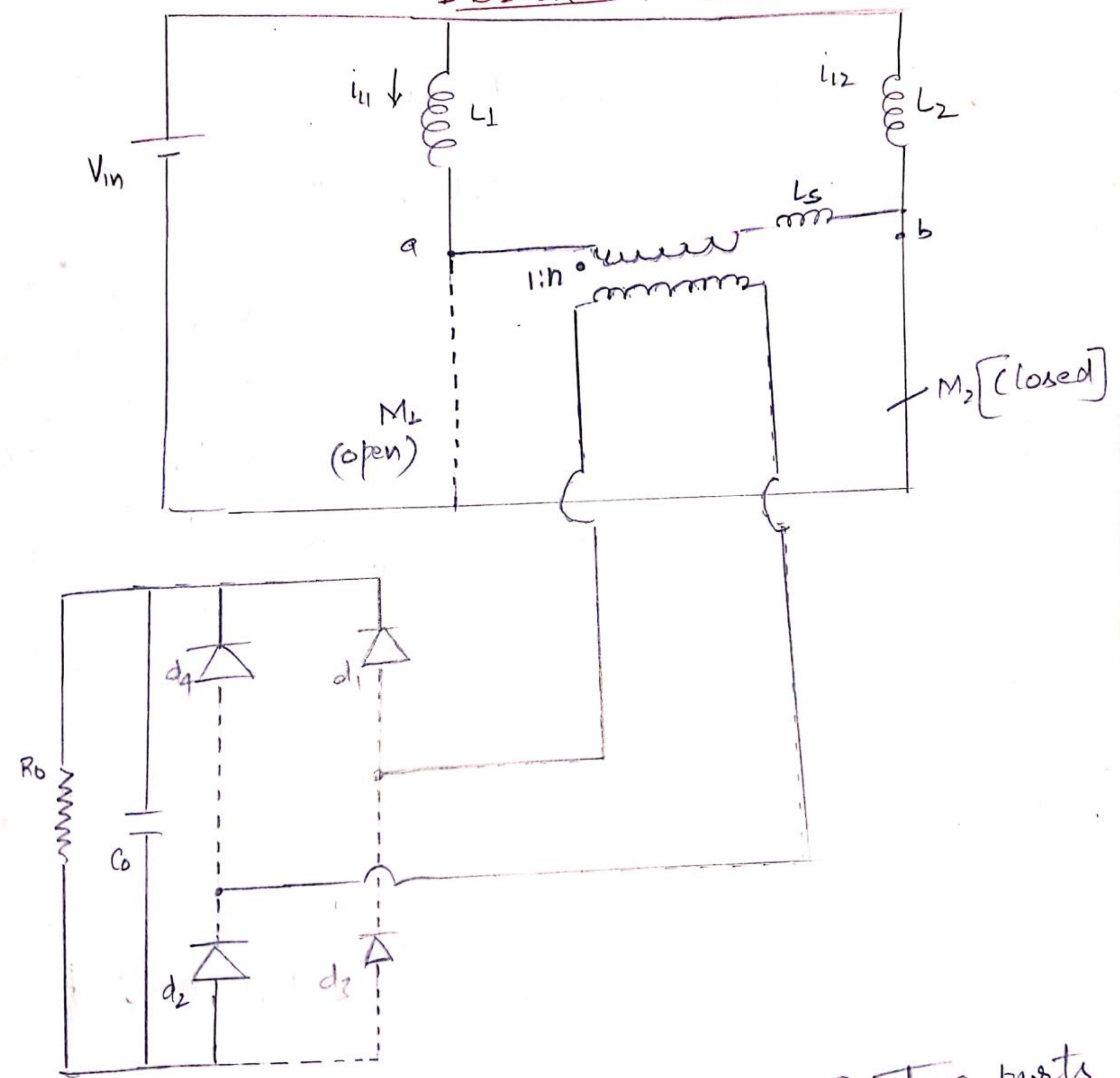
* By Applying KVL is Above circuit we can Get Voltage Across Series Inductor L_s = $\left(V_{in} - V_{ca} - \frac{V_o}{n}\right)$

Current Across L_s starts increasing Linearly.

* DR_1 & DR_2 Comes into Action/picture of operation and they start Conducting.

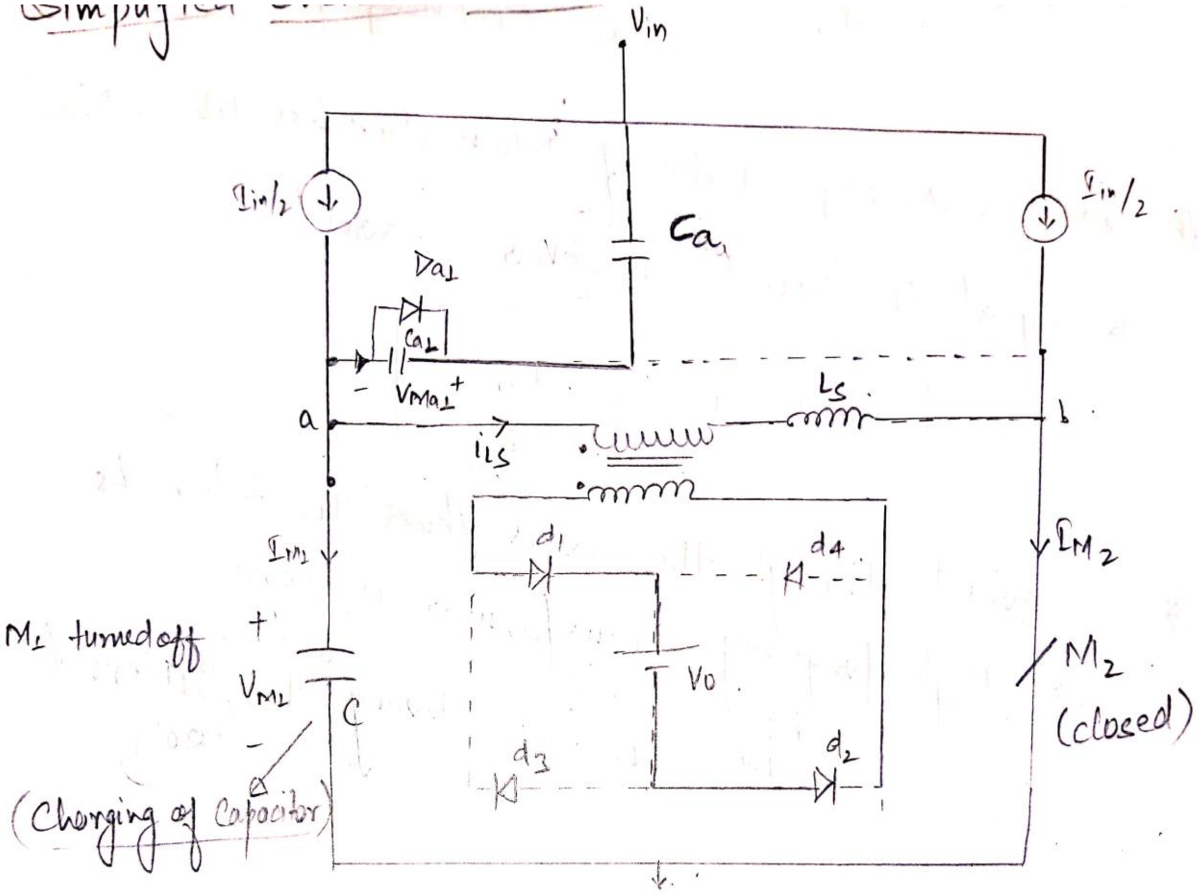
* Power is transferred to o/p during this Interval.

POWERING PHASE



Dotted part Show's Non-Conducting parts

Simplified



Dotted line Signifies Circuit Not Active during this Interval.

(*) Current through Series Inductor, i_{Ls} is Given as

$$i_{Ls} = \left(\frac{V_{ca} + V_{in} - \frac{V_o}{n}}{L_s} \right) \times (t - t_1) \text{ Amp}$$

(*) Current through Main switches is $\boxed{i_{M_2} = \frac{I_{in}}{2} + i_{Ls}}$

(*) At the End of this Interval, i_{c_1} & i_{ca_1} Reaches Zero at $t = t_2$, which Implies.

(a) C_{a_1} is discharged Completely i.e. $V_{ca_1}(t_2) = 0$

& $I_{ca_1}(t_2) = 0$

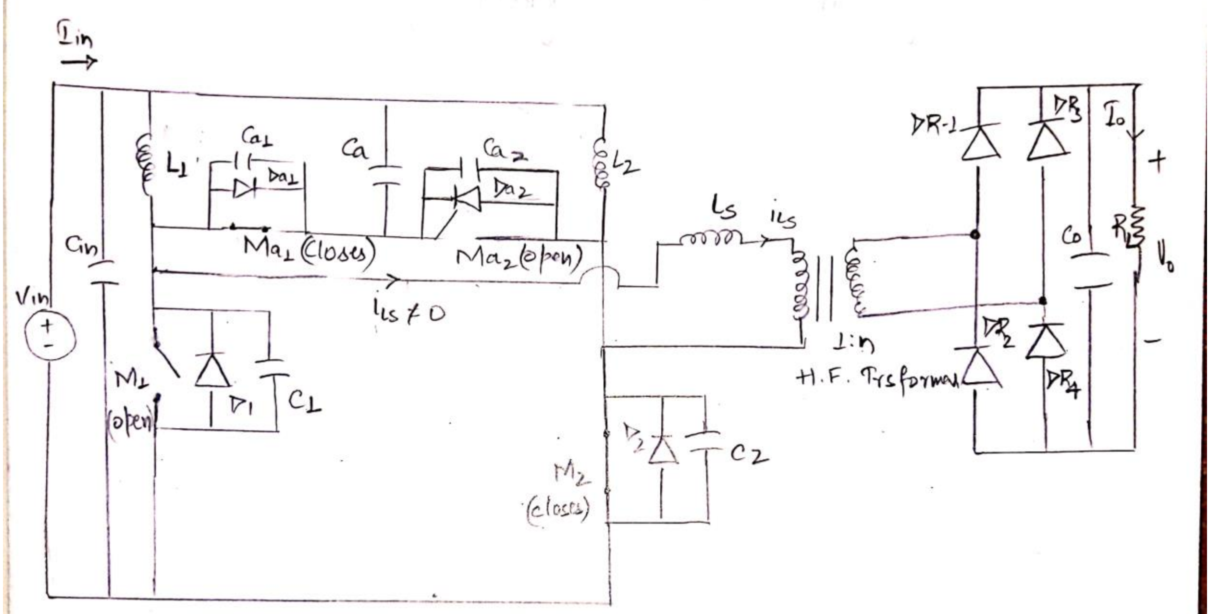
(b) Main Switch Snubber Capacitor C_1 is changed to it's full Voltage i.e.

$$\boxed{V_M(t_2) = V_{c_1}(t_2) = V_{in} + V_{ca} = \frac{V_{in}}{1-D}}$$

(*) By Applying Volt-sec Balance Rule on the Boost Inductor, the steady-state o/p Voltage Can be obtained as :→

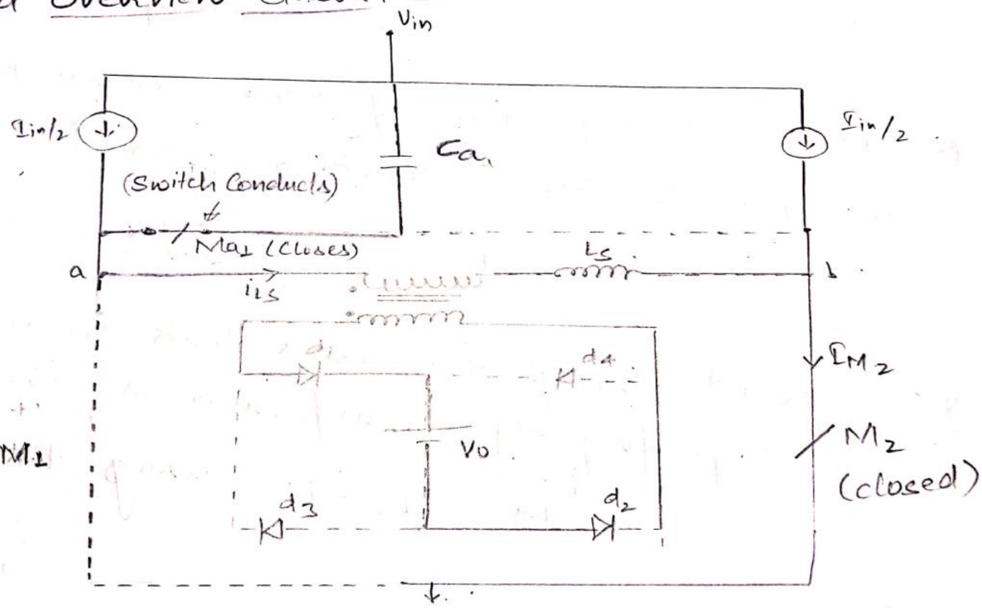
$$\boxed{V_o = \left(\frac{n}{1-D}\right) V_{in}} \quad \text{(for Duty Cycle > .5)}$$

INTERVAL 3: For time interval ranging $t_2 < t < t_3$



Equivalent Ckt during Interval.

Simplified Overview Circuit ⇒



Dotted line signifies Circuit Not Active during this Interval.

(*) for Interval $t_2 < t < t_3$, the Antiparallel body diode D_{a1} of Auxilary Switch M_{a1} Start's Conducting

(*) I_{Ls} increases with slope of $\frac{\left(V_{in} + V_{ca} - \frac{V_o}{n}\right)}{L_s}$.

$$i_{M2} = \frac{I_{in}}{2} + i_{Ls}.$$

at time t_2 (Start of Interval), Auxilary Capacitor Current i_{ca} has peak given by

$$\boxed{\left(I_{ca}\right)_{peak} = \frac{I_{in}}{2} - I_{Ls}(t_2)}$$

where $I_{Ls}(t_2) = \left(\frac{V_{ca} + V_{in} - \left(\frac{V_o}{n}\right)}{L_s}\right) \times (t_2 - t_1)$

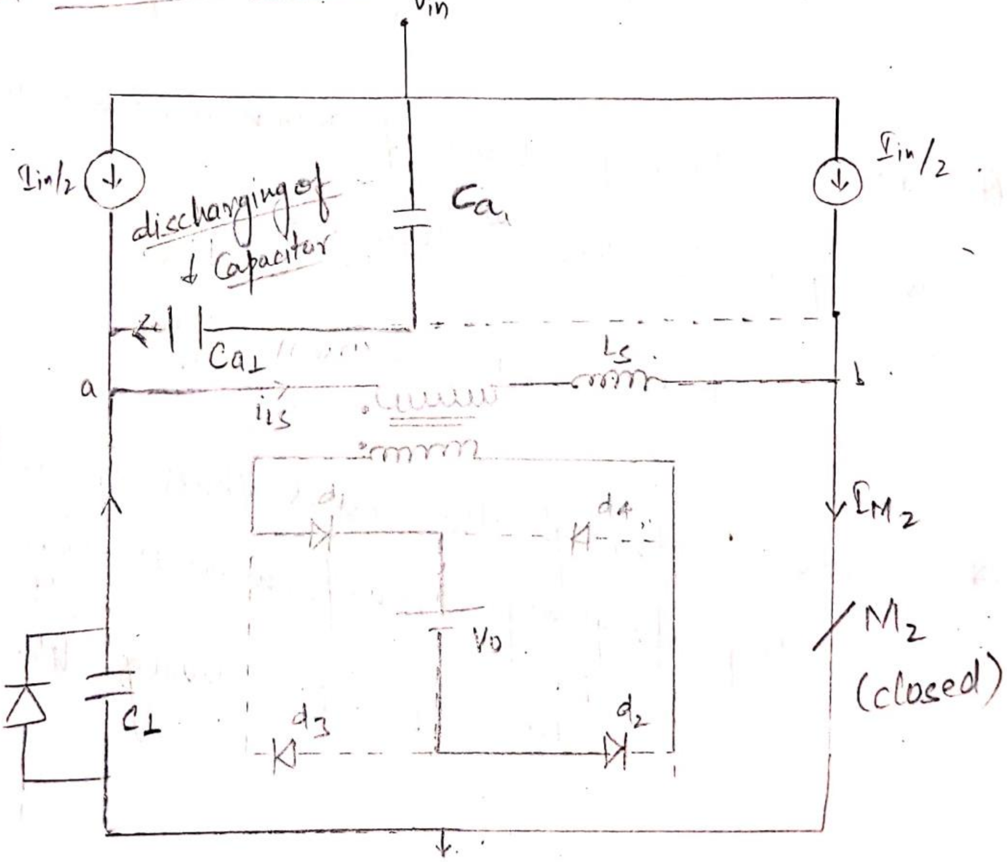
(*) A the End of this interval i.e. $(t = t_3)$, i_{ca} reaches zero & Series inductor Current Reaches $\frac{I_{in}}{2}$. The Auxilary Switch M_{a1} Can be Gated for ZVS turn on.

(*) final Values at the End of Interval.

$I_{Ls}(t_3) = \frac{I_{in}}{2}$; $I_{M_2}(t_3) = I_{in}$; $I_{ca}(t_3) = 0$

INTERVAL 4: For time interval ranging $t_3 < t < t_4$

Simplified Overview Circuit :>



Dotted line signifies circuit Not Active during this interval.

* In this Interval $t_3 < t < t_4$, Auxilary switch M_{a1} is turned on with ZVS. The Auxilary capacitor Current i_{ca} decreases Linearly (in -ve direction).

* The Series Inductor Current Increases Above $I_{in}/2$ with same Slope given by

$$i_{ca} = \frac{I_{in}}{2} - i_{Ls}.$$

* At t_4, Auxilary switch M_{a1} is turned off and According to the Amp-sec balance for the Auxilary Capacitor C_a, the Auxilary Current Rises to Negative (I_{ca}) peak. So, Approximately at the End of Interval.

$$I_{Ls}(t_4) = I_{Lsp} = I_{in}$$

$$I_{M2p} = \frac{3I_{in}}{2}.$$

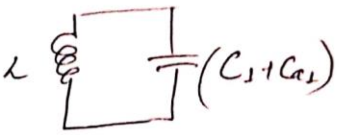
* Dead-band gap is required to be sufficient of time so as to allow the charging of Auxilary Switch Snubber Capacitor & Discharging of main Switch Snubber Capacitor by the Boost Inductor Current $\frac{I_{in}}{2}$, The Value is given by

$$T_{dg1} = \frac{(C_1 + C_{a1}) \cdot (V_{in}/(1-D))}{(I_{in}/2)}$$

INTERVAL 5: For time interval ranging $t_4 < t < t_5$

Interval-5, $t_4 < t < t_5$:->

(*) During this Interval, Series Inductor L_s starts Charging C_{a1} & discharging C_1 in a Resonant ~~fasion~~ fashion/Manner,

=> 

$$\omega_r = \frac{1}{\sqrt{L_s \cdot (C_1 + C_{a1})}}$$

(*) Voltage Across Capacitor C_1 or Switch M_1 is

$$V_{M1} = \left(\frac{V_{in}}{1-D}\right) - \left(I_{Lsp} - \frac{I_{in}}{2}\right)\sqrt{\frac{L_s}{(C_1 + C_{a1})}} \times \sin(\omega_r(t-t_4))$$

(*) $$i_{M2} = \frac{I_{in}}{2} + i_{Ls}(t - t_4)$$

(*) Voltage Across Switch M_{a1} is given by

$$v_{Ma1} = \left(I_{Lsp} - \frac{I_{in}}{2}\right) \cdot \sqrt{\frac{L_s}{(C_1 + C_{a1})}} \times \sin(\omega_r(t-t_4))$$

ZVS condition for main switches:

ZVS Condition for Main Switches M_1 & M_2 :

The Energy in Series inductor at time t_4 Must be Sufficient to charge & discharge the Capacitor C_{a1} & C_1, Respectively. The Capacitor C_{a1} is charged from Zero to $(V_{ca} + V_{in})$ and Capacitor C_1 is discharged from $(V_{ca} + V_{in})$ to Zero

$$0.5\left(L_s \cdot I_{Lsp}^2\right) \geq (0.5)(C_1 + C_{a1}) \cdot (V_{ca} + V_{in})^2$$

i.e. $$L_s \cdot I_{Lsp}^2 \geq (C_1 + C_{a1}) \cdot \left(\frac{V_{in}}{1-D}\right)^2$$

A the End of this Interval, the Capacitor C_1 discharges Completely & Capacitor C_{a1} charges to it's initial Voltage.

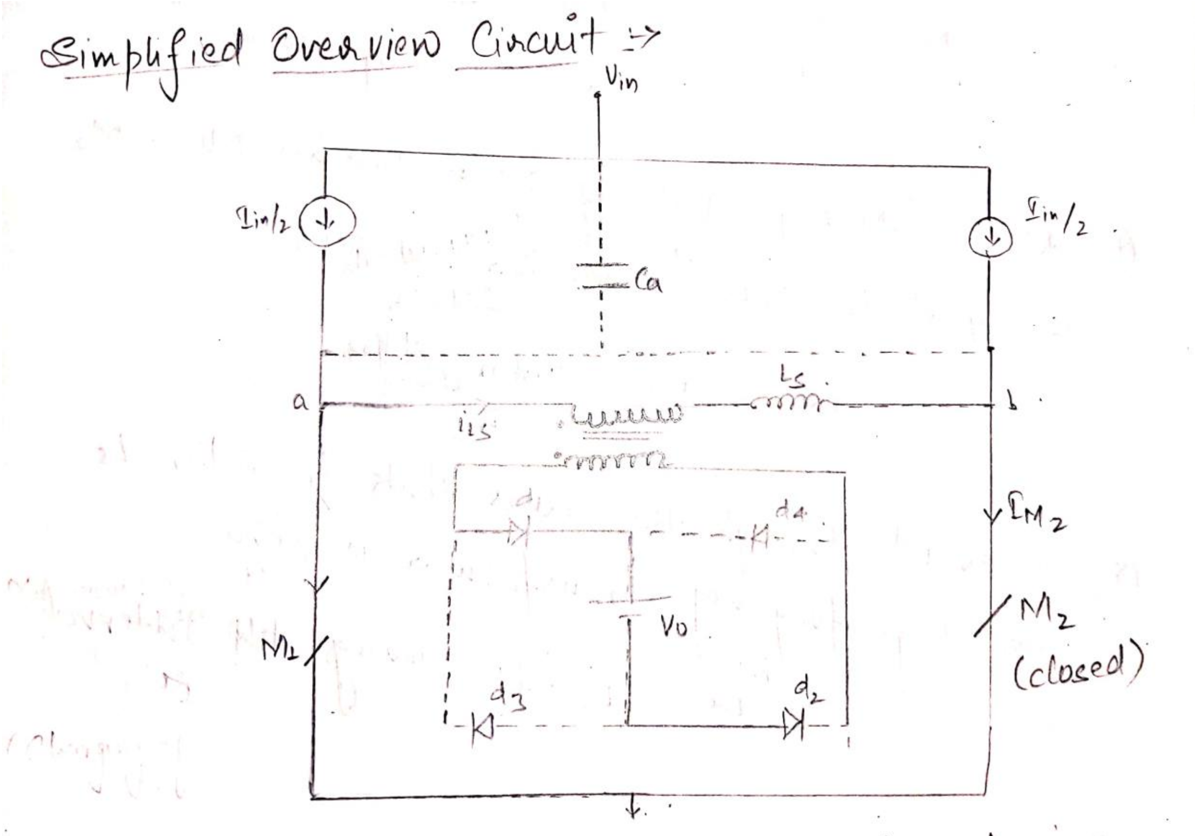
$$V_{M_1}(t_5) = 0.$$

$$V_{Ma}(t_5) = V_{ca} + V_{in}.$$

Switches M_1 and M_{a1} and operate under significantly different conditions. The switching of the switch M_1 moves the converter state from powering phase to boosting phase, while the switching of the switch M_{a1} moves it from boosting phase to powering phase. The ZVS of the switch M_{a1} is achieved by the energy stored in the boost inductor. Because the boost inductor is large enough to be considered as a constant current source, the voltage across the output capacitor of the switch M_{a1} is linearly decreased.

INTERVAL 6: For time interval ranging $t_5 < t < t_6$

Equivalent circuit for this interval:



Dotted line signifies circuit Not Active during this interval.

Operation :

* During this Interval $t_5 < t < t_6$, Anti-parallel body diode D_1 of Main Switch M_1 starts Conducting & Now the Switch M_1 Can be gated for ZVS turn. The Current i_{Ls} decreases with a Negative Slope of $[V_0/(n L_s)]$:

$$i_{Ls} = I_{Lsp} - \frac{(V_0/n)}{L_s} \cdot (t - t_5)$$

$$i_{D1} = i_{Ls} - I_{in}/2$$

* The Mode Ends when the Series Inductor Current Reaches $I_{in}/2$.

* final Value at the End of Interval.

$$I_{D1}(t_6) = 0$$

$$I_{Ls}(t_6) = I_{in}/2$$

INTERVAL 7: For time interval ranging $t_6 < t < t_7$

* During this Interval $t_6 < t < t_7$, Switch M_1 is turned on with ZVS. The Current through the Switch M_1 Starts Increasing & the Series Inductor Current Starts decreasing

$$i_{Ls} = \frac{I_{in}}{2} - \frac{(V_o/n)}{L_s}(t-t_6)$$

$$i_{M_1} = \frac{I_{in}}{2} - i_{Ls}$$

$$i_{M_2} = \frac{I_{in}}{2} + i_{Ls}$$

* This Interval Ends when the Series Inductor Current is transferred to Switch M_1. At the End of this Interval, i_{Ls} goes to Zero and Switch Current is Equal to $I_{in}/2$.

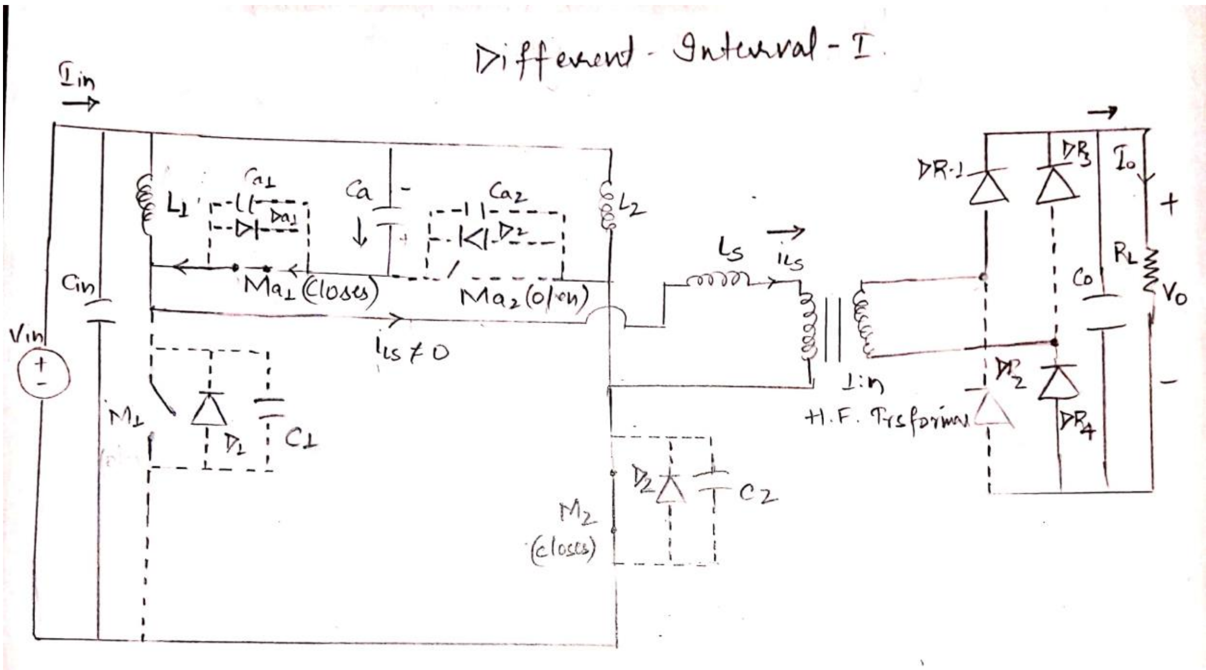
$$I_{M_1}(t_7) = \frac{I_{in}}{2}$$

$$I_{Ls}(t_7) = 0.$$

<u>Circuit analysis when boost inductors are designed for a permissible ripple current through them (practical case scenario) :</u>

- Under these circumstances, Booster inductor current can carry negative current, feeding power to input.
- These intervals appear when auxiliary capacitor discharges, i.e between interval 3 and 5, these intervals are described below:

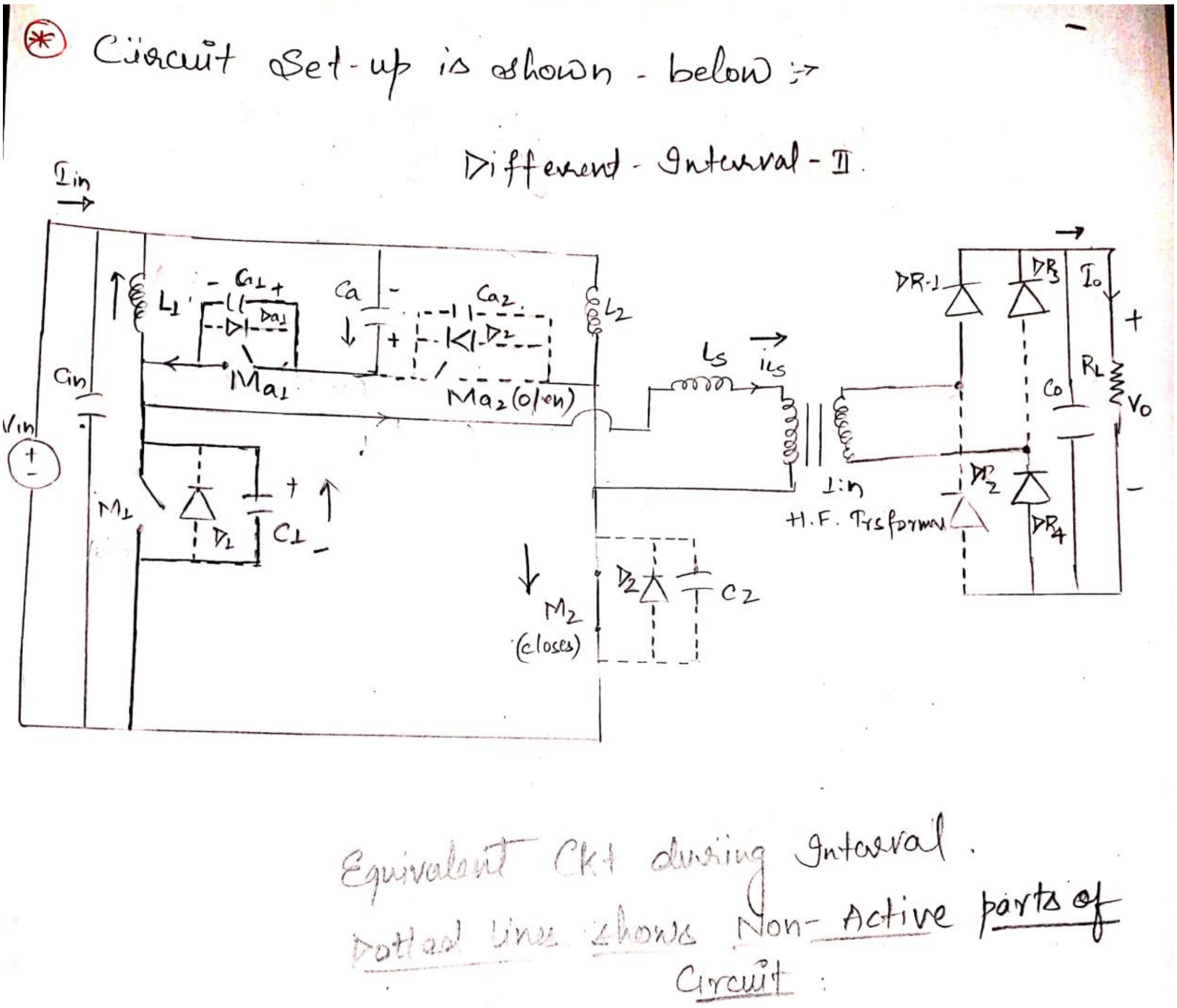
Different interval 1: During this interval, auxiliary switch M_{a1} is ON and capacitor C_a is discharging with $i_{L1} = i_{Ca} - i_{Ls}$. The boost inductor current becomes negative when $i_{Ca} > i_{Ls}$.



Equivalent Ckt during Interval.
Dotted lines shows Non-Active parts of Circuit :

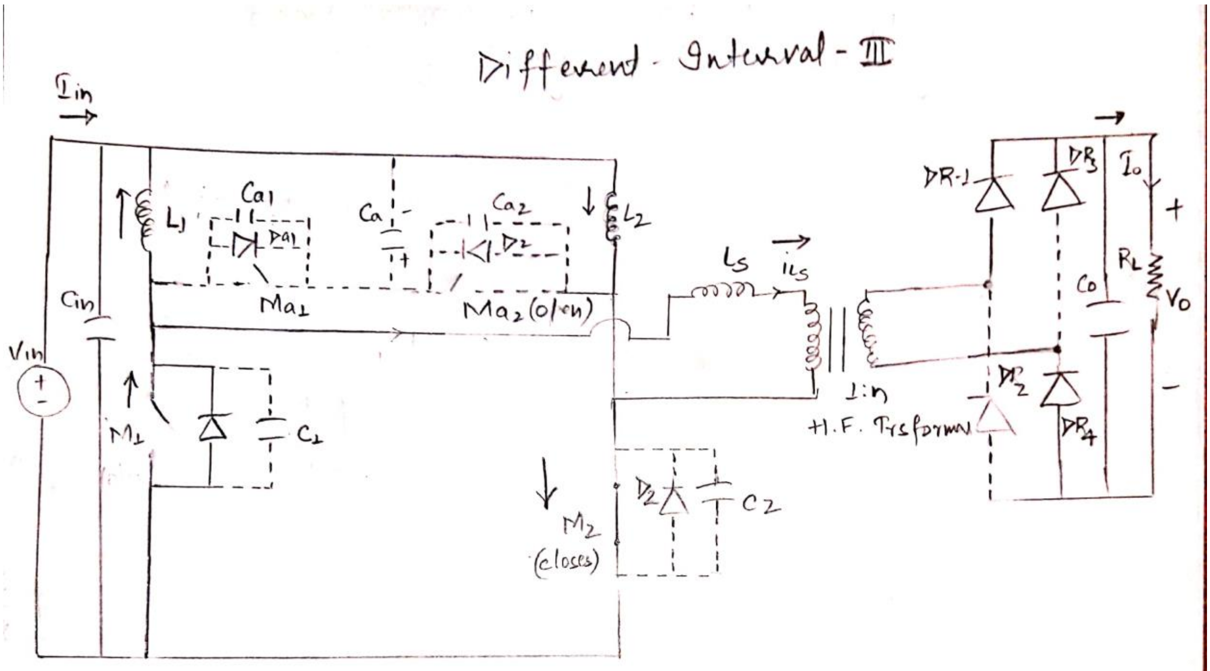
Different Interval 2:

- Charging and discharging of C_a and C_{a1} are as shown below and $i_{L1} = i_{C1} + i_{Ca} - i_{Ls}$.



Different Interval 3:

- Anti-parallel diode D_1 of main switch M_1 is conducting and in this interval, $i_{L1} = i_{D1} + i_{Ls}$



Equivalent Ckt during Interval.
Dotted lines shows Non-Active parts of Circuit.

Designing criterion and specifications:

- Transformer turns ratio $n = N_s/N_p$, is selected based on

$$D = 1 - (nV_{in}/V_o)$$

where D = duty ratio of main switches. In this converter, D should always be greater than 0.5 since the two main switches can't be turned-off at the same time. A minimum overlap is required at all varying load and line conditions. Higher value
of transformer turns ratio will allow transfer of higher power to the load. Maximum duty ratio (D_{max}) is selected at minimum input voltage condition. Higher value of maximum duty ratio will allow satisfactory range of voltage regulation and use of large value of series inductance to increase the ZVS range with variation in load and input voltage. Volt – amps rating is decided based on output power specification and voltage required at output.

VA rating of transformer is = $V_{OUT}*I_{OUT}$

- **RMS and Average currents through the switches and diodes**

1)Average current through main switches, $I_{sw,av} = I_{in}/2$.

2) Peak current through the main switches, $I_{sw,peak} = 3I_{in}/2$

3)RMS current through the main switches is,

$$I_{SW,rms}=[(I_{in}/2)^2*D + I^2_{LS,rms}]^{0.5}$$

4) RMS current through the auxiliary switches is ,

$$I_{Auxsw,rms} = I_{in}*[(1- D)/12)]^{0.5}$$

5) Average rectifier diode current

$$I_{DR,avg} = P_o/(2V_o)$$

Voltage rating of switches and diodes :-

1) Voltage rating of rectifier diodes, $V_{DR}=V_0$
2) Voltage ratings of main switch is decided by duty cycle ,i.e compromise between ZVS range and efficiency has to be made in designing aspect.

$$V_{SW(max)}= V_{in}/(1-D_{(max)})$$

CONVERTER GAIN :

* Voltage Conversion Ratio

for Analysis , dead-time between the switch M_1 & Ma_1 is Assumed to be Zero.

By imposing the Volt-sec Balance rule on the Boost inductor, the steady-state snubber capacitor voltage can be obtained as.

$$V_{ca} = \left(\frac{D}{1-D}\right) V_{in}$$

Considering current flow through the leakage inductor in DCM (Discontinuous Conduction Mode) and average value I_{Ls} is equal to that of load current reflected the primary side.

when $D \geq 0.5$ $n \frac{V_o}{R_L} = Avg(i_{Ls})$.

$$= \frac{(1-D)^2 T_s}{L_s}\left(\frac{N(V_{in}+V_{ca})}{V_o} - 1\right)(V_{in}+V_{ca})$$

* when $D \leq 0.5n \frac{V_o}{R_L} = Avg(i_{Ls})$

$$= \frac{D^2 T_s}{L_s}\left(\frac{N(V_{in}+V_{ca})}{V_o} - 1\right)(V_{in}+V_{ca})$$

$\therefore$ Overall System Voltage Conversion Ratio;

$$\frac{V_o}{V_{in}} = M = \frac{1}{2N}\left\{-\beta\frac{K^2}{1-D} + \sqrt{\frac{\beta^2 K^4}{(1-D)^2} + \frac{4N^2K^2}{(1-D)^2}\beta}\right\}$$

where $\beta = \frac{R_L t_s}{L_s}$

$K = D$, when $D \leq 0.5$ $K = 1-D$, when $D \geq 0.5$

Phase 2
Based on the analysis, design a 250 W converter with the following specifications:

Fuel cell voltage (dc) = 22 V (minimum) to 41 V (maximum).
Output voltage, *Vo* = 350 V.
Output power = 250 W.
Efficiency = as high as possible.
Isolation: high-frequency transformer, switching frequency desired is 100 kHz.
Design should include values and ratings of all components (inductors, capacitors, high frequency transformer, MOSFETs, diodes).

1)Transformer turns ratio $n = N_s/N_p$, is selected based on

$$D = 1 - (nV_{in}/V_o)$$

In design of this converter, *D* should always be greater than 0.5 since the two main switches can't be turned-off at the same time. A minimum overlap is required at all varying load and line conditions.

n is chosen in such a manner that D is not less than 0.5 for $V_{in(max)}$. So by substituting in above equation we get max value of transformer turns ratio n is 4. If we try to substitute n<3 then it makes duty ratio D very high at $V_{in(min)}$(i.e 22 volts) that will cause very narrow power transfer duration . Hence n is chosen to be 4 as higher value of transformer turns ration will allow transfer of higher power to load. So n=4 is selected for designing purpose.

for $V_{in(min)}$=22 Volts and V_o=350 volts with n=4 we get

D= 1-[(4*22)/350]
= 0.748 (approx.= 0.75)

for $V_{in(max)}$=41 Volts and V_o=350 volts with n=4 we get

D= 1-[(4*41)/350]
= 0.5314

(2) **D_{max}** ; Higher value of maximum duty ratio will allow satisfactory range of voltage regulation and use of large value of series inductance to increase the ZVS range with variation in load and input voltage. Maximum duty ratio (D_{max}) is selected at minimum input voltage condition i.e. V_{in} = 22 V. But in doing so maximum duty ratio should be selected for a theoretical maximum main switch voltage rating, $V_{SW(max)}$.

$$Dmax = 1- (Vin/V_{SW(max)})$$

Considering the evaluation of D for turns ratio, maximum duty ratio of 80% (D_{max} = 0.8) is selected. This gives the theoretical maximum switch voltage of 110 V.

For V_{IN}=22 Volts

$$V_{SW(max)} = \frac{Vin}{1-Dmax}$$
$$= 22/(1-0.8)$$
$$=110 \text{ volts}$$

So voltage rating of main switch has been evaluated as 110 volts. In practice, higher voltage rating switch should be selected to give safety margin.

(3) **Series Inductor L_S ;** The series inductor is selected at minimum input voltage and full load condition using

$$L_S = \frac{(1-D(max))*V(in)*Vo}{n*fs*Po} * [\frac{n*Vin}{Vo*(1-D(max)} - 1]$$

For $D_{(max)}$=0.8 and n=4

f_s = 100 kHz

P_0 = 250 Watts

V_{IN}=22 volts

V_o=350

On substituting above values in equation we get Ls as :

$$L_s = [\frac{0.2*22*350}{4*100000*250}]*[\frac{4*22}{350*0.2} - 1]$$

L_S = 3.96 μH

(4) **Average input current** is given by

$$I_{in} = \frac{Po}{\eta \times Vin}$$

Where **η is Efficiency and for design requirements it should be as high as possible, considering losses and external factors it has been selected as 95% as best possible scenario.**

At the same time optimum value of efficiency has been also considered as it was **considered in paper as 90%.**

Evaluations for both the cases has been carried out simultaneously for cross checking purpose.

P_O= 250 watts
For η= 95%

$$I_{In}= \frac{250\ watts}{.95*22}$$

$$\mathbf{I_{In} = 11.96\ Amps}$$

Similarly, for η= 90% we have

$$\mathbf{I_{in} = 12.62\ Amps}$$

(5)**RMS current through the series inductor *L_s***

Value for RMS Current is given by

$$\mathbf{I_{Ls,rms} = I_{in} * \sqrt[2]{\frac{2*n*Vin}{3*Vo}}}$$

For 95% efficiency with I_{in} = 11.96 amps

We get $I_{Ls,rms}$ = 11.96* $\sqrt[2]{\frac{2*4*22}{3*350}}$

$$\mathbf{I_{Ls,rms} = 4.89\ amps}$$

{similarly with 90 % efficiency we get $\mathbf{I_{Ls,rms}}$ **= 5.166 amps** }

(6) Values of Boost inductors :

$$\mathbf{L_1 = L_2 = \frac{Vin*D}{\Delta Iin*fs}}$$

Where ΔI_{In} is input ripple current and it is assumed to be 0.5 amps , which gives

$$L_1 = L_2 = \frac{22*0.8}{0.5*100000}$$

$L_1 = L_2 = 352\ \mu H$ (approx. = 350 µH)

(7) Switch current rating :

- Average current through main switches, $I_{sw,av} = I_{in}/2$

For 95% efficiency with I_{in} = 11.96 amps

Hence , $I_{sw,av} = \frac{11.96}{2}$ amps

$I_{sw,av}$ = 5.98 amps

{similarly with 90 % efficiency we get $I_{sw,av}$ = 6.31 amps }

- RMS current through the main switches is

$$\mathbf{I_{SW,rms}} = \sqrt[2]{\left[\left(\frac{Iin}{2}\right)^2\right] D + (Ils, rms)^2}$$

For 95% efficiency with I_{in} = 11.96 amps and $I_{LS,rms}$= 4.89 amps

$$I_{SW,rms} = \sqrt[2]{\left(\frac{11.96}{2}\right)^2 * 0.8 + (4.89)^2}$$

$I_{SW,rms}$= 7.24 amps

{Similarly For 90% efficiency **$I_{SW,rms}$= 7.65 amps** }

- RMS current through the main switches is

$$\mathbf{I_{auxsw,rms} = I_{in} * [\sqrt[2]{\frac{1-D}{12}}]}$$

For 95 % efficiency with I_{in}= 11.96 and D=0.8

$$I_{auxsw,rms} = 11.96 * [\sqrt[2]{\frac{1-0.8}{12}}]$$

<u>**$I_{auxsw,rms}$ = 1.544 amps**</u>

{Similarly for 90 % efficiency we get <u>**$I_{auxsw,rms}$ = 1.629 amps**</u> }

<u>(8) Auxilary capacitor :</u>

For V_{in} = 22 V and $D = D_{max}$ = 0.8 Auxiliary capacitor voltage is given by

$$\mathbf{V_{ca} = \frac{D*Vin}{1-D}}$$

We get V_{ca} = 88 Volts

Peak current through C_a is $I_{ca,peak} = I_{in}$ = 11.96 A. (For 95% efficiency)

The value of auxiliary capacitor $\mathbf{C_a}$ **is =** $\frac{Ica,peak * \sqrt[2]{\frac{2(1-D)}{3}}}{4\pi * fs * \Delta Vca}$

By considering ΔV_{ca}= 2.5 volts we get

$$C_a = \frac{11.96 * \sqrt[2]{\frac{2*0.2}{3}}}{4*\pi*100000*2.5}$$

C_a = 1.39 µF (For 95% Efficiency)

{Similarly for 90 % efficiency we get <u>**C_a = 1.46µF**</u> }

- **RMS current of auxiliary capacitor:**

RMS value through auxiliary capacitor is given by

$$I_{Ca,rms}= I_{Ca,peak} * \sqrt[2]{\frac{2*(1-D)}{3}}$$

So for 95 % efficiency we get $I_{Ca,peak}$ = 11.96

$I_{Ca,rms}$= 4.36 Amps

{Similarly for 90% efficiency we get **$I_{Ca,rms}$= 4.60 Amps**}

(9) Output filter capacitor:

RMS value of current for output filter capacitor is given by

$$\mathbf{I_{Co,RMS}} = \sqrt[2]{\frac{(Iin)^2*Vin}{3*n*Vo} + \left(\frac{Po}{Vo}\right)^2 * \left(1 - \frac{2*n*Vin}{Vo}\right)}$$

And value of output capacitor can be evaluated using below expression using $I_{Co,RMS}$ Found above

$$\mathbf{C_o} = \frac{\mathbf{Ico,rms}}{4*\pi*fs*\Delta Vo}$$

Considering 95% efficiency for ΔV_o = 0.65 V(allowable ripple in output voltage)

I_{in}= 11.96 amps
V_{in}= 22 Volts
P_O= 250 watts
V_O= 350 Volts

Substituting above values in formula we get :-

$I_{co,rms}$= 1.0 amps

$$C_O = \frac{1}{4*\pi*100000*0.65}$$

C_o= 1.22 µF

{Similarly for 90% efficiency we get **$I_{co,rms}$ = 1.04 Amps and C_O= 1.27 µF**}

(10) **Output rectifier diodes**

Average rectifier diode current is given by

$$I_{DR,Avg}= \frac{Po}{2Vo}$$

For P_O= 250 watts and output voltage as 350 volts

$$I_{DR,Avg}= \frac{250}{2*350} \text{ amps}$$

$$I_{DR,Avg}= 0.357 \text{ amps}$$

Voltage rating of rectifier diode = V_{DR}=V_O = 350 volts

OVERVIEW OF DESIGN FOR DIFFERENT EFFICIENCY :

Parameters	90%	95 %
I_{In}	12.62 amps	11.96 amps
$I_{Ls,RMS}$	5.166 amps	4.89 amps
$I_{sw,avg}$	6.31 amps	5.98 amps
$I_{SW,RMS}$	7.65 amps	7.24 amps
$I_{AUXsw,RMS}$	1.629 amps	1.544 amps
C_a	1.46 µF	1.39 µF
$I_{Ca,rms}$	4.60 amps	4.36 amps
C_o	1.27 µF	1.22 µF
$I_{co,rms}$	1.04 amps	1.0 amps

Phase 3:
Using PSIM simulation software, obtain various waveforms to verify its operation for the
following operating conditions (output voltage is regulated at *Vo* = 350 V):
1. *Vin* = 22 V, *Vo* = 350 V: Full load.
2. *Vin* = 41 V, *Vo* = 350 V: Full load.
3. *Vin* = 22 V, *Vo* = 350 V: Half-load.
4. *Vin* = 41 V, *Vo* = 350 V: Half-load.
5. *Vin* = 22 V, *Vo* = 350 V: 20% load.
6. *Vin* = 41 V, *Vo* = 350 V: 20% load.
Estimate the efficiencies for cases (1), (2), (3) and (4).
Summarize and comment (should include ZVS range) on the results.

1. *Vin* = 22 V, *Vo* = 350 V: Full load (Po=250 watts).

For designing aspect above parameters are considered and circuit is designed in PCIM as shown below:

L_s = 3.96 µH
C_a = 1.46 µF
L_1=L_2= 350 µF
C_0= 1.27 µF
C_1=C_2= 19.83 µF

C_1=C_2=C_{main} > C_{AUX} has been taken based on the following observation design in paper shown below:

- output capacitor of main power switch (e.g., 2SK2995): $C_{main} = C_1 = C_2 = 1.9$ nF;
- output capacitor of auxiliary power switch (e.g., IRF644N): $C_{aux} = C_{a1} = C_{a2} = 140$ pF.

In order to keep output voltage constant across load, desired output current has been evaluated as

P_o=output current × output voltage

Output current = $\frac{Po}{Vo} = \frac{250}{350}$

I_o= 0.7142 amps

R_L= Output resistance= $\frac{Vo}{Io} = \frac{350}{0.7142}$ = 612.15 Ω

For efficiency evaluation $P_{in}>P_{out.}$
Duty cycle = 0.8

Assuming $P_{in}> P_O$ as 270 watts slightly greater that output power

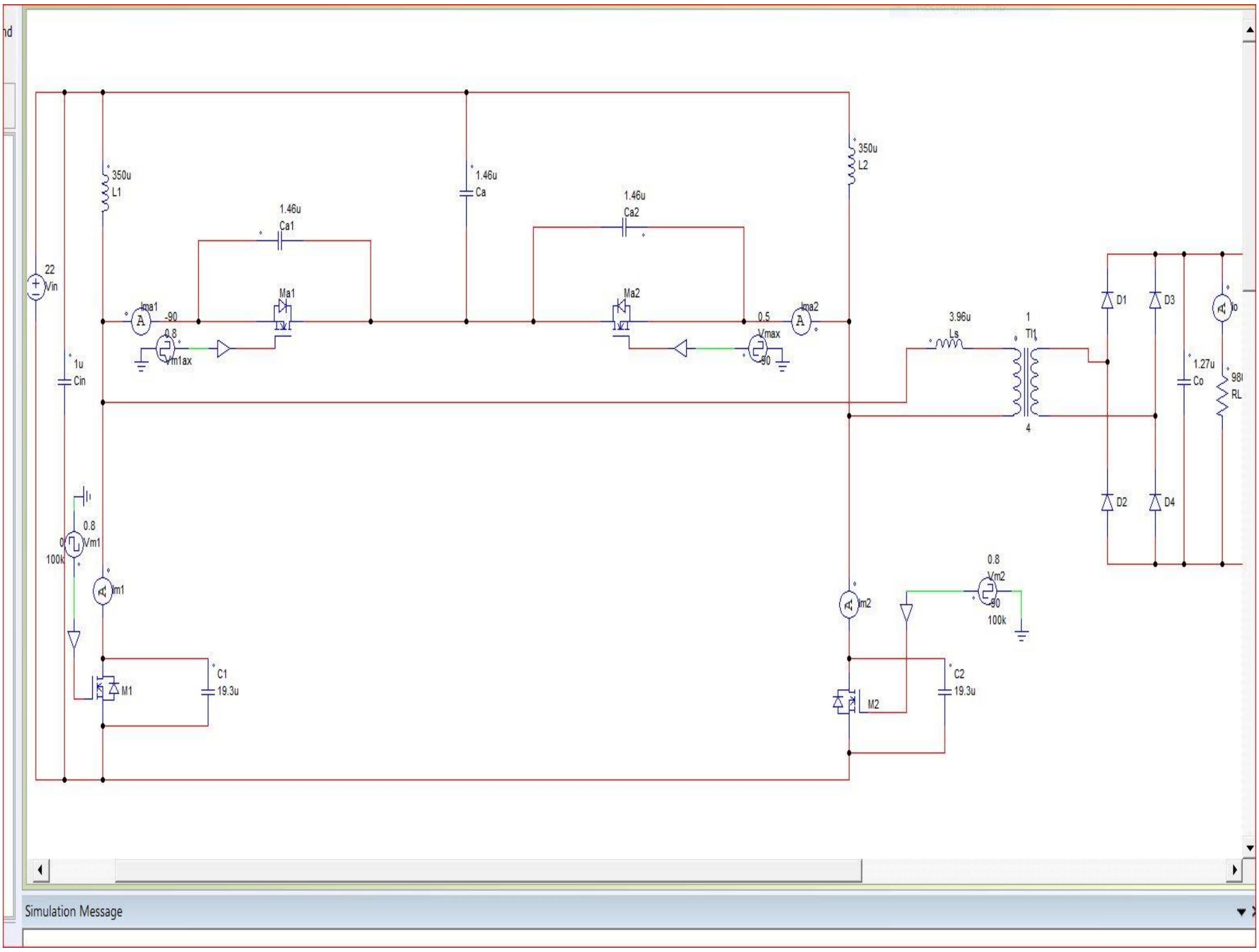
For total switch losses current in both main switches considering MOSFET (IRF 330 Configuration from notes $R_{ds=}$ 1.5) we get loss = 15.36 watts

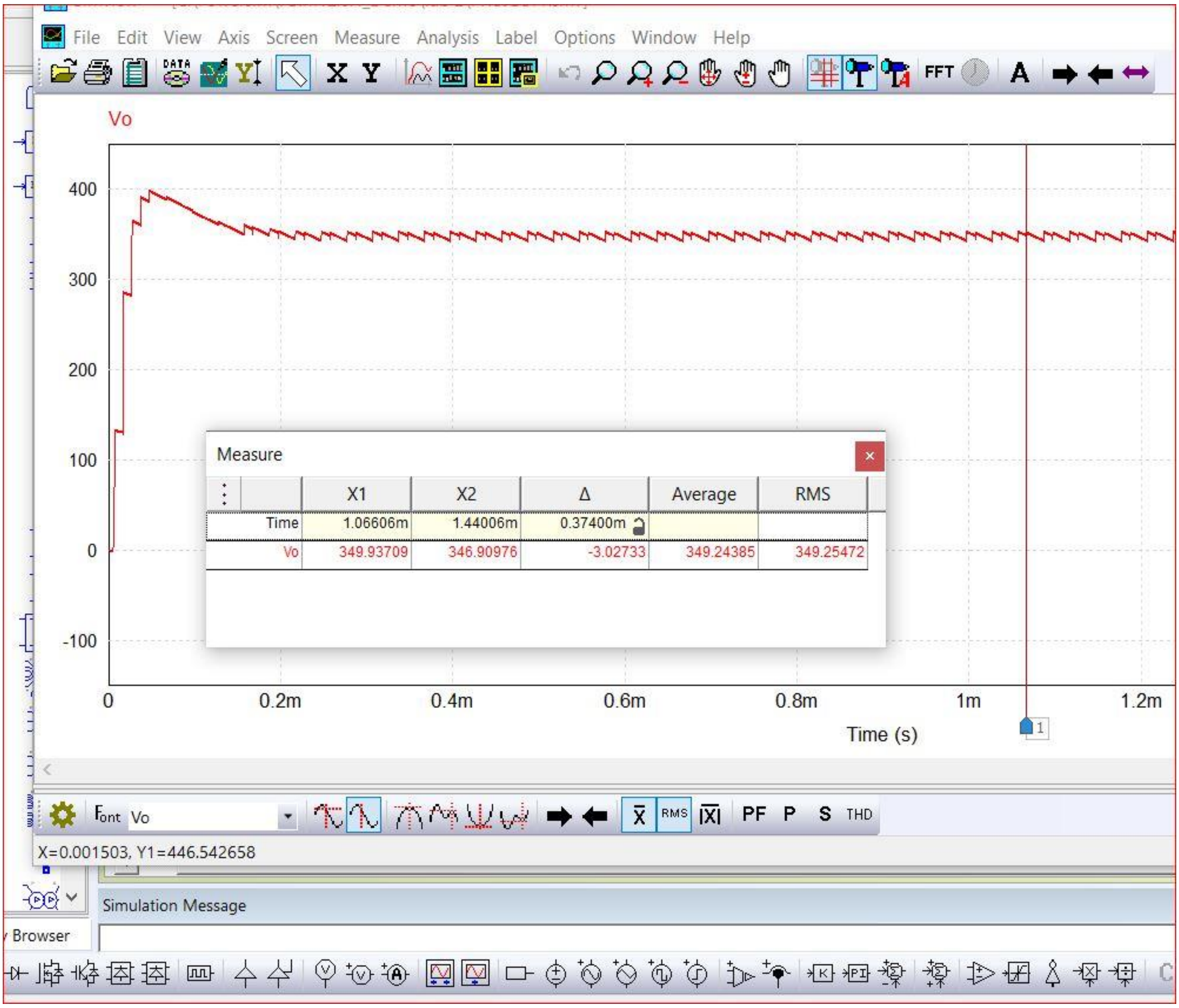
For output section diode current = output current = 0.721 amps
Diode loss = $I_D^2\ R_D$= 4.1 watts

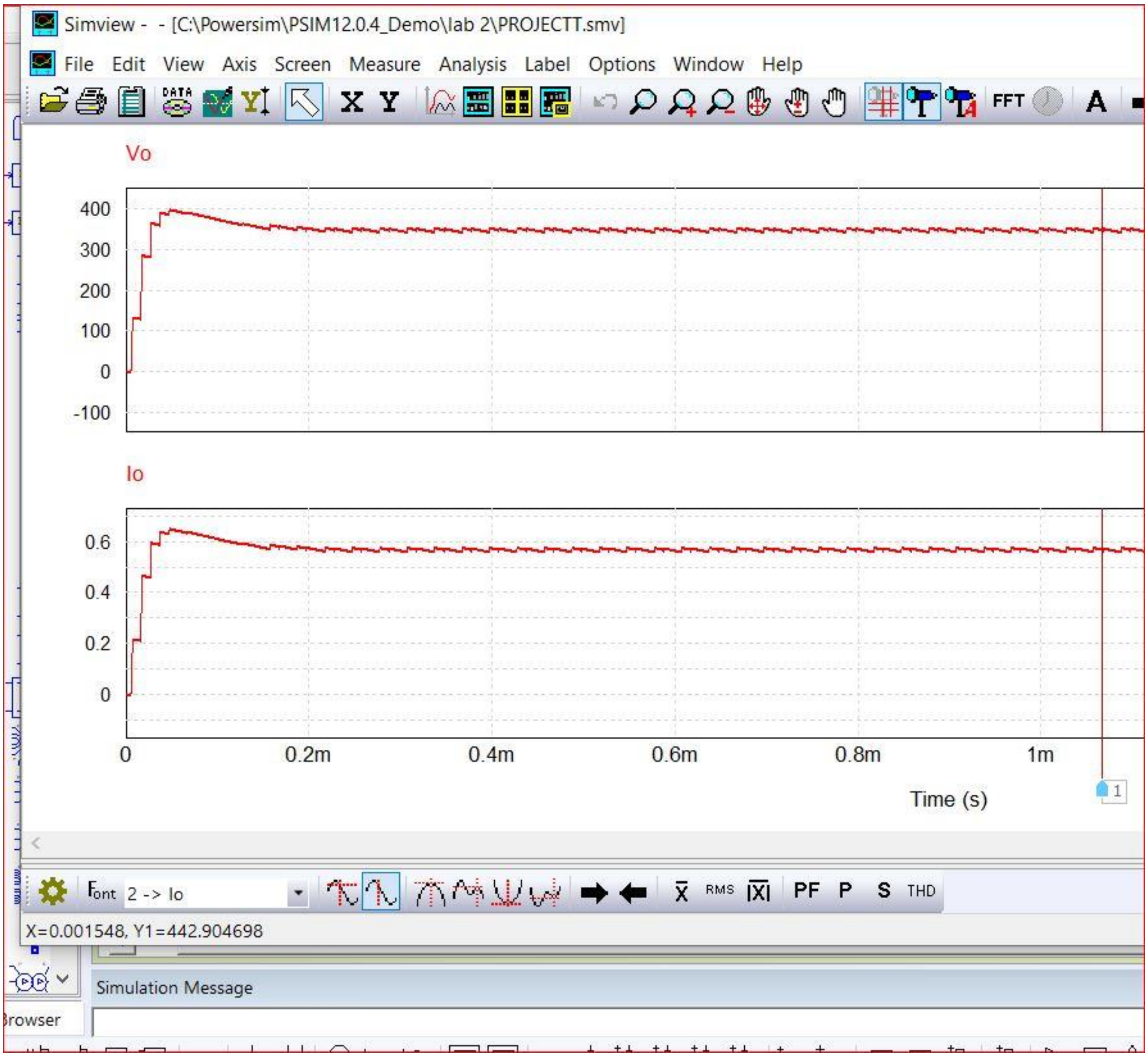
Totals losses = 19.46 watts

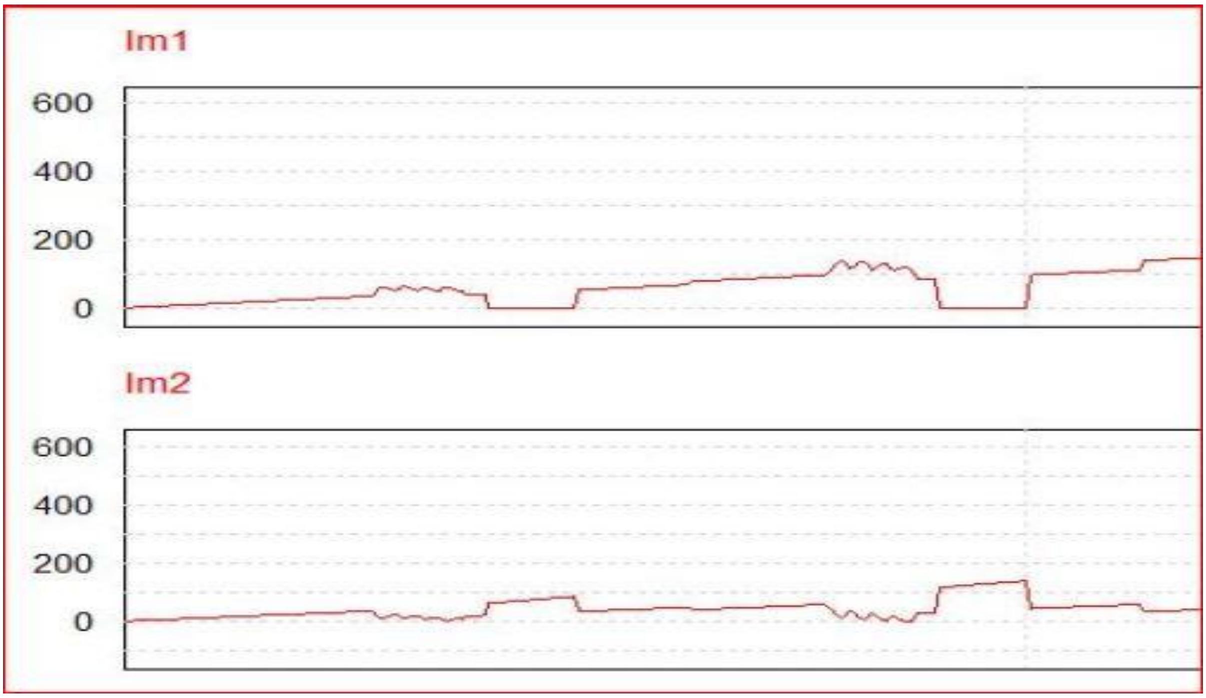
Efficiency = $\frac{OUTPUT}{INPUT} = \frac{270-19.46}{270}$ = 92.79 %

<u>**Simulation circuit diagram in PCIM :**</u>




File Edit View Axis Screen Measure Analysis Label Options Window Help
Vo
400
300
200
100
0
-100
0
0.2m
0.4m
0.6m
0.8m
1m
1.2m
Time (s)
Measure
X1
X2
Δ
Average
RMS
Time 1.06606m 1.44006m 0.37400m
Vo 349.93709 346.90976 -3.02733 349.24385 349.25472
Font Vo
PF P S THD
X=0.001503, Y1=446.542658
Simulation Message
Browser


Simview - - [C:\Powersim\PSIM12.0.4_Demo\lab 2\PROJECTT.smv]
File Edit View Axis Screen Measure Analysis Label Options Window Help
Vo
400
300
200
100
0
-100
Io
0.6
0.4
0.2
0
0
0.2m
0.4m
0.6m
0.8m
1m
Time (s)
Font 2 -> Io
RMS
PF P S THD
X=0.001548, Y1=442.904698
Simulation Message
Browser



2. *Vin* = 41 V, *Vo* = 350 V: Full load.

In order to keep output voltage constant across load, desired output current has been evaluated as

P_o=output current × output voltage

Output current = $\frac{Po}{Vo} = \frac{250}{350}$

I_o= 0.7142 amps

For efficiency evaluation $P_{in}>P_{out.}$

D = 1- ($Vin/V_{SW(max)}$)

Duty cycle has been adjusted to = 0.6 for V_{in}= 41 Volts

Cosidering $P_{in}> P_O$ as 270 watts slightly greater that output power

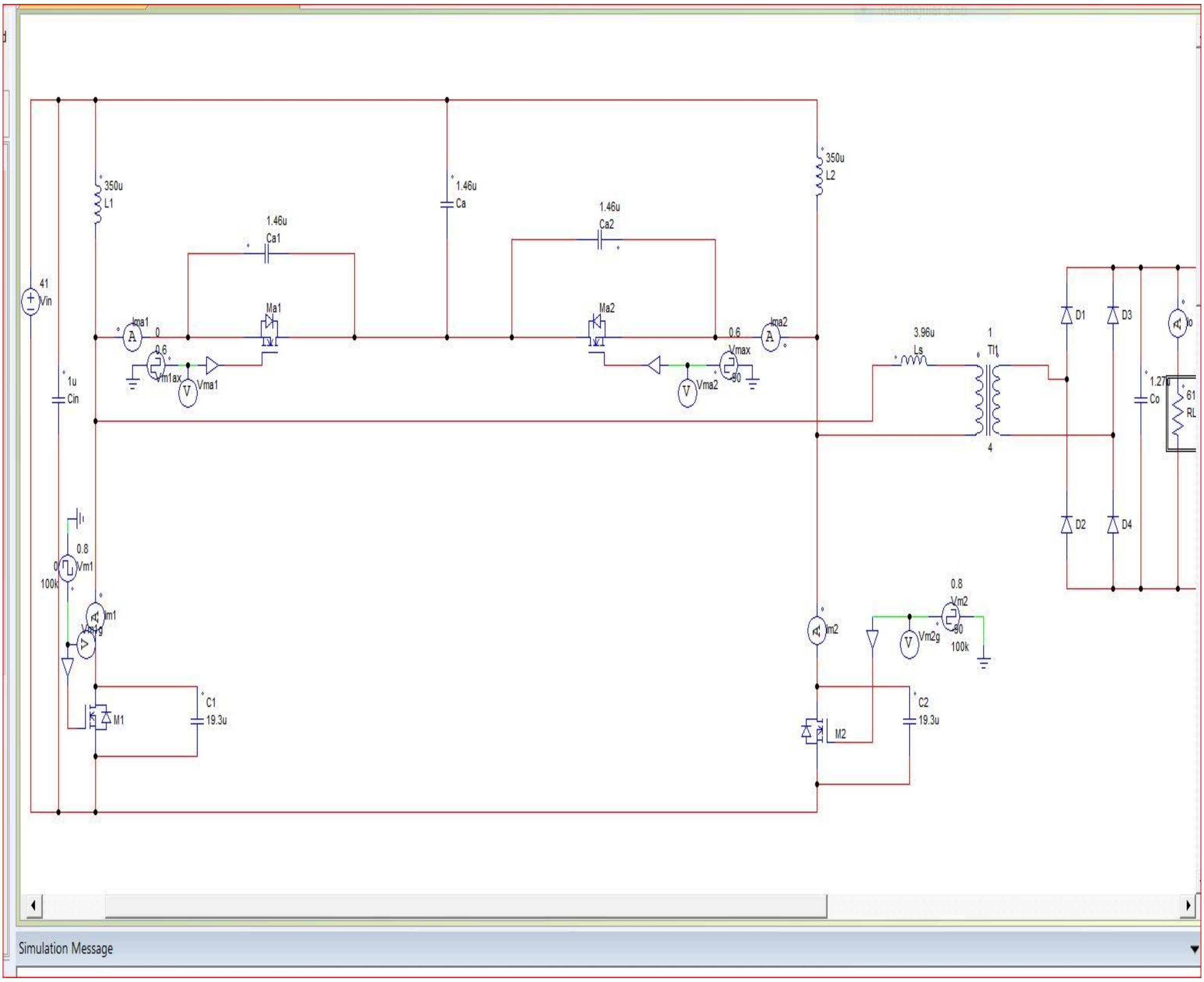
For total switch losses current in both main switches considering MOSFET, IRF 330 Configuration (referred from notes chapter 8(b) $R_{ds=}$ 1.5) we get loss = 18.36 watts

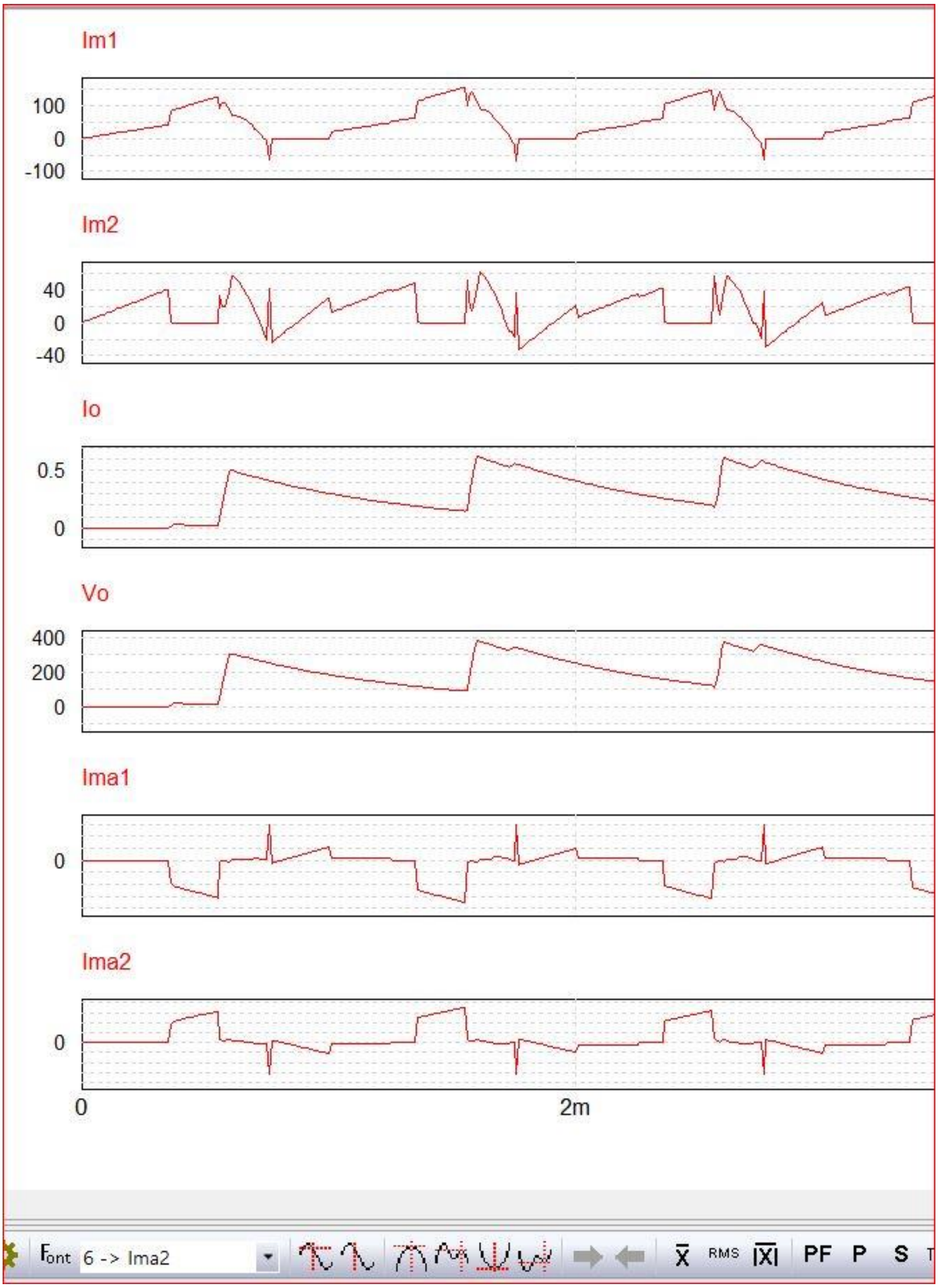
For output section diode current = output current = 0.721 amps
Diode loss = $I_D^2\ R_D$= 3.4 watts

Totals losses in switches and diode= 18.76 watts

Efficiency = $\frac{OUTPUT}{INPUT} = \frac{270-18.76}{270}$ = 93.05 %

SIMULATION FIGURE IN PCIM




Im1
100
0
-100
Im2
40
0
-40
Io
0.5
0
Vo
400
200
0
Ima1
0
Ima2
0
0
2m
Font 6 -> Ima2
RMS
PF
P
S

3. *Vin* = 22 V, *Vo* = 350 V: Half-load.

To keep output voltage constant across load, desired output current has been evaluated as

P_o=output current × output voltage = half load output power =125 watts

Output current = $\frac{Po}{Vo} = \frac{125}{350}$

Impact of half load :-

I_o= 0.3571 amps

Output resistance= $\frac{Vo}{Io} = \frac{350}{0.3571}$ = 980 Ώ

For efficiency evaluation P_{in}>$P_{out.}$
D = 1- ($Vin/V_{SW(max)}$)
Duty cycle has been adjusted to = 0.8

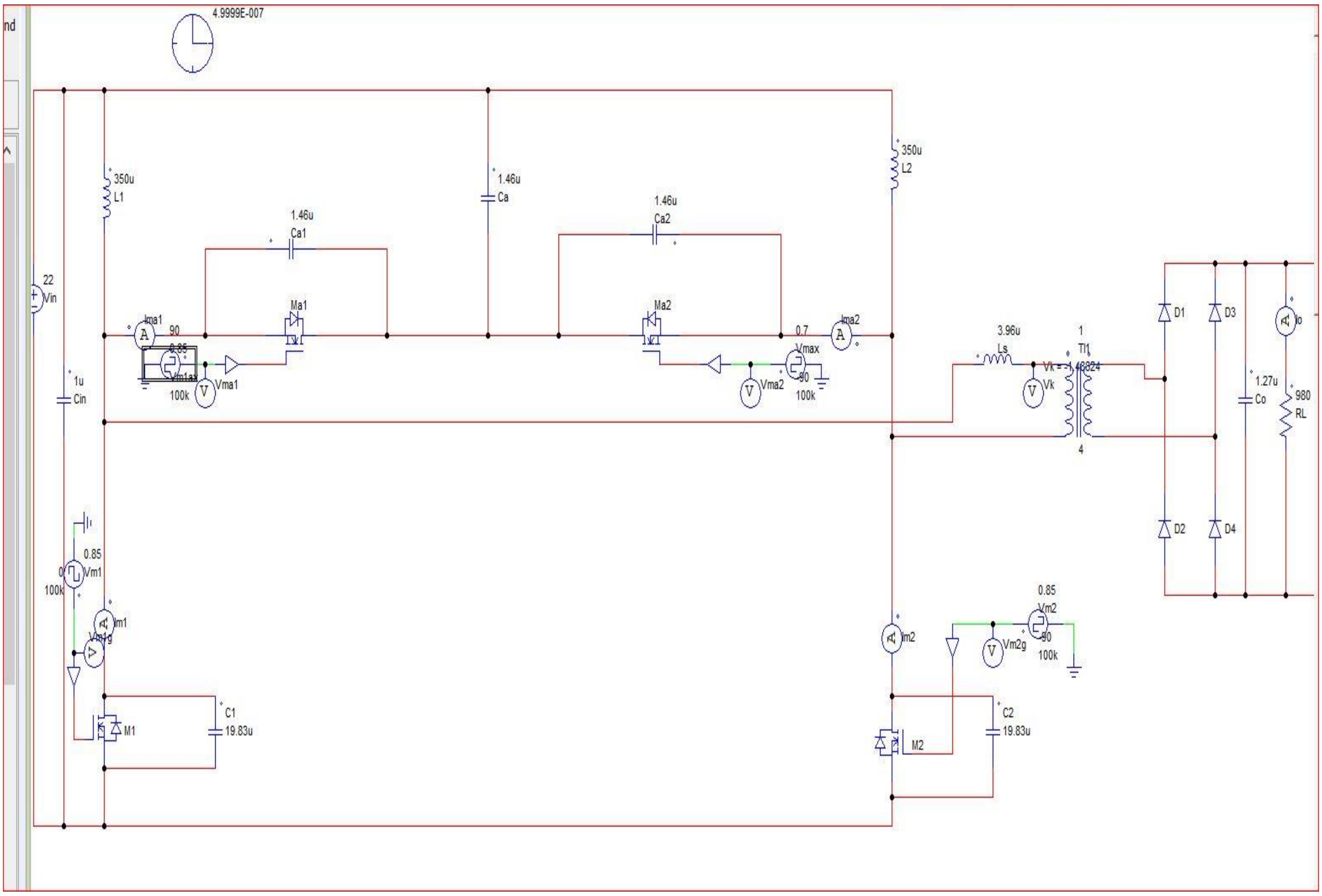
Taking P_{in}> P_O as 270 watts slightly greater that output power

For total switch losses current in both main switches considering MOSFET, IRF 330 Configuration (referred from notes chapter 8(b) $R_{ds=}$ 1.5) we get loss = 14.7 watts

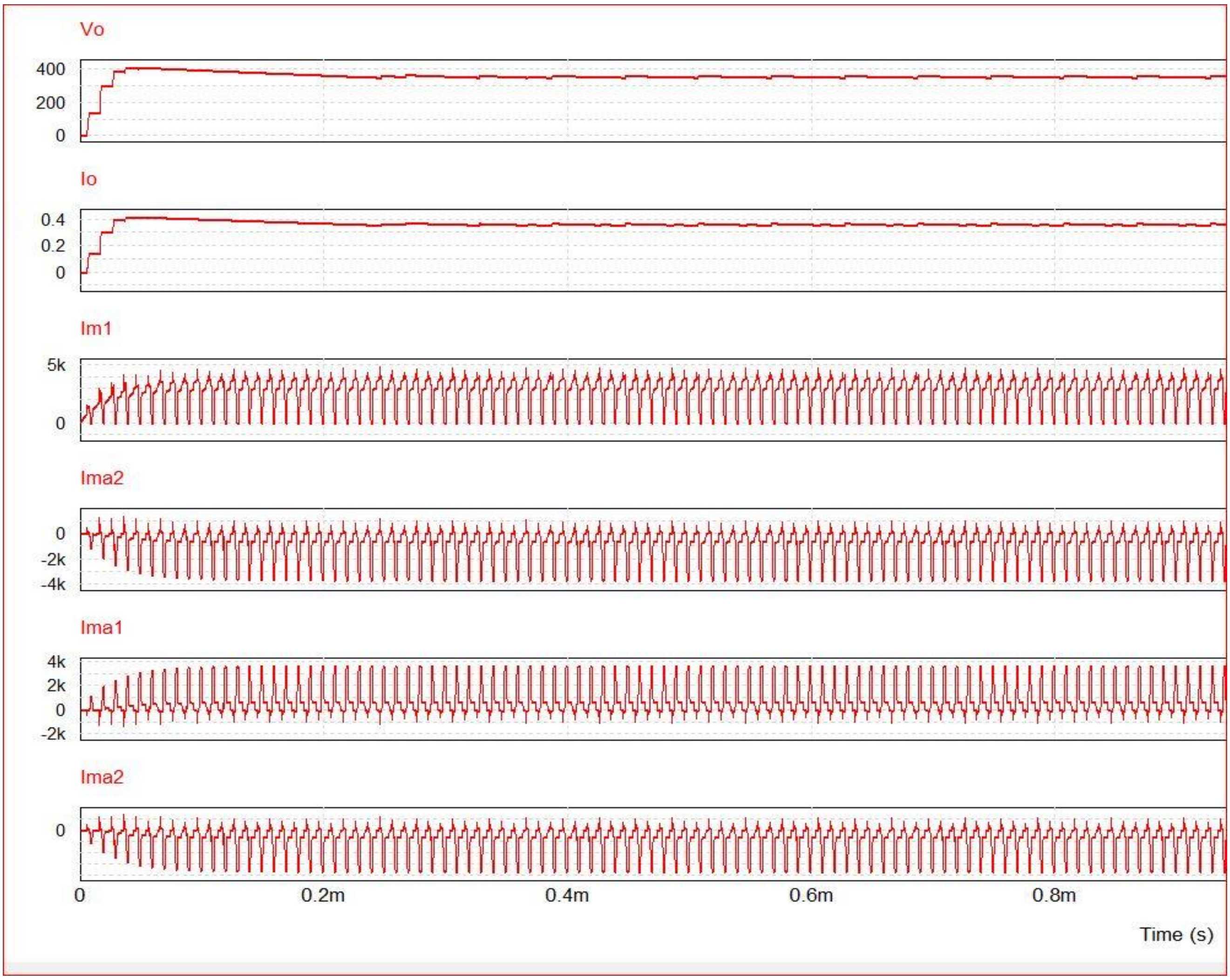
For output section diode current = output current = 0.3571 amps
Diode loss = I_D^2 R_D= 1.5 watts

Totals losses in switches and diode= 16.2 watts

Efficiency = $\frac{OUTPUT}{INPUT} = \frac{270-16.2}{270}$ = 94.00%



Vo
400
300
200
100
0
0
0.2m
0.4m
0.6m



4. *Vin* = 41 V, *Vo* = 350 V: Half-load.

To keep output voltage constant across load, desired output current has been evaluated as

P_o=output current × output voltage = half load output power =125 watts

Output current = $\frac{Po}{Vo} = \frac{125}{350}$

Impact of half load :-

I_o= 0.3571 amps

Output resistance= $\frac{Vo}{Io} = \frac{350}{0.3571}$ = 980 Ω

For efficiency evaluation $P_{in}>P_{out.}$
$D = 1- (Vin/V_{SW(max)})$
Max voltage across switch has been taken as 110 volts
Duty cycle has been adjusted to = 0.6

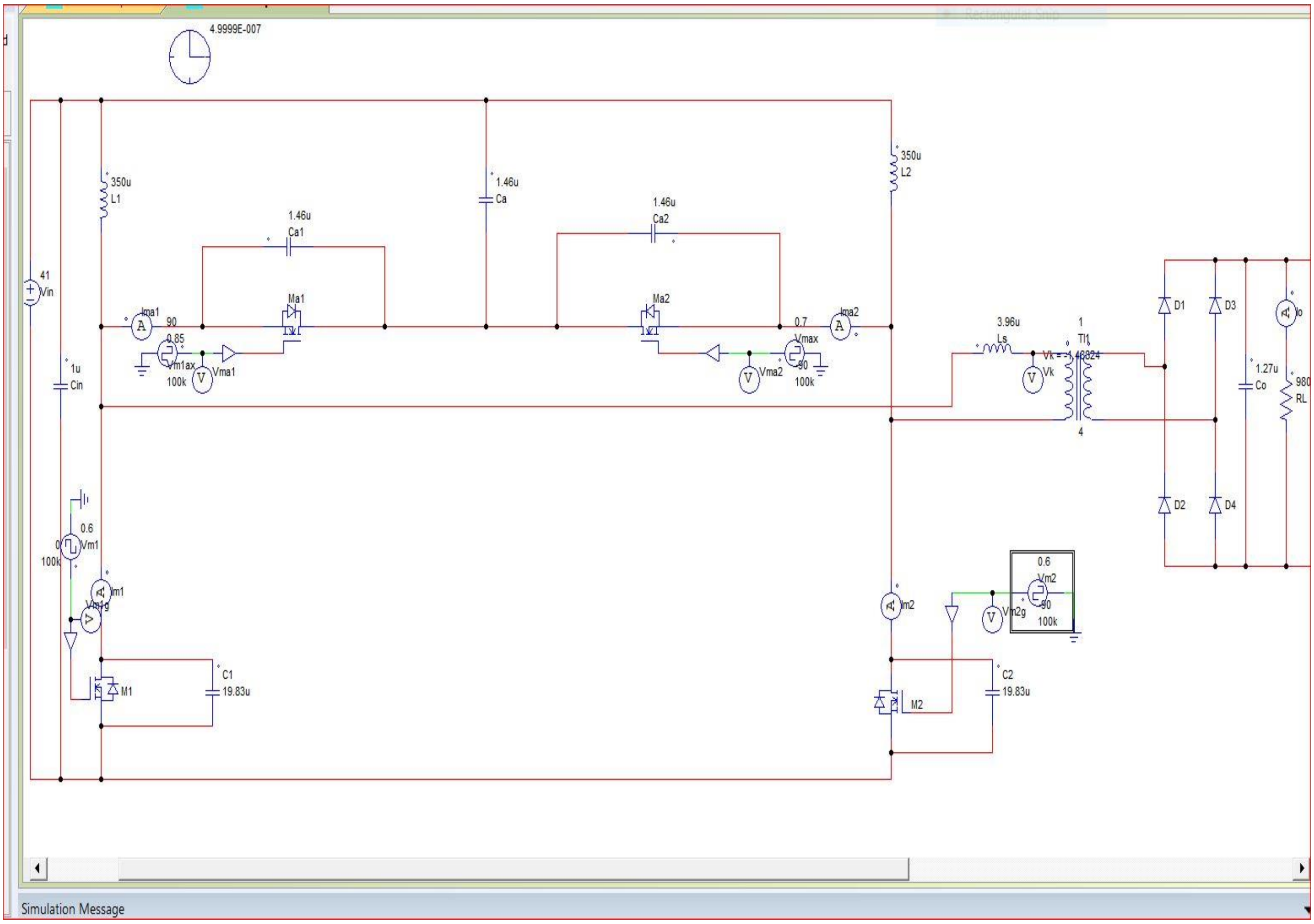
Taking $P_{in}> P_O$ as 270 watts slightly greater that output power

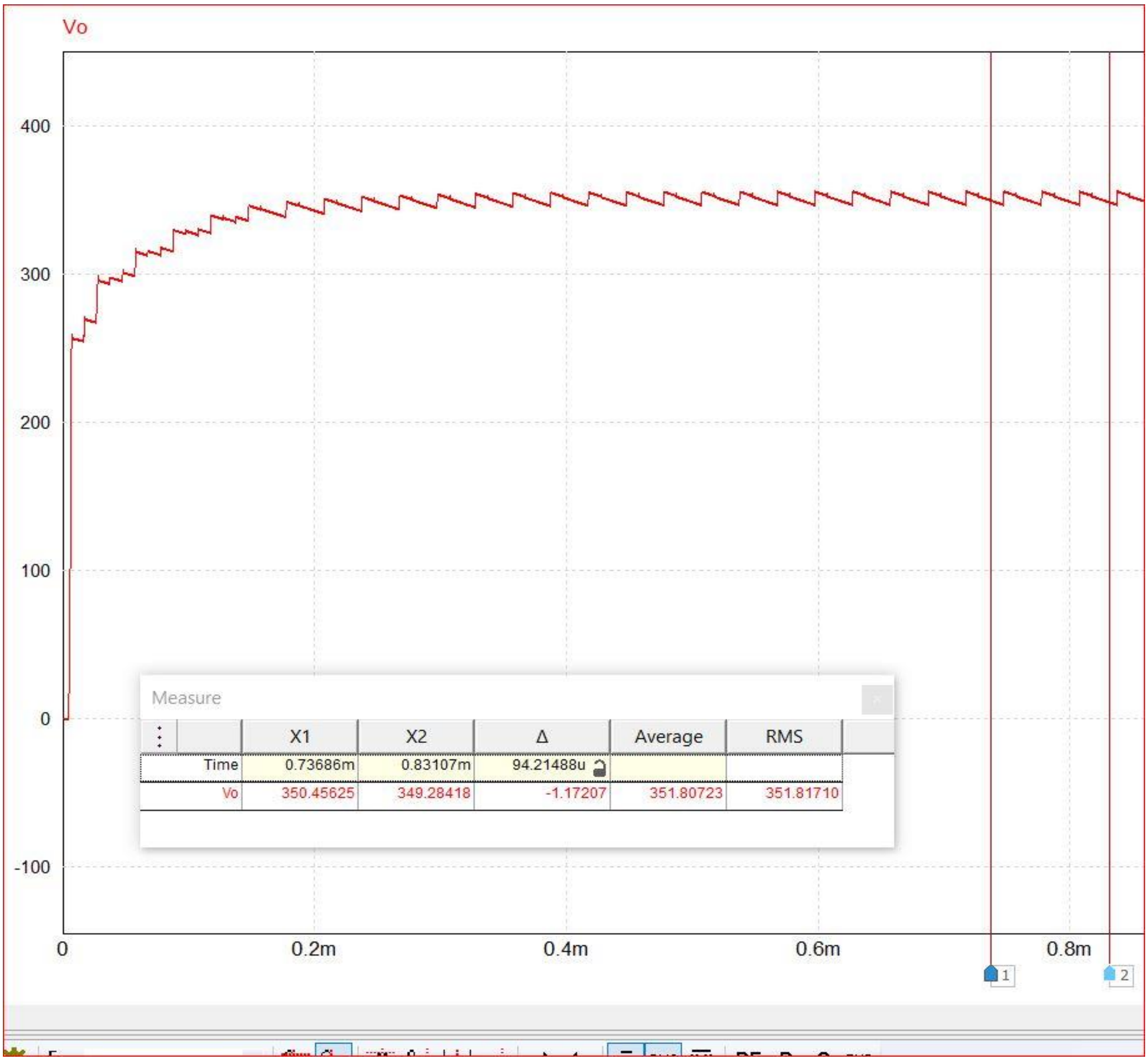
For total switch losses current in both main switches considering MOSFET, IRF 330 Configuration (referred from notes chapter 8(b) $R_{ds=}$ 1.5) we get loss = 13.8 watts

For output section diode current = output current = 0.3571 amps
Diode loss = $I_D^2\ R_D$= 2.2 watts

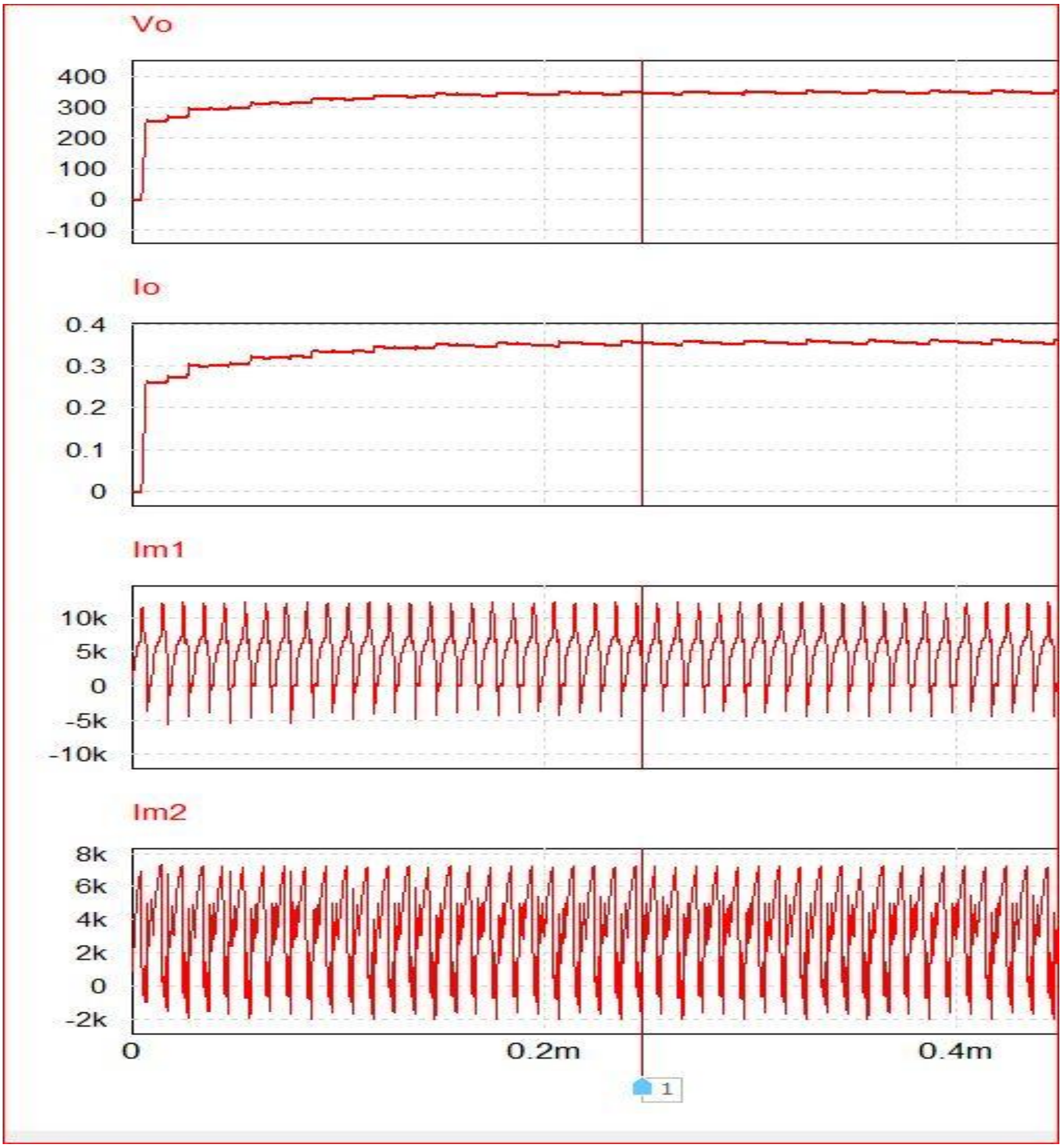
Totals losses in switches and diode= 16.0 watts

$$\text{Efficiency} = \frac{OUTPUT}{INPUT} = \frac{270-16.2}{270} = 94.074\%$$





Vo
400
300
200
100
0
-100
0
0.2m
0.4m
0.6m
0.8m
Measure
X1
X2
Δ
Average
RMS
Time
0.73686m
0.83107m
94.21488u
Vo
350.45625
349.28418
-1.17207
351.80723
351.81710
1
2



Vo
400
300
200
100
0
-100
Io
0.4
0.3
0.2
0.1
0
Im1
10k
5k
0
-5k
-10k
Im2
8k
6k
4k
2k
0
-2k
0
0.2m
0.4m
1

5. *Vin* = 22 V, *Vo* = 350 V: 20% load.

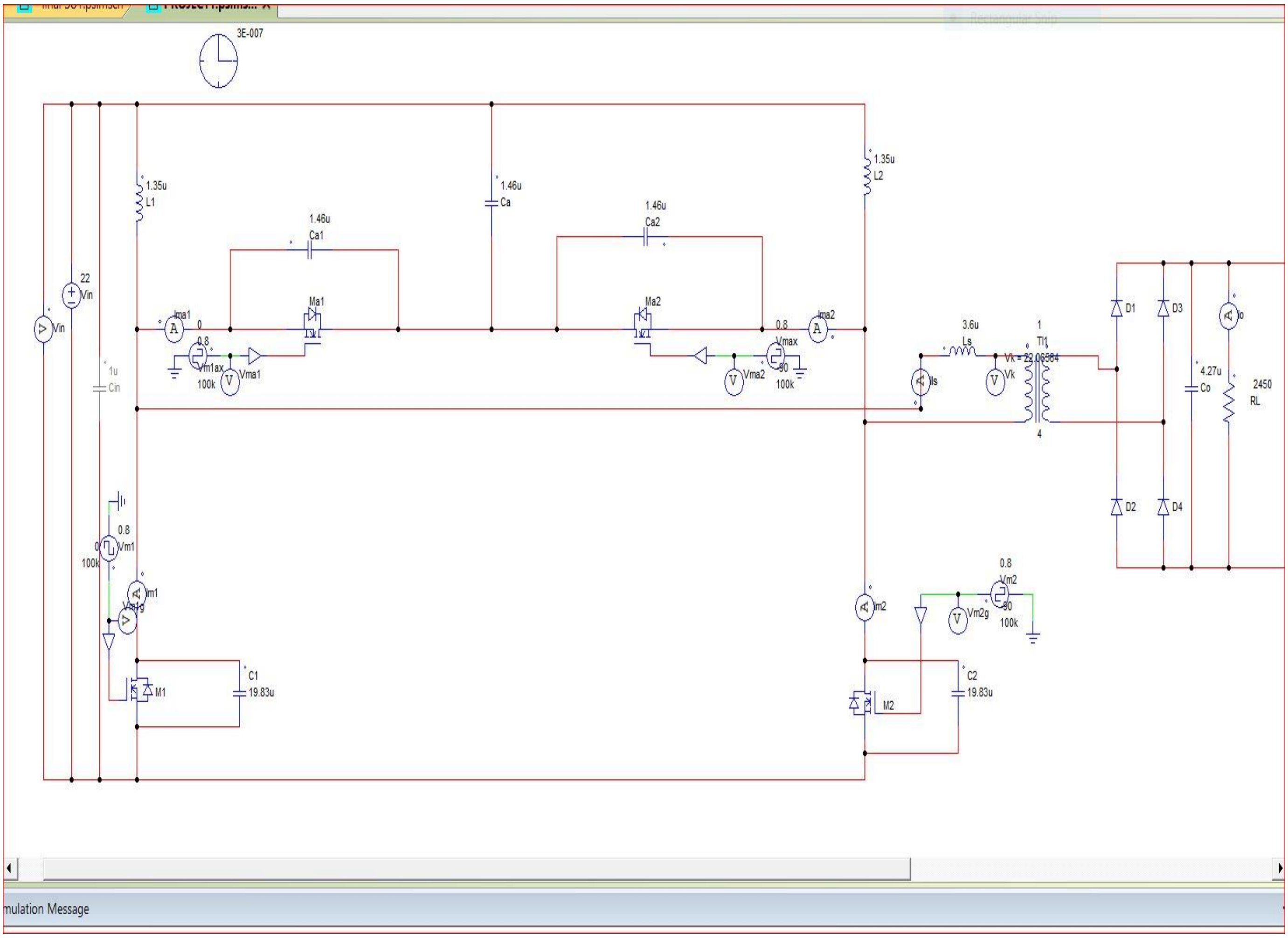
20% of output power = 50 watts

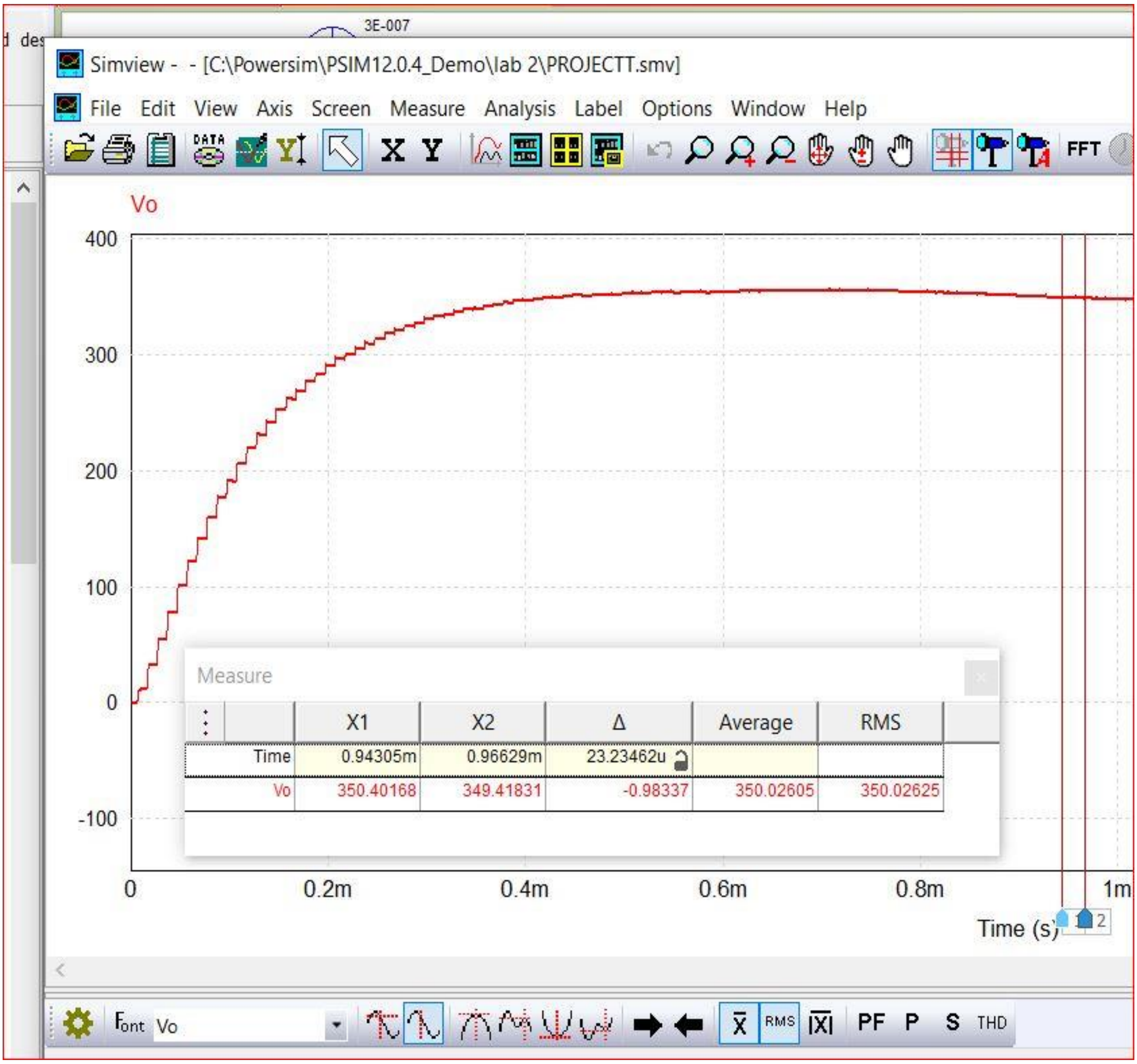
In order to maintain constant output voltage as 350 volts

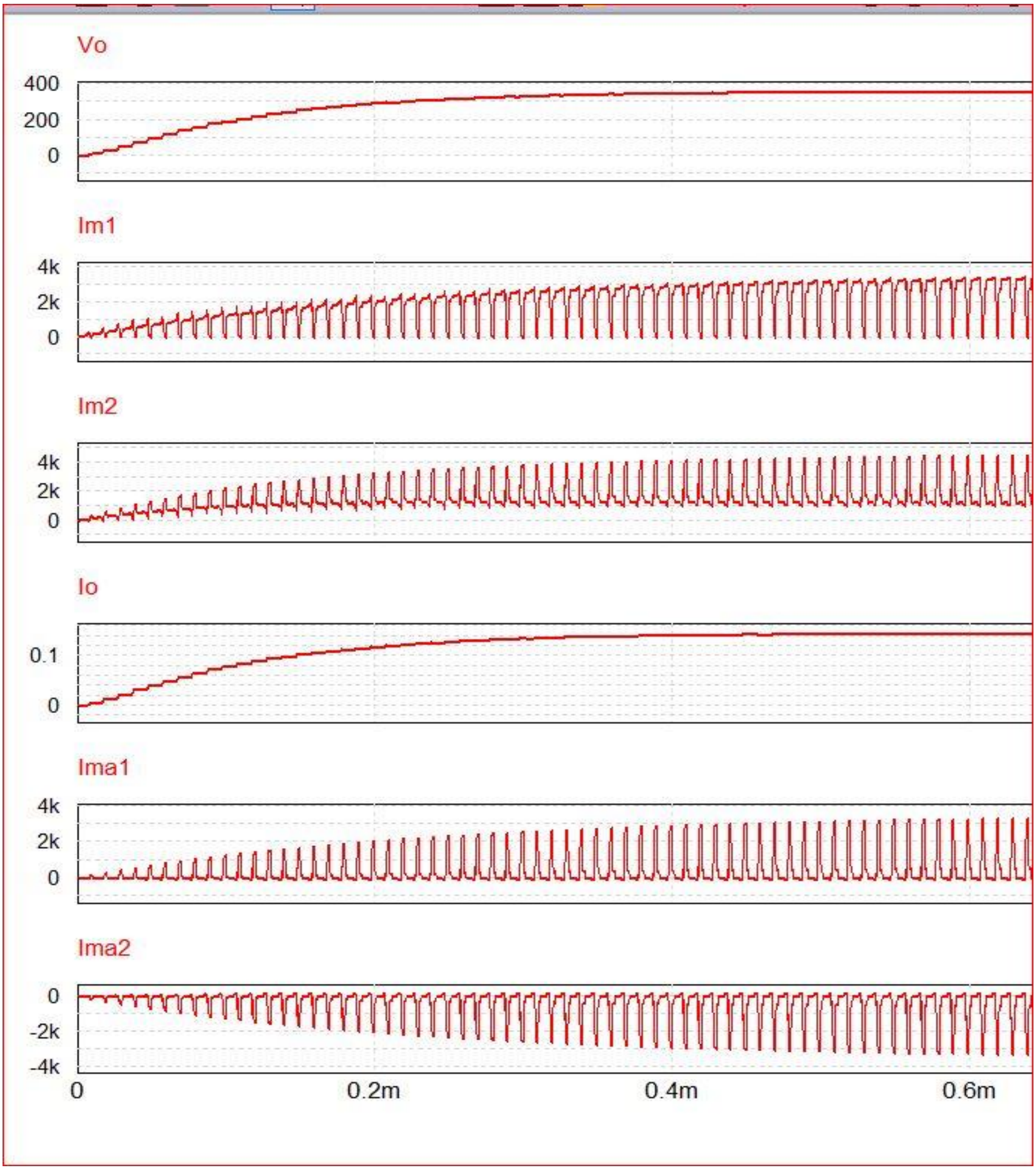
Output current is = $\frac{Po}{Vo} = \frac{50}{350}$= .1428

Then output resistance = $R_L = \frac{Vo}{Io} = \frac{350}{0.1428}$ = 2450 Ω

Max voltage across switch has been taken as 110 volts
Duty cycle has been adjusted to = 0.8




Simview - - [C:\Powersim\PSIM12.0.4_Demo\lab 2\PROJECTT.smv]
File Edit View Axis Screen Measure Analysis Label Options Window Help
Vo
400
300
200
100
0
-100
0
0.2m
0.4m
0.6m
0.8m
1m
Time (s)
Measure
X1
X2
Δ
Average
RMS
Time
0.94305m
0.96629m
23.23462u
Vo
350.40168
349.41831
-0.98337
350.02605
350.02625
Font Vo
PF P S THD


Vo
400
200
0
Im1
4k
2k
0
Im2
4k
2k
0
Io
0.1
0
Ima1
4k
2k
0
Ima2
0
-2k
-4k
0
0.2m
0.4m
0.6m

6. *Vin* = 41 V, *Vo* = 350 V: 20% load.

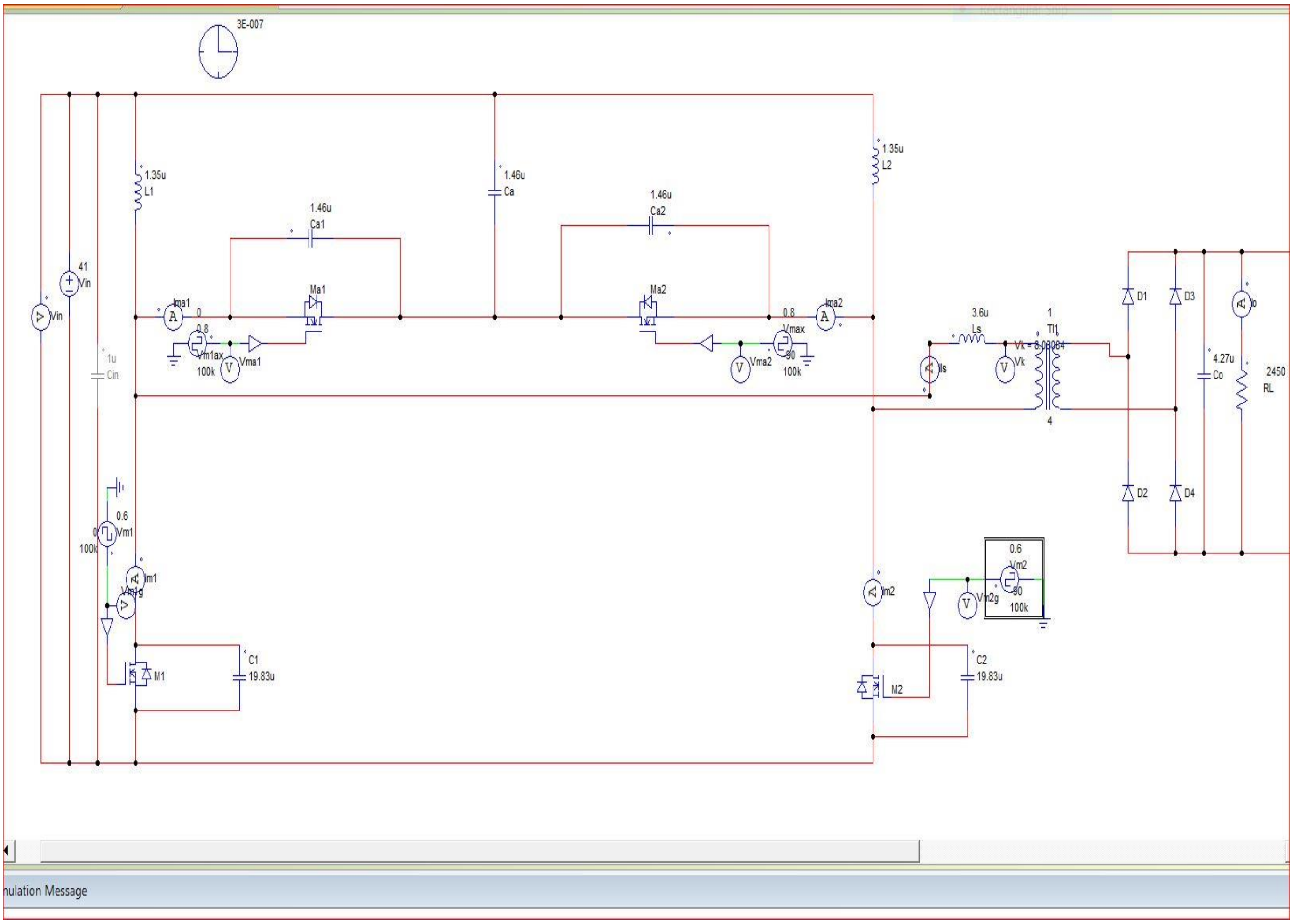
20% of output power = 50 watts

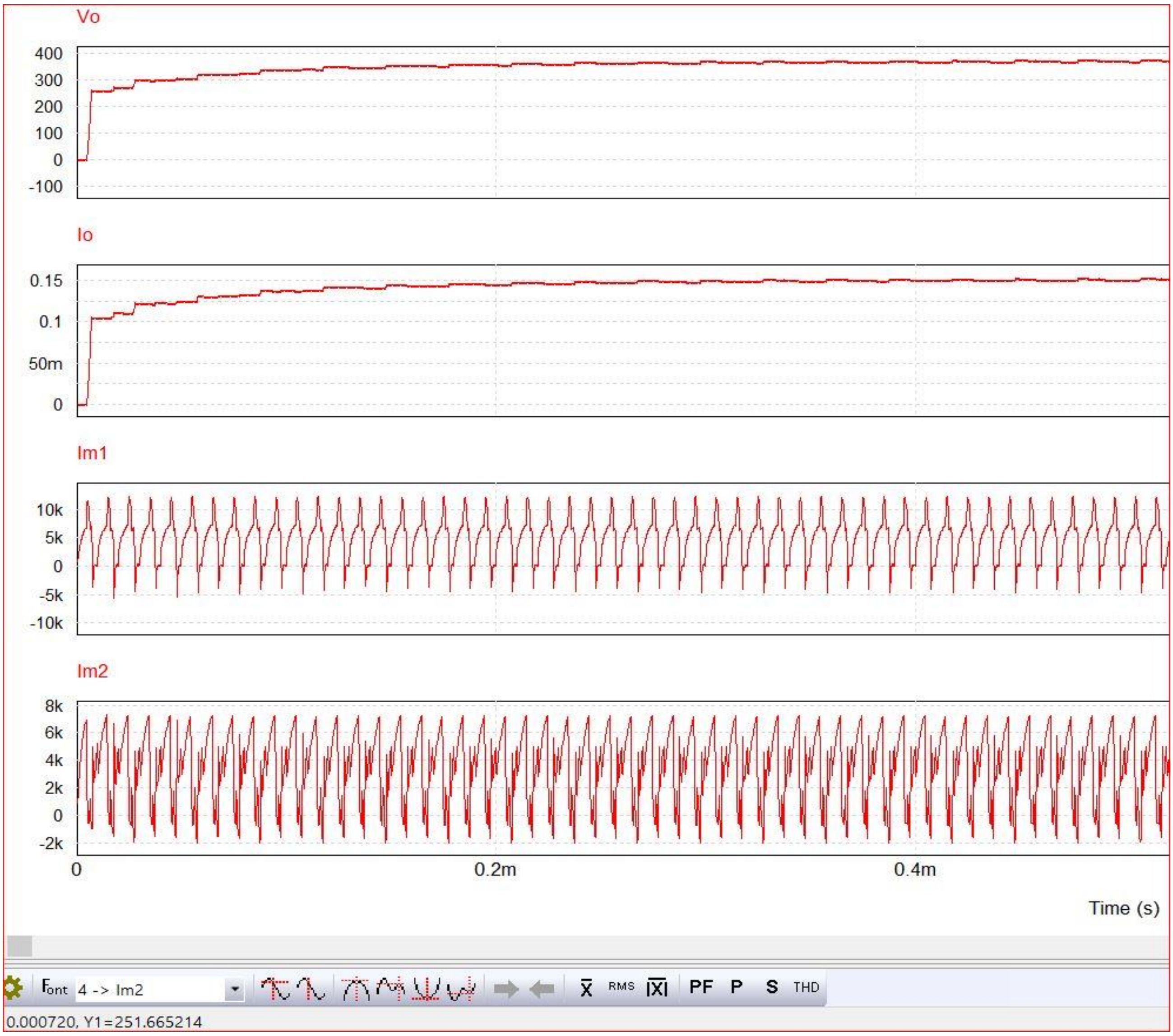
In order to maintain constant output voltage as 350 volts

Output current is = $\frac{Po}{Vo} = \frac{50}{350}$= .1428

Then output resistance = $R_L = \frac{Vo}{Io} = \frac{350}{0.1428}$ = 2450 Ώ

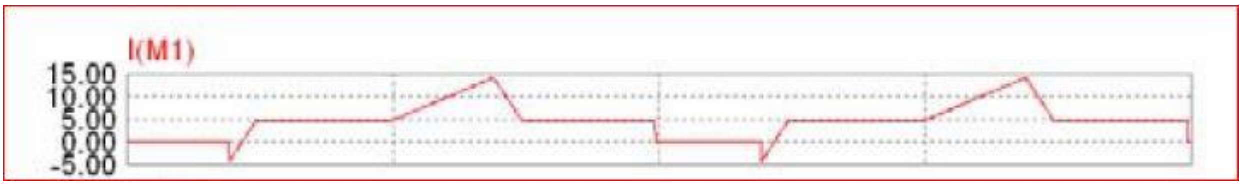
Max voltage across switch has been taken as 110 volts
Duty cycle has been adjusted to = 0.6





Comment:

While designing the active clamped ZVS current DC-DC converter as shown for above cases OUTPUT VOLTAGE was observed to be around 350 volts **but problem of high switch current could not be tackled in spite of trying to adjust duty cycle** in order to maintain constant output voltage. (maybe I would have made mistake in parameter evaluation). Expected output should have been like(not very high current) :



Load condition for ZVS is given by :

$$I_{O\_ZVS}=\frac{\frac{4Vo}{fsw*Ls*M}*\left[\sqrt[2]{\frac{2(Cmain+Caux)}{Ls}}\right]}{\frac{n}{fsw*Ls}+\sqrt[2]{\left(\frac{n}{fsw*Ls}\right)^2-\frac{8nM}{fsw*Ls}*\sqrt[2]{\frac{2(Cmain+Caux}{Ls}}}}$$

With $Ls = 3.96\ \mu H$

$C_a = 1.46\ \mu F$

$L_1=L_2= 350\ \mu F$

$C_{main}= C_1=C_2= 19.83\ \mu F$

$V_O= 350$

$M= \frac{Vo}{Vin}=\frac{350}{22}= 15.90$

$f_{sw}=100$ Khz

N=n=4

Considering the above evaluation and graphical explanation from the paper as shown below:

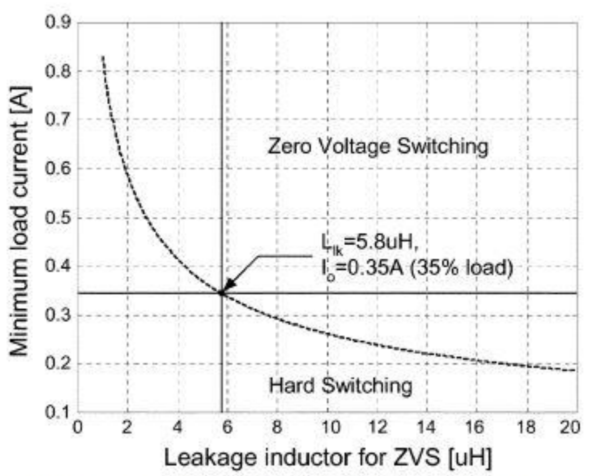


Fig. 12. Minimum load current for the ZVS according to the leakage inductor.

On similar lines

$I_{L(min)}$ = 0.1428(at 20% load) and $I_{L(max)}$= 0.7142(at full load) corresponding to this **ZVS range varies between 30 % to 65 %** .

It can be observed that this configuration absorbs the voltage surge across the turned off switch and achieves the ZVS of all power switches. Since the auxiliary switches of snubber circuit are complementarily turned on and off to main switches, its operation is quite simple. In Addition, it doesn't require any clamp winding besides additional 2 power switches and one capacitor. It features a simple structure and low cost of production compared with the conventional converter.

References:

1) IEEE paper " Analysis and design of active clamped ZVS current fed DC-DC Converter for fuel-cell to utility-interface application" by A.K.S Bhat , A Rathore and R. Orungarti
2) "A New active clamped ZVS PWM current fed half bridge converter" by Sang-kyoo,Gun-woo Moon , Myung-joong Youn, Yoon-ho kim and Kang -hee lee.