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Charging Infrastructure

Lecture-25

Three-phase AC-DC Converter-III

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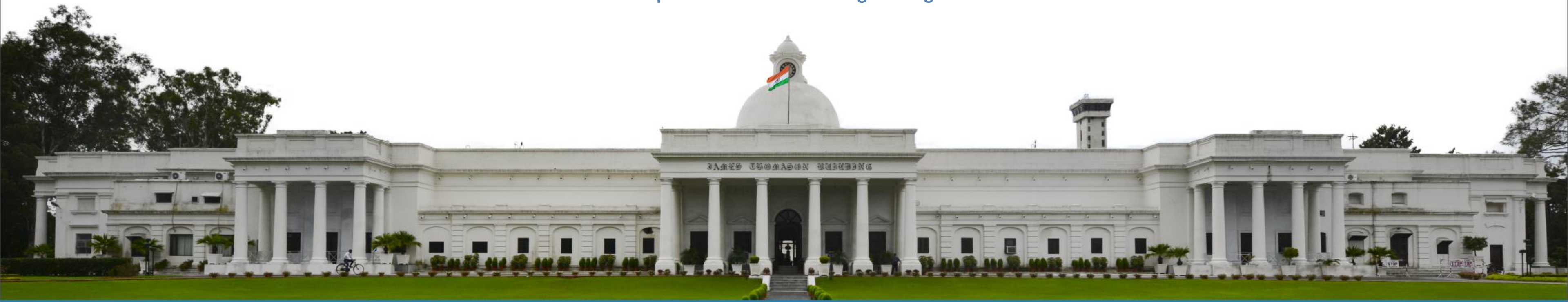
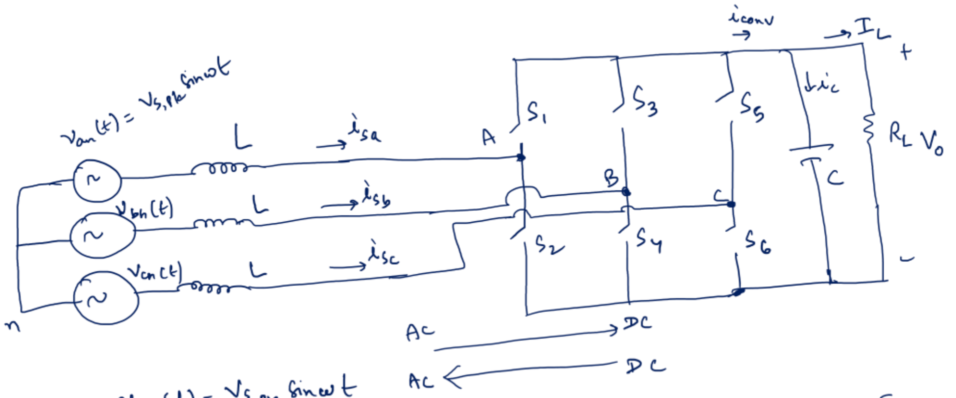
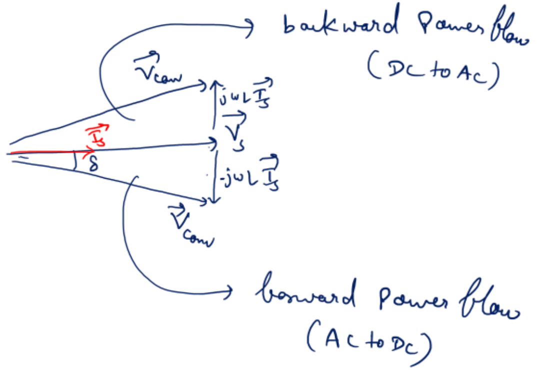


Recap





$v_{an}(t) = V_{s,pk} \sin\omega t$

$v_{bn}(t) = V_{s,pk} \sin(\omega t - 120)$

$v_{cn}(t) = V_{s,pk} \sin(\omega t - 240)$

FEC

→ $(\omega L \cdot I_{s,pk}) < 10\%$ of $V_{s,pk}$

⇑ ensured

$$L = \sqrt{\frac{\left(\frac{mV_0}{2}\right)^2 - V_{s,pk}^2}{(2\pi f_s \cdot I_{s,pk})^2}}$$

→ m → modulation index → designer's choice (0.8 to 0.9)

$V_{s,pk}$ → specification

V_0 → specification

f_s → line frequency given in specification

$I_{s,pk}$ → $\frac{P_L \times \sqrt{2}}{3V_{ph,rms}}$ ⇐ assuming no loss in the Power Converter

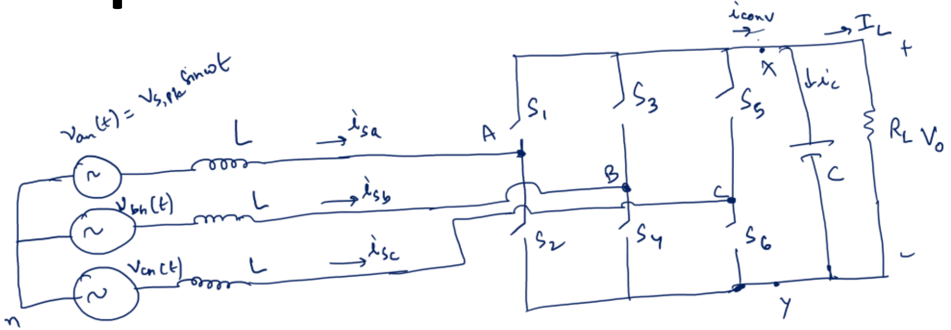
→ the voltage drop across inductor (corresponding to fundamental) must be less than 10% of the $V_{s,pk}$

Recap

Sizing of Capacitance

⇒ The output power (at XY terminal)
$= V_o \cdot i_{conv}$

Input power $= V_{s,pk}\sin\omega t\, I_{s,pk}\sin\omega t$ → assuming upf operation
$+ V_{s,pk}\sin(\omega t-120) I_{s,pk}\sin(\omega t-120)$
$+ V_{s,pk}\sin(\omega t-240) I_{s,pk}\sin(\omega t-240)$



If there is loss-less converter
Apply power balance
⇒ Input power = Output power

$$\Rightarrow V_o \cdot i_{conv} = V_{s,pk}\sin\omega t \cdot I_{s,pk}\sin\omega t + V_{s,pk}\sin(\omega t-120) I_{s,pk}\sin(\omega t-120) + V_{s,pk}\sin(\omega t-240) \cdot I_{s,pk}\sin(\omega t-240)$$

$$= V_{s,pk} I_{s,pk}\left(\sin^2\omega t + \sin^2(\omega t-120) + \sin^2(\omega t-240)\right)$$

$$= V_{s,pk} I_{s,pk}\left(\frac{1-\cos 2\omega t}{2} + \frac{1-\cos(2\omega t-240)}{2} + \frac{1-\cos(2\omega t-480)}{2}\right)$$

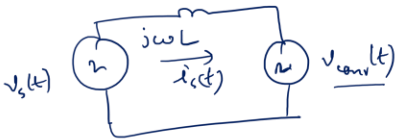
$$= V_{s,pk} I_{s,pk}\left[\frac{3}{2} - \left(\underbrace{\cos 2\omega t + \cos(2\omega t-240) + \cos(2\omega t-120)}_{=0}\right)\right]$$

Recap

$\Rightarrow V_0 \cdot i_{conv} = \frac{3}{2} V_{s,pk} \cdot I_{s,pk}$

$\Rightarrow i_{conv} = \frac{3}{2V_0} V_{s,pk} \cdot I_{s,pk}$ $\longrightarrow$ there is absence of 2^{nd} line freq. component (only DC - component exist)

fundamental frequency



$\longrightarrow$ single-phase equivalent circuit

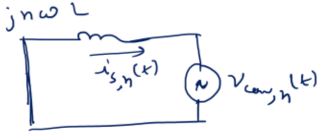
$i_s(t) = I_{s,pk} \sin \omega t$

$v_{conv}(t) \rightarrow$ fundamental component along with harmonics frequency component at side band of m_f $\left(m_f = \frac{f_c}{f_m}\right) \simeq$ carrier frequency $(i m_f \pm j)$

harmonic frequency component

The single phase equivalent circuit

$n = i m_f \pm j$

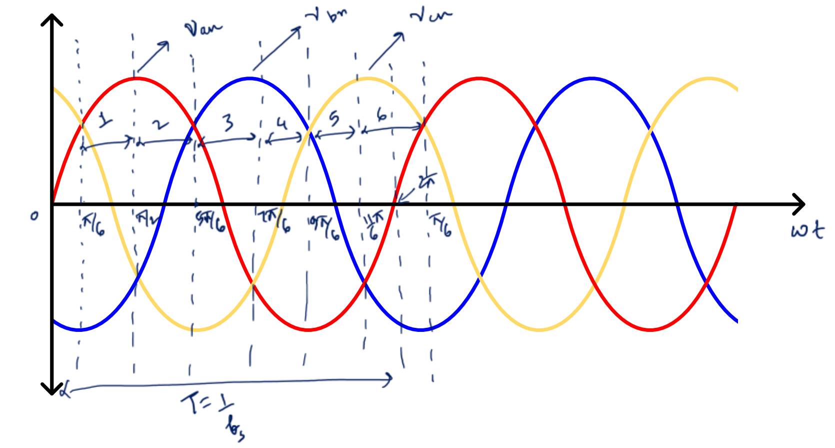


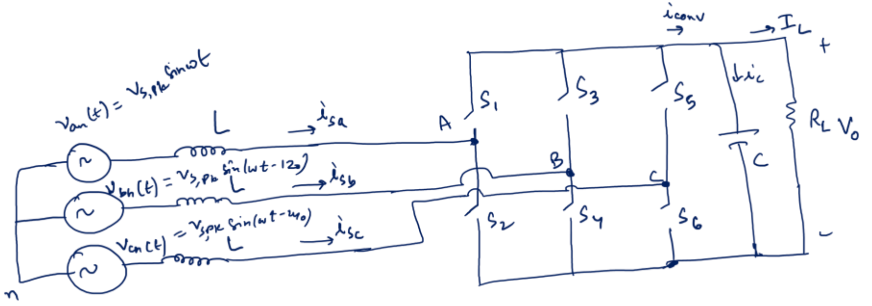
$\Rightarrow i_{s,n}(t) = \frac{v_{conv,n}(t)}{jn\omega L}$

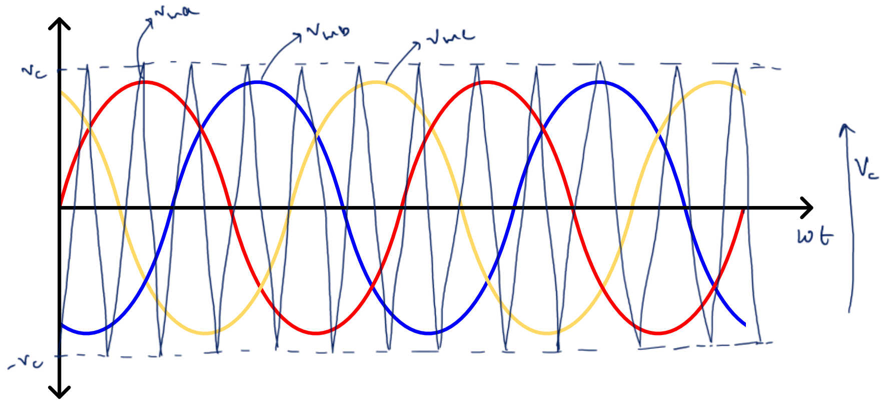
$\omega = 2\pi f_m$

$f_m = f_s$

$\omega = 2\pi f_s$







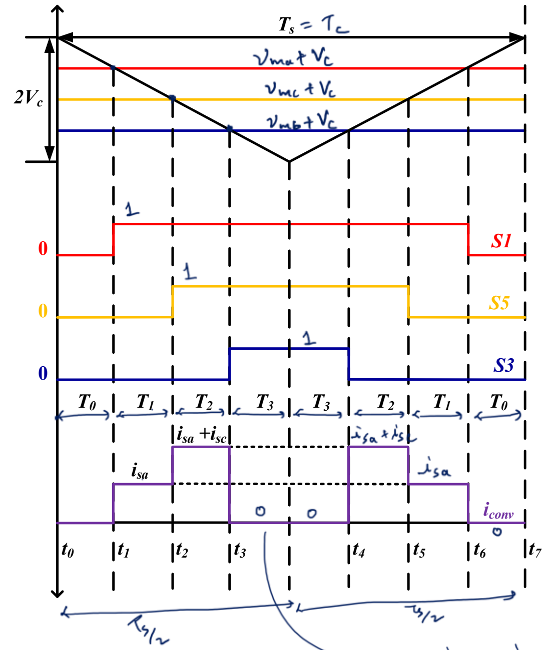
$$V_{ma} = V_m \sin\omega t$$

$$V_{mb} = V_m \sin(\omega t - 120)$$

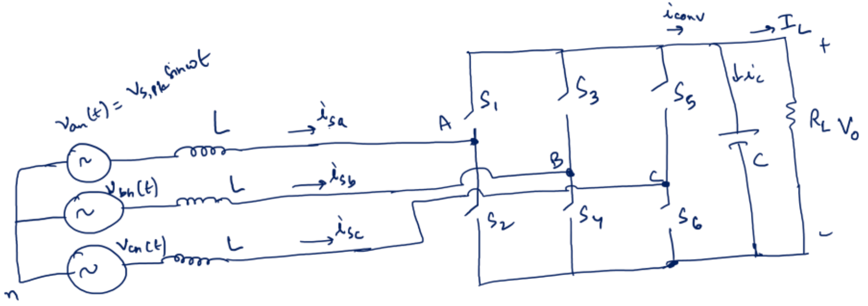
$$V_{mc} = V_m \sin(\omega t - 240)$$

→ operating mode - 1

$T_c = 1/f_c \simeq T_s = 1/f_{sw}$



$i_{sa} + i_{sc} + i_{sb} = 0$



if modulating wave > Carrier
Top Switch is ON
Bottom switch is OFF

else

Bottom Switch is ON
Top Switch is OFF

Assumption, balance 3-phase operation

$\Rightarrow i_{sa} + i_{sb} + i_{sc} = 0$

Source: J. Guo, J. Ye and A. Emadi, "DC-Link Current and Voltage Ripple Analysis Considering Antiparallel Diode Reverse Recovery in Voltage Source Inverters," in *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 5171-5180, June 2018, doi: 10.1109/TPEL.2017.2738327.

$$T_1 = \frac{T_s}{2}\left(\frac{(v_{ma}+V_c)-(v_{mc}+V_c)}{2V_c}\right)$$

$$T_1 = \frac{T_s}{4}\left(\frac{v_{ma}-v_{mc}}{V_c}\right) \longrightarrow (1)$$

$$T_2 = \frac{T_s}{2}\left(\frac{(v_{mc}+V_c)-(v_{mb}+V_c)}{2V_c}\right)$$

$$T_2 = \frac{T_s}{4}\left(\frac{v_{mc}-v_{mb}}{V_c}\right) \longrightarrow (2)$$

$$T_3 = \frac{T_s}{2}\left(\frac{v_{mb}+V_c}{2V_c}\right)$$

$$\Rightarrow T_3 = \frac{T_s}{4}\left(1+\frac{v_{mb}}{V_c}\right) \longrightarrow (3)$$

$$\Rightarrow T_0 = \frac{T_s}{2} - (T_1+T_2+T_3)$$

$$= \frac{T_s}{2} - \frac{T_s}{4}\left(\frac{v_{ma}-\cancel{v_{mc}}+\cancel{v_{mc}}-\cancel{v_{mb}}+V_c+\cancel{v_{mb}}}{V_c}\right)$$

$$= \frac{T_s}{2}\left[1-\left(\frac{v_{ma}+V_c}{2V_c}\right)\right]$$

$$\Rightarrow T_0 = \frac{T_s}{2}\left[\frac{2V_c - v_{ma} - V_c}{2V_c}\right]$$

$$T_0 = \frac{T_s}{4}\left[1 - \frac{v_{ma}}{V_c}\right] \longrightarrow (4)$$

$$v_{ma} = V_m \sin\omega t$$
$$v_{mb} = V_m \sin(\omega t - 120) \quad ; \quad m = \frac{V_m}{V_c}.$$
$$v_{mc} = V_m \sin(\omega t - 240)$$

$$T_1 = \frac{T_s}{4}\left[\frac{V_m \sin\omega t}{V_c} - \frac{V_m \sin(\omega t + 2\pi/3)}{V_c}\right]$$

$$T_1 = \frac{T_s}{4}\left(m \sin\omega t - m \sin(\omega t + 2\pi/3)\right) \longrightarrow (5)$$

$$T_2 = \frac{T_s}{4}\left[\frac{V_m \sin(\omega t + 2\pi/3) - V_m \sin(\omega t - 2\pi/3)}{V_c}\right]$$

$$T_2 = \frac{T_s}{4}\left(m \sin(\omega t + 2\pi/3) - m \sin(\omega t - 2\pi/3)\right] \longrightarrow (6)$$

$$T_1 = \frac{\sqrt{3}}{4} T_s m \sin(\omega t - \pi/6) \longrightarrow (7)$$

$$T_2 = \frac{\sqrt{3}}{4} T_s m \cos\omega t \longrightarrow (8)$$

Source: J. Guo, J. Ye and A. Emadi, "DC-Link Current and Voltage Ripple Analysis Considering Antiparallel Diode Reverse Recovery in Voltage Source Inverters," in *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 5171-5180, June 2018, doi: 10.1109/TPEL.2017.2738327.

$$i_{conv,avg,T_s} = \frac{1}{T_s}\left[\int_0^{T_s} i_{conv} \cdot dt\right]$$

$$= 2\times\frac{1}{T_s}\left[\int_{t_1}^{t_2} i_{sa}\cdot dt + \int_{t_2}^{t_3} (i_{sa}+i_{sc})\cdot dt + 0\right]$$

$$= \frac{2}{T_s}\left[i_{sa}(t_2-t_1) + (-i_{sb})\cdot(t_3-t_2)\right]$$

$$i_{conv,avg,T_s} = \frac{2}{T_s}\left[i_{sa}T_1 - i_{sb}T_2\right] \longrightarrow (9)$$

$$i^2_{conv,avg,T_s} = \frac{1}{T_s}\left[\int_0^{T_s} i^2_{conv}\cdot dt\right]$$

$$= 2\times\frac{1}{T_s}\left[\int_{t_1}^{t_2} i^2_{sa}\cdot dt + \int_{t_2}^{t_3} (i_{sa}+i_{sc})^2\cdot dt + 0\right]$$

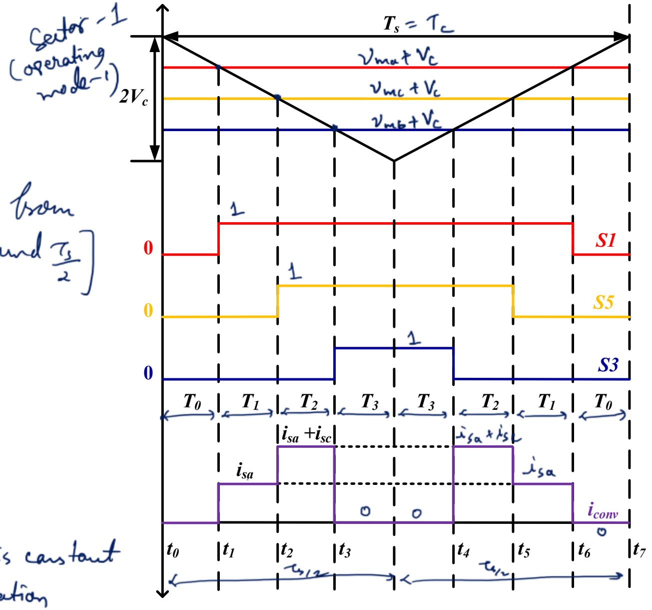
[the factor '2' comes from symmetricity around $\frac{T_s}{2}$]

$i_{sa}+i_{sb}+i_{sc}=0$

$\Rightarrow i_{sa}+i_{sc} = -i_{sb}$

$T_s \gg T$

$\Rightarrow i_{sa}, i_{sc}, i_{sb}$ is constant in T_s duration



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$$i^2_{cow,rms,T_s} = \frac{2}{T_s}\left[i_{sa}^2 \cdot T_1 + (i_{sa}+i_{sc})^2 T_2 \right]$$

$$i^2_{cow,rms,T_s} = \frac{2}{T_s}\left[i_{sa}^2 T_1 + i_{sb}^2 T_2 \right] \longrightarrow (10)$$

$$i_{cow,avg} = 3/\pi \left[\int_{\pi/6}^{\pi/2} i_{cow,avg,T_s} \cdot d(\omega t) \right]$$

$$= \frac{3}{\pi}\left[\int_{\pi/6}^{\pi/2} \frac{2}{T_s}\left(i_{sa} T_1 - i_{sb} T_2 \right) \cdot d(\omega t) \right] \quad \text{(from (9))}$$

$$i_{sa} = I_{s,pk} \sin\omega t$$
$$i_{sb} = I_{s,pk} \sin(\omega t - 2\pi/3)$$
$$i_{sc} = I_{s,pk} \sin(\omega t - 4\pi/3)$$
(assuming upf operation)

$$i_{cow,avg} = \frac{3}{\pi} \times \frac{2}{T_s}\left[\int_{\pi/6}^{\pi/2} I_{s,pk} \sin\omega t \left(\frac{\sqrt{3}}{4} T_s m \cdot \sin(\omega t - \pi/6) \right) \cdot d(\omega t) - \int_{\pi/6}^{\pi/2} I_{s,pk} \sin(\omega t - 2\pi/3) \cdot \frac{\sqrt{3}}{4} T_s m \cos\omega t \cdot d(\omega t) \right]$$

$$i_{cow,avg} = 3/4\, I_{s,pk}\, m \longrightarrow (11)$$

over the line cycle

Source: J. Guo, J. Ye and A. Emadi, "DC-Link Current and Voltage Ripple Analysis Considering Antiparallel Diode Reverse Recovery in Voltage Source Inverters," in *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 5171-5180, June 2018, doi: 10.1109/TPEL.2017.2738327.

from (10)

$$i_{conv,rms} = \sqrt{\frac{3}{\pi}\left[\int_{\pi/6}^{\pi/2} \left(i_{conv,rms,T_s}\right)^2 \cdot d(\omega t)\right]}$$

$$= \sqrt{\frac{3}{\pi}\left[\int_{\pi/6}^{\pi/2} \left(i_{sa}^2 T_1 + i_{sb}^2 T_2\right) \cdot d(\omega t)\right]}$$

(T_1 & T_2 from (7) & (8))

$$i_{conv,rms} = I_{s,pk}\sqrt{\frac{\sqrt{3}}{\pi}\cdot m \cdot 5/4} \longrightarrow (12)$$

↳ over the line cycle

$i_{conv,avg} \rightarrow$ going through the load (R_L)

$$i_{c,rms} = \sqrt{i_{conv,rms}^2 - i_{conv,avg}^2}$$

$$i_{c,rms} = \sqrt{I_{s,pk}^2\left(\frac{\sqrt{3}}{\pi} m\, 5/4\right) - \frac{9}{16} m^2 I_{s,pk}^2}$$

$$i_{c,rms} = I_{s,pk}\sqrt{\left(\frac{\sqrt{3}}{\pi} m\, 5/4\right) - \frac{9}{16} m^2}$$

$$I_{s,pk} = \frac{\sqrt{2}\, P_L}{3 V_{ph,rms}}$$ (converter is lossless)

Source: J. Guo, J. Ye and A. Emadi, "DC-Link Current and Voltage Ripple Analysis Considering Antiparallel Diode Reverse Recovery in Voltage Source Inverters," in *IEEE Transactions on Power Electronics*, vol. 33, no. 6, pp. 5171-5180, June 2018, doi: 10.1109/TPEL.2017.2738327.

Calculation of Capacitance value

Minimum DC-link Capacitor

$$C_{min} \geq \frac{\Delta P_{max} T_d}{2 V_0 \cdot \Delta V_0}$$

ΔP_{max} → specification

T_d → designer's choice

$V_0 \cdot \Delta V_0$ → specification

where ΔP_{max} → maximum power variation of the converter

T_d → response time of closed loop

ΔV_0 → the permissible voltage ripple

V_0 → output voltage

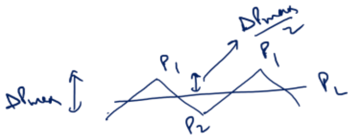
$$\Rightarrow \frac{1}{2} C_{min} V_1^2 - \frac{1}{2} C_{min} V_2^2 \geq \frac{\Delta P_{max} T_d}{2}$$

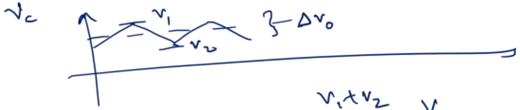
$$\Rightarrow C_{min} (V_1^2 - V_2^2) \geq \Delta P_{max} T_d$$

$$\Rightarrow C_{min} (V_1 + V_2)(V_1 - V_2) \geq \Delta P_{max} T_d$$

$$\Rightarrow C_{min}\, 2V_0 \cdot \Delta V_0 \geq \Delta P_{max} T_d$$

$$\Rightarrow C_{min} \geq \frac{\Delta P_{max} \cdot T_d}{2 V_0 \Delta V_0}$$





$$\frac{V_1 + V_2}{2} = V_0$$

$$\Rightarrow V_1 - V_2 = \Delta V_0$$

$$\boxed{\text{The voltage rating of Capacitor} > V_0 + \frac{\Delta V_0}{2}}$$

Thank You