EN 313 - Power Electronics

Phase Controlled Rectifiers

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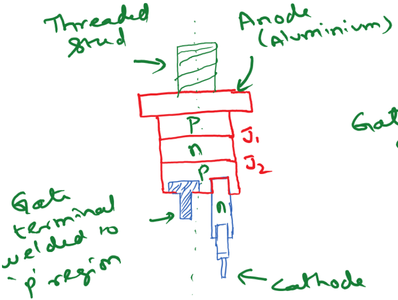
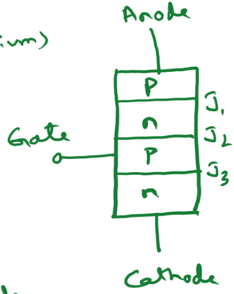
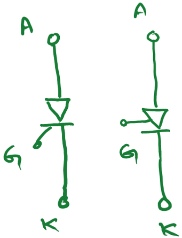
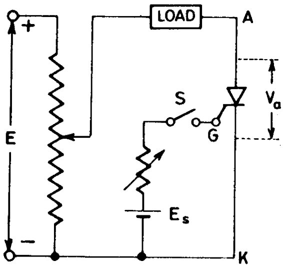
Thyristor- Construction, Characteristics

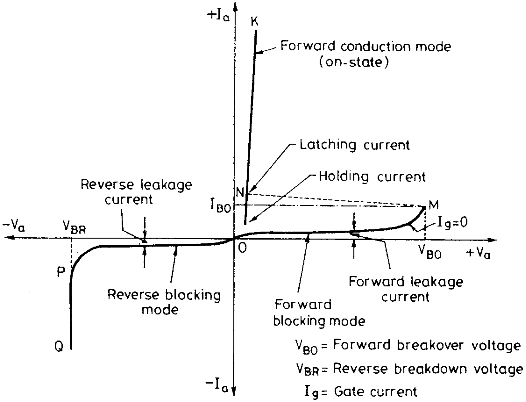






Thyristor- Construction, Characteristics





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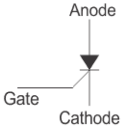
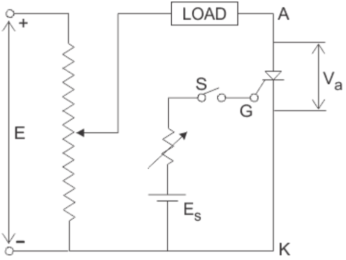
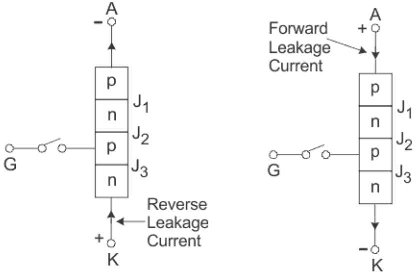


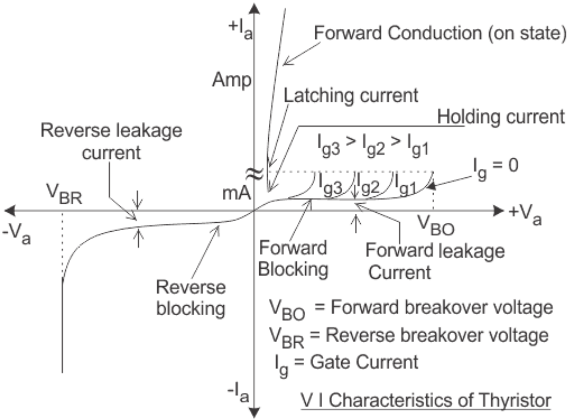
Thyristol Symbol



Circuit Diagram of Thyristor



Thyristor- Construction, Characteristics



V I Characteristics of Thyristor

Understanding- Characteristics

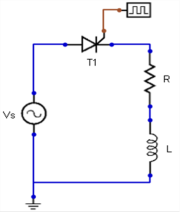
- Gate triggering is simple, reliable and efficient.
- Once SCR is conducting and forward current flowing, reverse bias across J2 doesnt exist and hence gate current is not required.
- Gate current now has no control over the conduction.
- Gate current should be choosen so that anode current will rise above the latching current
- Latch current may be defined as minimum amount of anode current which SCR must attain during turn-on process to maintain conduction when the gate signal is removed.

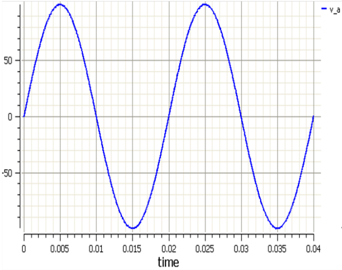
Understanding- Characteristics - Turn-Off

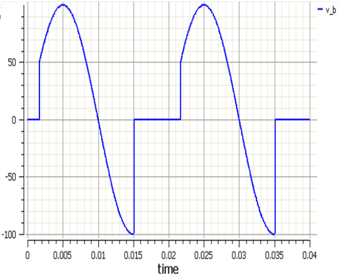
- The dynamic process of SCR changing its state from ON to OFF is called as commutation process or turn-off process.
- SCR can be turned off by reducing the anode current below holding current.
- It can be achieved through natural commutation or forced commutation.
- If a forward voltage is applied across SCR at the moment its anode current falls to zero, the device will not be able to block this forward voltage as the carriers in the four layers are still favourable for conduction.
- The device will therefore go into conduction immediately even though gate signal is not applied.
- In order to obviate such an occurrence, it is essential that the thyristor is reverse biased for a finite period after the anode current has reached zero.

Single Phase with R-L Load

$V_{s(peak)}$=100 V, R=0.5ohm, L=6.5mh, Firing angle(α)=30^0







Firing angle α - Definition

- It is defined as angle measured from the instant that gives maximum output voltage to the one at which it is actually triggered.
- It is measured from the angle that gives largest average output voltage.
- It is also defined as the angle measured from the instant SCR is forward biased to the instant it is triggered.

Single Phase with R-L Load - Analysis

- The SCR starts conductiong from $\omega t = \alpha$ where it is fired.
- At this instant load voltage is equal to the supply. The load current slowly rises because of presence of inductance.
- At $\omega t = \pi$ supply voltage is negative, but the SCR continues to conduct because of inductive load till the load current is not less than holding current.
- At some angle (extinction angle, $\beta > \pi$) the load current reaches zero and SCR will be turned off as it is already in reverse biased.
- The conduction angle (γ) is defined as $\gamma = \beta - \alpha$

Single Phase with R-L Load - Analysis

- The expression for load current can be derived as:

$$i_o = \frac{V_m}{Z}\sin(\omega t - \phi) - \frac{V_m}{Z}\sin(\alpha - \phi) exp\{-\frac{R}{\omega L}(\omega t - \alpha)\}$$

for $\alpha < \omega t < \beta$

- When $\beta = 0$, the load current is zero:

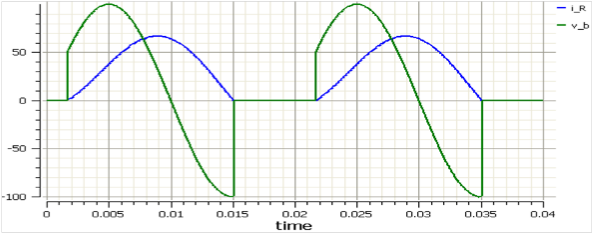
$$sin(\beta - \phi) = sin(\alpha - \phi) exp\{-\frac{R}{\omega L}(\beta - \alpha)\}$$

- If β (from above equation) and α are known then average voltage is given by:

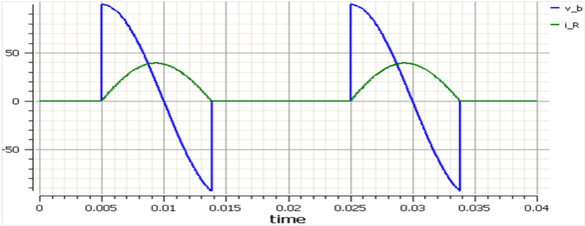
$$V_o = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin \omega t d(\omega t) = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

Single Phase with R-L Load

V_0 and I_R for $\alpha = 30^0$

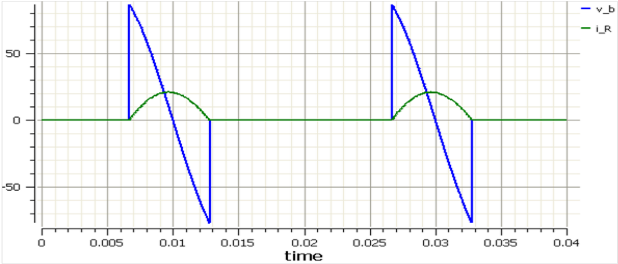


V_0 and I_R for $\alpha = 90^0$

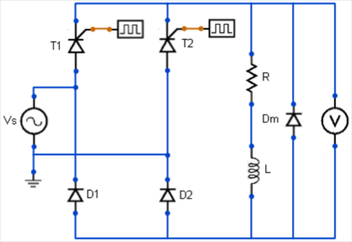


Single Phase with R-L Load

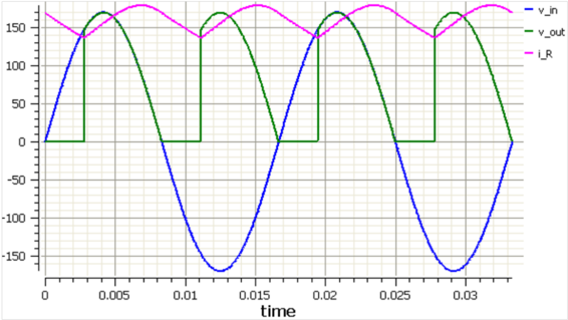
V_0 and I_R for $\alpha = 120^0$



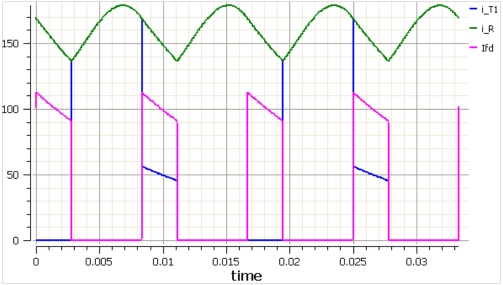
Single Phase Semi Converter

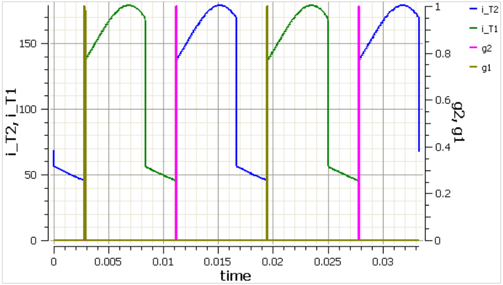


- $I_T + I_D = I_R$
- When the free wheeling diode is conducting, $V_0 = 0$
- When I_{T2} is triggered, commutation occurs from I_{T1} to I_{T2}

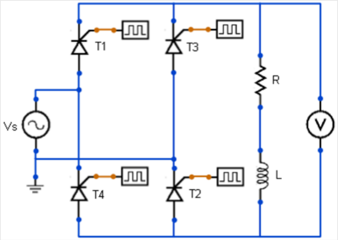


Single Phase Semi Converter

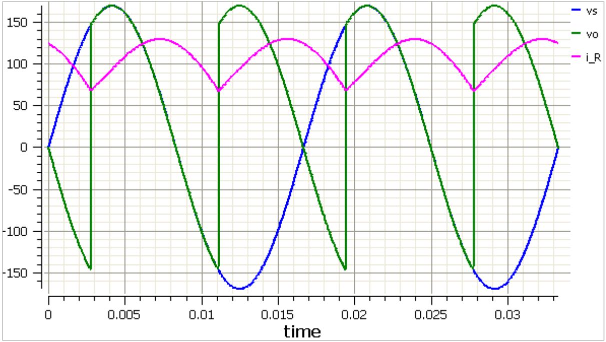




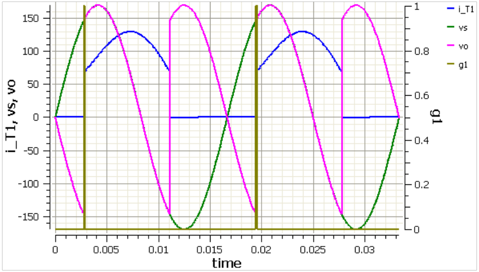
Single Phase Full Bridge Rectifier

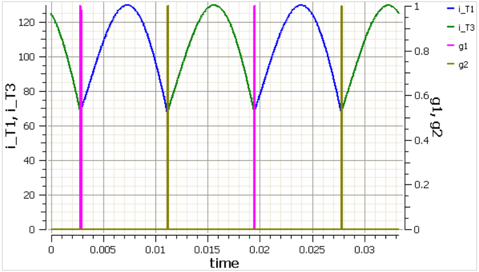


- When I_{T3} and I_{T4} are triggered, commutation occurs from I_{T1-3} to I_{T2-4}.



SPFBR- Gate Signals - Output Voltage - Switch current





Summary (Full/Semi/Un Controlled)

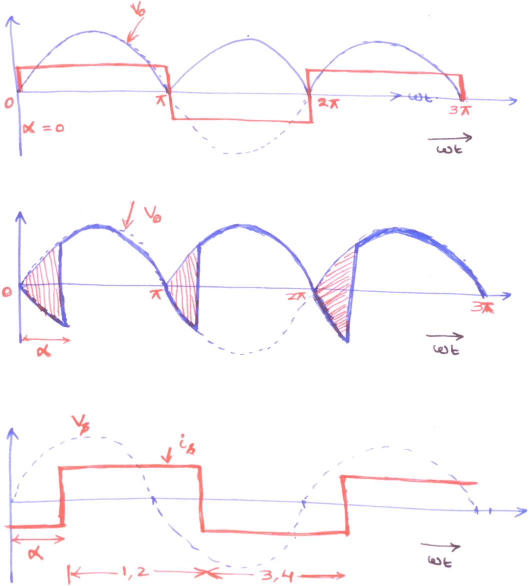
- In case of uncontrolled rectifier, diodes are used and there is no control over output voltage.
- A semiconverter comprises of diodes and SCRs and there is a limited control over the level of dc output voltage. It is a one quadrant converter and output voltage is given by:

$$V_o = \frac{V_m}{\pi}(1 + \cos\alpha)$$

- In a full bridge converter, it is possible to control the voltage polarity but the current direction cannot reverse because of thyristors. It is a two quadrant converter and output voltage is given by:

$$V_o = \frac{2V_m}{\pi}\cos\alpha$$

Waveform- Single Phase Thyristor Converters (Ideal)



Analysis- Single Phase Thyristor Converters (Ideal)

- α is delay with respect to instant of natural conduction measured in degrees.
- V_d is negative from 0 to α
- At $\omega t = a$, the commutation of current from T_3 and T_4 to T_1 and T_2 is instantaneous (since $L_s = 0$)
- $P = I_d V_d = 0.9 V_s I_d cos\alpha$, also V_d is negative when $\alpha > 90$ (inverter mode of operation)
- DC voltage has ripple whose frequency is twice of supply
- Input line current is square wave with amplitude of I_d and is shifted in phase by an angle α with respect to supply voltage

Analysis- Single Phase Thyristor Converters (Ideal)

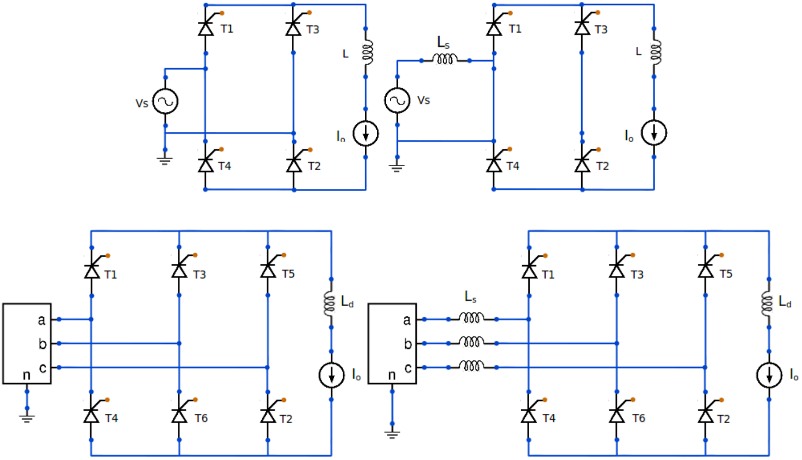
- Fourier Analysis:
  - Odd harmonics are present
  - $I_{s1} = 0.9I_d$, $I_{sh} = \frac{I_{s1}}{h}$
  - $\% THD = 48.43$
- Displacement power factor (DPF)$=$ $cos\alpha$
- Reactive Power $Q_1 = V_s I_{s1} sin\alpha$
- Power Factor $=$ DFxDPF $= \frac{I_{s1}}{I_s} DPF = 0.9cos\alpha$

Inverter Mode of Operation

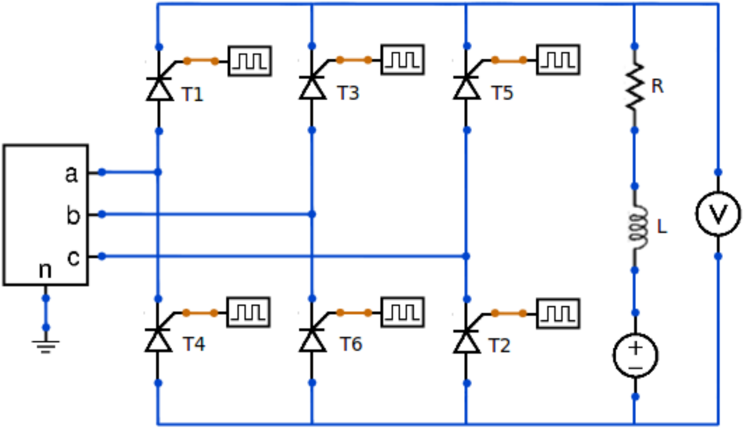
- For $90^0 < \alpha < 180^0$ the converter behaves as an inverter if there is a supply source on the dc side.
- The average power $V_d I_d$ is negative and it flows from dc side to ac side.
- Also, P_{ac} is negative as $\phi_1 > 90^0$.
- AC voltage source facilitates commutation of current from one pair of thyristors to another.

Thyristor Converters - 1ϕ, 3ϕ

Practical and Ideal

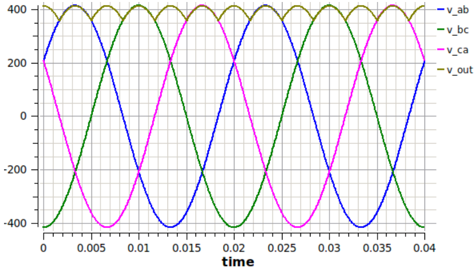


Three Phase Converter - RLE load

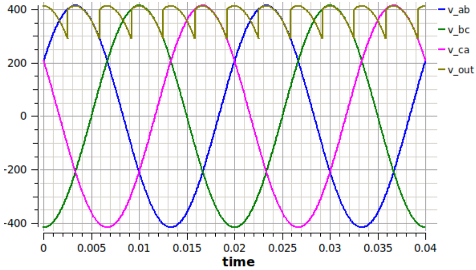


$V_s = 415V$, R=5 Ω, L=16.5mh, E=0V

Effect of α on V_{dc}

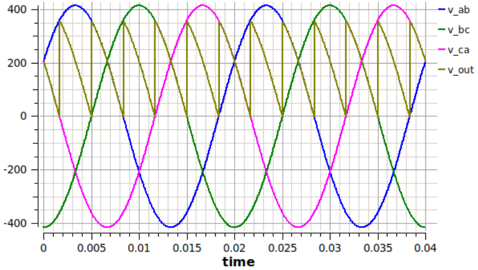


$\alpha = 0^o$

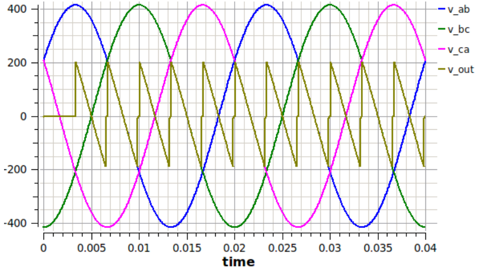


$\alpha = 15^o$

Effect of α on V_{dc}

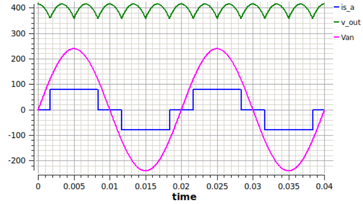


$\alpha = 60^o$

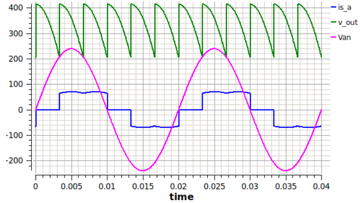


$\alpha = 90^o$

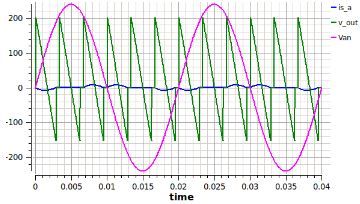
Effect of α on Line Current



$\alpha = 0^o$



$\alpha = 30^o$



$\alpha = 90^o$

Three Phase Converter - Analysis

- The current I_d flows through one of the thyristors in the top group (1,3,5) and one of the thyristors in bottom group(2,4,6).
- If gate currents were continuously applied, the circuit would have behaved like a diode bridge rectifier

$$V_{do} = \frac{3\sqrt{2}}{\pi} V_{LL}$$

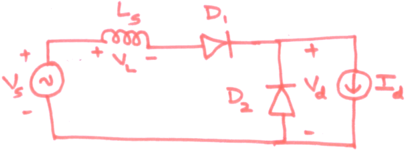
- Commutation of current from T5 to T1: T5 keeps conducting till T1 is fired, at which current commutates instantaneously as $L_s = 0$,

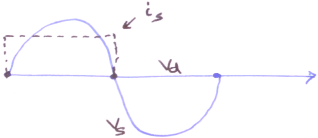
$$V_{d\alpha} = \frac{3\sqrt{2}}{\pi} V_{LL} cos\alpha$$

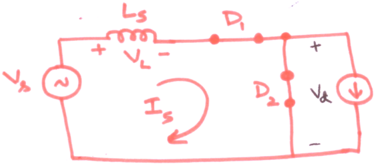
Three Phase Converter - Analysis

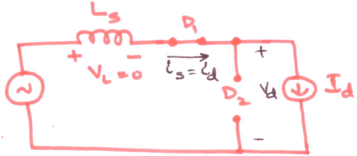
- The input currents are rectangular waveforms with an amplitude Id and is phase shifted by angle α. Hence named as Phase Controlled Rectifiers.
- Fourier series: Only nontriplen odd harmonics are present (1,5,7,11,13..) or $h = 6n \pm 1$ (n=1,2,3.).
- The rms value of the fundamental frequency component is $I_{s1} = 0.78 I_d$ and rms of harmonic component is $I_{sh} = \frac{I_{s1}}{I_h}$
- Distortion factor $= \frac{3}{\pi}$=0.955 and $THD = 31.08\%$

Effect of L_s on current commutation





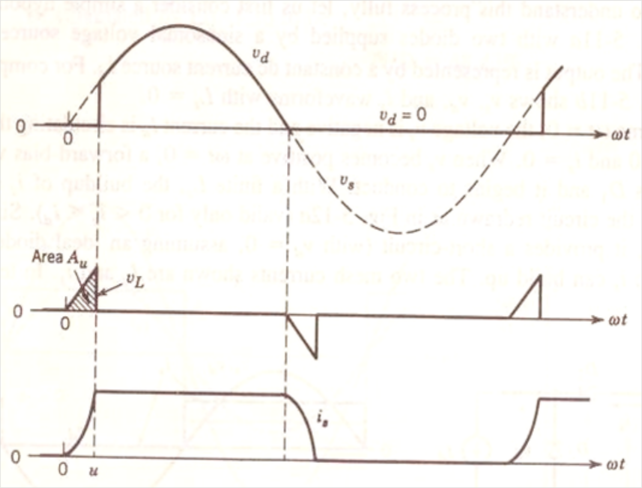




Analysis - Commutation

- The process where the current conduction shifts from one diode to other is called current commutation.
- Due to finite inductance L_s, it is not possible to have instantaneous transition of is from $+I_d$ to 0 or -I_d in case of full wave rectifier.
- Prior to $\omega t = 0$, D2 is conducting and V_s is negative, and I_d is circulating through D2.
- When V_s is positive at $\omega t = 0$, D1 is forward biased and it begins to conduct.
- $i_{D2} = I_d - i_s$ and therefore as i_s builds up to a value of I_d during the commutation interval $\omega t = u$ and during this interval I_{d2} is positive and hence D2 is conducting
- At $\omega t = u$, $I_d = I_s$ and hence D2 stops conducting

Analysis - Commutation



Analysis - Commutation

- i_s varies between 0 and I_d during commutation period and also, during the commutation period source voltage is applied across inductor.
- For $0 < \omega t < u$: $V_L = V_m sin\omega t = L_s \frac{di_s}{dt}$

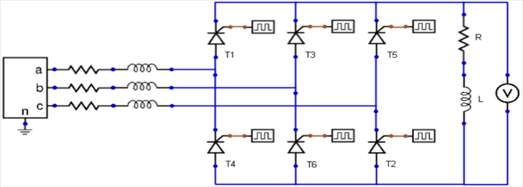
$$\int_0^u V_m \sin \omega t.d(\omega t) = \omega L_s \int_0^{I_d} (di_s)$$

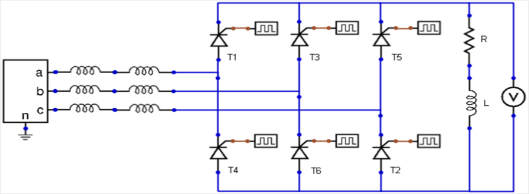
$$A_u = \int_0^u V_m \sin \omega t.d(\omega t) = \sqrt{2}V_s(1 - cosu) = \omega L_s I_d$$

$$cosu = 1 - \frac{\omega L_s I_d}{\sqrt{2}V_s}$$

$$\Delta V_d = \frac{areaA_u}{2\pi} = \frac{\omega L_s}{2\pi} I_d$$

Three phase controlled rectifier (Line Commutated)





Practical arrangement Ls=Ls1+Ls2, Point of Common Coupling.

Three phase controlled rectifier (Line Commutated)

- Inductor should be minimum 5% i.e., $\omega L_s \geq 0.05 \frac{V_{LL}}{\sqrt{3} I_{s1}}$
- For fixed α, current commutation takes finite commutation interval 'u'.
- The reduction in volt-radian due to commutation interval is

$$A_u = \int_0^{\alpha+u} V_{Ls} d(\omega t) = \omega L_s \int_0^{i_d} (di_a) = \omega L_s I_d$$

therefore the average dc output voltage is given by

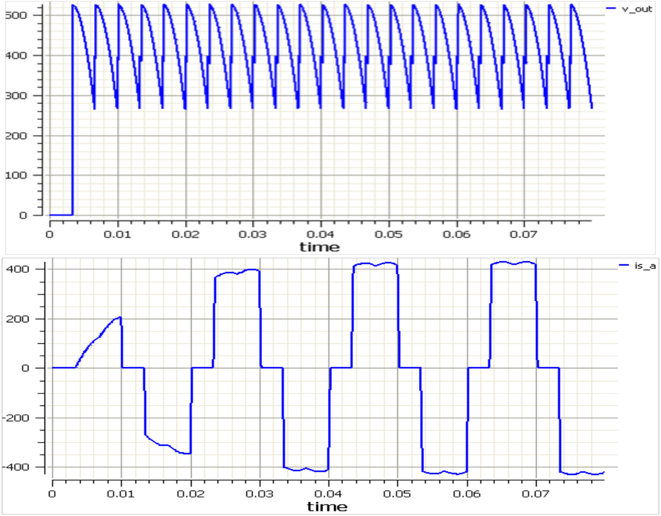
$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} cos\alpha - \frac{3\omega L_s}{\pi} I_d$$

$$cos(\alpha + u) = cos\alpha - \frac{2\omega L_s}{\sqrt{2} V_{LL}} I_d$$

knowing α and I_d, u can be calculated.

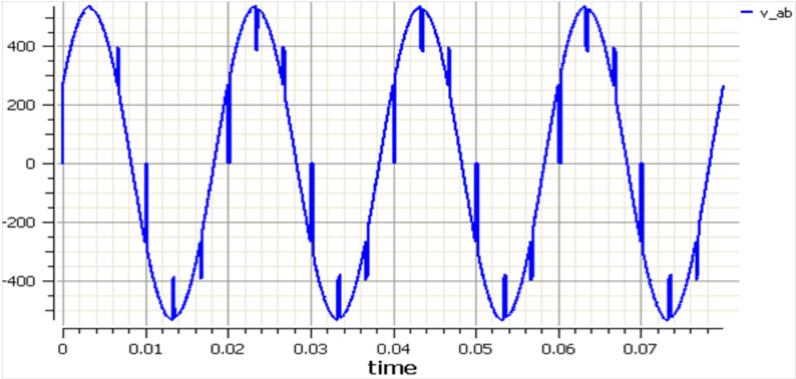
- The ac side inductance reduces the magnitude of the harmonic currents

Output Voltage and Source Current



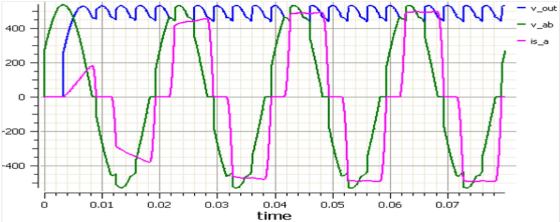
Voltage at PCC

R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.1m, $\alpha = 60^0$

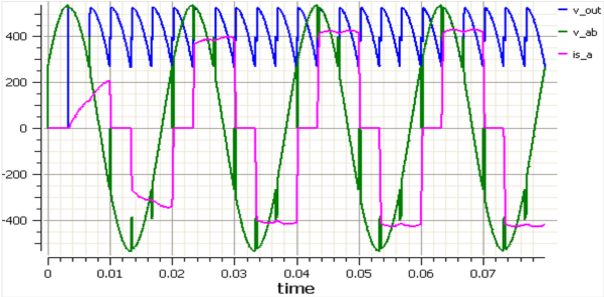


Effect of α on voltage at PCC

R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.1m, $\alpha = 0^0$

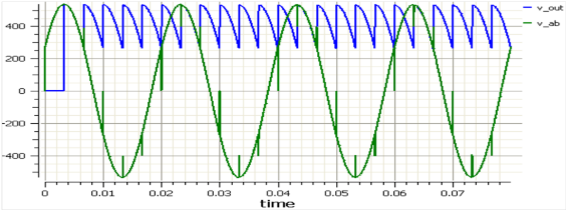


R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.1m, $\alpha = 30^0$

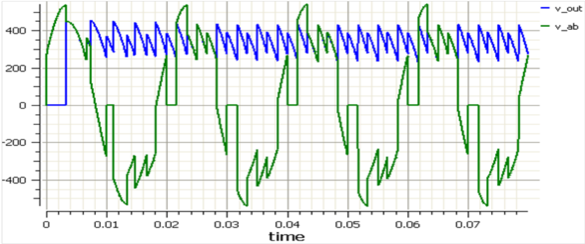


Effect of L_s on Notch Size

R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.01m, $\alpha = 60^0$



R=1.0 Ω, L=10mH, Rs=0.005 and Ls=1m, $\alpha = 60^0$



Summary

- AC/DC Converter
  - Single phase - Phase controlled rectifier with R, RL and RC loads.
  - Three phase - Phase controlled rectifier with R, RL and RC loads.
  - Effect of line impedance on commutation.

  Next Class
  - AC/DC Converter - PWM Rectifiers
- Thank you!!

For Further Reading:

- Power Electronics: Converters, Applications, and Design: N. Mohan, T. M. Undeland, W. P. Robbins, John Wiley and Sons.
- Power electronics and motor drives: advances and trends: Bimal K Bose. Pearson Education.