2

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(a) diode – uncontrolled device, conducts when forward biased

thyristor – Semicontrolled, conducts when forward biased and a gate signal is applied; it turns off when reverse voltage is applied.

4

GTO – a thyristor that can be turned off by applying a negative pulse current; fully controlled

MOSFET – a fully controlled device by applying a positive or negative gate-source voltage.

(b) air gap increases the maximum saturating current and hence the operating range of DC/DC converters.

Example show:- $L = \frac{N^2}{R_c + R_g}$ (inductance)

2

$$i_{sat} = \frac{B_{sat} A_c}{N} (R_c + R_g)$$

↑ air-gap reluctance

energy → $\underbrace{W = \frac{1}{2} L \cdot i_{sat}^2 = \frac{1}{2} B_{sat}^2 A_c^2 (R_c + R_g)}_{\text{increase in operation range!}}$

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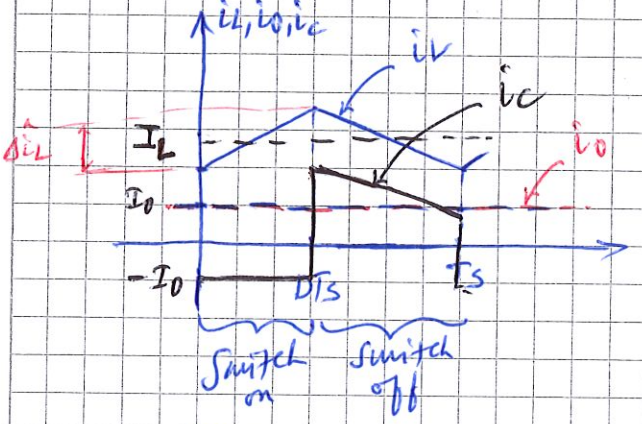
$V_0 = 16V$

$P_0 = 64W$

$V_d = 12V$

$f_{sw} = 20\,kHz$

(a) CCM ideal



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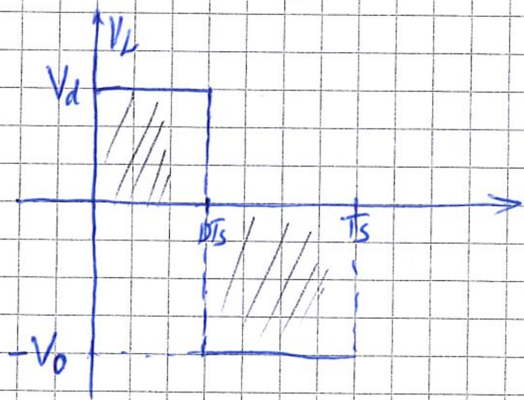
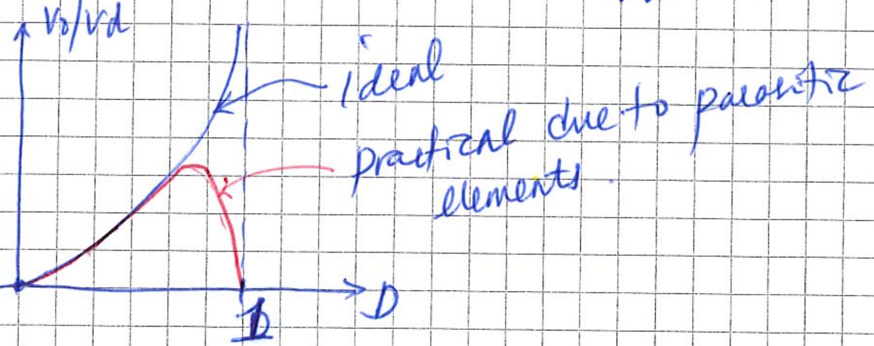


$$\Rightarrow V_L = \int_0^{T_s} v_L dt = 0$$

$$\Rightarrow D V_d - (1-D) V_0 = 0$$

$$\Rightarrow \frac{V_0}{V_d} = \frac{D}{1-D}$$ (Buck-boost Converter)



(b) $I_0 = P_0/V_0 = \frac{64}{16}A = 4A$, $\Delta i_L = 0.1 I_L = \underline{0.4A}$

$I_L = P_0/V_d + I_0 = I_d + I_0 = \frac{64}{12} + 4 = \underline{\underline{9.33A}}$

During on period : $v_L = L\frac{di_L}{dt} = L\frac{\Delta \hat{i}_L}{DT_s} = V_d$

$\Rightarrow L = \frac{DT_s V_d}{\Delta \hat{i}_L} = \frac{DV_d}{f_{sw}\Delta \hat{i}_L}$;

2

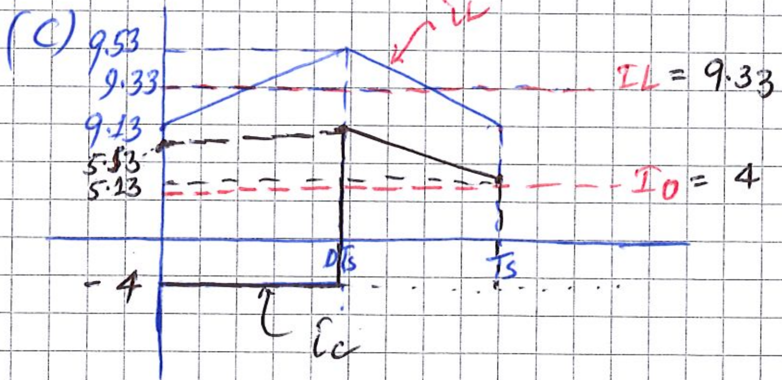
but $\frac{(\Delta \hat{i}_L)}{2} < I_L \Rightarrow$ CCM :

$\Rightarrow \frac{D}{1-D} = \frac{V_0}{V_d} \Rightarrow \frac{1-D}{D} = \frac{V_d}{V_0} = \frac{1}{D} - 1$

$\Rightarrow \frac{1}{D} = 1 + \frac{V_d}{V_0} = \frac{V_0+V_d}{V_0} \Rightarrow D = \frac{V_0}{V_0+V_d} = \underline{\underline{0.571}}$

$\Rightarrow L = \frac{(0.571)(12)}{20(10^3)(0.4)} H = \underline{\underline{0.857 mH}}$

(c)



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(d) $\Delta V_0 = 0.01 V_0 = 0.16V$

Consider the switch on period

$\Rightarrow \Delta V_0 = \frac{1}{C}\int_0^{DT_s} i_c dt = \frac{1}{C}\left(I_0 \cdot DT_s\right)$

2

$\Rightarrow C = \frac{I_0 D}{f_{sw} \cdot \Delta V_0} \Rightarrow C_{min} = \frac{D I_0}{f_{sw}[\Delta V_0]_{max}} = \frac{0.571(4)}{20(10^3)(0.16)} F$

$\Rightarrow C_{min} = \underline{\underline{0.714 mF}}$

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$N_1 : N_2 : N_3 = 1:2:1$

$V_d = 20V$

$f_{sw} = 20\,kHz$

$D = 0.3$

$L_m = 100\,\mu H$

$R_{load} = 10\,\Omega$

V_0, V_{sw}, i_d, i_0

Identify mode of operation.

if CCM ; $V_0 = \frac{D}{1-D} V_d = \frac{0.3}{0.7}(20) = 8.57 < \frac{N_3}{N_2} V_d = 10V$

winding N_2 not used.

$\Rightarrow I_m \geq \frac{\Delta \hat{i}_m}{2}$ $\Rightarrow$ During on period

$V_d = V_1 = L_m \frac{\Delta \hat{i}_m}{DT_s}$

$\Rightarrow \Delta \hat{i}_m = \frac{DV_d}{f_{sw} L_m} = \frac{0.3(20)}{20(10^3)(100 \cdot 10^{-6})} A = 3A$

but $I_m = I_d + I_0 \cdot \frac{N_3}{N_1} = I_d + I_0 \Rightarrow \boxed{I_m = \frac{I_0}{1-D}}$

But $I_0 = V_0 / R_{load} = \frac{8.57}{10} = 0.857A \Rightarrow I_m = 1.224A$

2

But $I_m = 1.224 < \frac{\Delta \hat{i}_m}{2} = 1.5A \Rightarrow$ Converter in DCM!

For DCM: $\frac{V_0}{V_d} = D\sqrt{\frac{R}{2L_m f_{sw}}}$ [should be derived first] $\rightarrow$ for $V_0 \leq \frac{N_3}{N_2} V_d = 10V$

1

$\Rightarrow V_0 = 0.3\sqrt{\frac{10}{2(100 \cdot 10^{-6})(20 \cdot 10^3)}} \cdot 20\,V = 9.487\,V < 10V$

(winding N_2 not used!!!)

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So for DCM,

$\Delta \hat{i}_m = 3A$

For the off period,

$v_1 = -\frac{N_1}{N_3} V_0 = L_m \left(-\frac{\Delta \hat{i}_m}{\Delta_1 T_s} \right)$

$\Rightarrow V_0 = L_m \frac{\Delta \hat{i}_m}{\Delta_1 T_s} \Rightarrow \Delta_1 = \frac{L_m \Delta \hat{i}_m}{V_0 T_s}$

$\Rightarrow \Delta_1 = \left(\frac{L_m \Delta \hat{i}_m}{D T_s} \right) \cdot \frac{D}{V_0}$

$\underbrace{}_{V_d}$

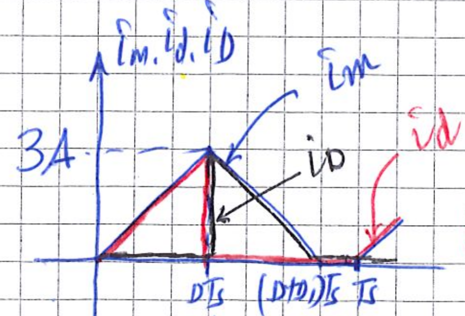
1

$\Rightarrow \Delta_1 = \frac{V_d}{V_0} \cdot D = \frac{20}{9.487} * 0.3 = \underline{\underline{0.632}}$

During the off period, $i_D = \frac{N_1}{N_3} i_m \Rightarrow i_m$; $i_d = 0$, $V_{sw} = V_d + \frac{N_1}{N_3} V_0$

During on period, $i_D = 0$, $i_d = i_m$, $V_{sw} = 0$

For current off period (total demagnetization), $V_{sw} = V_d$, $i_d = i_D = i_m = 0$



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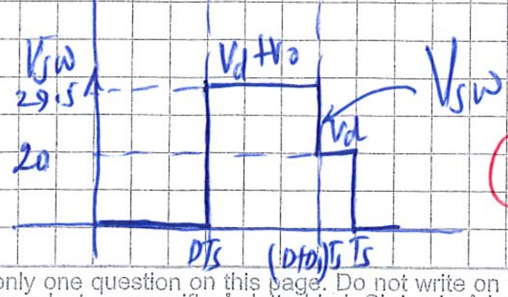

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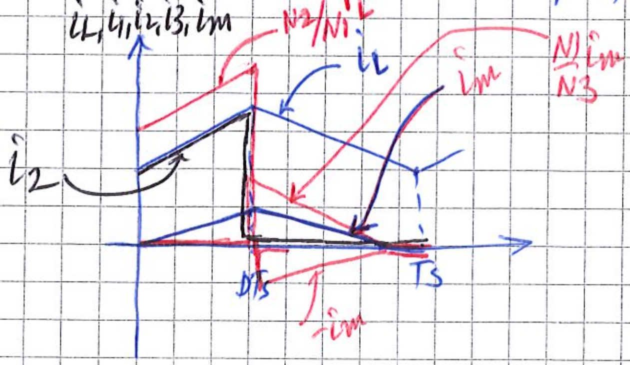
(a) For a proper operation of the forward converter, the magnetic core of the transformer should be totally demagnetized by the start of each switching cycle.

3



When switch on, i_m, i_L increases

$i_2 = i_L$; $i_1 = \frac{N_2}{N_1} i_1 = \frac{N_2}{N_1} i_L$, $i_3 = 0$

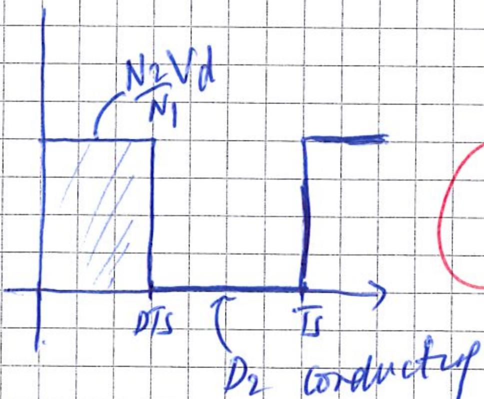
When switch off, i_m, i_L decreases

$i_2 = 0$, $\underbrace{i_1 = -i_m}_{i_{sw} = 0}$, $i_3 = -\frac{N_1}{N_3} i_1 = +\frac{N_1 i_m}{N_3}$

after total demagnetization

$i_1 = i_3 = i_m = 0$

(b) $V_0 = V_{oi} = \frac{1}{T_s}\int_0^{T_s} v_{oi}\,dt$



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$\rightarrow V_0 = \frac{1}{T_s}\left(DT_s \cdot \frac{N_2}{N_1} V_d\right) \rightarrow \frac{V_0}{V_d} = \frac{N_2}{N_1} D$

(c) For magnetic core demagnetization of the transformer. This also prevents overvoltage on the switch due to leakage inductances.

1

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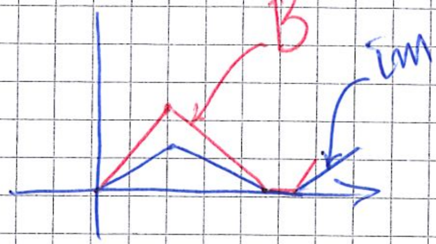
d) (ϕ) flux ~ magnetizing current (i_m); flux ~ flux density (B)

$\Rightarrow B \sim i_m$

$\Rightarrow$



2

- unipolar excitation core
- high saturation flux
- high mutual inductance to require small magnetizing current
  $\Rightarrow$ no air-gap in the core

(e) For flyback
- unipolar excitation
- higher saturation flux as for core

2

- low mutual inductance hence higher magnetizing current for higher operating range!
  $\Rightarrow$ air-gap in the core!

2

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(a) the phase voltages are calculated from the neutral voltage and converter phase leg output voltage

$$v_{A,B,C} = \underbrace{V_{C,A,B,C}}_{\Rightarrow \text{ converter phase voltage}} - V_N$$

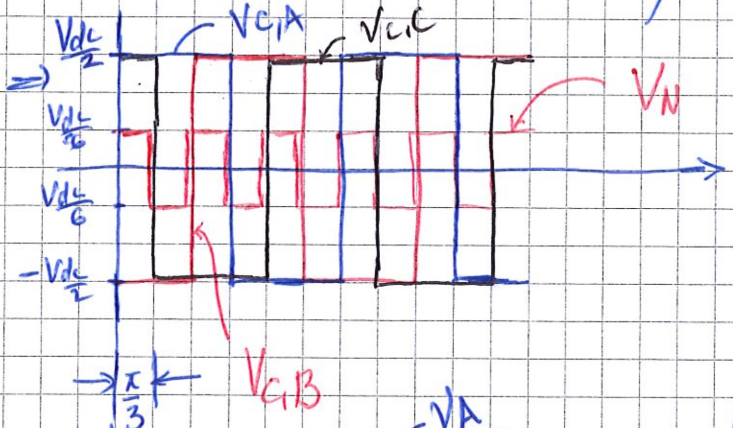
for a balanced system

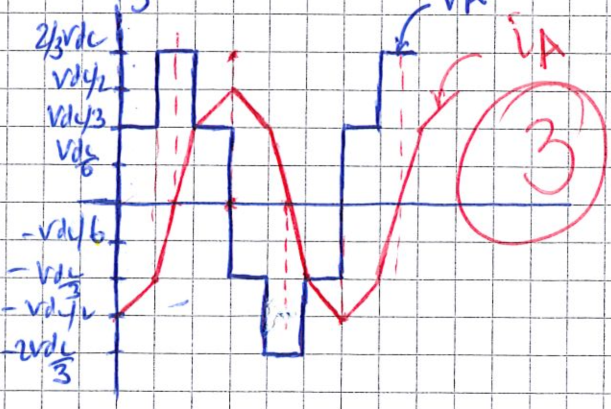
$$v_A + v_B + v_C = V_{C,A} + V_{C,B} + V_{C,C} - 3V_N = 0$$

$$\Rightarrow V_N = \frac{V_{C,A} + V_{C,B} + V_{C,C}}{3}$$

2

$V_{C,A}$, $V_{C,B}$ and $V_{C,C}$ are 120° phase-shifted square waves.





3

$\Rightarrow$ plot v_A + i_A, the other voltage + currents are 120° phase-shifted!!

$$L\frac{di_A}{dt} = v_A$$

$$\Rightarrow i_A = \frac{1}{L}\int v_A dt$$

$\Rightarrow$ i_A is linearly increasing or decreasing based on the sign of v_A.

* i_A is maximum at the zero crossing of v_A.

2

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(b) inductive load $\Rightarrow$ Power = zero

$\Rightarrow V_d \cdot I_d = 0 \Rightarrow I_d = 0$ 1

the average dc-current is zero.

* Due to the square-wave & three phase operation the harmonic components in the dc-current are multiples of the 6th order harmonics.

$\Rightarrow 6n, \quad n = \pm 1, \pm 2, \ldots$ 1

* For a PWM operation, the harmonics orders will be around the switching frequency 1

(c) PWM, $\hat{V}_{A(1)} = m_a \cdot \frac{V_{dc}}{2} = \frac{V_{dc}}{2}$ (peak value) 1

square-wave, $\hat{V}_{A(1)} = \frac{4}{\pi} \cdot \frac{V_{dc}}{2}$ = [Fourier calculation] 2

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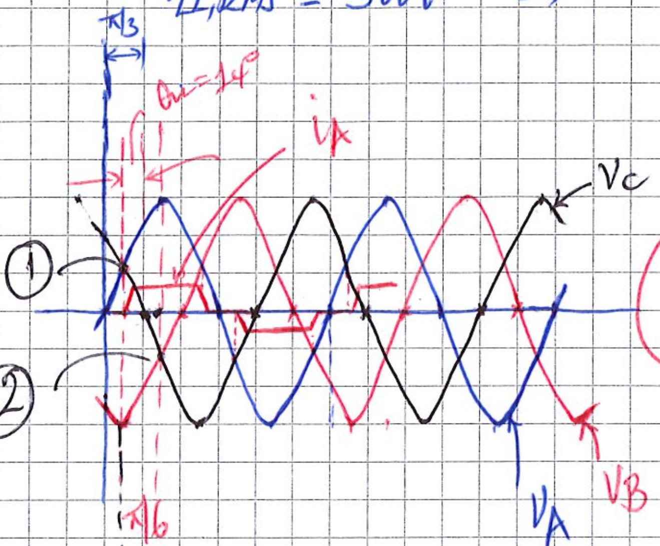
$I_d = 10A$,

$L_s = 2mH$

$f = 50Hz$

$V_{LL,RMS} = 300V \Rightarrow V_{phase,peek} = \frac{300}{\sqrt{3}} \times \sqrt{2} = \underline{\underline{245}}\,V$



2

$\Rightarrow V_A = 245 \sin(2\pi \cdot 50 t)$

$V_B = 245 \sin(2\pi \cdot 50t - 2\pi/3)$

$V_C = 245 \sin(2\pi \cdot 50t + 2\pi/3)$

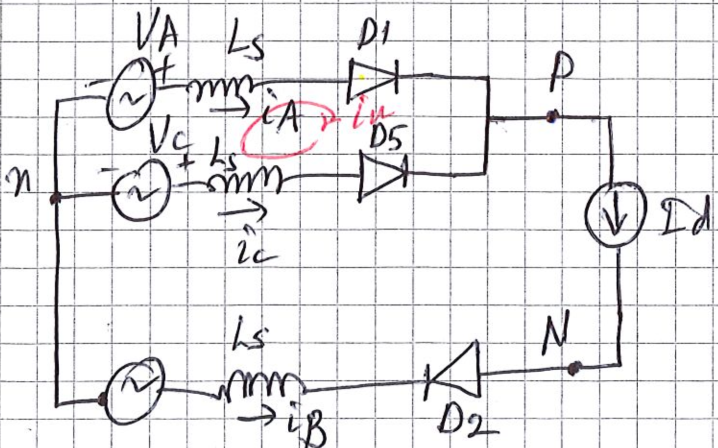
Current flows in each phase when voltage is maximum or minimum & continuous to flow during commutation.

Commutation period = ?

at 1 current should commutate from phase C (D5) to phase A (D1)

at 2 current should commutate from phase B (D6) to phase C (D2)

$\Rightarrow$ During commutation at 1 i_a grows from 0 to I_d, where the commutation circuit is given by



i_u grows from 0 to I_d.

$i_A = i_u$

$i_C = I_d - i_u$

$\Rightarrow V_A - V_C - L_s \frac{di_A}{dt} + L_s \frac{di_C}{dt} = 0$

$\Rightarrow 2L_s \frac{di_u}{dt} = V_A - V_C$

$\Rightarrow 2L_s \omega_s \frac{di_u}{d\theta} = V_A - V_C$

$\Rightarrow 2L_s \omega_s I_d = \int_{\pi/6}^{\pi/6 + u} (V_A - V_C)\,dt$

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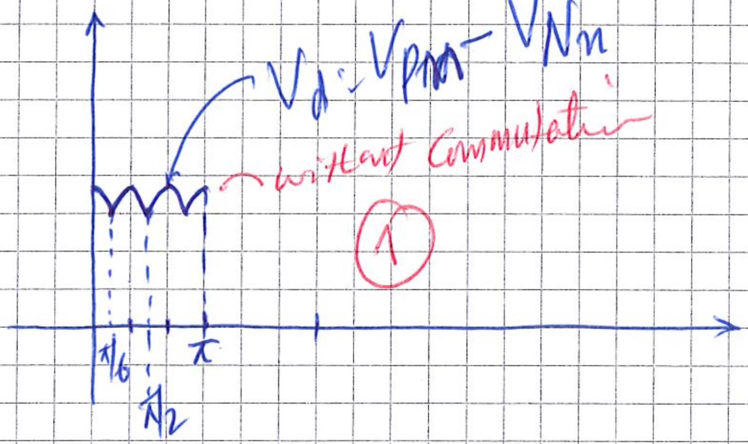
$$\Rightarrow 2L_s\omega_s I_d = \int_0^{\theta_u} \sqrt{2}V_{LL}\sin(\theta)\,d\theta = \sqrt{2}V_{LL}(1-\cos\theta_u)$$

$$\Rightarrow \cos\theta_u = 0.97\,04 \quad \Rightarrow \quad \theta_u = 0.2439\text{ rad} \approx \underline{\underline{14^\circ}}$$

Look the plot in the previous page for i_a 1

the DPF $\approx \cos\left(\frac{\theta_u}{2}\right) = \cos(7^\circ) \approx \underline{\underline{0.9926}}$

(b) Check plots of V_d in the previous page for reference



For one cycle from $\pi/6$ to $\pi/2$ without commutation

$$V_{d0} = \frac{1}{\pi/3}\int_{-\pi/6}^{\pi/6} \sqrt{2}V_{LL}\cos\theta\,d\theta = \frac{3\sqrt{2}}{\pi}V_{LL} = \underline{\underline{405\text{ V}}}$$

for each cycle, there is one commutation, that reduces the average voltage by $\Delta V_d = \dfrac{\text{Area}^{\text{loss}} \text{ due to commutation}}{\pi/3}$

For point 1, $V_{pN}(\text{ideal}) = V_A$

$$V_{pN}(\text{comm}) = V_A - L_s\frac{di_A}{dt} = V_A - L_s\frac{di_u}{dt} = \frac{V_A+V_C}{2}$$

$$\Rightarrow A_u = \int_0^{\theta_u}\left(V_A - \frac{V_A+V_C}{2}\right)d\theta = \int_0^{\theta_u}\frac{(V_A-V_C)}{2}\,d\theta = L_s\omega_s I_d \quad 1$$

$$\Rightarrow V_d = V_{d0} - \frac{3L_s\omega_s I_d}{\pi} = \underline{\underline{399\text{ V}}}$$

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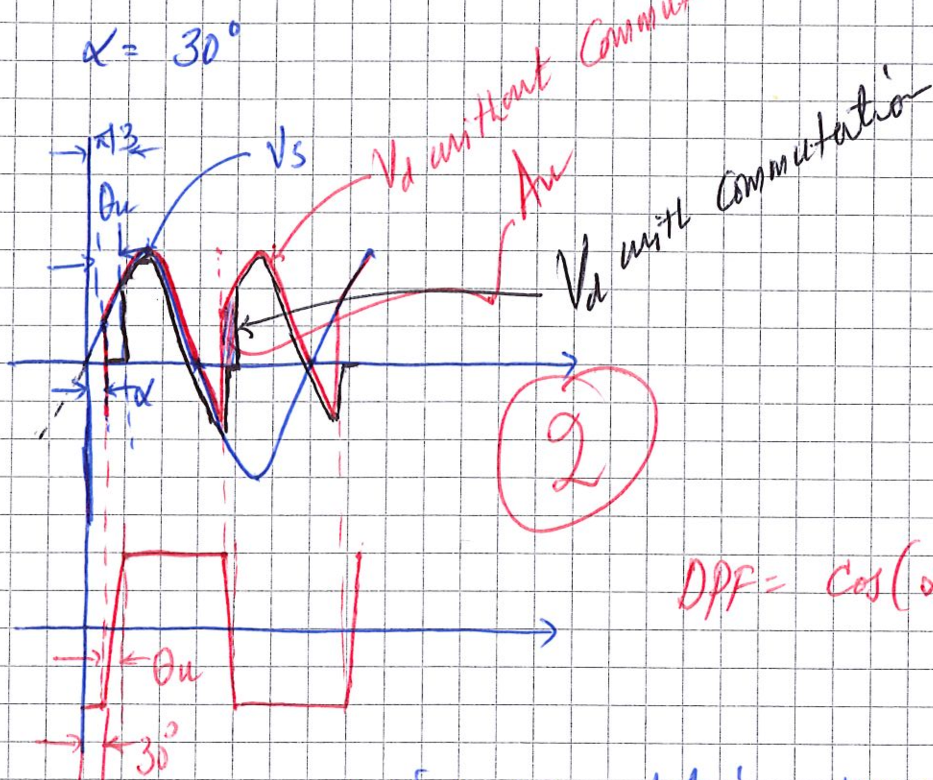
$L_s = 5mH$

$V_s = 300\,V$ (peak)

$\Rightarrow v_s = 300 \sin(2\pi \cdot 50 t)$

$i_d = 20A$

(a) $\alpha = 30°$



$DPF = \cos(\alpha + \theta_u/2)$

During commutation, $V_d \approx 0$, all thyristors conduct.

$$\Rightarrow L_s \frac{di_s}{dt} = V_s \Rightarrow L_s \omega_s \frac{di_s}{d\theta} = V_s$$

$$\Rightarrow \int_{-I_d}^{I_d} L_s \omega_s \, di_s = \int_{\alpha}^{\alpha+\theta_u} V_s \, d\theta$$

$$\Rightarrow 2L_s \omega_s I_d = -300 \cos\theta \Big|_{\alpha}^{\alpha+\theta_u} = 300(\cos(\alpha) - \cos(\alpha+\theta_u))$$

$$\Rightarrow \cos(\alpha+\theta_u) = -\frac{2L_s\omega_s I_d}{300} + \cos\alpha$$ 1

$$\Rightarrow \cos(\alpha+\theta_u) = 0.6566 \Rightarrow \theta_u = 0.331\,\text{rad}$$
$$= \underline{\underline{19°}}$$

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(b) $V_d = V_{d0} - \frac{A_u}{\pi}$

$$A_u = \int_{\alpha}^{\alpha+\theta u} v_s \, d\theta = 2 L_s \omega_s I_d$$

$$V_{d0} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} v_s \, d\theta = -\frac{300 \cos\theta}{\pi}\Bigg|_{\alpha}^{\pi+\alpha}$$

$$= 300\{\cos\alpha - \cos(\pi+\alpha)\}$$

$$= \frac{600\cos\alpha}{\pi} = 165.4V$$

2

$$\Rightarrow V_d = V_{d0} - \frac{2 L_s \omega_s I_d}{\pi} = 145.4V$$

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