EN 206 - Power Electronics and Machines

Phase Controlled Rectifiers

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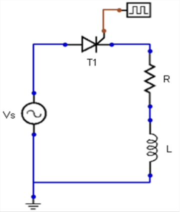
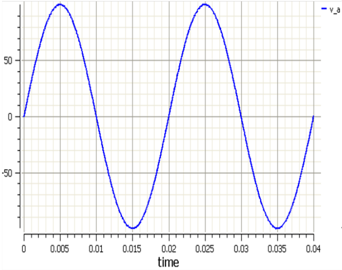
Lecture Organization - Modules

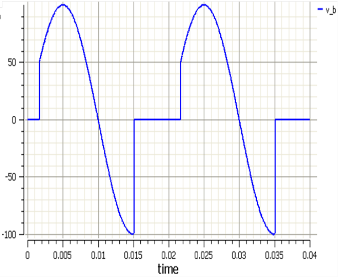
- Introduction and Power Semiconductor Switches
- Module 1: Transformers
- Module 2: AC/DC converter / Rectifier
- Module 3: DC machines and Drives
- Module 4: DC/DC converter
- Module 5: Induction Machine
- Module 6: DC/AC converter / Inverter
- Module 7: AC/AC converter / Cyclo converter
- Module 8: Synchronous Machine
- Module 9: Special Topics: Machines, HVDC, APF

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 $\alpha < \omega t < \beta$

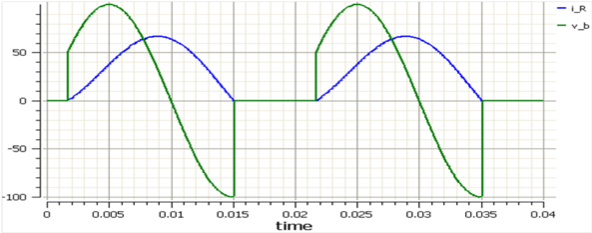
- When $\beta = 0$, the load current is zero:

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

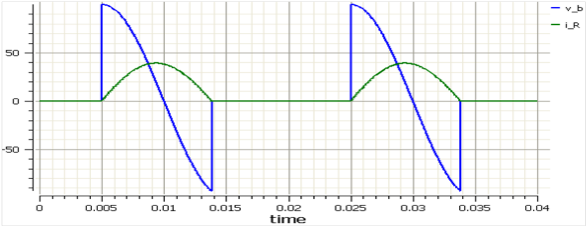
- If β (from above equation) and α are known then average voltage is given by:

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

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

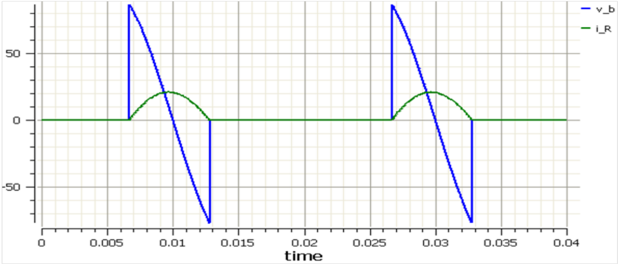


V_0 and I_R for $\alpha = 90^0$

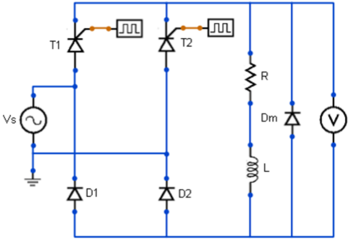


Single Phase with R-L Load

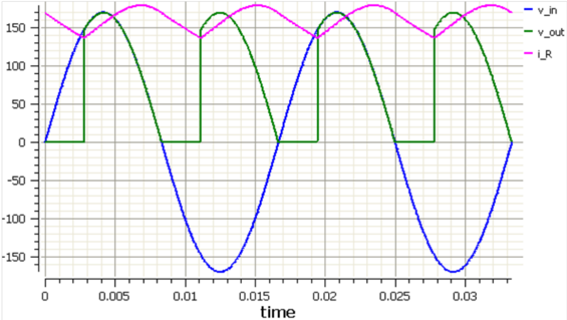
V_0 and I_R for $\alpha = 120^0$



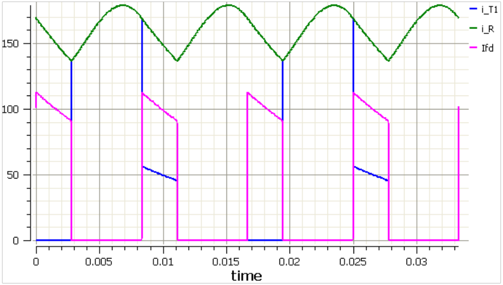
Single Phase Semi Converter

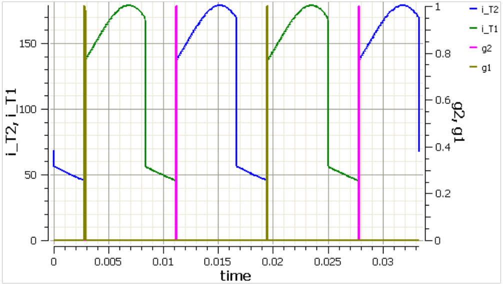


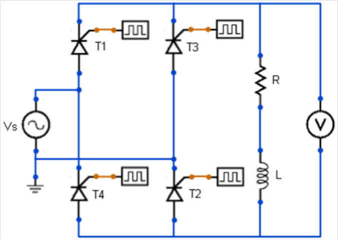
- $I_T + I_D = I_R$
- When the free wheeling diode is conducting, $V_0 = 0$
- When I_{T2} is triggered, commutation occurs from I_{T1} to I_{T2}



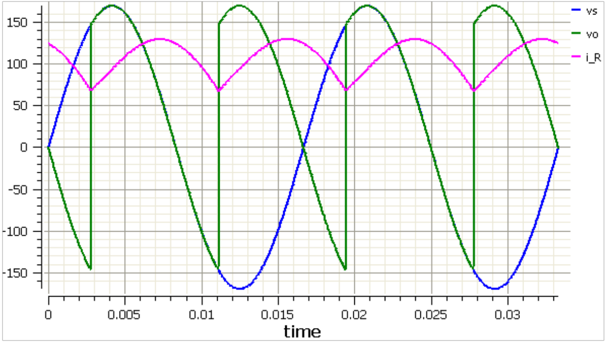
Single Phase Semi Converter



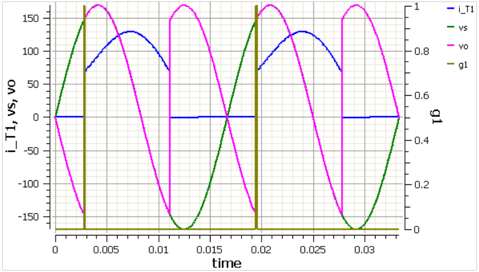


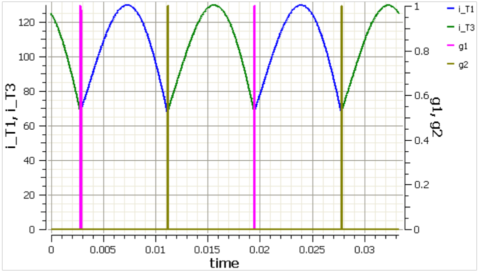


- When I_{T3} and I_{T4} are triggered, commutation occurs from I_{T1-3} to I_{T2-4}.

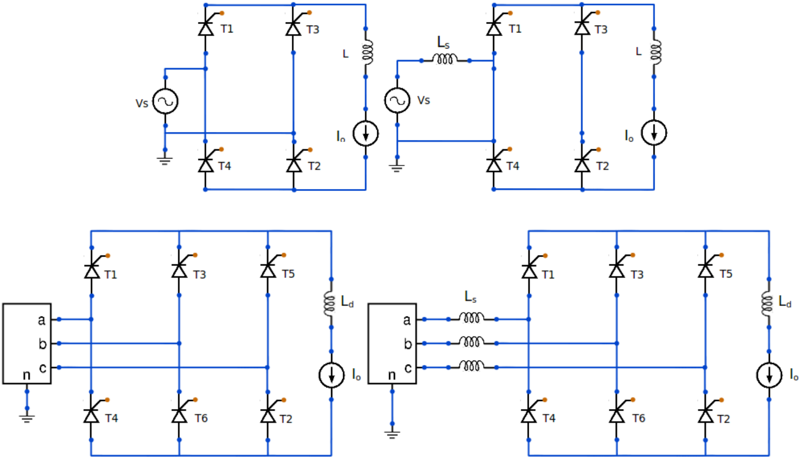


SPFBR- Gate Signals - Output Voltage - Switch current

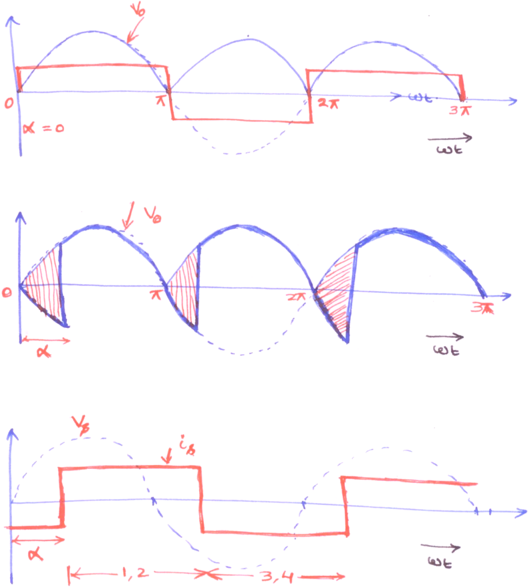




Practical and Ideal



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.

Full-Semi-Un Controlled Converters - Summary

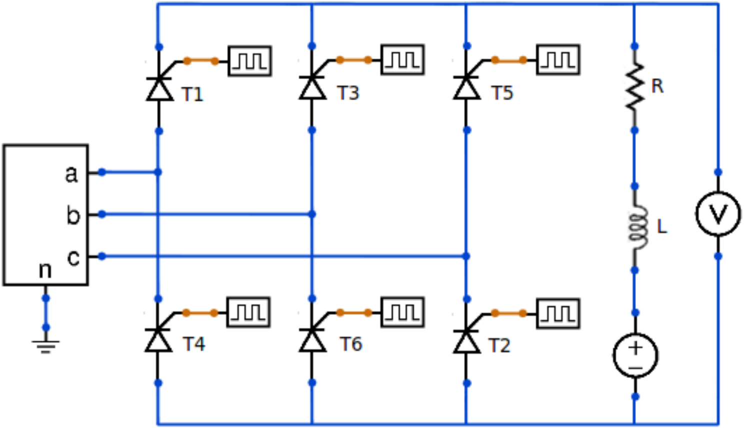
- In case of uncontrolled rectifier, diodes are used and there is no control over output voltage.
- A semiconverter comprises of diodes and SCRs and there is a limited control over the level of dc output voltage. It is a one quadrant converter and output voltage is given by:

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

- 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:

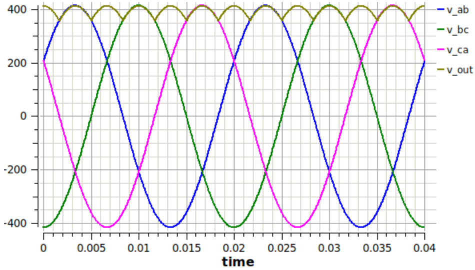
$$V_o = \frac{2V_m}{\pi}\cos\alpha$$

Three Phase Converter - RLE load

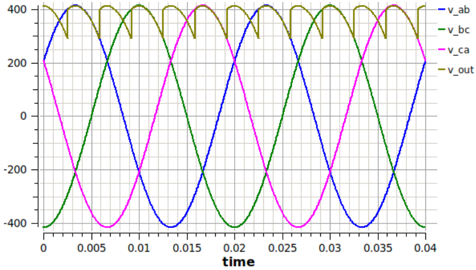


$V_s = 415V$, R=5 Ω, L=16.5mh, E=0V

Effect of α on V_{dc}

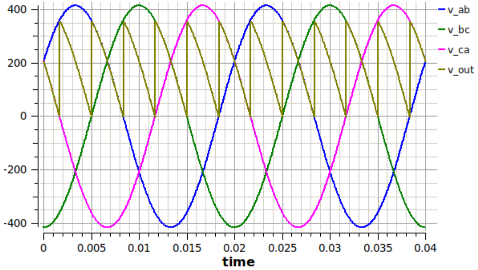


$\alpha = 0^o$

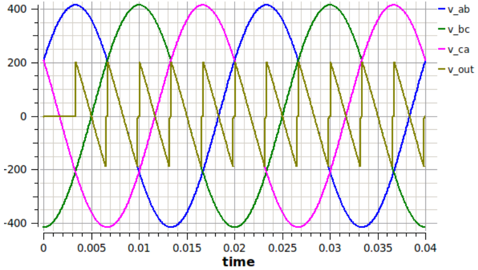


$\alpha = 15^o$

Effect of α on V_{dc}

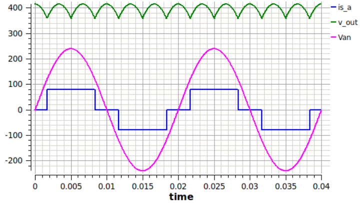


$\alpha = 60^o$

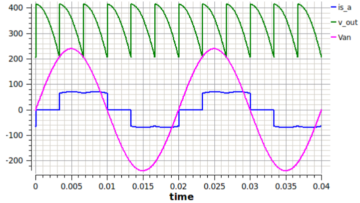


$\alpha = 90^o$

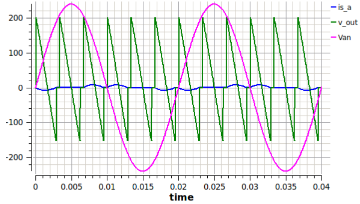
Effect of α on Line Current



$\alpha = 0^o$



$\alpha = 30^o$



$\alpha = 90^o$

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

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

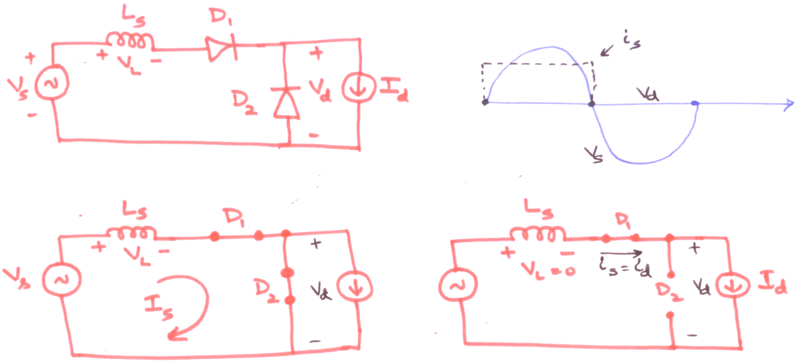
- Commutation of current from T5 to T1: T5 keeps conducting till T1 is fired, at which current commutates instantaneously as $L_s = 0$,

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

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 $THD = 31.08\%$

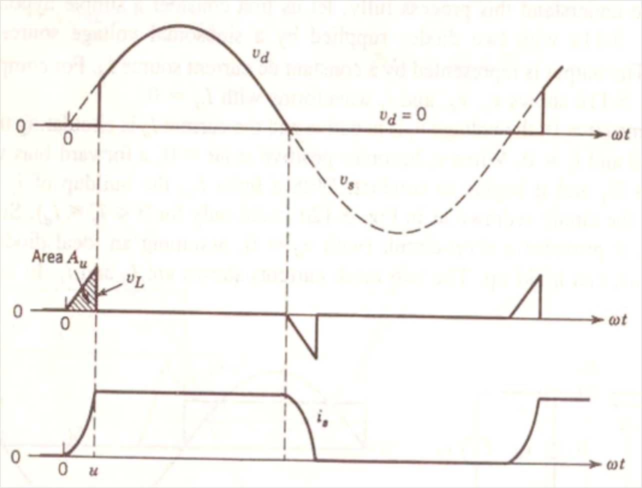
Effect of L_s on current commutation



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 $0 < \omega t < u$: $V_L = V_m sin\omega t = L_s \frac{di_s}{dt}$

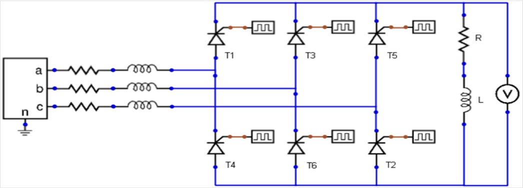
$$\int_0^u V_m \sin \omega t . d(\omega t) = \omega L_s \int_0^{I_d} (di_s)$$

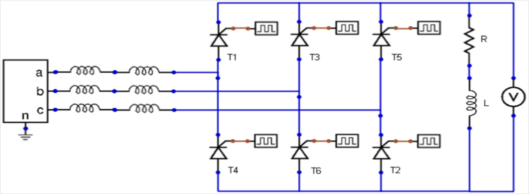
$$A_u = \int_0^u V_m \sin \omega t . d(\omega t) = \sqrt{2} V_s (1 - cosu) = \omega L_s I_d$$

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

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

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

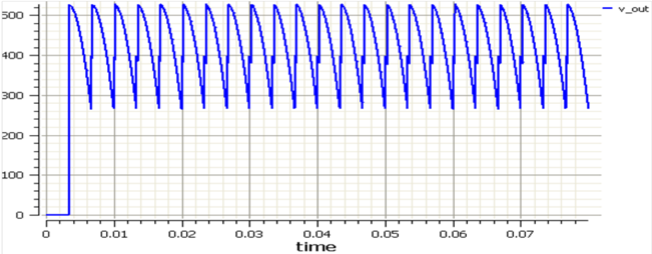
$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} cos\alpha - \frac{3\omega L_s}{\pi} I_d$$

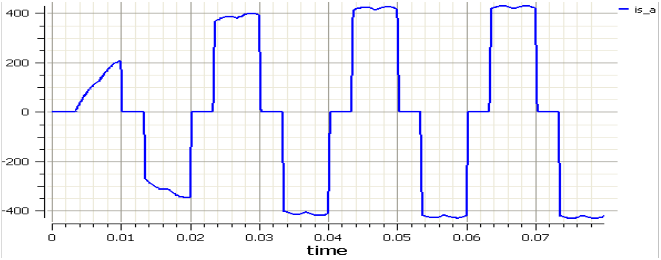
$$cos(\alpha + u) = cos\alpha - \frac{2\omega L_s}{\sqrt{2} V_{LL}} I_d$$

knowing α and I_d, u can be calculated.

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

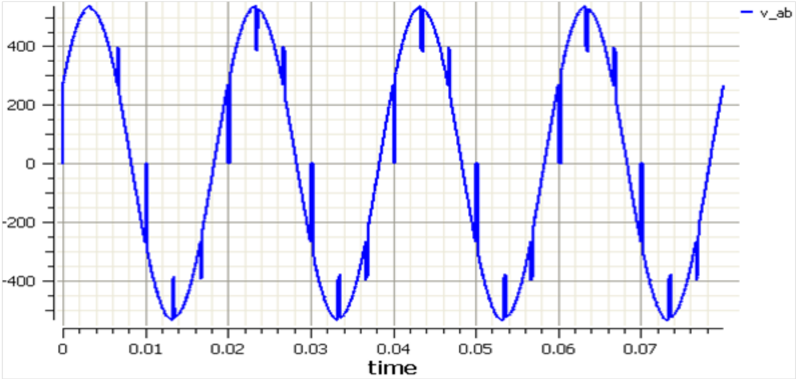
Output Voltage and Source Current



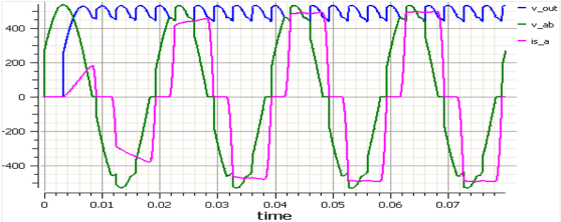


Voltage at PCC

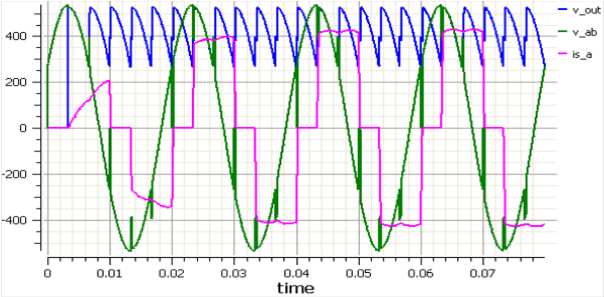
R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.1m, $\alpha = 60^0$



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

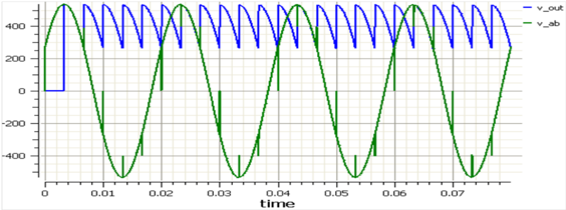


R=1.0 Ω, L=10mH, Rs=0.005 and Ls=0.1m, $\alpha = 30^0$

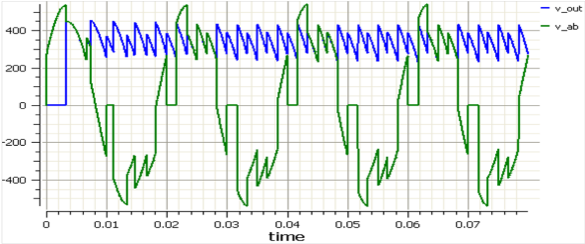


Effect of L_s on Notch Size

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.