EXPERIMENT – 3

Thyristor (SCR) Based Buck Converter

(Equipped with Class-D Commutation Circuit)

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1.Design Problem

Design a Buck converter with following specifications-

$V_i = 800 \pm 20\%\ V$

$V_o = 500\ V$

$I_o = 25\ A$

$t_q(main\ thyristor) = 30\mu s$

$\Delta V_{o(p-p)} = 5\%\ of\ Vo$

$F_s = 500\ Hz\ \ \&\ T_s = 1/F_s$

Converter should operate in C.C.M always.

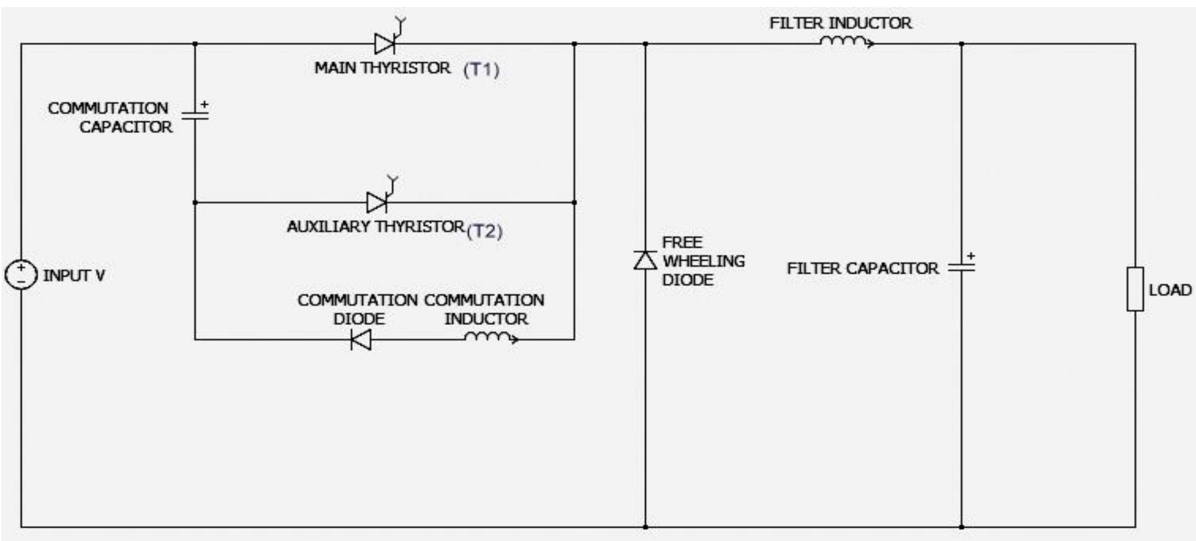


Figure 1 Circuit Diagram

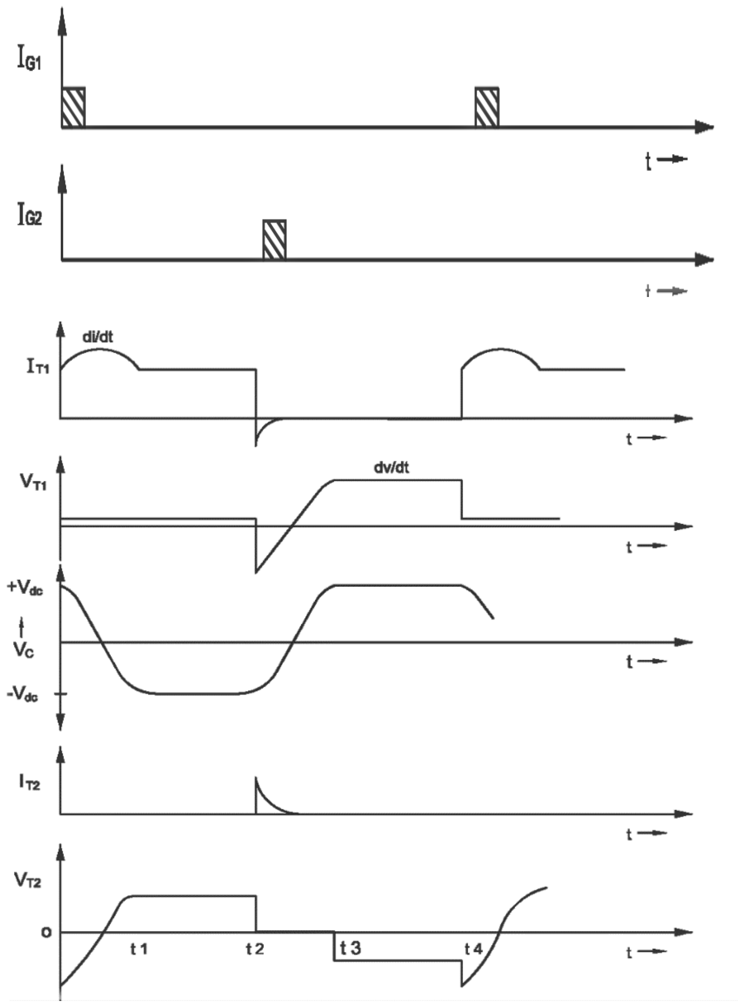


Figure 2 Key Waveforms

Solution:

2.Filter Designing

Let us first estimate the filter inductor (L_{filter}) & the filter capacitor (C_{filter}).

As per the given condition-

$V_i^{max} = 960V$

$V_i^{min} = 640V$

So,

$D_{min} = 0.52083 \ \& \ D_{max} = 0.78125$

$$R = \frac{V_o}{I_o} = 20\ \Omega$$

For C.C.M the condition is like following-

$$\frac{2 \times L_{filter}}{R \times T_s} \geq (1 - D)$$

So even in the worst case the condition for filter inductor would be-

$$L_{filter} \geq \frac{(1 - D_{min}) \times R \times T_s}{2}$$

$$L_{filter} \geq 9.5834\ mH$$

Let us take, $L_{filter} = 15\ mH$

Maximum current through L_{filter} = $I_o + \frac{\Delta I}{2}$ = 25 + $\frac{500 \times (1 - Dmin)}{500 \times 2 \times 15 \times 10^{-3}}$ = 41 A

Now, we can calculate the capacitor value like following-

$$\frac{(1 - D) \times V_o}{8 \times f_{sw}^2 \times L_{filter} \times \Delta V_o} \leq C_{filter}$$

Even in worst case condition for maintaining prescribed amount of ripple the condition for capacitor would be-

$$\frac{(1 - D_{min})}{8 \times f_{sw}^2 \times L_{filter}} \times \frac{100}{5} \leq C_{filter}$$

$$C_{filter} \geq 319.446\ \mu F$$

Let us take, $C_{filter} = 330\ \mu F$

Now as our filter designing is done, we can concentrate to **Commutation Circuit Design**.

3.Commutation Circuit Designing

Here we are using class-D commutation circuit

If t_c is the chosen circuit turn-off time (in seconds) then the required commutation capacitor (C_{com}) value is given by the following relation-

$$C_{com} \geq \frac{D \times t_c}{R}$$

This relation is valid when negligible ripples are there in inductor current.

This t_c must be greater or at least equal to t_q (device turn-off time) for faithful commutation.

We are taking $t_c = 100\mu s$

So, for the worst case condition

$$C_{com} \geq \frac{D_{max} \times t_c}{R}$$

$$C_{com} \geq 3.905\mu F$$

When there is considerable amount of ripple in inductor current, the following formula would give a better estimation-

$$C_{com} \geq \frac{(1 + \frac{\Delta I_{o(p-p)}}{2I_o}) \times D_{max} \times t_c}{R}$$

We should choose a capacitor of the nearest higher version of calculated value.We chose,

$$C_{com} = 4.7\mu F$$

To find out the L_{com} value, we need to consider another important constraint of the commutation circuit. It is discussed below-

Looking carefully into the waveforms you can find that whenever the main thyristor get fired, it turns on & the voltage of the commutation capacitor swings from $+V_i$ to$-V_i$. This phenomenon is absolutely critical to turn-off the main thyristor by firing the auxiliary thyristor.

This voltage swing needs $\pi \times \sqrt[2]{L_{com} \times C_{com}}$ sec. time.

We are considering that this voltage swing must occur in 1/10th of the minimum turn-on time.So, the relationship is-

$$\pi \times \sqrt[2]{L_{com} \times C_{com}} \leq \frac{D_{min} \times T_s}{10}$$

If you have the value of C_{com} from the previous condition you can easily find out the L_{com} value from the relation.

We chose, $L_{com} = 0.25\, mH$

I_{rms} for L_{com} = $\sqrt{\frac{1}{T_s}(\int_0^{0.5T_r}(I_m \sin(w_r t)^2 dt}$ = 20.6 A (Vi = 960V)

Notes:

1) One important aspect which is dependent on the choice of L_{com} & C_{com} is the current through the main thyristor. The peak current through the main thyristor is given by the following relation-

   $i_{main}^{peak} = I_o + V_i\sqrt{\frac{C_{com}}{L_{com}}}$ When there is very low ripple in inductor current.

   If there is considerable ripple in inductor current then the expression is more likely to be -

   $i_{main}^{peak} = i_L^{min} + V_i\sqrt{\frac{C_{com}}{L_{com}}}$

2) From the above discussion & expressions it's clear that if someone chooses a C_{com} of very high value (thinking that it will buy me more circuit turn-off time) the peak current through the main thyristor will increase considerably.
3) If someone thinks that lets just scale the L_{com} & C_{com} both by same factor, then it won't affect the i_{main}^{peak} as a consequence the voltage swing time of the commutation capacitor will be increased by same factor & it might breach the limiting condition which might lead to commutation failure.

So, one has to make a very judicious choice of L_{com} & C_{com} for executing faithful commutation.

4.Closed Loop Control of Converter:

Inductor Current Control:

With the proper design parameters found out using the previous discussion, we can simulate the circuit in open loop.

If we do this, we will eventually find out that the circuit's steady state performance is good enough but the transient response is very peaky. It will be more evident if we analyze the inductor current. To get better transient performance we have to execute close-loop control of the converter.

This could be done by controlling the **inductor current** or the **output voltage** as the load used here is constant.

In this segment **inductor current control** would be discussed. In the next segment **output voltage control** will be discussed.

- *Converter Transfer Function:*
  For a buck converter the relationship of inductor current $(\widehat{\iota_L(s)})$ & duty cycle $(\widehat{d(s)})$ in Laplace domain is given by the transfer function –

$$\frac{\widehat{\iota_L(s)}}{\widehat{d(s)}} = \frac{V_i(1 + sCR)}{s^2LCR + sL + R}$$

  L, C, R is parameters' values as per your design.
  Here, $L \equiv \ L_{filter}$ & $C \equiv \ C_{filter}$.

  Replace this parameters with the previous designed values.

  Then the t/f would look like following-

$$\frac{\widehat{\iota_L(s)}}{\widehat{d(s)}} = \frac{V_i(1 + s \times 6.6 \times 10^{-3})}{s^2(\frac{99}{10^6}) + (s \times 15 \times 10^{-3}) + 20}$$

To do its stability analysis, draw the bode plot of the t/f using MATLAB command.

You would get following result-

V_i (Input Voltage)	G_m (gain margin)	P_m (Phase margin)	ω_{gc} (gain crossover frequency)	ω_{pc} (phase crossover frequency)
640	∞	$90°$	4.27×10^4	∞
960	∞	$90°$	6.4×10^4	∞

- *Controller Designing*

We can see that the current loop is inherently stable.

But **we want our loop t/f (G(s)H(s)) to have a gain crossover frequency (ω_{gc}) 1/10th of the switching frequency (ω_s)**, also we have to provide some stability margin .

Here, $\omega_s = 2\pi F_s$

To do that we would connect a PI controller in cascade with the plant t/f (i.e $\frac{\widehat{i_L(s)}}{\widehat{d(s)}}$).

General expression of a PI controller t/f is like following-

$$(K_p + \frac{K_i}{s})$$

For our ease of use we would use the PI t/f in the following format –

$$K(1 + \frac{\omega_z}{s})$$

After adding PI controller the forward path gain looks like-

$$G(s)H(s) = K(1 + \frac{\omega_z}{s})(\frac{V_i(1 + s \times 6.6 \times 10^{-3})}{s^2\left(\frac{99}{10^6}\right) + (s \times 15 \times 10^{-3}) + 20})$$

Let's take a phase margin of $30°$. (for stability phase margin must be +ve, higher the phase margin higher would be the stability)

Let us now find the K & ω_z

From the phase criteria we would get-

$$< G(j\omega)H(j\omega)_{\omega=\omega_{gc}} = -180° + P.M = -180° + 30° = -150°$$

Solving this equation we get,

$$\omega_z = 52.47$$

& from the gain criteria we would get-

$$|G(j\omega)H(j\omega)|_{\omega=\omega_{gc}} = 1$$

$$K = 4.8474/V_i$$

Now we can take the signal which is coming out of PI controller & compare it with a saw tooth wave of frequency F_s & generate gate pulses to trigger both the thyristors (Main & Auxiliary).

<u>Output Voltage control</u>

- *Converter Transfer Function:*

  For a buck converter the relationship of output voltage ($\widehat{V_o(s)}$) & duty cycle ($\widehat{d(s)}$) in Laplace domain is given by the transfer function –

$$\frac{\widehat{V_o(s)}}{\widehat{d(s)}} = \frac{V_i}{s^2LC + s\frac{L}{R} + 1}$$

  L, C, R is parameters' values as per your design.

  Here, $L \equiv L_{filter}$ & $C \equiv C_{filter}$.

  Then the t/f would look like following-

$$\frac{\widehat{V_o(s)}}{\widehat{d(s)}} = \frac{V_i}{s^2(4.95 \times 10^{-6}) + (s \times 7.5 \times 10^{-4}) + 1}$$

To do its stability analysis, draw the bode plot of the t/f using MATLAB command.

You would get following result-

V_i (Input Voltage)	G_m (gain margin)	P_m (Phase margin)	ω_{gc} (gain crossover frequency)	ω_{pc} (phase crossover frequency)
640	∞	$0.764°$	1.14×10^4rad/s	∞ rad/s
960	∞	$0.624°$	1.39×10^4 rad/s	∞ rad/s

- *Controller Designing*

We can see that the Voltage loop is stable by very low P.M.

For Stability:- (P.M. > 0 and G.M. > 0)

we want our loop t/f (G(s)H(s)) to have a gain crossover frequency (ω_{gc}) 1/7th of the switching frequency (ω_s), also we have to provide some stability margin .

Here, $\omega_s = 2\pi F_s$

To do that we would connect a PI controller in cascade with the plant t/f (i.e $\frac{\widehat{V_o(s)}}{\widehat{d(s)}}$).

PI Controller - $K(1 + \frac{\omega_z}{s})$

After adding PI controller the forward path gain looks like-

$$G(s)H(s) = K(1 + \frac{\omega_z}{s})(\frac{V_i}{s^2(4.95 \times 10^{-6}) + (s \times 7.5 \times 10^{-4}) + 1})$$

Let's take a phase margin of $55°$. (for stability phase margin must be +ve, higher the phase margin higher would be the stability)

Let us now find the K & ω_z

From the phase criteria we would get-

$$< G(j\omega)H(j\omega)_{\omega=\omega_{gc}} = -180° + P.M = -180° + 55° = -125°$$

Solving this equation we get,

$$\omega_z = 23.22$$

& from the gain criteria we would get-

$$|G(j\omega)H(j\omega)|_{\omega=\omega_{gc}} = 1$$

$$K = 1/(2.25V_i)$$

Now we can take the signal which is coming out of PI controller & compare it with a saw tooth wave of frequency F_s & generate gate pulses to trigger both the thyristors (Main & Auxiliary).

5.Magnetics Design

1. Filter Inductor Magnetics

Inductor Value(L)	15mH
Peak Inductor current(Ip)	41A
Rms Inductor current(Ir)	25A
Winding Factor(Kw)	0.5
Current density(J)	4A/mm^2
Max. Flux Density(Bm)	1wb/m^2

Design Procedure

- Area Product(Ap) = $\frac{L\times Ip\times Ir}{Kw\times J\times Bm}$ = 7.6*10^6 mm^4

165.1 mm OD Toroid core is Chosen (From magnetics design Table),whose area product is just higher than calculated area product.

Ap=7.92*10^{6}mm^4,Aw(winding area)= 8030 mm^2 ,Ac(crossaction area)=987mm^2

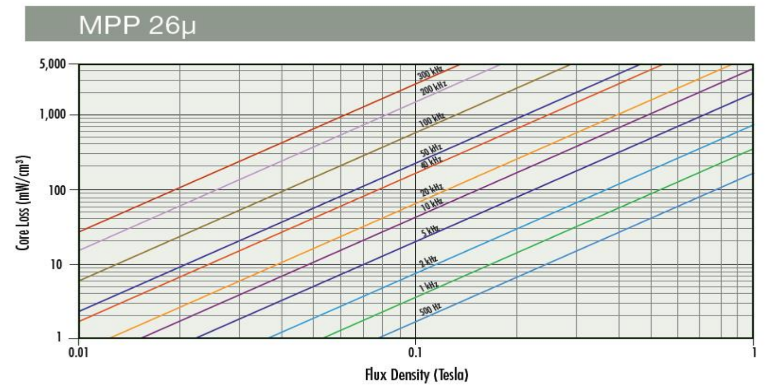
- Number of turns (N) = $\frac{L\times Ip}{Bm\times Ac}$= $\frac{15\times10^{-3}\times41}{1\,T\times987mm2}$ =623
- Winding crossaction area(a_w) = $\frac{Ir}{J} = \frac{25}{4} = 6.25$mm^2

Thus **SWG11 wire gauge** chosen (a_w = 6.818mm^2)

- Air gap (lg) = $\frac{\mu o\times N\times Ip}{Bm}$ =30mm
- Updated J= $\frac{Ir}{aw}$ =$\frac{25}{6.818}$ = 3.66A/mm^2
- Updated K_w = $\frac{N\times aw}{Aw}$= $\frac{623\times6.818}{8030}$ = 0.52
- Average length of each turn of coil = 2× (HT+OD-ID) =18.88cm
- Total length of coil = N×18.88cm = 117meter
- Resistance of wire per meter = 2.529×10^{-3} ohm
- Total resistance(R_t) = 117×2.529×10^{-3} = 0.29 ohm
- Updated area product = 7.4*10^{6}mm^4
- Copper loss = R_t*I_r^2= 185 W

From core loss density curve ,for selected core permeability was 26μ,and for 500Hz ,1wb/m^2 ,core loss per unit volume = 180mW/cm^3 and Volume of core is 407000mm^3

- Core loss = Core loss Per unit volume *Volume =73.26W



2. Commutation Inductor magnetics

Inductor Value(L)	0.25mH
Peak Inductor current(Ip)	132A
Rms Inductor current(Ir)	20.62A
Winding Factor(Kw)	0.5
Current density(J)	3A/mm^2
Max. Flux Density(Bm)	1wb/m^2

Design Procedure

- Area Product(Ap) = $\frac{L\times Ip\times Ir}{Kw\times J\times Bm}$ = 4.5*10^5 mm^4

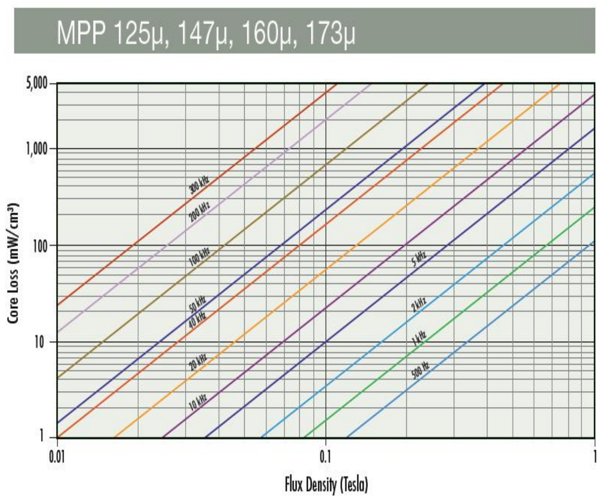
77.8 mm OD Toroid core is Chosen (From magnetics design Table),whose area product is just higher than calculated area product.

Ap=5.5*10^{5}mm^4,Aw(winding area)= 1150 mm^2 ,Ac(crossaction area)=478mm^2

- Number of turns (N) = $\frac{L\times Ip}{Bm\times Ac}$= $\frac{0.25\times10^{-3}\times132}{1\times478}$ =70
- Winding crossaction area(a_w) = $\frac{Ir}{J} = \frac{20.62}{3} = 6.87$mm^2

Thus **SWG10 wire gauge** chosen (a_w = 8.3mm^2)

- Air gap (lg) = $\frac{\mu o \times N \times Ip}{Bm}$ =11.6mm
- Updated J= $\frac{Ir}{aw}$ =$\frac{20.92}{8.3}$ = 2.519A/mm^2
- Updated K_w = $\frac{N \times aw}{Aw}$= $\frac{70 \times 8.3}{1150}$ = 0.505
- Average length of each turn of coil = 2× (HT+OD-ID) =12.86cm
- Total length of coil = N×12.86cm =9meter



- Resistance of wire per meter = 2.077×10^{-3} ohm
- Total resistance(R_t) = $9 \times 2.077 \times 10^{-3}$ = 0.0186 ohm
- Updated area product = $4.49 * 10^5 mm^4$
- Copper loss = $R_t * I_r^2$= 7.94W

From core loss density curve ,for selected core ,permeability was 125μ and for 500Hz,1wb/m^2 core loss per unit volume = 110mW/cm^3 and Volume of core is 81500mm^3

- Core loss = Core loss Per unit volume * Volume = 8.96W

Magnetics design table for both core:- https://www.mag-inc.com/Design/Design-Guides/Inductor-Cores-Material-and-Shape-Choices

Figure 3 Toroid Core winding , Filter Inductor Core, Commutating Inductor core with OD(outer diameter),ID(inner diameter),HT(height)

6.Losses:

S No.	Device Name	For 640 Volts			For 960 Volts			Losses
		Iav(A)	Irms(A)	Ipeak(A)	Iav(A)	Irms(A)	Ipeak(A)	In Watt
1	Main Thyristor	15.71	24.15	102.2	11.47	26.43	141.1	35.194
2	Auxiliary Thyristor	3.00	9.60	33.19	4.51	13.06	41.53	10.09
3	Commutation Diode	3.00	14.36	87.6	4.50	21.54	131.4	5.217
4	Free Wheeling Diode	6.40	12.13	32.06	11.88	17.94	40.47	14.77
5	Commutation Capacitor	4.11e-3	17.27	87.59	5.5e-3	25.19	131.4	9.518
6	Filter Capacitor	8.3e-2	5.36	8.46	8.25e-2	9.892	17.23	0.293
7	Commutation Inductor	3.00	14.36	87.6	4.50	21.54	131.4	16.9
8	Filter Inductor	22.12	23.06	32.25	23.36	25.47	41.78	258.26

1) Main Thyristor -
   Part no.- VS-ST083S12
   1200V; 85A; V_{tm}= 2.15V ; r_t =2.32m ohm
   https://datasheetspdf.com/pdf/989814/Vishay/VS-ST083S12/1

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
15.71	24.15	102.2	35.194	11.47	26.43	141.1	26.28

2) Auxiliary Thyristor –
   Part no.- VS-ST083S12
   1200V; 85A; V_{tm}= 2.15V ; r_t =2.32m ohm
   https://datasheetspdf.com/datasheet/VS-ST083S12.html

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
3.00	9.60	33.19	6.66	4.51	13.06	41.53	10.09

3) Commutation Diode –
   Part no.- SKN70/16
   1600V; 94A; Rt=3m ohm; Vto=0.85V; Vf=1.5V
   https://www.tme.com/in/en/details/skn70_16/stud-mounting-universal-diodes/semikron/

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
3.00	14.36	87.6	3.168	4.50	21.54	131.4	5.217

4) Free Wheeling Diode –

Part no.- SKNa47/36
3600V; 50A; Rt=9m ohm; Vto=1V; Vf=1.8V
https://www.alldatasheet.net/datasheet-pdf/pdf/217364/SEMIKRON/SKNA47/36.html

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
6.407	12.13	32.06	7.731	11.88	17.94	40.47	14.77

5) Filter Capacitor–
Part no.- 947C331K112BCHS
330 microF
1.1kV; 55A; ESR=3m ohm; +/-10%
https://in.element14.com/cornell-dubilier/947c331k112bchs/cap-330-f-1-1-kv-10-pp-can-panel/dp/1832257

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
8.3e-2	5.366	8.46	0.086	8.25e-2	9.892	17.23	0.293

6) Commutataion Capacitor–
Part no.- UNL15W4P7K-F
4.7 microF
1.5kV; ESR=15m ohm; +/-10%
https://in.element14.com/cornell-dubilier/unl15w4p7k-f/cap-4-7-f-1-5-kv-10-pp-can/dp/2361816

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
4.11e-3	17.27	87.59	4.473	5.5e-3	25.19	131.4	9.518

7) Filter Inductor–
Part no.-
15mH;

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
22.12	23.06	32.25	227	23.36	25.47	41.78	258.26

8) Commutation Inductor–
Part no.-
0.25mH;

For 640 Volts				For 960 Volts			
Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)	Iav(A)	Irms(A)	Ipeak(A)	Losses(Watt)
3.006	14.36	87.6	12.79	4.50	21.54	131.4	16.9

7.Heat Sink Designing:

Heat sink of the switches are designed considering the highest loss that might occur in the operating range.

While designing heatsink limit we have considered maximum virtual junction temperature (T_{vj}) for semiconductor switches.

The generalized formula that we used to find the heatsink limit is like following (though similar analysis could be done from the characteristic graphs given in the datasheets of the switches)-

$$P_{TAV} \times [R_{th\ j-c} + R_{th\ c-s} + R_{th\ s-a}] \leq T_{vj}^{max} - T_{ambient}$$

For all the switches we have considered the $T_{ambient}$ to be $40°C$.

Main Thyristor:

$$P_{TAV} = 35.194\ W$$

$$T_{vj}^{max} = 125°C$$

$$R_{th\ c-s} = 0.08\ K/W$$

$$R_{th\ j-c} = 0.195\ \ K/W$$

This $R_{th\ j-c}$ parameter varies with the conduction angle & the shape of current. In this condition the current conduction angle is aprrox. 248.94 deg square shape. So, we have taken the $R_{th\ j-c}$ value for D.C continuous current.

After calculation we get, $R_{th\ s-a} \leq 2.14\ K/W$

So, let us choose a heatsink of 2 K/W.

Auxiliary Thyristor:

The same device is used here.

But here,

$$P_{TAV} = 10.09\ W$$

& as in this condition the current carried by this thyristor is of rectangular wave shape & the conduction angle is approx. $40°$, there would be an increment in the value of $R_{th\ j-c}$ by an amount $\Delta R_{th\ j-c} = 0.111$.

So, $R_{th\ j-c}^{new} = 0.195 + 0.111 = 0.306$

Now, solving the equation we get, $R_{th\ s-a} \leq 8.03 K/W$

let us choose a heatsink of 8 K/W.

<u>Commutation Diode:</u>

For commutation diode

$$P_{TAV} = 5.217\ W$$

$$T_{vj}^{max} = 180°C$$

$$R_{th\ c-s} = 0.2\ K/W$$

$$R_{th\ j-c} = 0.55\ K/W$$

By calculation we get, $R_{th\ s-a} \leq 26.08\ K/W$

let us choose a heatsink of 25 K/W.

<u>Freewheeling Diode:</u>

$$P_{TAV} = 14.77\ W$$

$$T_{vj}^{max} = 150°C$$

$$R_{th\ c-s} = 0.25\ K/W$$

$$R_{th\ j-c} = 0.6\ K/W$$

By calculation we get, $R_{th\ s-a} \leq 6.6\ K/W$

let us choose a heatsink of 6 K/W.

All the devices are stud-mounted, so we have to choose heatsinks according to that.

8.Efficiency Calculation

Vin = 640V

%Eff. =$\frac{Output}{Output+Losses}$ =$\frac{12500W}{12500W+297W} = 97.6\%$

Vin = 960V

%Eff. =$\frac{Output}{Output+Losses}$ =$\frac{12500W}{12500W+341.28W} = 97.5\%$

References

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