EN 206: Power Electronics and Machines

Un-Controlled Rectifiers

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Rectifiers - AC/DC Converters

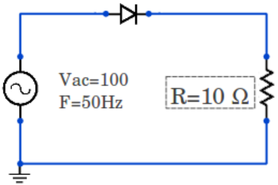
- Applications:
  - Front end for power supplies (old)
  - Battery chargers
- The power semi conductor devices are always forward biased due to dc supply voltage.
- Diode is best suited for this converter.
- Power factor is poor

Lecture Organization - Modules

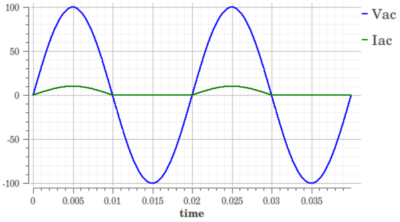
- Introduction and Power Semiconductor Switches
- Module 1: Transformers
- Module 2: AC/DC converter / Rectifier
- Module 3: DC machines and Drives
- Module 4: DC/DC converter
- Module 5: Induction Machine
- Module 6: DC/AC converter / Inverter
- Module 7: AC/AC converter / Cyclo converter
- Module 8: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

A Simple Diode Rectifier

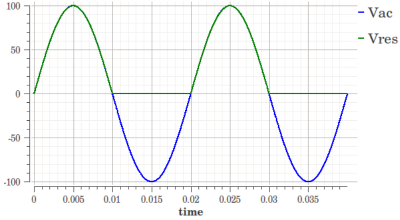
Circuit



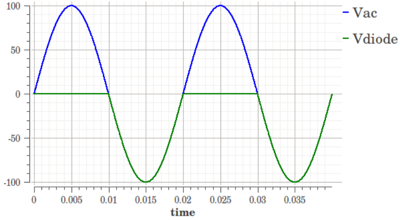
Supply Voltage and Current



Supply and Load Voltage



Supply and Diode Voltage



Definitions

- Average value (DC) of function, F(t), is given by

$$F_{avg} = \frac{1}{T}\int_0^T f(t)dt$$

- RMS value of function, F(t), is given by

$$F_{rms} = \sqrt{\frac{1}{T}\int_0^T f^2(t)dt}$$

- Form factor, $F_{FF} = \frac{F_{rms}}{F_{avg}}$
- Ripple factor,

$$F_{ripple} = \frac{\sqrt{F_{rms}^2 - F_{avg}^2}}{F_{avg}} = \sqrt{F_{FF}^2 - 1}$$

Analysis

Average value of output voltage:

$$V_o = \frac{1}{T}\int_0^T V_m Sin(\omega t) dt = \left[-\frac{V_m}{\omega T} Cos(\omega t) \right]_0^{T/2} = \frac{V_m}{\pi}$$

RMS value of output voltage:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T (V_m Sin\omega t)^2 dt} = \frac{V_m}{2}$$

Form Factor of output voltage:

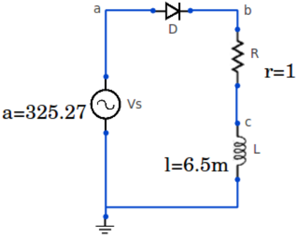
$$FF = \frac{V_o}{V_{rms}} = \frac{2}{\pi}$$

Ripple Factor of output voltage:

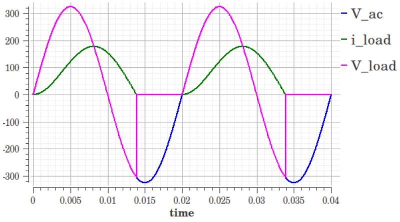
$$RF = \sqrt{(\frac{2}{\pi})^2 - 1}$$

Half Wave Rectifier - RL Load

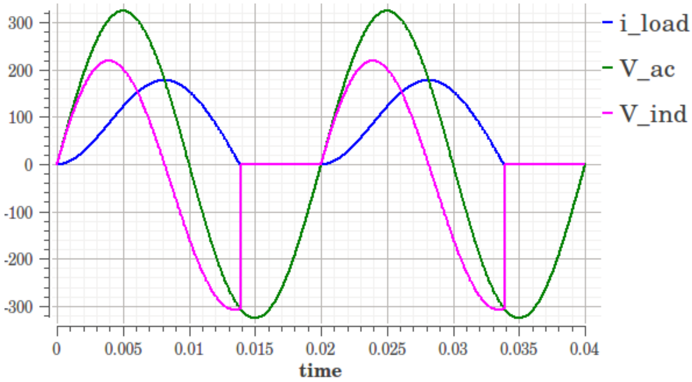
Circuit



Supply voltage, load current and voltage



- At t=0.01s, supply voltage moves from positive to negative half cycle.
- The load current is positive and cannot change instantaneously and hence voltage continues to follow till the inductor current becomes zero. Load voltage follows supply voltage.
- Once the load current (i_{load})reaches zero, the diode is reverse biased and hence opens the circuit till it is forward biased.


300
200
100
0
-100
-200
-300
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
time
i_load
V_ac
V_ind

Analysis

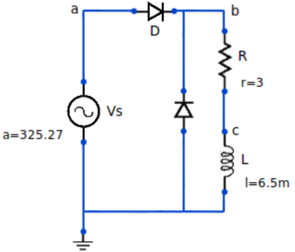
- Because of inductive load, the current flows in the circuit even when V_ac is negative.
- The total period for which the diode is conducting is termed as 'β'
- Average value of output voltage:

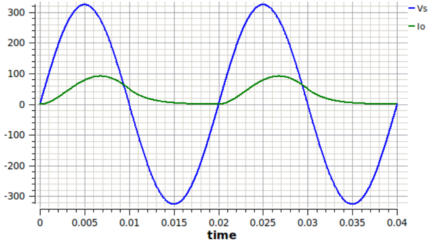
$$V_o = \frac{1}{2\pi}\int_0^{\beta} V_m Sin(\theta)d\theta = \left[-\frac{V_m}{2\pi}Cos(\theta)\right]_0^{\beta} = \frac{V_m}{2\pi}(1 - cos\beta)$$

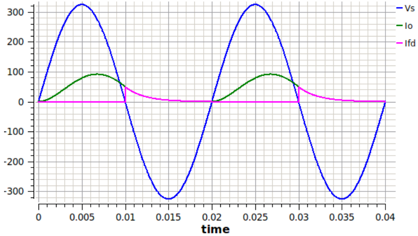
- RMS value of output voltage:

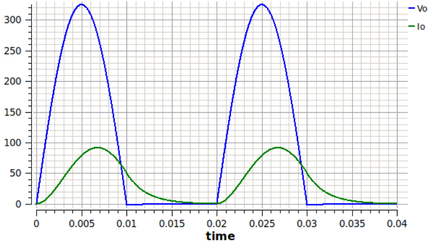
$$V_{rms} = V_m\sqrt{\frac{2\beta - cos\beta}{2\pi}}$$

Effect of Freewheeling diode





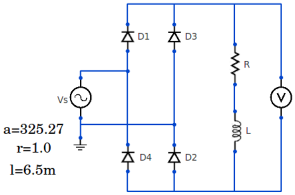


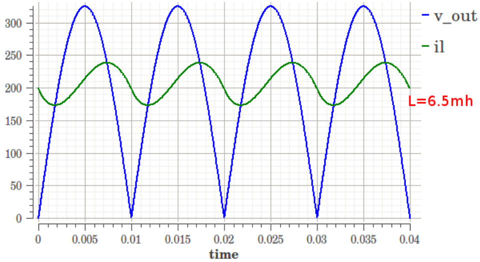


Comparison SPHWR- with R and RL Load

	R-Load	RL-Load
V_{avg}	$\frac{V_m}{\pi}$	$\frac{V_m}{\pi}(\frac{1-cos\beta}{2})$
V_{rms}	$\frac{V_m}{2}$	$V_m\sqrt{\frac{2\beta-cos\beta}{2\pi}}$
Ripple Factor	$\frac{1}{2}\sqrt{\pi^2-4}$	$\sqrt{\frac{\pi(2\beta-sin2\beta)}{2(1-cos\beta)^2}-1}$

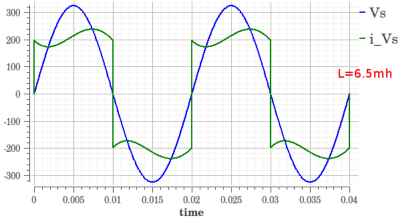
Single Phase Full Bridge Rectifier -RL Load

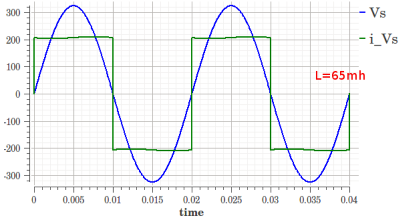


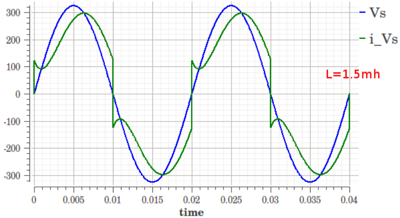


- The output voltage is positive in both positive and negative half cycles on input supply.
- The diodes (D1,D2) and (D3,D4) conduct in pairs.
- The load current is continuous.
- By increasing the value of inductance in the load, the ripple in load current is reduced ensuring a constant dc curent at the load.

Effect of inductance on supply current







- If the load on the DC side is large (inductive), then the input current drawn by the rectifier is square wave.
- By applying fourier transform, the harmonic components of the input current waveform can be computed.

Definitions

- Crest Factor, $CF = \frac{F_{peak}}{F_{rms}}$
- Distortion Factor, $DF = \frac{F_1}{F_{rms}}$
- Fundamental: It is the rms value of sinusoidal component in the waveform with frequency 1/T.
- Harmonic: It is the rms value of sinusoidal component in the waveform with frequency K/T
- Total Harmonic Distortion (THD): It is a measure of distortion of the waveform from its fundamental
- $THD = \sqrt{\sum(\frac{F_K}{F_1}^2)} = \frac{\sqrt{1-DF^2}}{DF}$

Definitions

- Displacement Factor: If ϕ_1 is the phase angle between fundamental component of voltage and current then displacement factor is given by $DPF = cos(\phi)$
- Power factor is defined as ratio of real power to apparent power and is given by $PF = \frac{V_1 I_1 cos\phi}{V_{rms} I_{rms}}$
- If we assume that the input voltage to the rectifier is sinusoidal, then $V_1 = V_{rms}$, therefore, $PF = \frac{I_1 cos\phi}{I_{rms}}$, $PF = DPF \times DF$
- Power factor is product of displacement factor and distortion factor.
- TUF is a measure of how effectively the transformer being utilized. It is ration of average output power to product of input rms voltage and current.

Comparison HW, full wave rectifiers

Parameters	Half-wave	Full wave	
		Centre -tap	Bridge
DC output voltage	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
RMS output voltage	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$
Ripple factor	1.211	0.482	0.482
Peak Inverse Voltage	V_m	$2V_m$	V_m
TUF	0.2865	0.672	0.8106

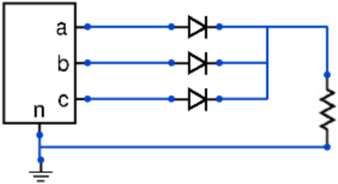
Three phase Rectifier

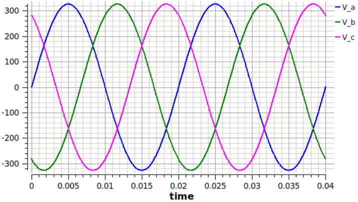
- Higher dc output voltage, better TUF
- Better input power factor
- Less ripple content in the output current hence better load performance
- Lower filter size because of high ripple frequency.

Classification:

- Three phase half wave rectifier
- Three phase mid-point 6-pulse rectifier
- Three phase bridge rectifier
- Three phase 12-pulse rectifier

Three phase Half Wave Rectifier - R Load



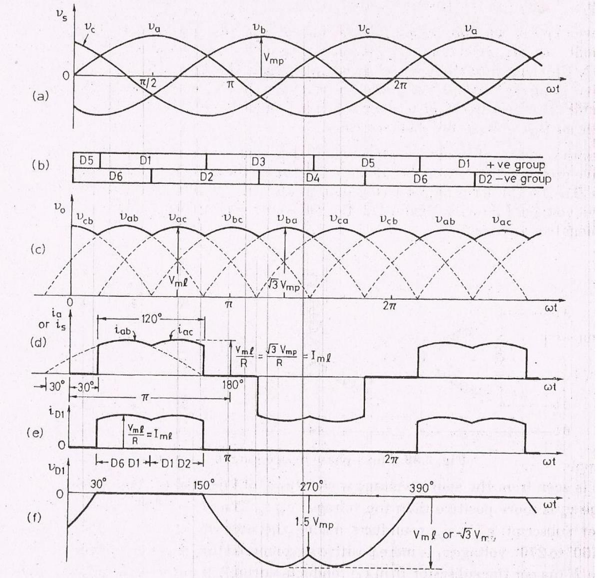


- Cathodes of three diodes are connected to the load
- The rectifier element connected to the line at the highest positive instantaneous voltage can only conduct.
- D1 conduct from $\omega t = 30^o$ to $\omega t = 150^o$ as it senses most positive voltage, D2 conduct from $\omega t = 150^o$ to $\omega t = 270^o$, D1 conduct from $\omega t = 270^o$ to $\omega t = 390^o$.
- Average output voltage $V_o = \frac{3}{2\pi} \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} V_{mp} sin\omega t d(\omega t) = \frac{3\sqrt{3}}{2\pi} V_{mp}$
- $V_{rms} = 0.84 V_{mp}$, ripple factor=0.1826, TUF=0.6644.

Three phase diode bridge rectifier - R Load

- Upper diodes constitute the positive group diodes (D1, D3, D5)
- Lower diodes constitute the positive group diodes (D2, D4, D6)
- Positive group of diodes conduct when these have the most positive anode.
- Negative group of diodes conduct when these have the most negative anode.
- D1(30-150), D3(150-270), D5(270-390), D2(90-210), D4(210-330), D6(330-450). All angles are in degrees.

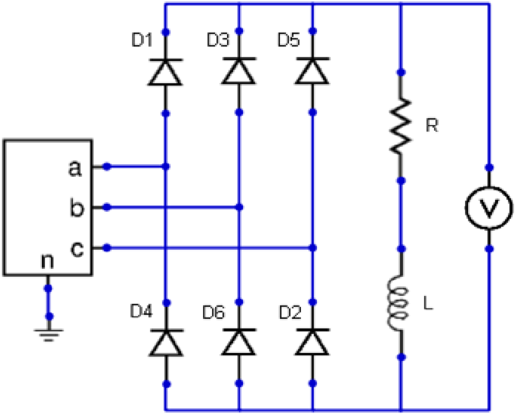
Three phase diode bridge rectifier - R Load



Three phase diode bridge rectifier - R Load

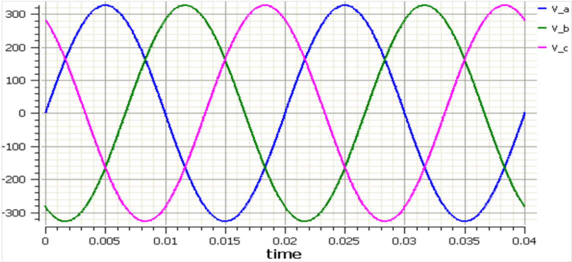
- Average o/p voltage $V_o = \frac{3}{\pi} \int_{\frac{\pi}{6}}^{\frac{\pi}{2}} V_{ml} sin(\omega t + 30^o) d(\omega t) = \frac{3V_{ml}}{\pi}$
- $V_o = \frac{3V_{ml}}{\pi} = \frac{3\sqrt{2}V_{LL}}{\pi} = \frac{3\sqrt{6}V_p}{\pi}$
- $V_{rms} = = 0.9558 V_{ml}$, ripple factor = 0.0427
- Transformer utilization factor (TUF) = 0.9541

Three phase Diode Bridge Rectifier - RL Load

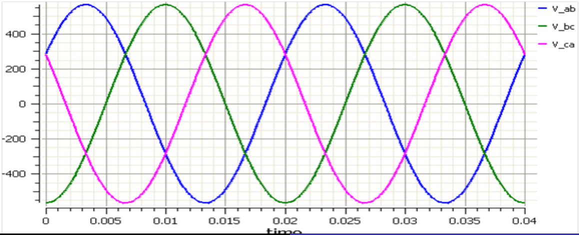


Three phase Diode Bridge Rectifier - RL Load

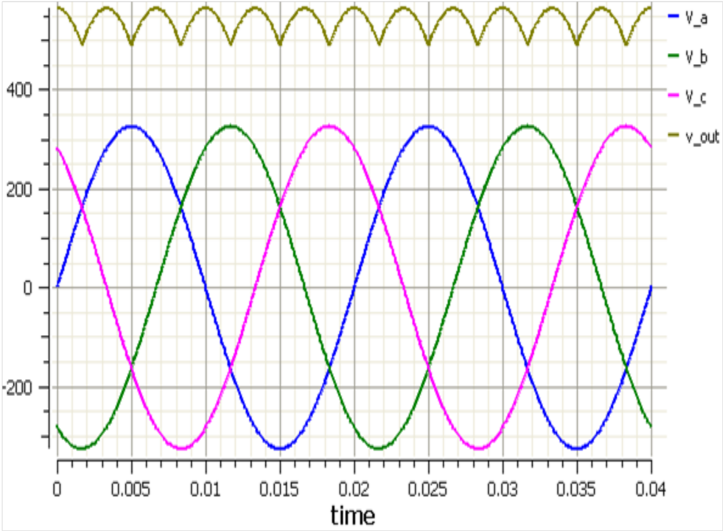
Supply Voltage(Phase)



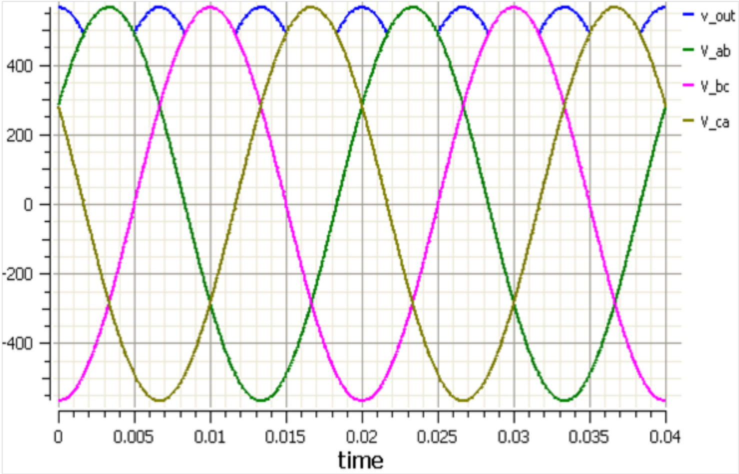
Supply Voltage(Line-Line)



Output Voltage and Input phase voltage

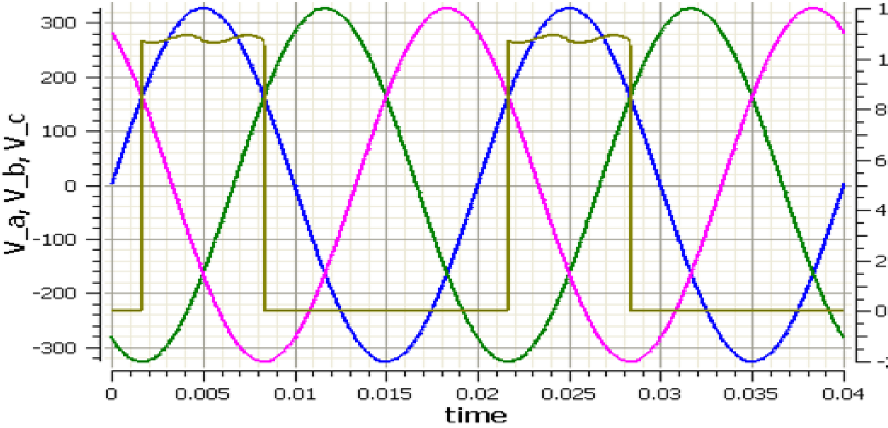


Output Voltage and Input phase voltage

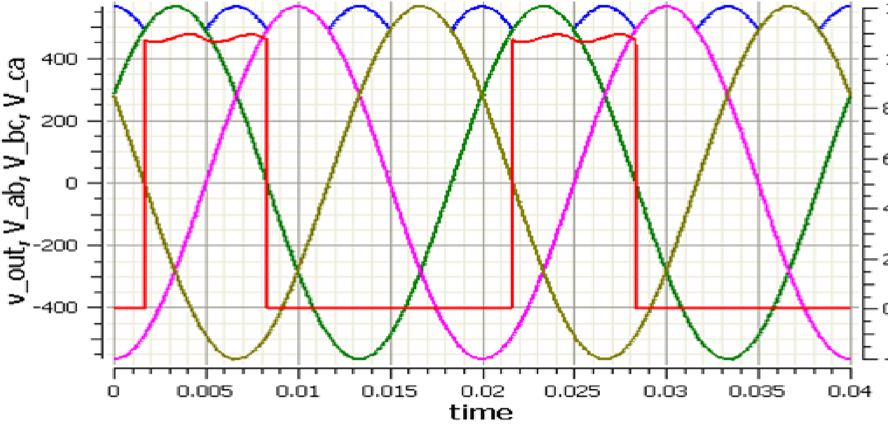


- Conduction Sequence: A(D1), B(D3), C(D5)
- AB-AC, BC-BA, CA-CB

Phase Voltage and Diode Current

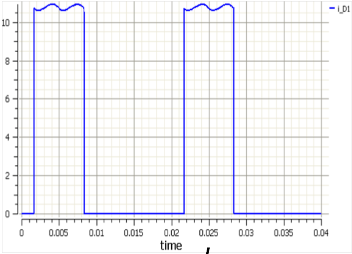


Line Voltage and Diode Current

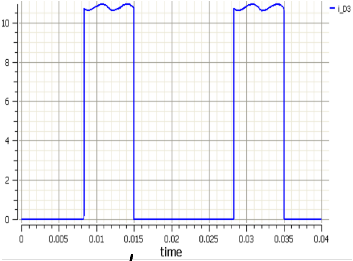


Diode and Source Current

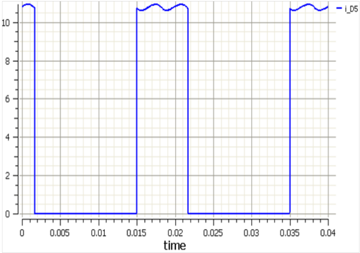
I_{D1}



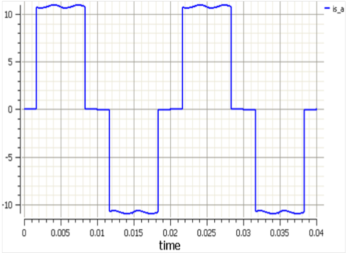
I_{D2}



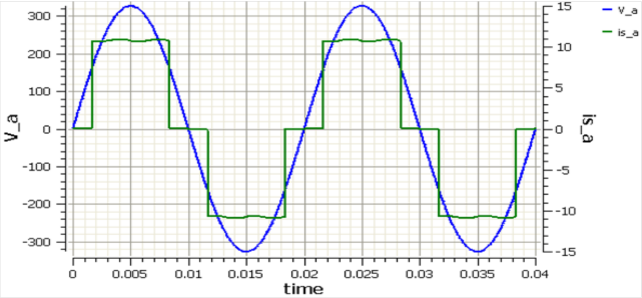
I_{D3}



I_{sa}

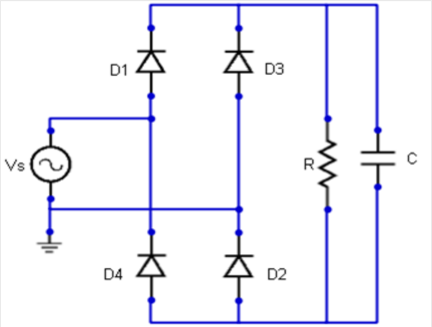


Input Voltage and Source Current



- Assume that peak current is flat in nature, $I_{rms} = I_o\sqrt{\frac{2}{3}}$
- $b_1 = \frac{2\sqrt{3}}{\pi} I_o$ (Using Fourier Transforms)
- What happens to power factor assuming the supply is pure sinusoidal?
- Distortion factor= 0.9549, Total Harmonic Distortion =31.08%
- Power Factor= $DF \times DPF$

Classical Diode Bridge Rectifier



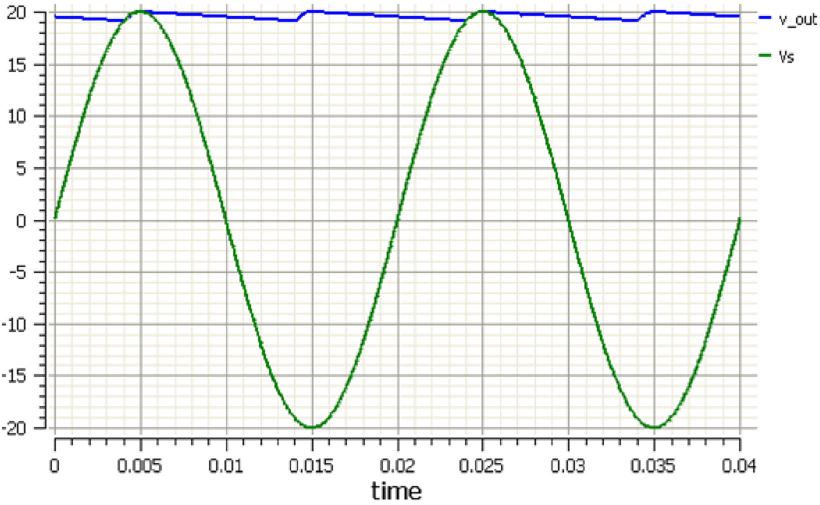
- Simplicity in circuit and hence used in most of the applications as a front end.
- Possible to have flat dc voltage but generates peaky input current
- These converters have led to poor power factor and major problem to utility(current distortion)

Classical Diode Bridge Rectifier

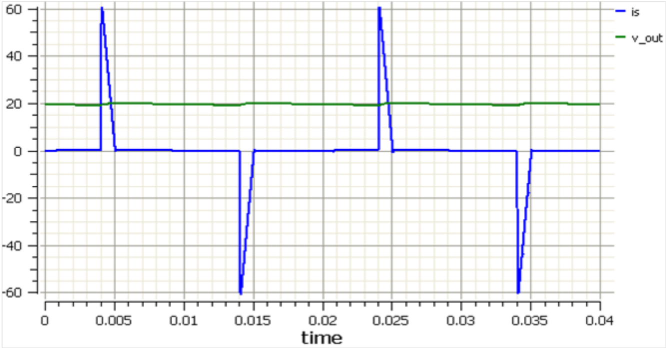
- When diode pair is ON, $V_{out} = |V_{in}|$.
- When the diode is OFF, V_{out} decreases exponentially depending on the time constant of RC circuit.
- Diode is OFF when $I_R + I_C = 0$, i.e., when capacitive current and resistive current balance out.
- The decay will continue as long as diodes are reverse biased, i.e., $|V_{in}| < V_{out}$
- To have low ripple, RC time constant should be much greater than the half of the input waveform period.

Classical Diode Bridge Rectifier

System: $V_s = 20sin(\omega t)$, R=6,C=0.33000uF



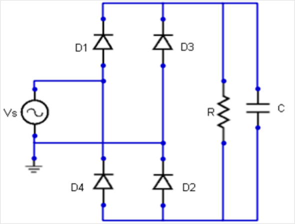
Classical Diode Bridge Rectifier

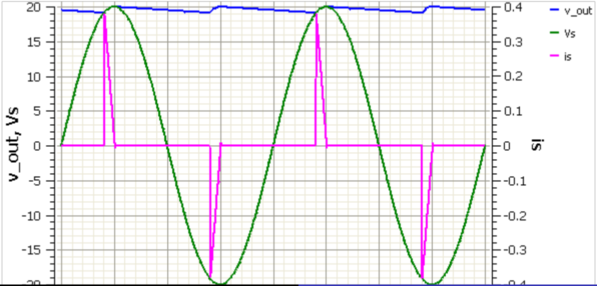


- Output is directly linked with peak of input and hence line regulation is poor. To achieve good load regulation large capacitor is required.
- Transformer provides isolation between input and output, but average value is restricted once transformer is selected.

Diode Bridge Rectifier - RC Load

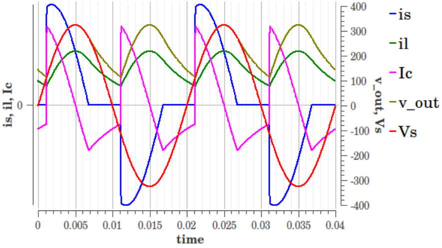
$V_{s,peak} = 20$, F=50 Hz, $r = 1k\Omega$, c=200u, $r_{on} = 0.1m\Omega$, $r_{off} = 1M\Omega$





Diode Bridge Rectifier - RC Load

$V_{s,peak} = 325$, F=50 Hz, $r = 1k\Omega$, c=5u.



- When diode is conducting, capacitor current leads supply voltage.
- When capacitor current is zero, $I_R = I_s$. Capacitor current slowly increases in negative direction.
- After sometime, $I_c = -I_R$, therefore supply current is zero and hence diode will stop conducting.
- Capacitor starts discharging, output voltage starts falling till diode start conducting again.

Summary

- Uncontrolled Rectifiers
  - Single phase diode rectifier with R, RL and RC loads.
  - Three phase diode rectifier with R, RL and RC loads.

  Next Class
  - AC/DC Converter - Phase Controlled 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.